Velocity dependence of HF2V devices using different shaft configurations

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ABSTRACT: High-Force-to-Volume lead dampers (HF2V) have been recently developed through an experimental research program at University of Canterbury – New Zealand. Testing of the device and applications on beam column joints have demonstrated stable hysteretic behaviour with almost no damage. This paper reports testing of HF2V devices with straight, bulged and constricted shaft configurations subjected to velocities of 0.15 - 5.0mm/s. The effect of the shaft configuration on the hysteresis loop shape, design relationships and the effect of the velocity on the resistive force of the device are described. Results show that hysteresis loop shape of the device is almost square regardless of the shaft configuration, and that devices are characterized by noticeable velocity dependence in the range of 0.15-1.0mm/s.

1 INTRODUCTION

High Force-to-Volume (HF2V) devices were developed by Rodgers et.al (2007). Applications of the device on concrete and steel beam column joint subassemblies have experimentally demonstrated a repeatable hysteretic behaviour with minimal damage on the subassembly (Rodgers (2009), Mander et.al (2009)). The development and validation of the HF2V device concept was based on using bulged shafts and testing with maximum velocities of 1mm/s. Aiming to extend this concept to different shafts configurations and to determine the velocity dependence of device research was undertaken to answer:

i) What is the effect of the shaft configuration on hysteresis loop shape?

ii) What is a design relationship applicable to different shaft configurations?

iii) What is a simple approach to predict resistive forces of HF2V devices with straight shaft?

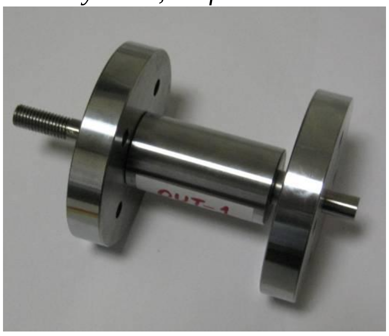
iv) What is the velocity effect on the resistive force of the device?

2 HF2V DEVICE CONCEPT

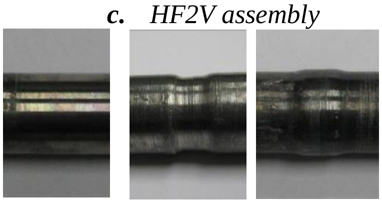
High Force-to-Volume (HF2V) devices can be defined as lead dampers characterized by small sizes, low maintenance and stable hysteresis behaviour. HF2V devices consist of a straight, bulged or constricted shaft encased in a thick walled cylinder. The space between the cylinder and the shaft is filled with lead, which is kept in place by two end caps fitted at the cylinder ends. The assembling process is based on connecting the end caps with threaded rods; these threaded rods are gradually bolted at the same time that a pre-stress force ranging from 100 to 150 kN is applied on the end caps. **Figure 1** shows components and assembly of HF2V devices.

a. *Cylinder, shaft and lead*

b. *End cap*



c. *HF2V assembly*



d. *Straight, constricted and bulged shaft*

e. *Pre-stressed HF2V*

Figure 1. *HF2V device components and assembly*

The dissipation mechanism of HF2V devices is based on forcing the lead to flow through the orifice formed by the bulge and the cylinder when the shaft moves relative to the cylinder. In this extrusion process the lead deforms plastically and recrystallizes simultaneously, thus recovering immediately its mechanical properties (**Robinson & Greenbank (1976)**). The magnitude of the resistive force developed by HF2V devices depend on the shaft configuration, the cross section at the extrusion zone and the extrusion velocity.

