Velocity Effects on the Behaviour of High-Force-to-Volume Lead Dampers (HF2V) Using Different Shaft Configurations

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SUMMARY

High-Force-to-Volume lead dampers (HF2V) are recently developed and validated as seismic devices. Testing and experimental applications on 50-80% full scale beam column joints have shown an efficient hysteretic behaviour with almost no damage. This paper reports testing of HF2V devices with bulged and constricted shaft configurations subjected to velocities in the ranges of 0.15 – 190 mm/s. Effects of velocity on hysteresis loop shape and resistive force developed are presented. A simple model to consider the velocity dependence for each shaft configuration is also presented. Results show that HF2V devices are velocity dependant at low velocity levels and almost independent above velocities of 50mm/s. Hysteretic behavior is stable and repeatable at all velocity levels without degradation.

Keywords: High Force to Volume, Lead damper, Extrusion damping, Energy dissipation, Low damage.

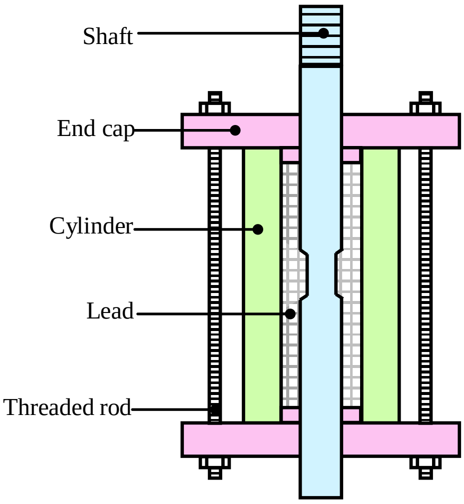
1. INTRODUCTION

The concept of applying the mechanical properties of lead for damping was initially proposed for large dampers comprised of constricted cylinders where the lead was extruded by the movement of a co-axial shaft (Robinson and Greenbank, 1976). Given the stable hysteretic behaviour and low velocity dependence exhibited, they were adopted and successfully applied in New Zealand as a supplemental damping alternative for buildings and bridges (Skinner et al. 1980). Later studies (Cousins and Porritt, 1993) implemented the concept of bulged shafts on large lead dampers, where results showed the capability of the device to undergo a considerable number of cycles without significant degradation. Recently, Rodgers et al. (2007) experimentally developed HF2V lead dampers characterized by relatively very small sizes and high force levels. Testing on the damper itself, as well as on concrete and steel beam column joint subassemblies, demonstrated repeatable hysteretic behaviour, minimal damage, and low maintenance. The development of the HF2V concept by Rodgers et al. (2007) was based on bulged shafts and velocity testing up to 1mm/s. This paper describes work that extends the concept to constricted shaft configurations and determines the velocity dependence of the device, through answering the following:

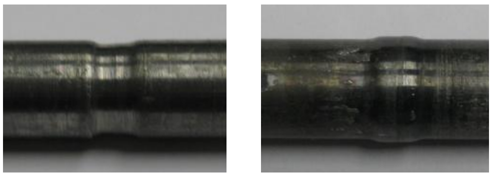
1. What is the effect of velocity on the hysteresis loop shape of HF2V devices with constricted and bulged shaft configurations?
2. Is the resistive force developed by HF2V devices velocity dependent?
3. What is a simple model to predict the velocity dependence of HF2V devices?

2. HIGH–FORCE–TO–VOLUME DEVICES (HF2V)

High-force-to-volume devices (HF2V) comprise a cylinder, two end caps and a shaft with a bulge or constriction. Lead is cast in the space between the cylinder and the shaft, and it is confined by means of pre-stress forces of 100-150 kN applied on the end caps. The energy dissipation mechanism is based on extruding the lead through the space between the bulge and the cylinder when the shaft is moving relatively to the cylinder. Hysteresis loops of HF2V devices can be described as almost square (Rodgers et al. 2008, Rodgers 2009, Rodgers et al. 2012); enclosing areas of 80 and 90% of a perfect square hysteresis Coulomb model have been reported for bulged and constricted shafts (Chanchí et al. 2011). Fig. 2.1. shows components, assembly and hysteresis loop shape of an HF2V device with constricted shaft.

