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Experimental testing of a re-centring viscous damper with non-Newtonian damping fluid

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ABSTRACT

Hybrid damping devices combining different energy dissipation mechanisms can provide an overall response which can perform across a large range of near-fault and far-fault earthquakes with different frequency and velocity characteristics. Prior research has investigated the combination of ring-springs and viscous fluid dampers to create an overall re-centring viscous fluid damper, but only with linear force-velocity response in the viscous damper component.

Non-linear force-velocity behaviour from the use of Non-Newtonian damping fluid has several advantages over linear viscous dampers that use a standard Newtonian fluid. In most structural applications, the likely damper input velocity is relatively unknown due to uncertainty in the input ground acceleration that may be experienced at a given site. This research experimentally investigates a hybrid damper that uses re-centring ring springs with a viscous fluid damper with high viscosity silicone fluid to provide a non-linear force-velocity response.

Proof-of-concept experimental testing with sinusoidal displacement inputs are undertaken on the hybrid device as well as its individual components. Input amplitudes of *[20-30] mm* over a range of frequencies *[0.1-4] Hz* are used to create input velocities *[10-300] mm/s*. At peak speed, maximum resistive device force is *~50kN* where *~25kN* comes from the ring spring and *~25kN* from the viscous damper. A non-linear force-velocity characteristic is seen in the viscous damping component of the hybrid device, as a result of the Non-Newtonian characteristics of the silicone damping fluid. The individual components of the device are tested in addition to the hybrid device to delineate the contributions to response.

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1 INTRODUCTION

Supplemental dissipation devices play an important role in seismic structural response mitigation and thus reduce the costs associated with earthquake ground motions. (Pekcan, Itani et al. 2014) Previous research has shown the efficacy of hybrid damping in terms of reduced peak/permanent displacements obtained using a combination of ring-springs and viscous dampers (Golzar, Rodgers et al. 2018). In this device the re-centring of the mechanism depends on the stiffness of the ring-spring and the dissipative characteristics of the mechanism depends both on the viscosity of the damping fluid as well as the dissipation capacity of the ring-spring (Golzar, Rodgers et al. 2018).

This research investigates the impact of damping fluid viscosity on the damping force of the viscous device and a hybrid device. The hybrid device consists of a non-linear viscous damper to provide dissipation and a re-centring ring-spring damper to provide restoring force and moderate damping. In particular, the potential to obtain relatively large damping forces as a nonlinear function of the input velocity is considered using high-viscosity silicone oils.

2 DEVICE DESIGN

2.1 Viscous device (VD)

A viscous device with a typical configuration consisting of a fluid filled steel housing and a shaft-piston coupling along its axis is designed and manufactured, as shown in Figure 1. The piston is fixed on the shaft and divides the fluid cavity into two chambers. Shaft motion forces the fluid inside the housing to flow from one side of the piston to the other side through the orifices on the piston, imposing a resistive damping force against shaft motion. Commercial silicone oils spanning a viscosity range of *100 - 100,000* centi-Stokes (cSt) together with an axle oil with a viscosity of *140 cSt* are used as the damping oils.