3 EXPERIMENTAL METHODS

A group of six HF2V devices including straight, bulged and constricted shaft configurations were tested. Devices are geometrically characterized by the area ratio expression presented in **Equation 1 (**Rodgers (2009)**),** where, *AR* is the area ratio, $Ø_{bulge}$ is the bulged or constricted diameter, $Ø_{shaft}$ is the shaft diameter, and $Ø_{cylinder}$ is internal cylinder diameter. **Table 1** presents a summary of the HF2V dimensions, area ratios and pre –stress forces.

$$AR = \frac{\left|\phi_{bulge}^{2} - \phi_{shaft}^{2}\right|}{\phi_{cylinder}^{2} - \phi_{shaft}^{2}} \qquad (1)$$

Table 1. Dimensions and pre-stress forces used for assembling HF2V devices

Device	Configuration	Shaft Diameter	Shaft Bulge	Cylinder Internal Diameter	Cylinder Internal Height	Stroke	Area Ratio	Pre-Stress
	( )	(mm)	(mm)	(mm)	(mm)	(mm)	( )	(kN)
STR - 12	Straight	12.0	12.0	17.0	56.0	5	0.0	100
STR - 16	Straight	16.0	16.0	20.0	66.0	10	0.0	150
IN - 12	Constricted	12.0	11.0	17.0	56.0	5	0.16	100
IN - 16	Constricted	16.0	15.0	20.0	66.0	10	0.22	150
OUT - 12	Bulged	12.0	13.0	17.0	56.0	5	0.17	100
OUT - 16	Bulged	16.0	17.0	20.0	66.0	10	0.23	150

Testing was carried out on a shaking table using a horizontal setup as shown in **Figure 3.** HF2V devices were connected to a reaction beam and a moving bracket attached to the shaking table. The test setup was instrumented with a load cell connected in series with the device and the moving bracket, and with a potentiometer across the device shaft. Devices were tested with maximum velocities of 0.15-5.0 mm/s, for this range of velocities and a stroke of 5mm frequencies ranged from 0.0025 to 0.08 Hz, at each velocity devices were subjected to 3 sinusoidal cycles.

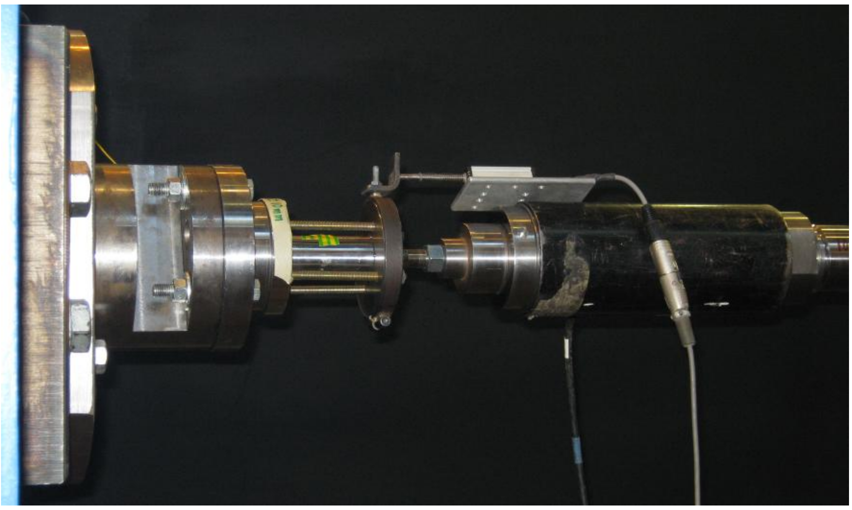
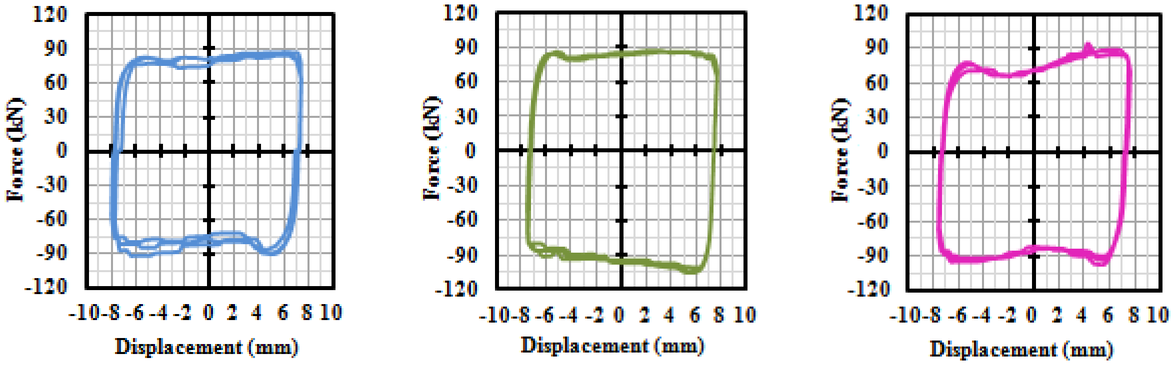