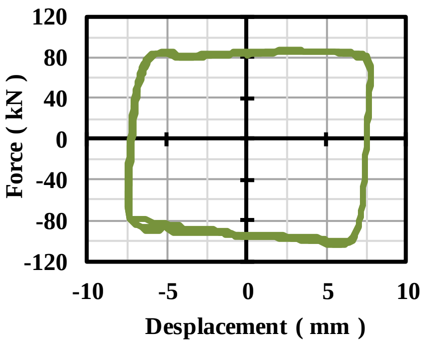


a. Internal view of constricted HF2V



b. Constricted shaft **c.** Bulged shaft

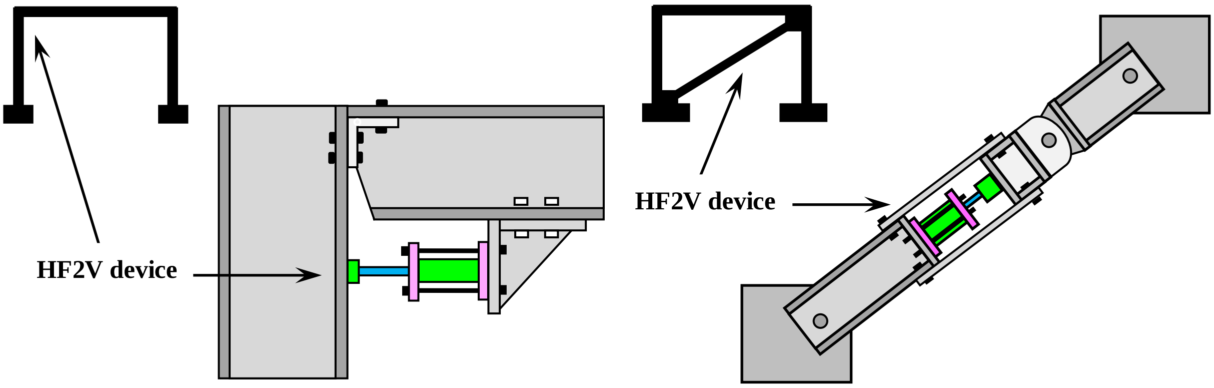
d. HF2V assembly



e. Hysteresis loop of constricted HF2V

Figure 2.1. Internal view, shaft configurations, assembly and hysteresis loop of HF2V devices

HF2V devices are characterized by small sizes, low maintenance, repeatable behaviour, and minimal damage (Rodgers et al. 2007). They can be considered as an alternative to provide supplemental damping to steel framing systems subjected to seismic solicitations. Possible configurations are based on placing the device on beams, either below the bottom flange or at both sides of the web (Mander et al. 2009). In this case the device develops resistive forces against the beam rotations. It is also possible to place the device within braces where the device develops resistive forces against the brace elongation (Chanchí et al. 2011). In both configurations, the structural system dissipates energy by extrusion in the device rather than yielding any component of the frame, making the structural system a low damage solution. Fig. 2.2. shows two possible applications of HF2V devices on steel framing systems.



a. Beam-column joint configuration **b.** Brace Configuration

Figure 2.2. Two possible configurations of HF2V devices on steel framing systems

3. EXPERIMENTAL METHODS

Two HF2V devices with constricted and bulged shaft configurations were considered. Devices were assembled using shaft diameters of 16mm, internal cylinder diameters of 20mm, and pre-stress forces of 150 kN. Constricted and bulged configurations were built by respectively reducing and increasing the shaft diameter by 1mm in the machining. Geometrical properties of devices are presented in Table 3.1.

Table 3.1. Geometry of HF2V devices

Configuration	Shaft diameter (mm)	Bulge diameter (mm)	Stroke (mm)	Pre-stress (kN)
Constricted	16.0	15.0	10.0	150
Bulged	16.0	17.0	10.0	150

Testing was carried out on a shaking table using a horizontal setup instrumented with a load cell in series with the device and a potentiometer across the device stroke. Devices were subjected to a sinusoidal displacement regime with amplitude of 10mm, velocities in the range 0.15 – 190 mm/s, and frequencies of 0.0025-3 Hz. Fig. 3.1. presents testing setup and typical displacement regime applied at each velocity level.