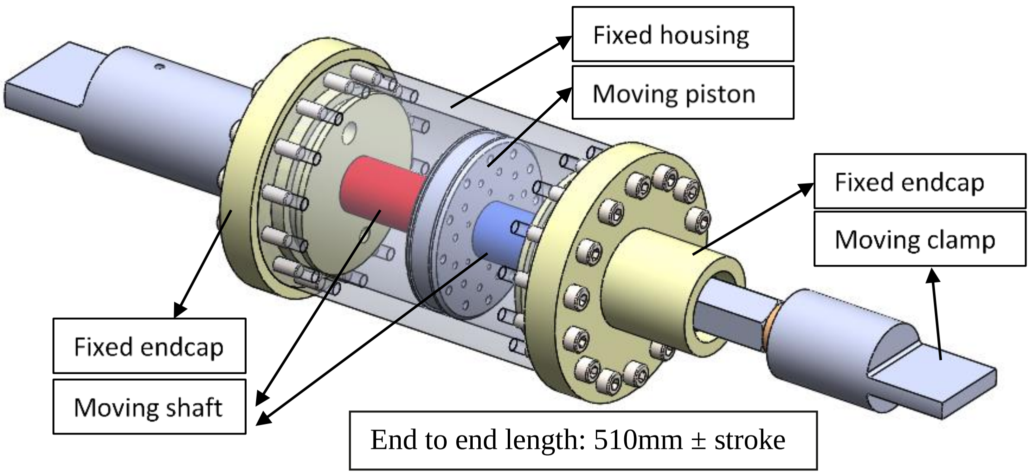

Figure 1: CAD model of the prototype viscous device

2.2 Ring-spring damper (RS)

The ring-spring is shown in Figure 2. It consists of a ring stack mounted on a shaft that also acts as an inner guide. The ring stack is enclosed inside a housing which plays the role of an outer guide. The guides ensure axial motion of the rings by constraining the rings to move axially, preventing bulging or misalignment of the spring stack. Ringfeder rings of type 1205 with a peak design force of 26kN were selected for the hybrid device. The total ring spring stack was comprised of 19 inner rings and 20 outer rings (RINGFEDER Gmbh Germany). This ring-spring damper has an overall length of 670 mm when unloaded.

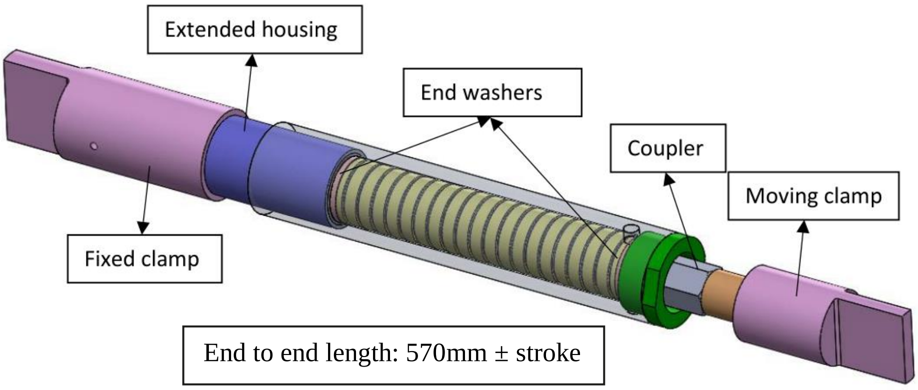

Figure 2: CAD model of the prototype ring-spring component.

2.3 Hybrid device

The hybrid device consists of a parallel combination of the ring-spring and viscous device in terms of input motion and reaction forces. To enable a parallel setup, the shafts of the two components were connected using threaded couplers. Thus, as the shaft moves within the hybrid device, the ring-spring displacement will be equal to the piston displacement inside the viscous device. The combined hybrid device is shown in Figure 3 using colour codes to show the parts of the hybrid device with equal motion.

