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

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ABSTRACT: Seismic codes are continuously modified to incorporate the latest knowledge in structural behaviour and increased hazard or performance expectations of newly designed structures. On the other hand, many existing structures, designed to older design provisions and requirements, do not offer the same level of seismic performance as newly designed structures and it is desirable to improve these in-place. Fluid viscous dampers can add energy dissipation without requiring major structural modification. However, their addition can lead to increases in the maximum base shear and column axial forces in non-linear structures. These increases in demand would likely require strengthening of the columns and the foundations, thus increasing cost and reducing the ease and the benefits of this approach. The 2-4configuration 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 the peak base shear loads compared to a conventional viscous damper.

The paper studies the seismic performance of a 1/2 scale, two storey steel frame building retrofitted with passive 2-4 D3 dampers and 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 a unique retrofit option that would not require columns and the foundations to be strengthening.

1 INTRODUCTION

When not designed to remain elastic under a severe seismic event, many if not most existing structures, as well as new structures, would 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, leading to lower damage and repairable structures.

Fluid viscous damping adds energy dissipation to a structural system in the lateral direction 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 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 with a standard viscous device subject to sinusoidal loading 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 (in parallel) 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 on a resettable stiffness air damper.

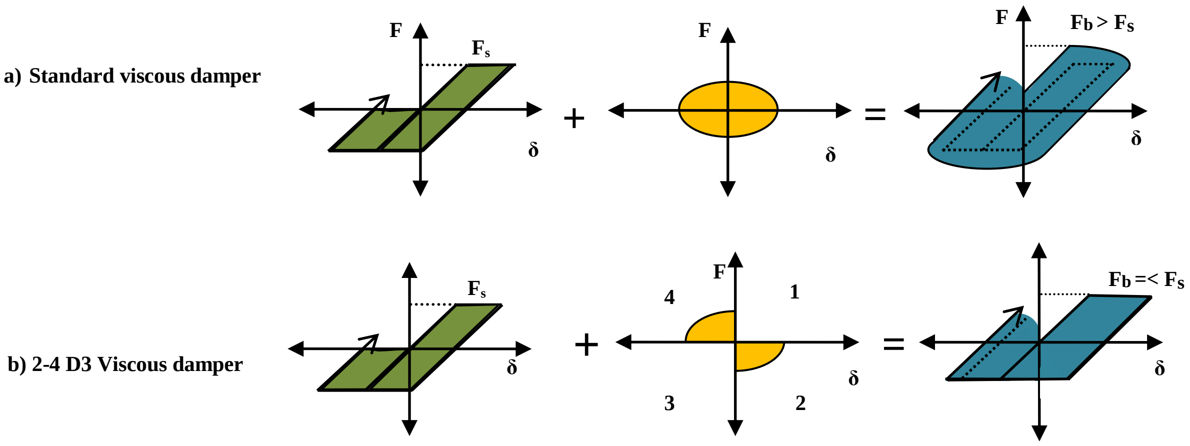


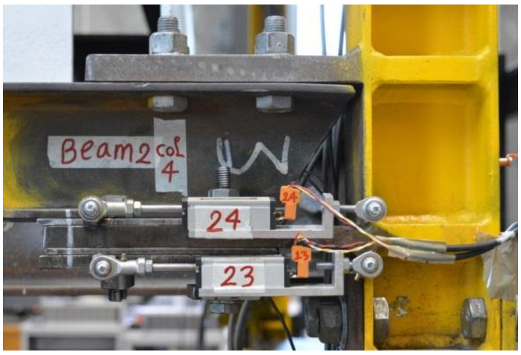
Figure 1. Schematic hysteresis for a standard viscous damper and a 2-4 D3 device, F_b = total base shear, F_S = base shear for undamped structure. $F_b > F_S$ indicates an increase due to the additional damping.

In this study, the structural performance of a 1/2 scale, 13 tonnes, twostorey 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 under design level earthquake event (1-in-500 year earthquake shaking) based in Wellington, with Z=0.4 and soil type C.

Asymmetric friction connections AFC was developed over a number of years by Clifton (2005) and has been further developed by MacRae et al. (2010). The AFC is designed to rotate about the top flange plate and slide only in the bottom flange plate, which minimises the interaction with the overlaying floor slab and the effects of beam elongation. The test specimen is composed of two steel frames with 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.



(b) Beam column joints

(a) Constructed test building frame **(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 local earthquake events and the NGA database(Chiou et al. 2008), and are listed in Table 2

Table 1. Properties of the two-storey 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 Section	100 UC 14.8
Beam Section	100 UC 14.8

Table 2. Input motions

Earthquake event	Station Name	Year	Scale (%)	PGA (g)
Northridge, US	Sylmar	1994	90	0.44
Kobe, Japan	KJM	1995	100	1.02
Christchurch, NZ	CCCC	Feb. 2011	60	0.49
Christchurch, NZ	REHS	Feb. 2011	50	0.40
Bam, Iran	Bam	2003	50	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 as a diagonal bracing system at the 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 the force-displacement hysteresis 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.