Figure 2. *Test setup of HF2V devices*

4 RESULTS AND ANALYSIS

4.1 Hysteresis loop shape

HF2V devices exhibited a stable and repeatable hysteretic behaviour as shown in **Figure 3**. Devices with straight and constricted shaft were characterized by almost square loops with spiky corners and devices with bulged shafts were characterized by square loops with concavities across the plateau. When comparing the hysteresis loop shapes with a perfect hysteresis Coulomb Model, ratios of 80% for bulged devices and 90% for straight and constricted devices were found.



a. *16mm – straight shaft* *b.* *16mm – constricted shaft* *c.* *16mm – bulged shaft*

Figure 3. *Hysteresis loop shape at 0.50 mm/s for HF2V devices with different shaft configurations*

4.2 Design relationships in quasi-static conditions.

Peak forces of the devices normalized by the internal cylinder diameter and area ratios are plotted in **Figure 3.** A predominant linear relationship can be noticed and expressed through **Equation 2,** where, *NF* is the normalized force, and *AR* is the area ratio.

$$NF = 0.5347AR + 3.6098 \tag{2}$$

$$NF = 8.1247AR + 0.5586 \tag{3}$$

Although, the linear tendency matches with results reported by **Rodgers (2009)**, a disagreement can be noticed when comparing **Equation 3** and **Equation 4** (**Rodgers (2009)**). This difference can be attributed to the limited data used in this research, mainly concentrated on small area ratios values, and the lack of experimental data on devices with straight shaft on the research work carried out by **Rodgers 2009.**

