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Structural strengthening with displacement and direction dependent (D3) viscous dampers using aftershocks – shaking table study

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ABSTRACT

Buildings can have post-earthquake residual deformations. Aftershocks or subsequent earthquakes can induce further displacements, increasing the probability of collapse and affecting nearby buildings. In particular, the likelihood of increased displacement in the direction of residual displacements may exceed 50% due to P- Δ and other effects.

Structural modification or devices can mitigate further movement in the direction of residual displacements. However, many such devices provide resistive forces in both directions, which can negate their benefits. There is thus a need for smart devices, which can modify their response behaviour during an earthquake to manage the risks due to residual displacements and further improve structural performance during aftershocks.

This paper presents shake table testing of a 1/2 scale, two-story steel frame building with an initial 0.7% residual deformation from a prior earthquake. This structure was strengthened using two passive D3 dampers, which resist only motion away from the desired central structural position. The D3 viscous damper has an amount of out of phase action based on the residual deformation changing the neutral position of the structure, but not the device. This out of phase action can passively change during an earthquake to ameliorate and help restore structure recanting. The overall results show the simultaneous reduction of peak and residual drifts are available with the D3 viscous damper in the main shock and subsequent aftershock ground motions. The proposed device offers the adaptability of semi-active devices in an entirely passive device design, providing a unique retrofit opportunity.

1 INTRODUCTION

If they have a positive post-elastic stiffness to elastic stiffness ratio, structures with residual deformation tend to yield toward the origin, and it tends to increase displacements in one direction if they have a negative post-elastic to elastic stiffness ratio (MacRae, 1994). Rad et al. (2015a) displayed that 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. 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. (2015-2018) introduced and tested the Direction Displacement Dependent (D3) viscous damper. This device could provide damping force in any desirable quadrant. Therefore, it could be a suitable device to retrofit these kind of structures, providing selective damping forces during different phases of response to support straightening of structures with residual displacements from prior earthquakes.

This study illustrates the effect of the D3 viscous damper in the retrofit of structures with post-earthquake residual deformations. Shake table testing is conducted on a half-scale two-story steel frame, under a sequence of ground motions, with the use of either conventional viscous dampers or using D3 viscous dampers, applied to the structure between the primary earthquake and the aftershock.

2 MODELLING 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 2.0 % 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 AFC connections at the column base and beam ends had design ductility of 3.0 and 6.0 respectively (Rad et al. 2019.a).

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 1. 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.

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 for the aftershock testing used a ground motion from the Kobe earthquake with $PGA=1.02$ g, with details provided in Table 2.

The Bam ground motion is the first motion applied to the structure (considered the primary earthquake motion) as it produced a large residual drift (0.7%), which was desirable to investigate methods of straightening for subsequent testing. Figure 2 shows the drift response of the structure under Bam record in three different tests. It shows that the structure produced repeatable displacement response and residual displacements within 2.0% accuracy for a straight structure subject to same record (Bam ground motion) after each run (Rad et al. 2019.b). The frame was manually returned to its initially straight position, and new bolts were inserted and tightened before each run.