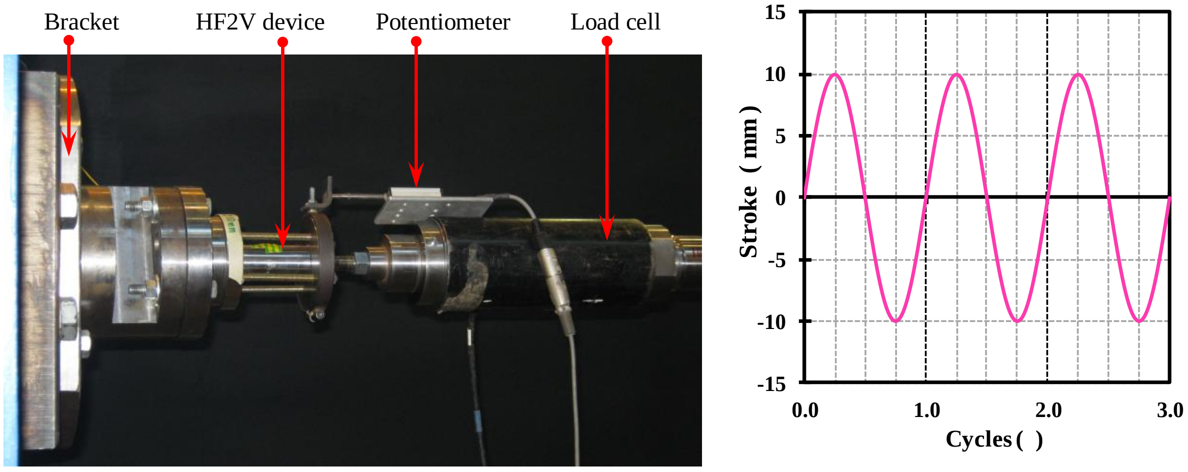
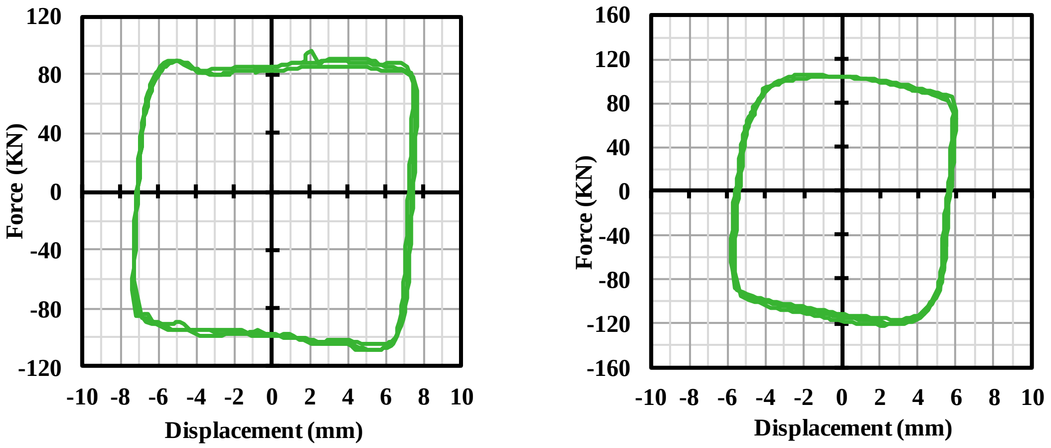