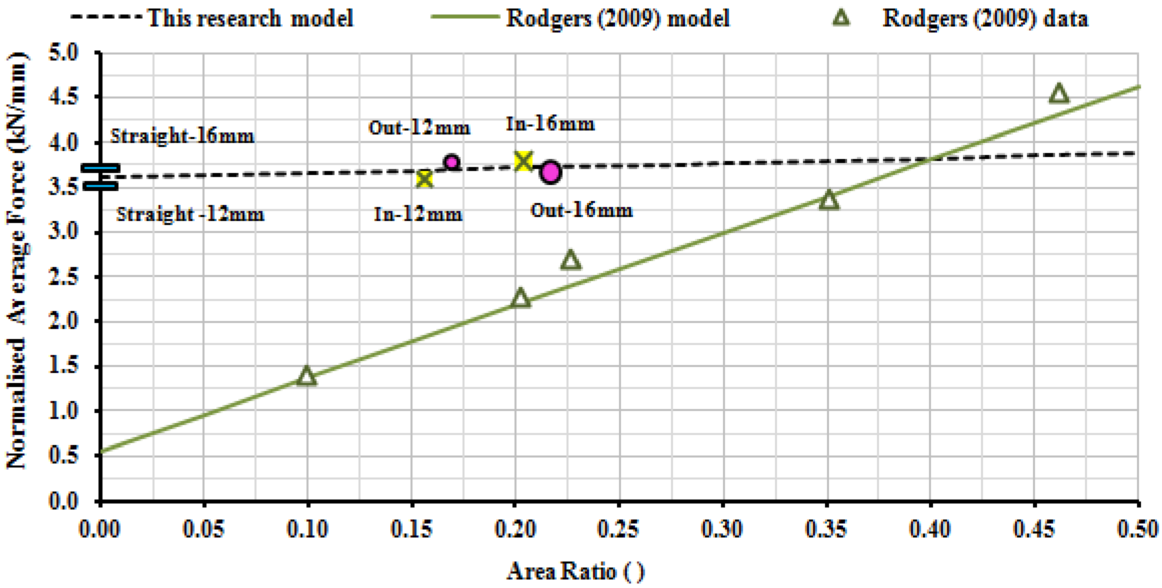
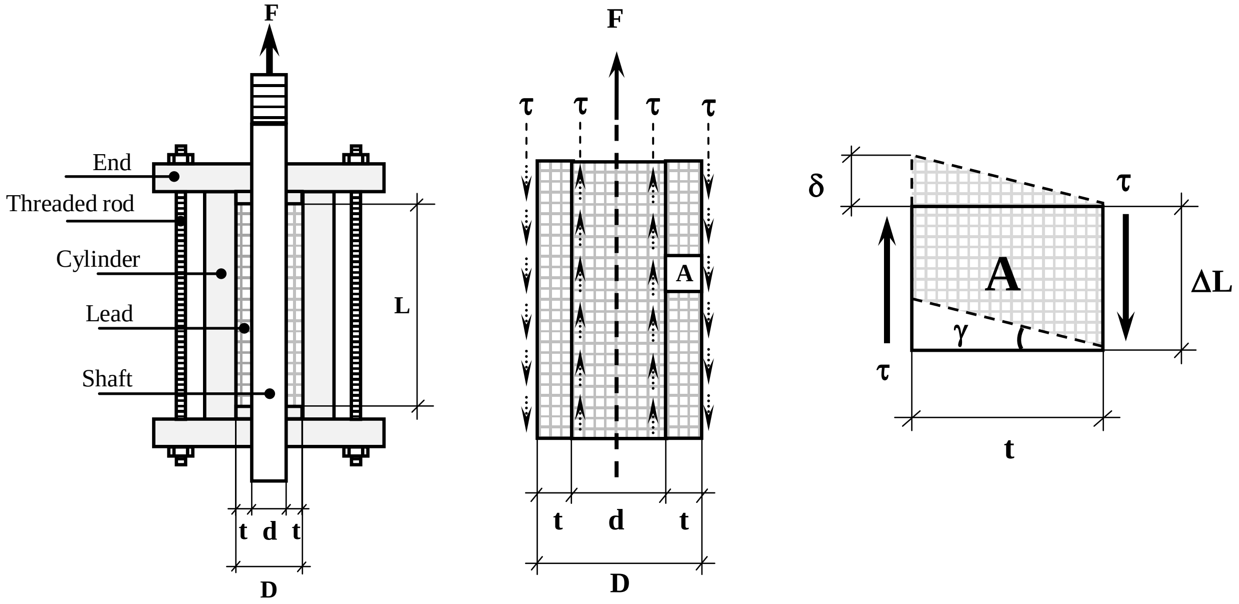


Figure 4. *Existent and proposed HF2V design relationships*

4.3 **Inherent Friction Force**

The quasi-static behaviour of straight devices was modelled assuming elastic behaviour and that the working material is subjected to single shear as shown in **Figure 5.** From this condition the resistive force was predicted using **Equation 4,** where, G is the shear modulus, t is the lead thickness, A_s is the surface shaft area in contact with lead, and δ is the lead longitudinal deformation at yield condition.



a. *HF2V Internal view* ***b.*** *Stress state on lead* ***c.*** *Plain deformation of a lead particle*

Figure 5. *Stress based model of HF2V devices with straight shaft*

$$F = G\frac{\delta}{t}A_s \tag{4}$$

Using a shear modulus of 130 MPa (**Couradelli and Reira (2007)**) and longitudinal lead deformations of 0.50mm and 0.375mm as shown in **Figure 6,** normalized resistive forces of 3.22 and 3.87 kN/mm were respectively predicted for 12 and 16mm devices. These values are close to those experimentally recorded as shown in **Figure 4.**

