Testing of Lead Extrusion Damping Devices Undergoing Representative Earthquake Velocities

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ABSTRACT: In recent years, significant research has been undertaken into the development of lead-extrusion damping technology. The high force-to-volume (HF2V) devices developed at the University of Canterbury have been the subject of much of this research. However, while these devices have undergone a limited range of velocity testing, limitations in test equipment has meant that they have never been tested at representative earthquake velocities. Such testing is important as the peak resistive force provided by the dampers under large velocity spikes is an important design input that must be known for structural applications.

This manuscript presents the high-speed testing of HF2V devices with quasi-static force capacities of 250-300kN. These devices have been subjected to peak input velocities of approximately 200mm/s, producing peak resistive forces of approximately 350kN. The devices show stable hysteretic performance, with slight force reduction during high-speed testing due to heat build-up and softening of the lead working material. This force reduction is recovered following cyclic loading as heat is dissipated and the lead hardens again. The devices are shown to be only weakly velocity dependent, an advantage in that they do not deliver large forces to the connecting elements and surrounding structure if larger than expected response velocities occur. This high-speed testing is an important step towards uptake as it provides important information to designers.

1 INTRODUCTION

In recent research, high force-to-volume (HF2V) lead based dampers have been developed to provide large resistive forces and maintain compact outer dimensions (Rodgers et al. 2007; Rodgers et al. 2008a). These devices have been implemented into several large-scale experiments, using both jointed-precast concrete and steel beam-to-column rigid connections (Mander et al. 2009; Rodgers et al. 2008b). During these experimental investigations, testing has always been of a quasi-static nature and it was not possible to test the HF2V damping devices at representative earthquake velocities.

Testing at high speeds that represent maximum response velocities that could occur in large near-fault events with very high local accelerations are necessary to facilitate uptake by the profession. Although the HF2V dampers are only weakly velocity dependent, any device that exhibits velocity dependence should be thoroughly tested before being used in a structural application, due to increased resistive force that may be applied to the surrounding structural elements.

1.1 HF2V Device Mechanics

In a bulged-shaft lead extrusion damper, such as that used in this research, lead is confined within a cylinder with the bulged-shaft through the centre, as shown in Figure 1. As the shaft is forced through the cylinder, the lead is forced to flow through the annular restriction created by the bulge. This plastic flow absorbs a large amount of energy due to the shearing and deformation that occurs, providing high resistive forces. These high resistive forces enable an extrusion damper to be much stiffer and absorb far more energy, than an equivalent sized fluid viscous damper. The heat produced by the damper on repeated cycles softens the surrounding lead and reduces the resistance provided. Therefore, careful characterisation of the velocity dependence and force drop-off with heating is required.

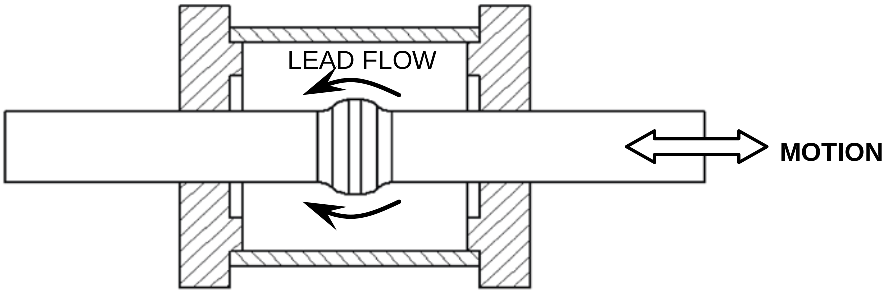


Figure 1: HF2V device schematic.

2 METHODS

2.1 Required Input Velocity

To undertake high speed validation testing of HF2V devices, it was necessary to determine a maximum likely response velocity for typical structural applications. The most likely applications for HF2V devices are within rocking connections or rocking walls, or within structural bracing. While the maximum velocity imparted into a damping device is dependent on a number of factors, such as the eccentricity from a rocking edge, structural natural period, and the maximum ground motion velocity, most applications would dictate a peak velocity for a Maximum Considered Event (MCE) on the order of 100-300 mm/s. This velocity is well beyond the maximum input velocity previously tested in studies such as Mander et al (2009), where maximum velocities were approximately 10 mm/s.