Figure 3.1. Testing setup and displacement regime at each velocity level

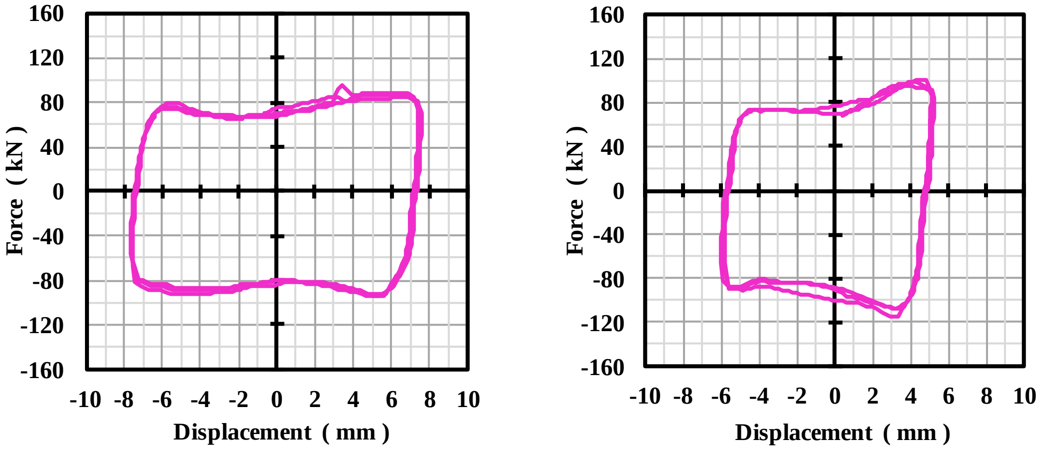
4. RESULTS AND ANALYSIS

4.1. Velocity effects on the hysteresis loop shape

HF2V devices exhibited a repeatable and consistent behaviour in quasi-static and high velocity conditions. Hysteresis loop shape of constricted and bulged devices was found to be square. For devices with constricted shaft, only slight differences were noted when comparing the shape at low and high velocity levels. Increased force at corners exhibited at low velocities were not noticed at high velocities, instead rounded corners were recorded. In the case of devices with bulged shaft, hysteresis loop shape changed from almost square at low velocities to square with increased forces at two corners at high velocities. For both shaft configurations, the post – yielding zone was found to change from a horizontal disposition with constant resistive forces to a slightly inclined disposition with changes on the resistive between 10 and 20% of the maximum resistive force due to velocity. In addition, discontinuities on the displacement at zero force condition were noted on hysteresis loops at high velocity levels. This discontinuity is likely due to flexibility in the testing setup and poor shake table control (Chase et al. 2005). Fig. 4.1. shows hysteresis loop shapes of both types of HF2V devices tested at low and high velocity levels.



a. Constricted – 0.75 mm/s **b.** Constricted – 150 mm/s



c. Bulged – 0.75 mm/s **d.** Bulged – 150 mm/s

Figure 4.1. Hysteresis loop of HF2V devices at different velocity levels

4.2. Velocity effects on the resistive force

Restive forces calculated as the average value across the hysteresis loop plateau of bulged and constricted devices were found to be velocity dependant. This dependence was more accentuated for constricted rather than for bulged devices. Strong velocity dependency was noticed for velocities in the range of 0.15-5.0mm/s, where increments up to 92 and 97% of the maximum resistive force were respectively recorded for bulged and constricted devices. For velocities in the range 10 – 190 mm/s resistive forces are effectively constant for bulged devices and increase by 8% for constricted devices. In addition, it was found that across the velocity testing range, constricted devices develop resistive forces slightly greater than those developed by bulged devices; average differences between 4-11% of the maximum resistive force were found. Fig. 4.2. shows the variation of the resistive force for tested devices in the range 0.15 – 190 mm/s.