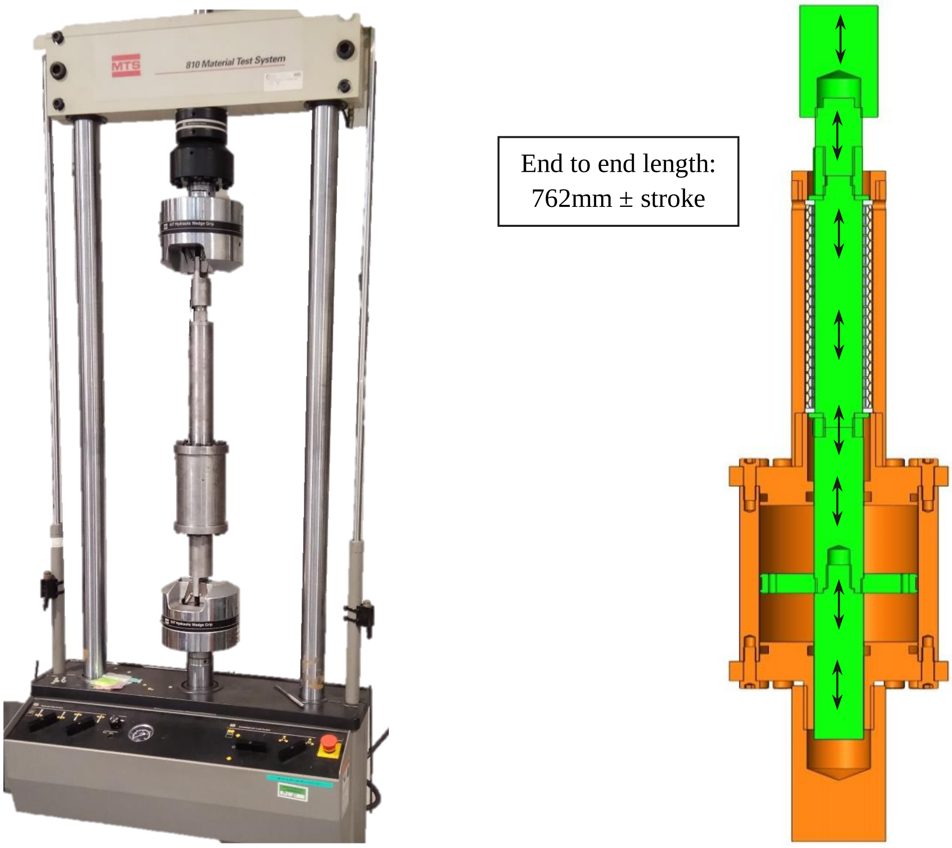

Figure 3: Left: Hybrid device setup in the MTS-810 machine; Right: Relative motion within the hybrid device; elements in green move together inputting equal displacement to the viscous device and ring-spring

3 EXPERIMENTAL ANALYSES

A series of sinusoidal input displacements are used to obtain a comprehensive range of force displacement plots, and to determine damping coefficients for the viscous device. The inputs consisted of combinations of stroke and frequency which would create peak input velocities up to ~320 mm/s. The full set of inputs is designed to calculate damping characteristics for a full range of expected velocities and amplitudes. Each test consisted of 3 complete cycles, and after every 5 tests, the device was allowed to cool so built-up heat in the damping fluid did not impact its viscosity and thus the damping characteristics.

Sinusoidal displacement inputs with equal stroke but different frequencies were used for the ring-spring tests to validate its velocity-independent behaviour. The ring-spring had 25mm available stroke capacity and a 34% pre-load applied to it before testing. The hybrid device tests are done using sinusoidal displacement inputs where the input strokes had to match the minimum available stroke for the two components of the hybrid damping device.

4 RESULTS AND DISCUSSION

Figure 4 shows force-displacement graphs for the hybrid device under cyclic testing. The combination of two device behaviours creates a unique hysteresis loop summing the forces from each of the individual components. The combination of the parallel forces create the hybrid device force. The overall hysteretic loop has a squared-off shape and offers a higher damping capacity than the ring-springs alone, as the area enclosed by the force-displacement hysteresis loop is larger.

It is worth noting that the contribution of the viscous device to the overall hybrid device force depends on the input stroke and peak input velocity. The force contribution from the viscous damper component to the overall response could range a span of zero (at very low velocities) up to close to 100% (at very high velocities) which means the overall response of the hybrid device is now both displacement (stroke) and velocity-dependent, due to the two different damping components with different inherent response mechanisms.

Figure 5 shows force-displacement graphs for 3 input parameter sets with different peak velocities and all 6 damping oils (v = *100-100,000 cSt*). The device geometry is kept constant as the damping fluid is changed, resulting in much higher response forces for the fluid with higher viscosities. Each graph in the figures shows the force-displacement plot for 3 cycles with 50 mm stroke and peak input velocities as shown.

The peak damping force occurs at the peak input velocity, which corresponds to the zero displacement position. The oils display different peak force values and force-displacement envelopes. Low viscosity silicone oils with viscosities, v = *100 - 1,000 cSt*, lead to elliptic graphs, which indicates Newtonian fluid behaviour that produces a relatively linear force-velocity damping behaviour. Conversely, the silicone fluids with higher viscosities of v = *10,000 & 100,000 cSt*, exhibit a non-Newtonian behaviour with shear-thinning that results result in semi square graphs as a result of their nonlinear force-velocity behaviour. For these oils, the damping force increases rapidly for the beginning part of the input stroke and then plateaus to a maximum value due to the drop in apparent viscosity at the higher shear rates caused by the non-Newtonian characteristics of the high viscosity silicone fluid.

Figure 6 shows the peak output damping forces for the peak input velocities, V = *[1 - 320] mm/s*. Each point on the graph corresponds to a single test on the viscous device with 3 cycles of sinusoidal displacement input. The damping force increases for higher velocities as expected. However, this increase is not entirely linear for all the damping fluids. The viscous device with silicone oil possesses a more nonlinear force-velocity trend compared to the results of the previous research that used Newtonian fluids.