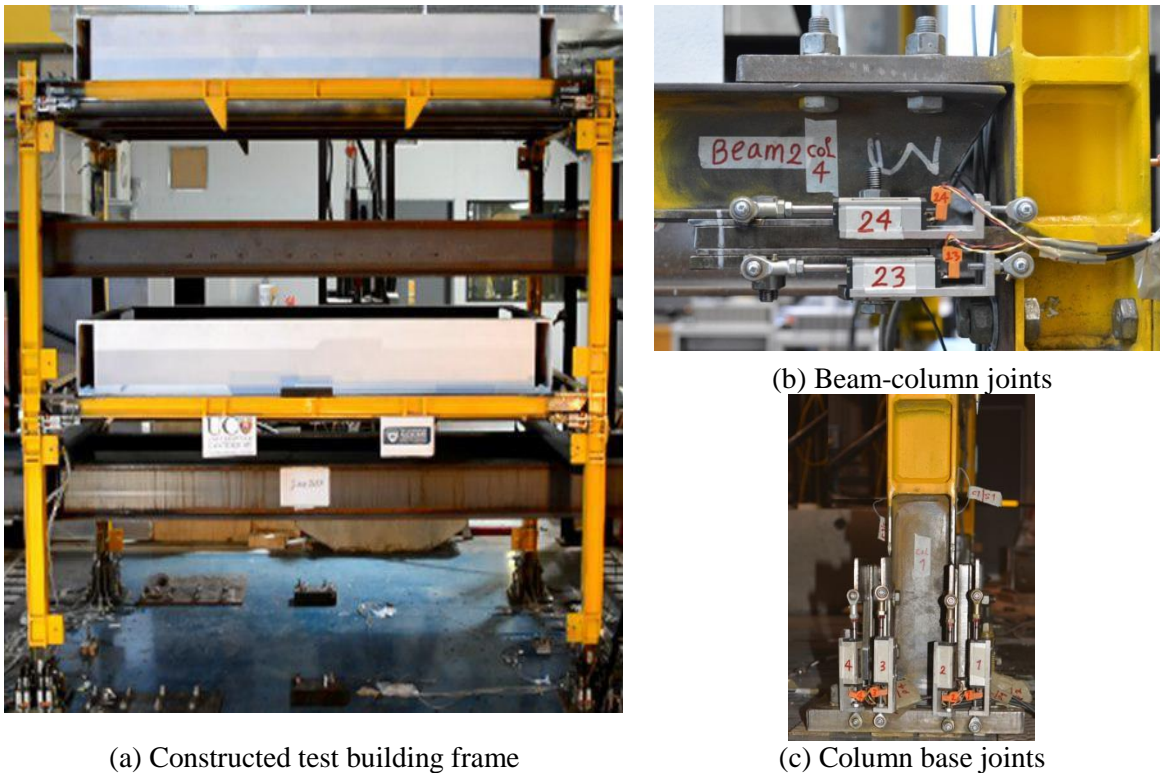


Figure 1: Test building constructed frame. Two steel frames with asymmetric friction connections (AFC) in the column base and beam-to-column joints.

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)
Kobe, Japan	KJM	1995	1.02

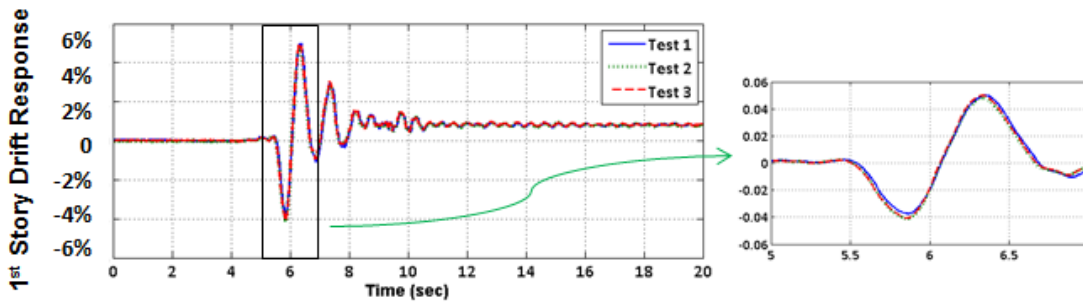


Figure 2: Consistent residual drift under repeatable shaking

To retrofit the structure and reduce the drift and residual deformation two D3 viscous dampers are added to the structure in the first floor, as shown in Figure 3. To apply the D3 device to a tilted structure with a residual drift, the dampers need to be installed offset from their normal neutral position. As such, the dampers will initially provide an asymmetric response behaviour with different damping forces in each direction. Damping forces will be provided if the structure moves further in the original out-of-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 behaviour is shown schematically in Figure 4.