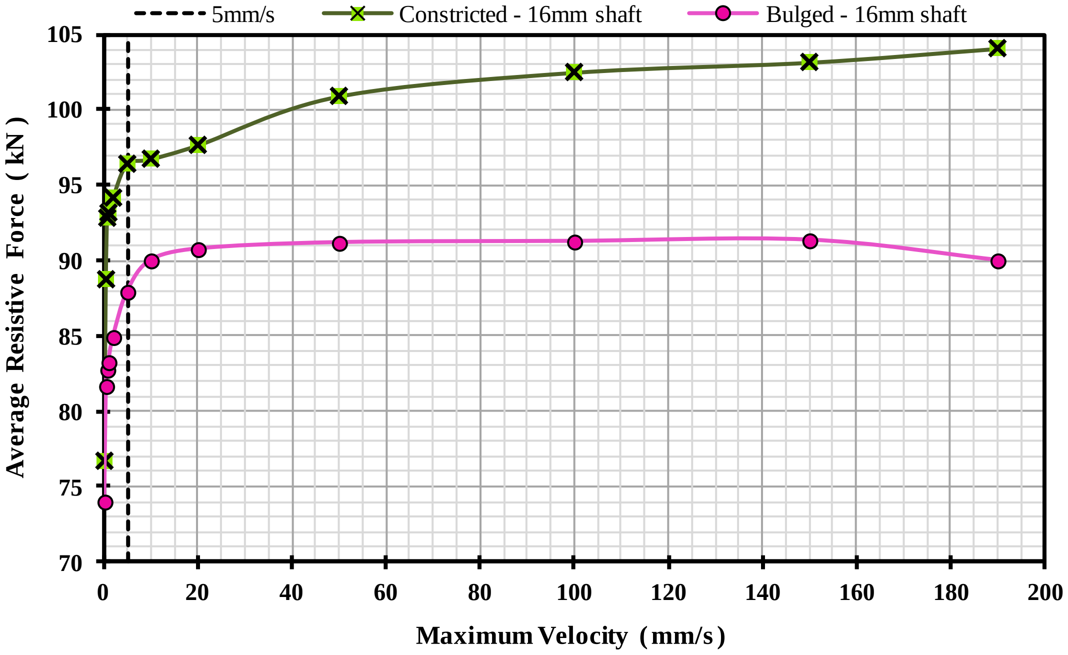


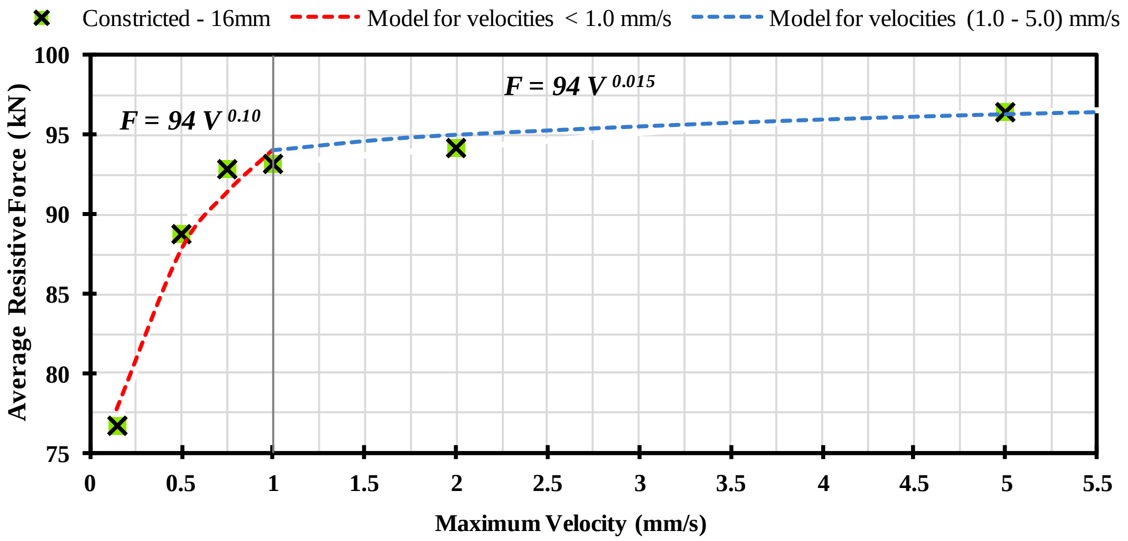
Figure 4.2. Resistive force of bulged and constricted HF2V devices at different velocity levels