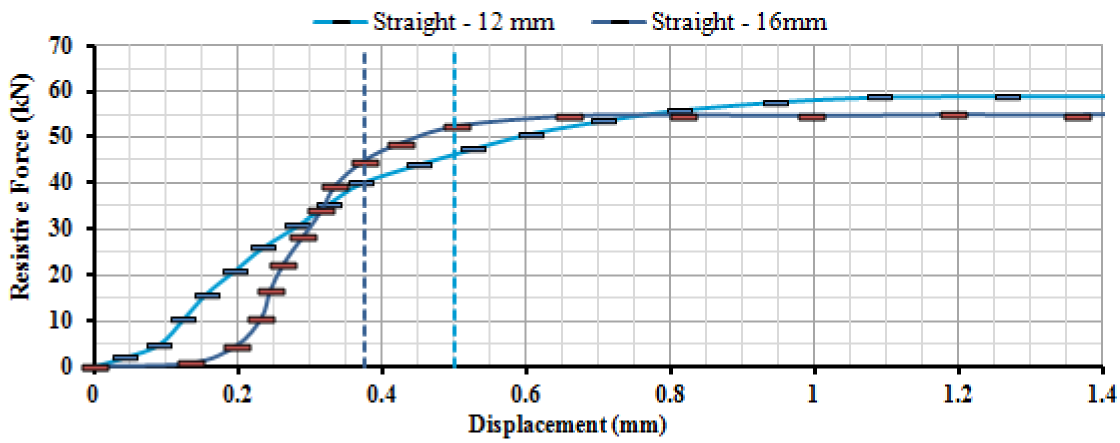


Figure 6. *Initial segment of hysteresis loop of HF2V devices with straight shaft*

For predicted resistive forces shear stresses on the lead of 23-26MPa were found. It can be seen in

Figure 7 that these values match with the beginning of the lead plastic zone on the shear stress and strain curve reported by **Monti (1994).**

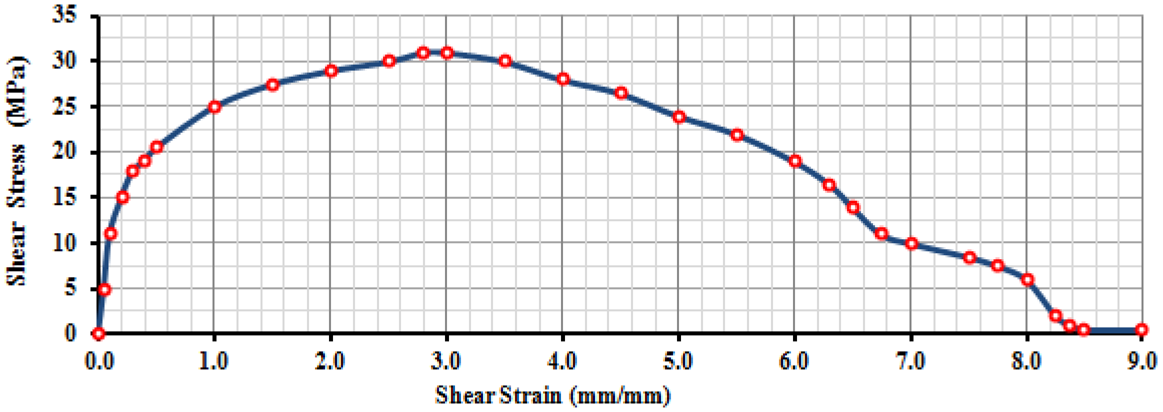


Figure 7. *Stress and strain curve for lead tested in unidirectional shear (adapted from Monti (1994))*

4.4 **Velocity effects**

Peak forces that 12mm shaft HF2V devices exhibited at velocities of 0.15 – 5.0 mm/s are presented in **Figure 5.** Results show that maximum resistive forces are developed by bulged shafts and that resistive force of constricted devices can be estimated as 95% of the resistive force of bulged devices. In addition, devices were found to be velocity dependent for velocity ranges of 0.15-1.0mm/s where drastic increments of force are presented for small velocities increments.