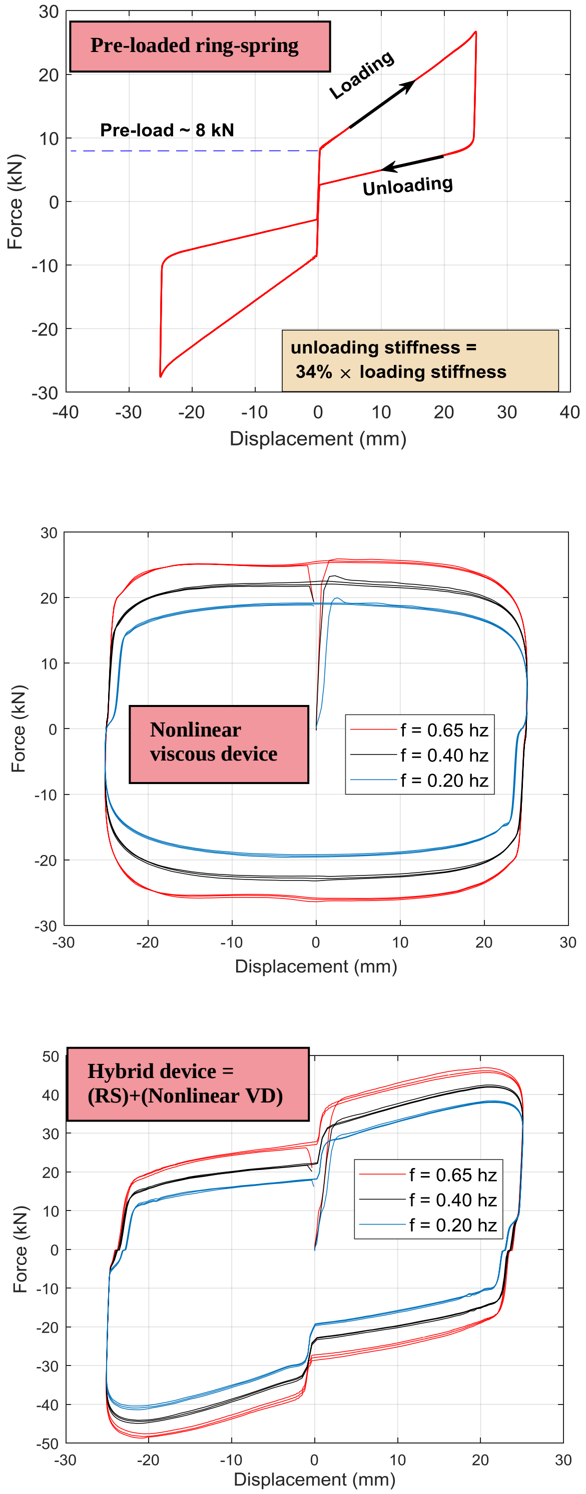

Figure 4: Force displacement graphs for the ring-spring, the non-linear viscous device (using 100,000 cSt silicone fluid), and the hybrid device, s = 25 mm, pre-load = 34%