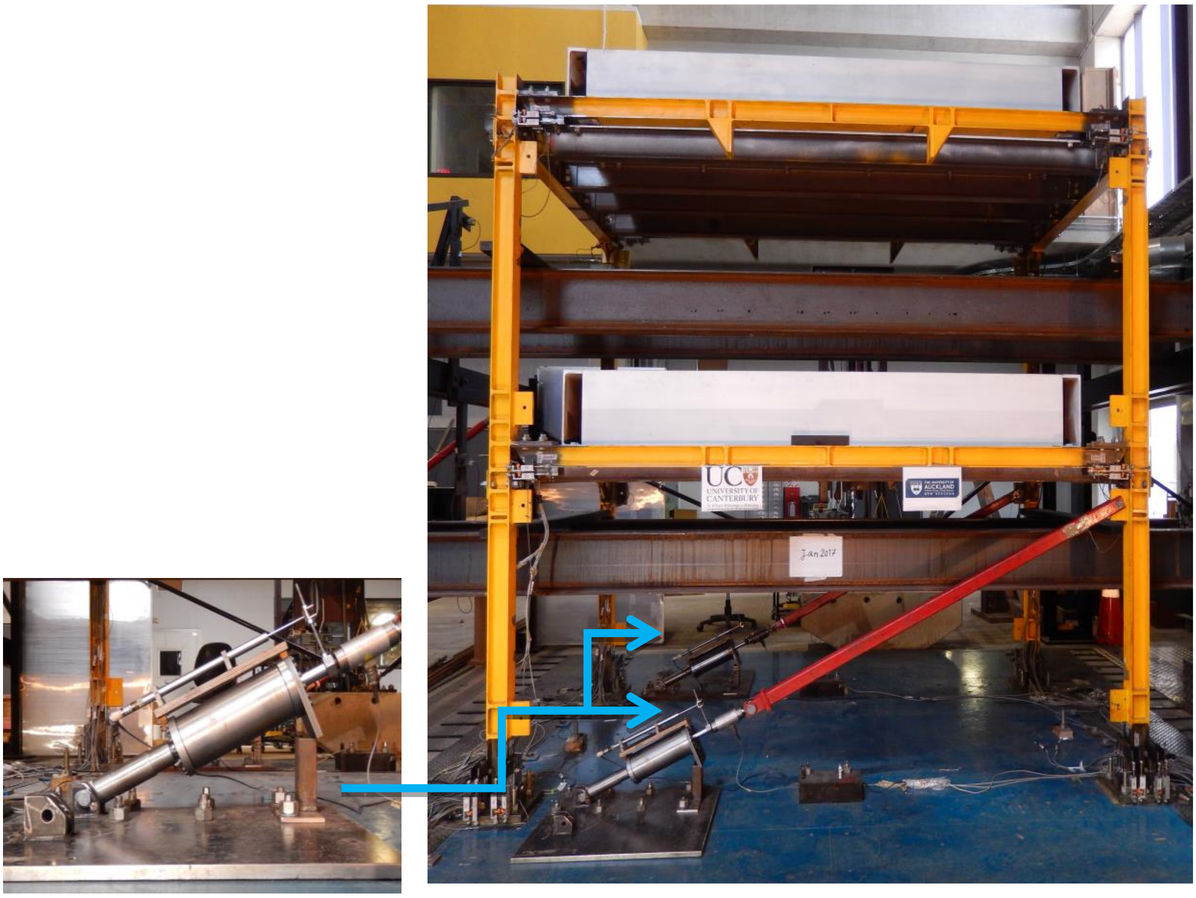


Figure 3. Constructed test building frame was retrofitted with two 2-4 D3 viscous damper prototypes.

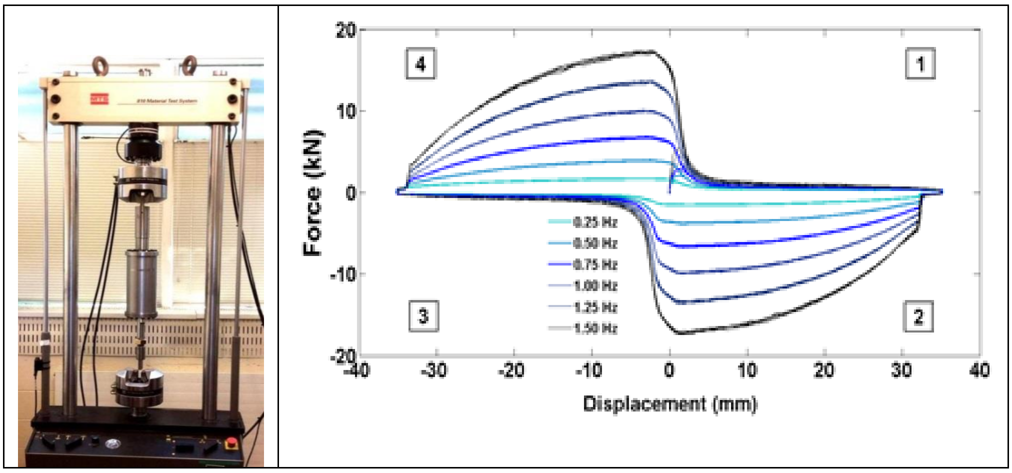


Figure 4. Force-displacement of the 2-4 D3 device when providing damping force under sinusoidal input loading with different frequencies and an input amplitude 35 mm. The experimental test setup in the MTS-810 machine (Hazaveh et al. 2016).