2.2 Hydraulic Test Equipment

To locate a hydraulic test system to undertake validation testing proved a challenging task. Many of the test machines located within New Zealand are either low force (up to 100kN) and high velocity (400 mm/s or higher) or high force (10 MN or higher) but with very limited velocity capacity (up to 10-15 mm/s). Very few machines were set up to provide capacity in the intermediate range of force and velocity.

Another important aspect that was apparent was that, depending on the hydraulic accumulators available, many machines could provide a high velocity for only one-to-two cycles. Therefore, two considerations were made: 1) The peak, one-shot velocity that could be obtained (limited by the accumulators) and 2) the maximum velocity able to be sustained for repeated cyclic loading (limited by the rate at which the pump could supply the high-pressure fluid).

As it was determined that HF2V device force levels of up to 400kN were required, no hydraulic test set-up could be located that allowed the devices to be tested in a direct-drive sense. The closest hydraulic test set-up was located at Quest Integrity in Gracefield, Lower Hutt. Their Instron 1344, shown in Figure 1a, was capable of 250kN peak force and cross-head velocities up to 400 mm/s at near full load. As this was the set-up with capability closest to that required, it was selected as the location of testing. A two-to-one lever-set-up, shown in Figure 1b, was designed to reduce the velocity and increase the force capacity, allowing up to 500kN and 200mm/s to be imparted into the HF2V damping device.

Data acquisition was provided by a Hengstler rotational encoder and string-line and force was provided both directly from the cross-head and through a P.T. Ltd 500 kN Universal loadcell. Force and displacement was recorded directly off the device due to the slight variation in lever-arm length through the range of motion, elastic flexibility of the lever-arm system and friction within the pin joints reducing force transferred.

a) Instron 1344 at Quest Integrity Ltd, Gracefield.

b) Lever-system to increase force capacity

Figure 1: Details of the device test configuration.

2.3 **Input displacement profiles**

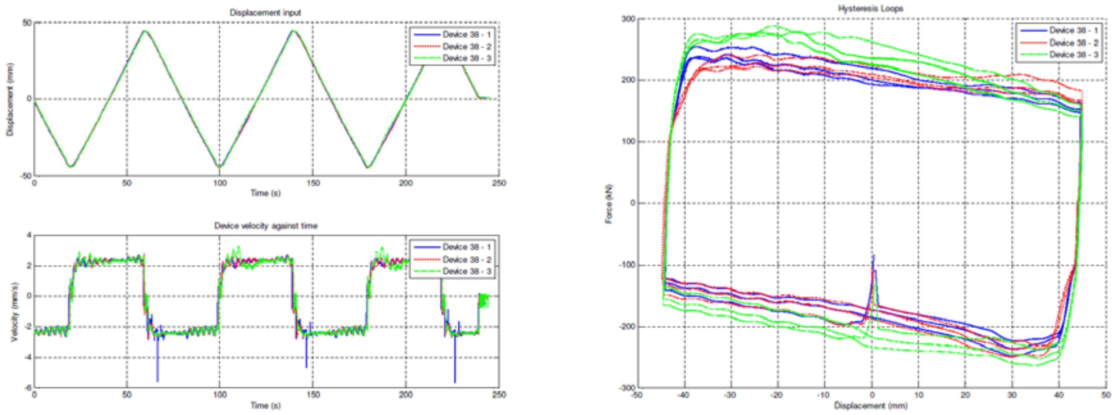
HF2V damping devices were subjected to three fully reversed cycles at near full-stroke (±45mm amplitude) at a range of device velocities from 2.5 mm/s through to 200 mm/s, corresponding to 5-400mm/s in the Instron cross-head. For velocities up to 25 mm/s, three or more fully reversed cycles could be sustained without loss of hydraulic pressure and consequently loss of machine position control. At higher velocities (50, 100 and 200 mm/s), only part of the input profile could be sustained before the loss of position control. Multiple devices of the same design were tested to indicate repeatability between devices.