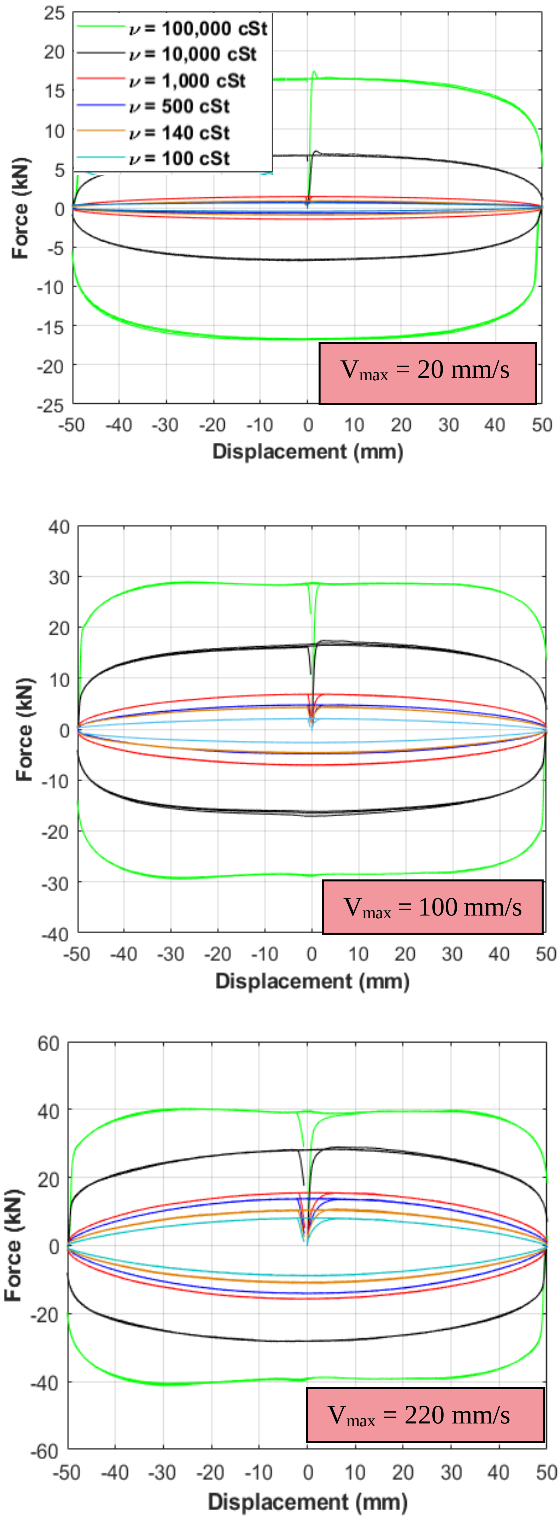

Figure 5: Force displacement graphs for the viscous device (linear and nonlinear), s = 50 mm

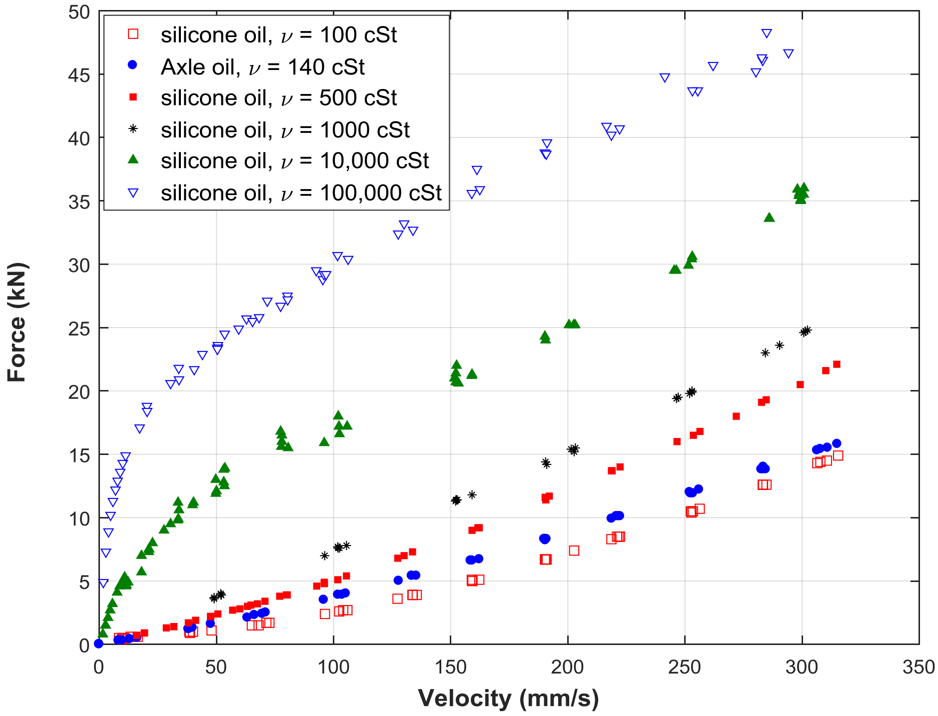

Figure 6: Force velocity graphs for viscous device with different damping oils (6 open orifices on the piston)

5 CONCLUSIONS

A pre-loaded ring-spring damper, a nonlinear viscous device with 6 different damping oils, and a hybrid device was experimentally validated. The damping oils covered a range of viscosities *[100 – 100,000] cSt* and produced resistive forces up to ~50 kN in the viscous device. The overall outcomes show:

- The viscous device provides consistent rate-dependent dissipative behaviour.
- The ring-spring provides a consistent velocity independent, flag-shaped behaviour offering re-centring with a level of added dissipation proportional to displacement.
- The hybrid device provides a parallel combination of displacement and force outputs of the individual components with no loss of efficiency in the hybrid device load transfer.
- The force-displacement envelope of the device for viscosities [100 – 1,000] cSt was elliptic indicating largely linear damping response from Newtonian damping fluids.
- The force-displacement envelope of the device for higher viscosities [10,000 – 100,000] cSt exhibited a slightly "squared-off" hysteresis loop from the non-Newtonian fluid characteristics.

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