3 RESULTS AND DISCUSSION

Figure 5a 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 retrofit this structure and reduce the maximum drift, the 2-4 configuration of D3 viscous damper was used.

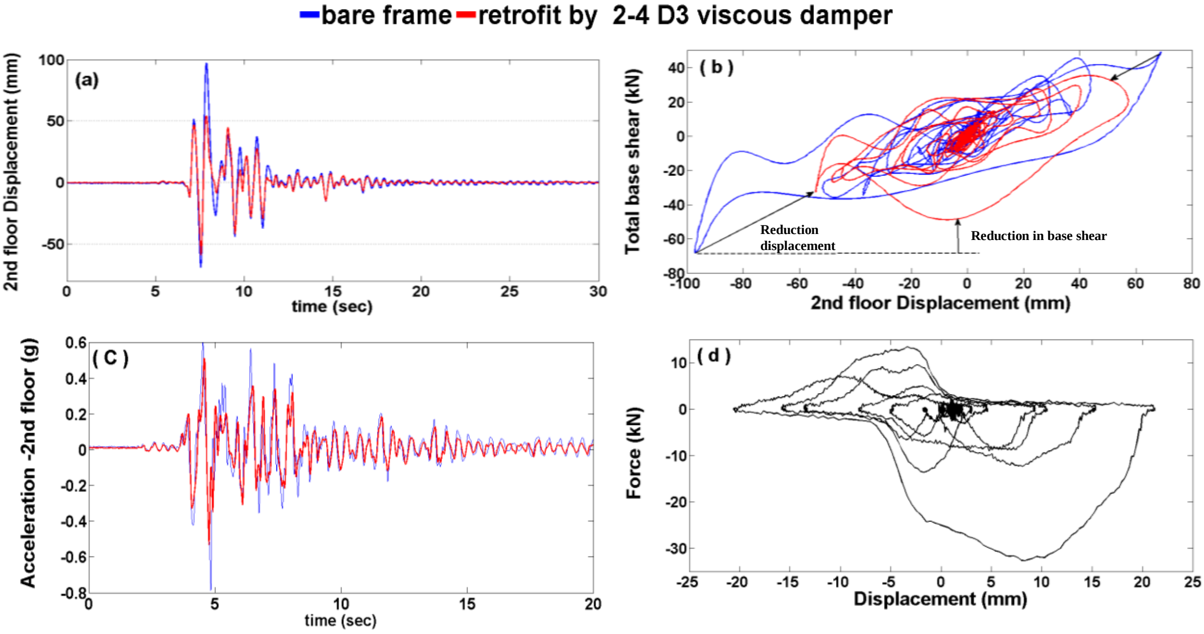


Figure 5. Structural response under Kobe earthquake before and after retrofit, (a) Displacement of second floor (b) hysteresis loop of the structure, (c) acceleration of second floor (d) force-displacement of the 2-4 D3 viscous damper.

After retrofitting the structure with 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 Figures 5b-c. In particular, Figure 5b 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 5d. 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 5c) are also reduced. Hence, there is no additional foundation demand, structural displacement demand or damage 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 dampers under five earthquake ground motions. Drift of second floor for the bare frame is about 4.58%, 3.47%, and 3.3% under CCCC, Northridge and REHS earthquakes, respectively. These are all higher than the design drift (2.5%). The structure is retrofitted with the 2-4 viscous dampers and the maximum drift is reduced between 27% and 47% to 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 2^{nd} floor [1]	Base shear (kN) [2]	Drift 2^{nd} 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	47.5%	36.8%
Northridge	3.47%	62.38	2.51%	44.29	27.6%	29.0%
Kobe	3.04%	63.43	1.83%	46.13	39.9%	27.3%
Bam	2.44%	55.39	1.57%	46.40	35.6%	16.2%
Christchurch-REHS	3.30%	54.15	2.12%	49.21	35.9%	9.1%

It should be noted that there are two accelerometers in each floor to measure the acceleration. Figure 4 shows that the maximum acceleration of the 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 also 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 (%)
	2^{nd} floor(%) [1]	2^{nd} floor(%) [2]	([1] - [2]) / [1]
Christchurch-CCCC	0.93	0.73	21.7%
Northridge	0.71	0.51	27.9%
Kobe	0.99	0.56	43.8%
Bam	0.93	0.49	47.8%
Christchurch-REHS	1.33	0.66	50.5%

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 a half scale two story steel structure under different earthquake ground motions. The results show that retrofitting the structure with the 2-4 D3 viscous damper could reduce the displacement and interstorey 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.

5 ACKNOWLEDGEMENT

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