Finally, to test the influence of heat build-up and softening of the lead, 10 fully reversed cycles at near-full stroke were undertaken at the maximum sustainable velocity of 10 mm/s. Beyond this velocity, only a maximum of 3 cycles could be achieved before a loss of hydraulic pressure.

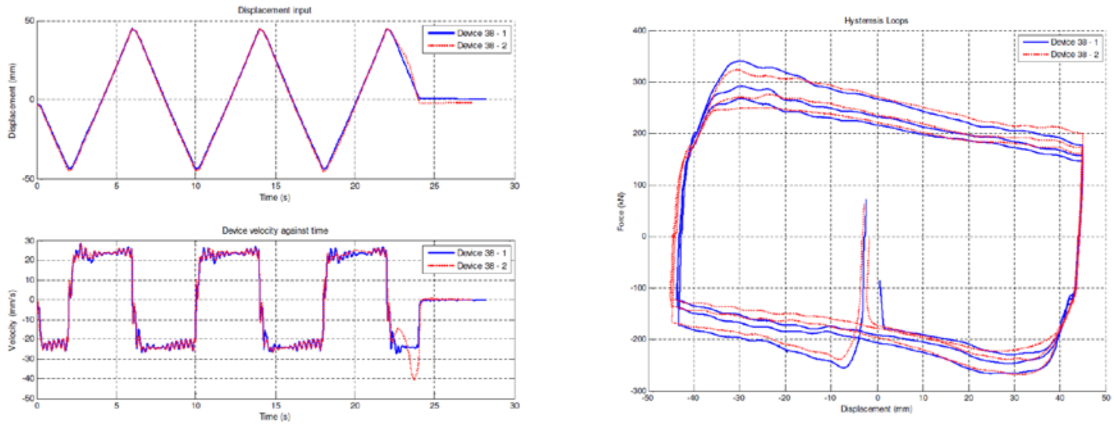
3 **RESULTS AND DISCUSSION**

Figure 2 presents a range of device results for different input velocities. Force, displacement and velocity values represent those within the devices and not those of the machine cross-head. It is evident in Figures 2 a-b that the input displacement is very similar between tests and that the machine cross-head is tracking the command input well. However, in Figures 2 c-d, it is evident that once the hydraulic pressure in the accumulators is lost, displacement tracking is very poor and inconsistent between tests. This is simply due to the limitations in the hydraulics used to drive the test machine.

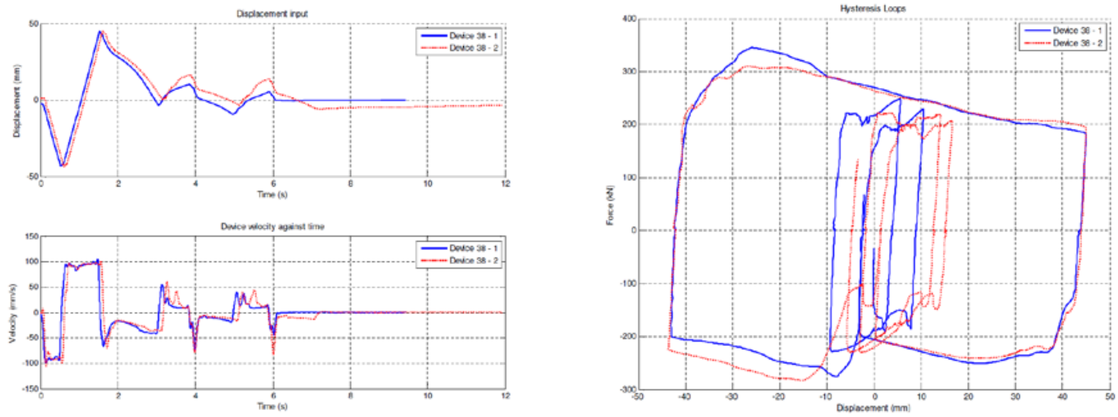
Overall, it is evident in Figure 2 that the HF2V devices exhibit only very weak velocity dependence. This observation is attributed to the fact that the overall resistive force is made up of a combination of frictional resistance and extrusion resistance. Frictional resistance is generally considered to be velocity-independent, and extrusion only weakly dependent on velocity. Moreover, it is apparent in the testing results of Figure 2 that the frictional component may actually reduce with higher input velocities, as the transition from static to kinetic friction is more rapid. Therefore, this balances out the increased extrusion force, to provide a device whose resistive force is almost independent of the input velocity. This can be considered advantageous from a structural point of view, as high response velocities will not impart large damping forces into the structure.