Figure 3: 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).

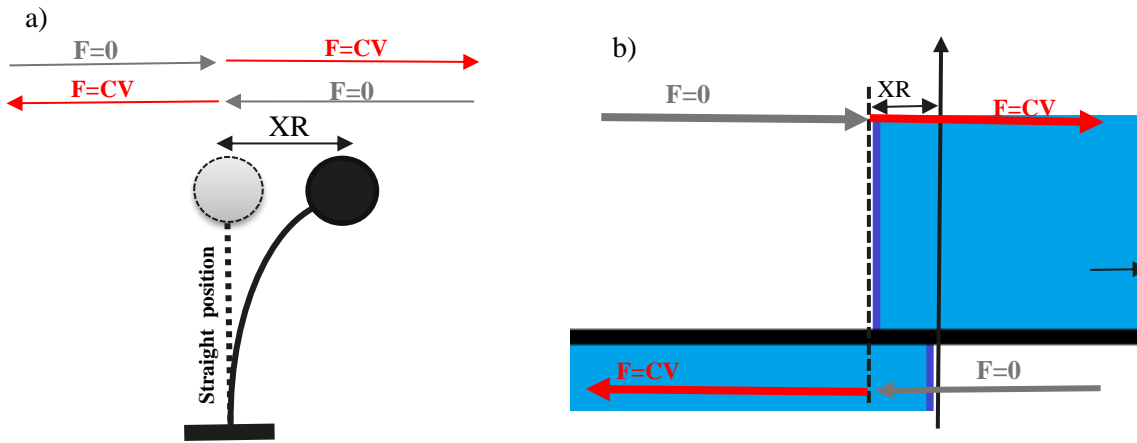


Figure 4: the desirable hysteresis loop of D3 device to retrofit of a structure with a residual deformation

3 RESULTS AND DISCUSSION

Figure 5 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.

