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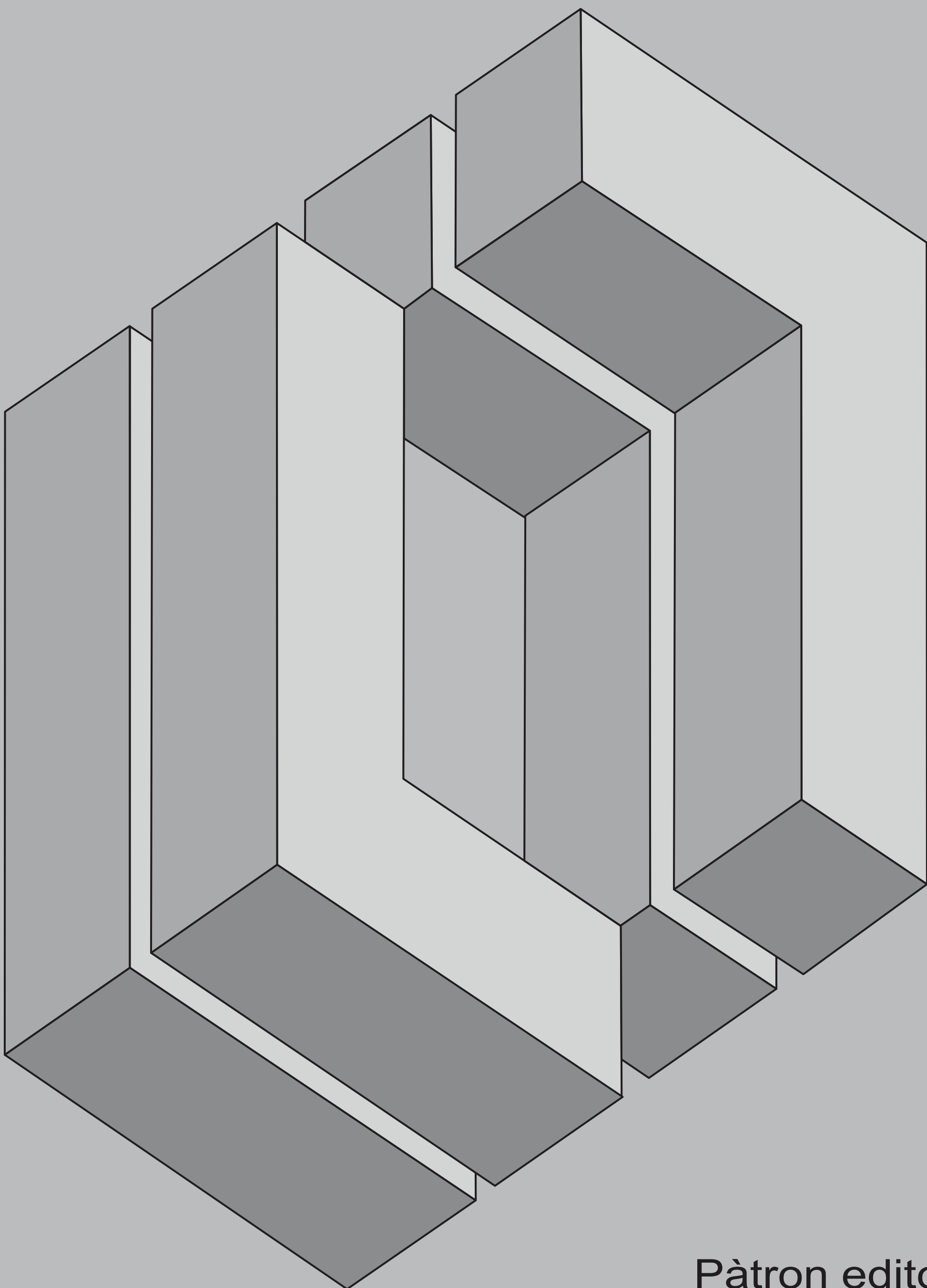

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Sommario/Contents

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EXPERIMENTAL DETERMINATION OF VISCOUS DAMPER PARAMETERS IN LOW VELOCITY RANGES

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SUMMARY: *In the last decades many strategies for seismic vulnerability mitigation of structures have been developed through analytical studies and experimental tests. Among these, energy dissipation by external devices assumes a great relevance for the relative design simplicity, even if applied to complex structures, and the effectiveness in reducing seismic demand. In particular, the use of fluid viscous dampers represents a very attractive solution because of their velocity-dependent behaviour and relatively low costs. The application on structures requires specific study under seismic excitation and a particular care of structural details. In this context the use of proper constitutive models for the dampers assumes a fundamental role. Seismic codes, as well as literature models generally provide a velocity-dependent relationship with two characteristic constants defining the shape of the force-displacement curve.*
In this paper an experimental campaign aimed at the determination of the damper constants in the range of low velocities is presented. A fluid viscous damper is tested with different ramp velocity functions. Results show that the assumption of velocity independence of the damper constants fails for the case of low velocity, giving rise to new issues about the limit of validity of the constitutive models generally adopted for viscous dampers.