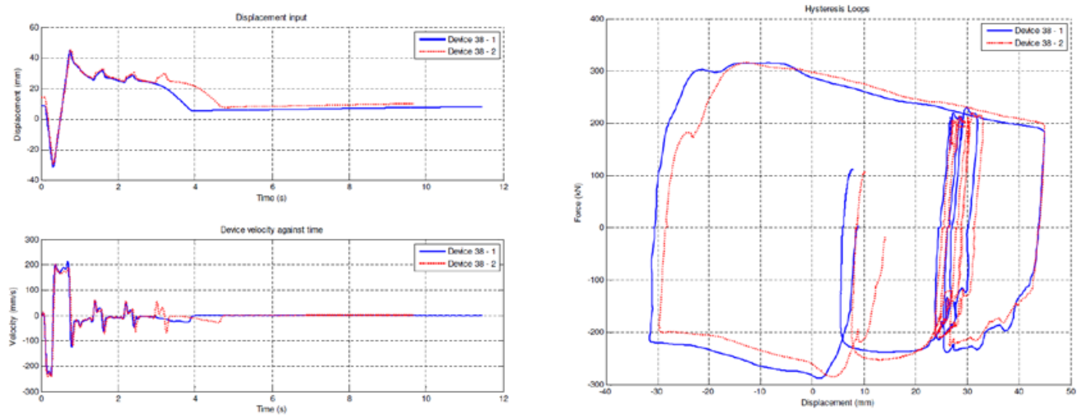
a) 3 fully reversed cycles at 2.5 mm/s device velocity



b) 3 fully reversed cycles at 25 mm/s device velocity



c) 3 fully reversed cycles command (but not achieved) at 100 mm/s device velocity



d) 3 fully reversed cycles command (but not achieved) at 200 mm/s device velocity

Figure 2: Representative results showing a range of commanded velocity inputs.

Figure 3 presents the results of two identical devices subjected to 10 fully reversed cycles at 10 mm/s device velocity, the maximum sustainable input velocity. It is evident in Figure 3 that there is a reduction in resistive force due to the heating effects and softening of the lead. Overall, peak forces drop from approximately 300kN on the first cycle, down to about 180kN over the 10 cycles. While this represents a maximum loss of up to 40% in resistive force, it is important to note that this is a temporary effect. Once the HF2V devices were allowed to cool off after testing, resistive forces returned to their original values. Moreover, the input of 10 fully reversed, near full-stroke cycles is unlikely to ever be experienced in service. The stroke tested here, represents a typical peak response amplitude for the Maximum Consider Seismic Event, but in such a response, only 1-2 cycles could be expected at this peak amplitude.