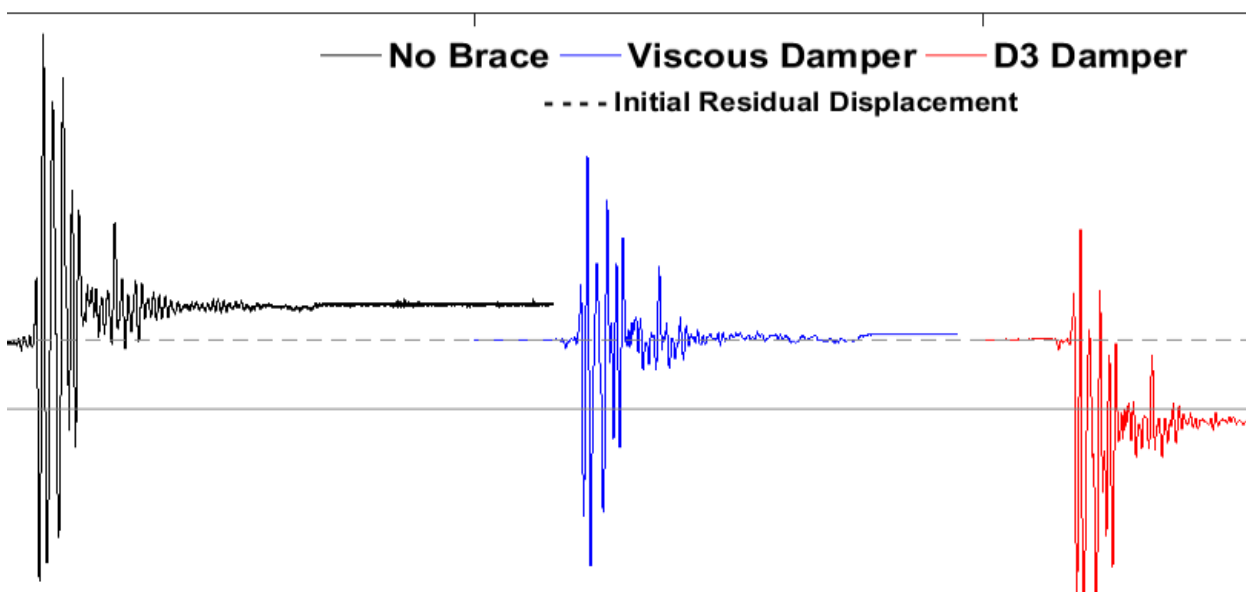


Figure 5: The drift of the structure under Kobe Earthquake a) without any brace, b) with viscous damper, c) with D3 viscous damper

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 drift 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 3: 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

Figure 6 shows the experimental hysteresis loop of a D3 device during the Kobe ground motion as a second shake (aftershock) from its initial post-event position. The zero displacement datum in Figure 6 refers to the initial displaced position with 0.7% residual drift following the Bam ground motion applied as the main shock. The D3 damper initially provides asymmetric damping from the residual displacement position to prevent further deformation in that direction, due to its offset start point relative to the damper's internal neutral position piston configuration. As such, it has not provided resistive force as the structure moves inwards towards its original neutral position. This out of phase action of the device can passively change during an earthquake, based on the level of residual displacement, to allow the structure to re-center itself during subsequent aftershocks.

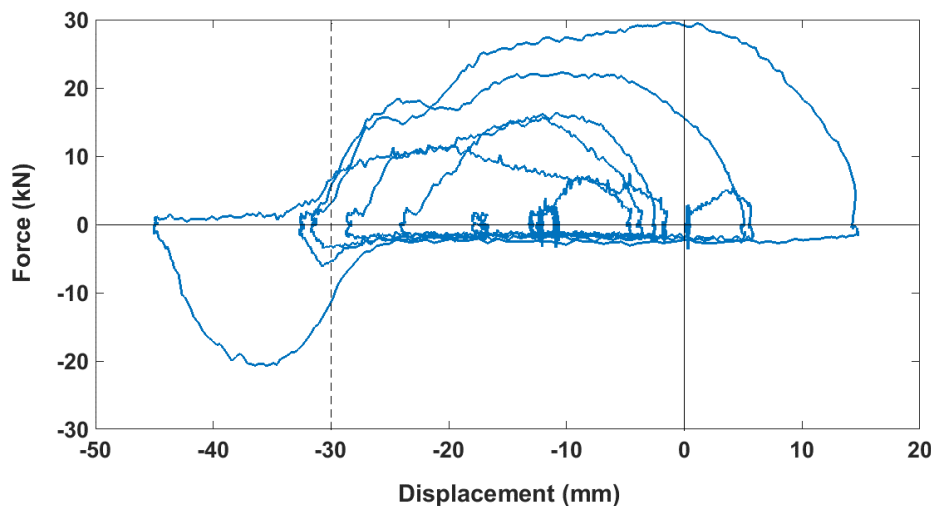


Figure 6: Force-Displacement of the D3 viscous damper under Kobe earthquake

4 CONCLUSIONS

This paper presents a novel method to straighten structures with residual displacements. To mitigate further movement in the direction of residual displacements, structural modification by means of providing viscous damping forces in the out-of-plumb direction only may be helpful. In this way, the D3 damper could have a desirable hysteresis loop. To evaluate the performance of a structure retrofitted by either the D3 viscous

damper or a conventional viscous damper, shake-table testing was conducted on a half-scale low-damage steel structure. The results showed that retrofitting with the conventional viscous dampers could reduce maximum displacements, but did not reduce the residual displacement. Conversely, the D3 viscous damper could provide the suitable hysteresis loop to simultaneously reduce both the maximum and residual displacement during aftershock. Therefore, strengthening the structure with D3 viscous devices dramatically reduce the probability of collapse or further damage and reduces the overall displacements during aftershocks or subsequent earthquakes.

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