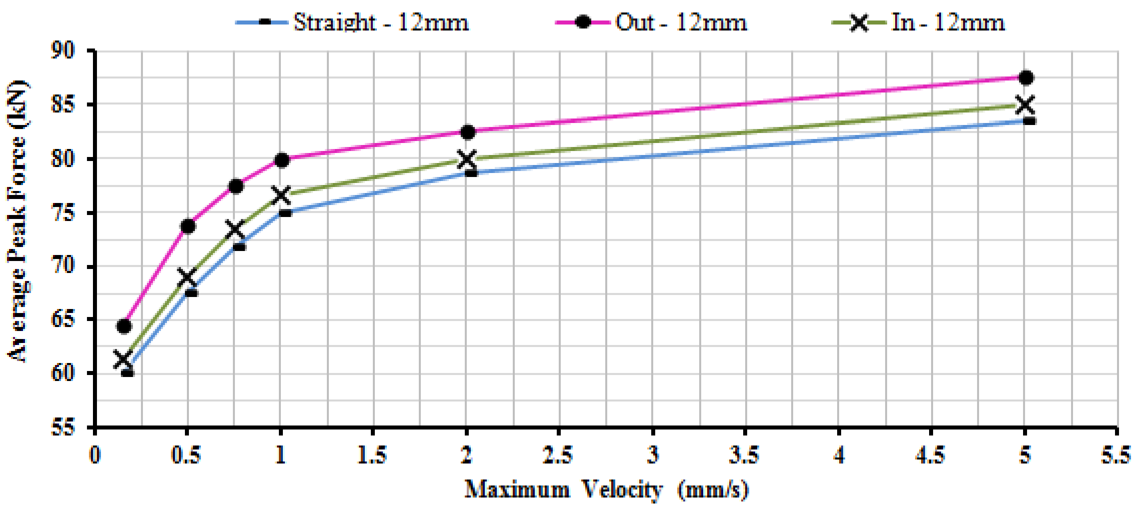
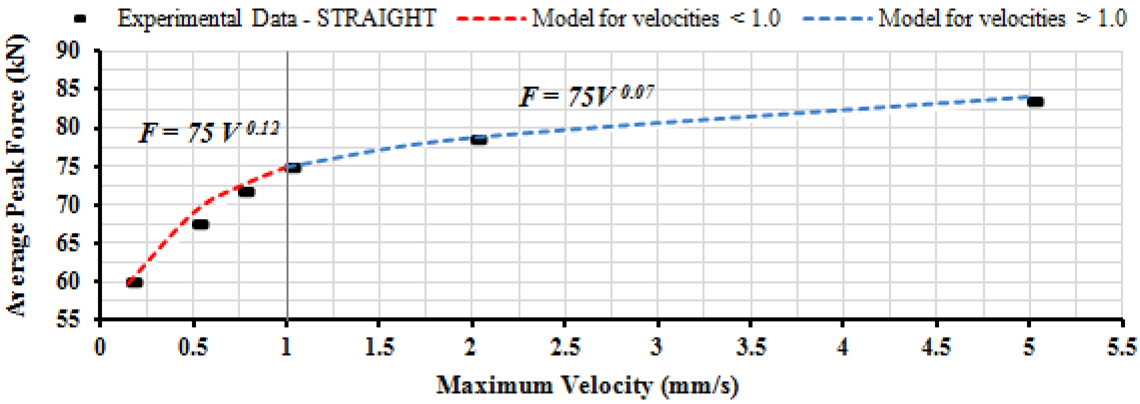


Figure 8. *Velocity dependence of HF2V devices with different shaft configuration*