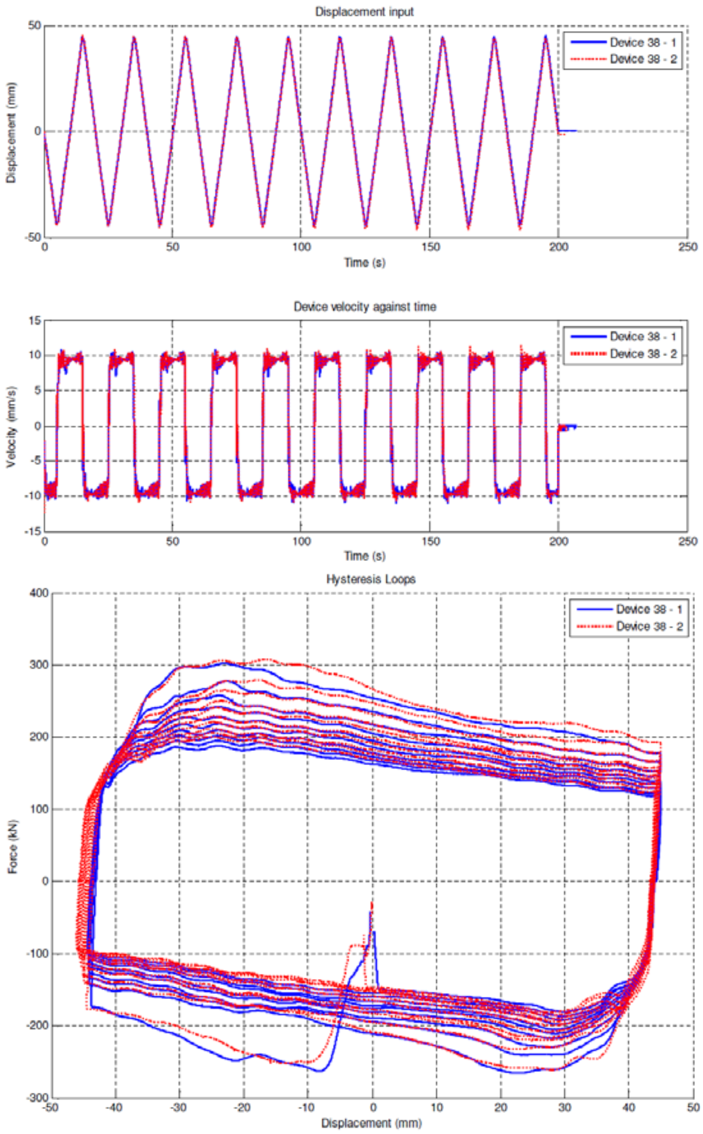


Figure 3: Two identical devices subjected to 10 fully-reversed, near full-stroke displacement cycles at 10 mm/s.

It is also important to put the results of Figure 3 into context. With the exception of lead-rubber bearings in base-isolation applications and some viscous dampers, it is unlikely that any other seismic energy dissipation methods or devices could achieve this level of response without notable (and permanent) loss of force capacity. Yield steel fuse-bars and buckling-restrained braces would most likely have failed due to low-cycle fatigue if they were subjected to 10 cycles at this level of yield displacement (Solberg 2007; Solberg et al. 2008). Moreover, any stiffness or strength degradation observed would most likely be permanent and not recovered during cool-down post-event. Likewise, if energy was to be absorbed via sacrificial damage, it is unlikely that the building would be serviceable or have much remaining capacity if it were to be subjected to this level of demand.

4 CONCLUSIONS

This manuscript has presented the high-speed testing of High Force-to-Volume (HF2V) lead extrusion damping devices. A range of input velocities from 2.5 to 200 mm/s were presented to investigate the relationship between resistive force and input velocity. The HF2V devices were seen to be almost independent to velocity, due to a combination of a loss of frictional resistance at high speed and an increase in extrusion resistance. These two effects largely counteract one another, to produce resistive forces not affected by the shaft velocity.

Sustained cyclic testing showed that these devices do suffer some dynamic strength degradation due to heat build-up softening the lead working material. However, these effects are temporary and the strength capacity is restored once the devices cool down after testing. As the lead working material is the only part of the device undergoing plastic deformation and all other parts remain within the elastic region, low-cycle fatigue is not an important design consideration.

Overall, these HF2V damping devices are shown to produce resistive forces that are almost independent to input velocity and the devices show a strong robustness to repeated cycles, even at the full design stroke.

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