4.3. Velocity Model

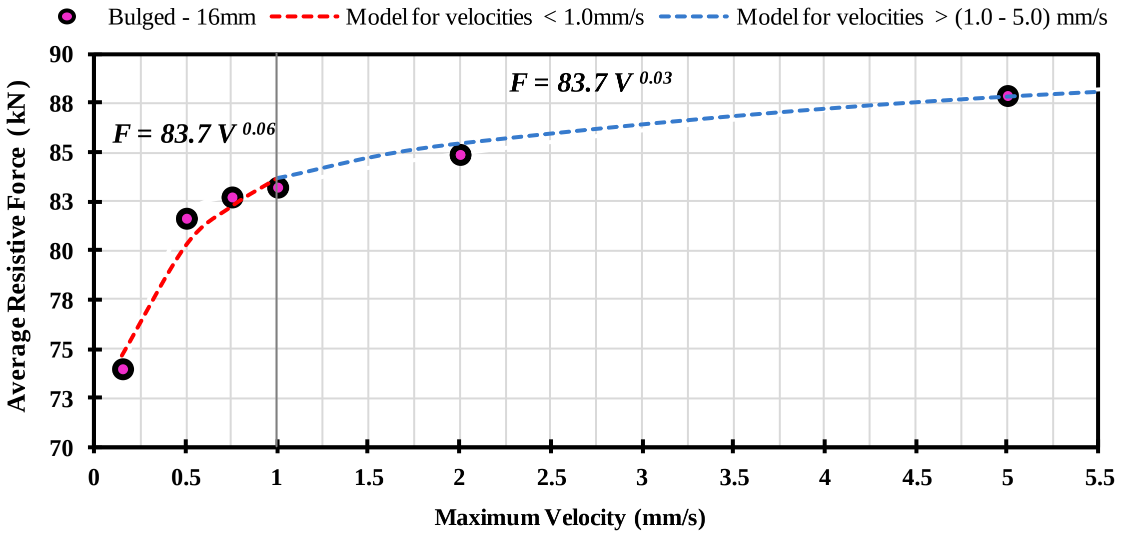
Velocity dependence of HF2V devices was modelled using the approach suggested by Pekcan et al. (1995) and Rodgers et al. (2007). In this approach the resistive force (*F*) is predicted in terms of a constant (*C*) associated with the geometrical properties of the device, and a velocity exponent (α) representing the device velocity dependence (Eqn. 4.1)

$$F = C \times V^{\alpha} \tag{4.1}$$

A bilinear model based on Eqn. 4.1 was fitted on the average resistive forces developed by constricted and bulged devices in the velocity range of 0.15 – 5.0 mm/s. Results show that the velocity exponent ranges between 0.06 and 0.10 for velocities below of 1 mm/s, and between 0.015 for 0.030 for velocities of 0.15 – 5.0 mm/s. These values were found to be less than those reported by Rodgers (2009), where a velocity exponent of 0.12 was reported when testing slightly larger bulged devices with velocities up to 1.0 mm/s. However, they agree partially with those from even larger devices reported by Robinson & Greenbank (1976) where a velocity exponent of 0.03 was suggested for bulged and constricted devices tested with velocities above 0.017 mm/s. Given the disagreement on the velocity coefficient value, additional research is suggested to confirm the values reported in this research. Fig. 4.3. shows velocity dependence model for constricted and bulged shaft configurations.



a. HF2V device with 16 mm constricted shaft



b. HF2V device with 16 mm bulged shaft

Figure 4.3. Velocity dependence model of HF2V

4.4. Future research required

These tests were for sliding amplitude of ±10 mm and sinusoidal motion. Typical earthquake applications as shown in Fig. 2.2 will require larger amplitudes of movement and larger, more rapid changes in acceleration. The effect of both these parameters needs experimental investigation.

5. CONCLUSIONS

This paper describes velocity effects on the hysteretic behaviour of HF2V devices with different shaft configurations, it was shown that:

1. HF2V devices exhibited a stable and repeatable hysteretic behaviour. Only minor changes on the hysteresis loop shape were noticed at high velocity levels for constricted shaft configurations. For bulged shafts, the hysteresis loop shape changed from square at low velocities to square with force increments at two corners at high velocities. The post-yielding zone tendency changed from horizontal to slightly negative slope for those with constricted shafts. For those with bulged shafts, the average post-yielding stiffness in one direction increased, while in the other it decreased.

2. Resistive forces developed by HF2V devices are velocity dependent for velocities below 5.0 mm/s. Resistive forces developed by constricted and bulged shaft configurations with similar geometrical properties generally differed less than 11% for tested devices with velocities in the range of 0.15 – 190 mm/s

3. Velocity dependence of HF2V devices can be modelled using an exponential bilinear model with velocity exponents varying in the range of 0.015 - 0.10. Additional research needs to be addressed to define a reliable value of the velocity exponent especially for devices with different geometric considerations.

4. Additional research is also required to address the “spiky” nature of earthquake loading and the effects of larger amplitude displacements.

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