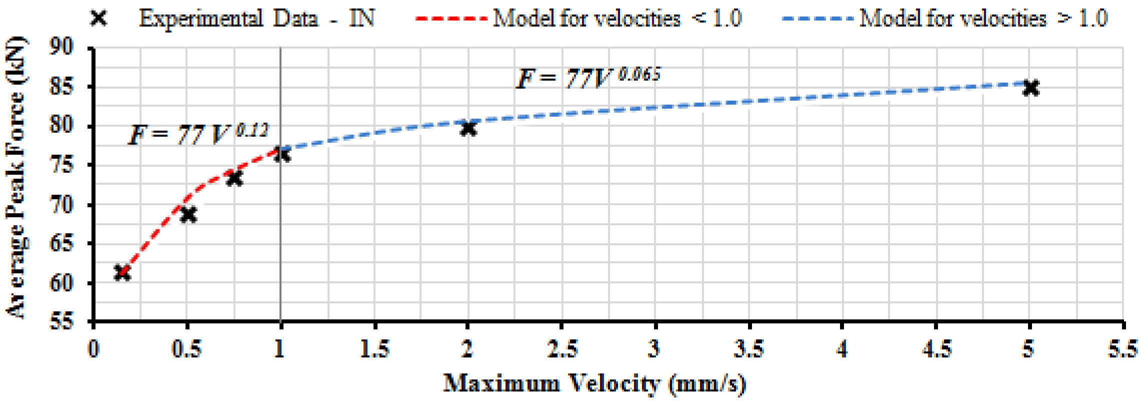
Velocity dependence of devices was modelled using the approach suggested by **Rodgers 2009.** In this approach an exponential relationship constituted by a damper constant (C) depending on the device geometry and a velocity exponent (α) associated with the device dependence was proposed as presented in **Equation 5**.

$$F = CV^{\alpha} \tag{5}$$

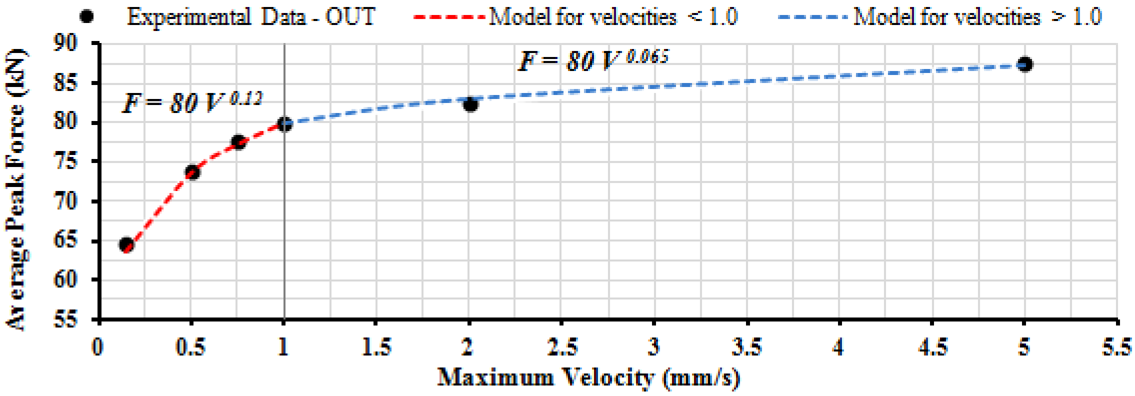
Results show that an exponential bilinear model can represent accurately the velocity dependence as shown in **Figure 9.** A velocity exponent of 0.12 was found for velocities less than 1.0 mm/s and between 0.065 - 0.07 for velocities in the range 1-5mm/s. Values of the velocity exponent agree well with those reported with Rodgers **(2009)**. However, agree partially with those reported by **Robinson and Greenback (1974),** where a velocity exponent of 0.03 was reported for velocities above 1mm/s.



a. *HF2V device with 12mm straight shaft*



b. *HF2V device with 12mm constricted shaft*



c. *HF2V device with 12mm bulged shaft*

Figure 9. *Velocity model for HF2V devices with different shaft configuration*

5. CONCLUSIONS

This paper describes the velocity dependence of HF2V devices, it was shown that:

1. The hysteresis loop shape of HF2V devices is almost square. Square shapes with spiky corners were found for straight and constricted shafts, and square shapes with concavities for bulged shafts.

2. The relationship between normalized peak force and area ratio was found to be linear. A linear design relationship for HF2V devices with area ratios less than 0.20 was presented.

3. Resistive forces of HF2V devices with straight shafts can be predicted considering that the working material is subjected to single shear; a simple force prediction model considering this condition was presented.

4. HF2V devices were found to be velocity dependent, an exponential bilinear model was suggested for predicting resistive forces when the device is subjected to velocities of 0.15-5.0mm/s.

6. REFERENCES

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