KEYWORDS: *Fluid viscous dampers, Dissipation, low velocity, Seismic protection, Experimental testing.*

1 Introduction

Today many approaches are possible to efficiently protect civil structures from earthquakes. Among the different strategies a prominent role is surely that of base isolation and energy dissipation. Base isolation consists in interposing special sliding devices (elastomeric or frictional bearings) between the base of a building and its foundation. Seismic demand on the superstructure is drastically reduced because of the large period elongation. Base isolation is mainly used for new buildings since for the case of existing structures this approach, despite possible, is expensive and involves significant structural modifications [Haskell and Lee, De Iuliis and Castaldo, 2012, Castaldo *et al.*, 2015, Palazzo *et al.*, 2015, Castaldo and Ripani, 2016, Castaldo *et al.*, 2017, Castaldo *et al.*, 2017]. Energy dissipation, or in-structure damping, consists in the use of devices that in presence of ground motions dissipate a rate of the energy transmitted by the ground to the structure. Such energy dissipation devices can work as passive, active and semi-active systems [Symans *et al.*, Castaldo and De Iuliis, 2014, Lavan, 2015, Alotta *et al.*, 2016].

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Passive systems operate without an external power source. They use the motion of the structure to dissipate energy and have fixed mechanical characteristics. Hysteretic dampers, friction damper, viscoelastic and viscous dampers belong to this category. They can be introduced as structural components in new and existing buildings without making significant structural changes. Hysteretic dampers are generally made of steel and can be configured to yield in flexure, shear or axially. Besides energy dissipation they provide additional strength and stiffness. In most cases, the higher is the stiffness, the higher is the energy dissipation.

Viscoelastic dampers are generally composed of two layers of polymer bonded between a central driving plate and two outer plates. They provide a velocity dependent damping force and have an elastic stiffness in addition to damping. Generally for these devices damping is a linear function of velocity and produces an elliptical force-displacement function where the inclination of the major axis corresponds to the stiffness of the device.

Finally viscous dampers provide a resisting force proportional to the applied velocity. In most cases viscous dampers are fluid dampers. Dampers forces are out of phase with displacements and so with restoring forces. For this reason peak forces achieved by viscous dampers do not add up to the peak restoring forces, in fact maximum damping forces occur in correspondence of null interstorey drifts. Furthermore these devices offer negligible resistance against service loads (e.g. thermal distortion) as these occur at very slow velocities. Viscous dampers can be thus used without changing the stiffness of a structure and for this reason they are mainly preferred for existing structures with respect to other type of devices.

Many studies have been carried out on the optimal design criteria for viscous dampers. Constantinou and Symans, 1993 studied the effect of adding linear viscous dampers to steel structures and compared experimental results with the analytical predictions. [Gluck *et al.*, 1996], suggested a design method for supplemental dampers in multi-story structures, adapting the optimal control theory to design linear passive viscous or viscoelastic devices depending on their deformation and velocity. Fu and Kasai, 1998, investigated the properties of viscoelastic and viscous systems by conducting a parametric study, in which mathematical expressions for viscoelastic and viscous damper-brace components were derived as a function of two fundamental dimensionless parameters. A simplified theory to predict and compare seismic performance of viscoelastic and elasto-plastic damped passive control systems was proposed by Kasai *et al.*, 1998. Optimal design methodologies were also presented by Yang *et al.*, 2002, based on two different performance levels, named $H\infty$ and H2. Sadek *et al.*, 2000, investigated the effect of increased viscous damping on the seismic response of structures and assessed the accuracy of the linear static and linear dynamic procedures recommended by FEMA 273. Li and Li, 2011 presented a simplified seismic design and analysis method for buildings equipped with nonlinear fluid viscous dampers based on Chinese design response spectrum. Lin *et al.*, 2003, proposed a seismic displacement-based design method for new and regular buildings equipped with passive energy dissipation systems. The substitute structure approach for the building structure was used and the mechanical properties of the passive energy dissipation devices were simulated by the effective stiffness and effective viscous damping ratio. Uetani *et al.* 2003, proposed an innovative optimum design system for structures with passive-type dampers. In their work hysteretic dampers and viscous dampers were considered. The effectiveness of fluid viscous dampers in reducing seismic demand was also tested by Miyamoto and Hanson, 2002. Zhou *et al.*, 2012, proposed a standardized design method for a more widespread and routine inclusion of viscous dampers in structural

design practice. Finally, Alotta *et al.*, 2016, provided an efficient-design method for fluid viscous dampers with linear and non-linear behavior in moment resisting RC structures.
The preliminary design procedures are based on the very common assumption that the viscous damper restoring force is proportional to the product of a constant and a power of the velocity experimented by the viscous damper itself. These two parameters are generally provided by the producers. However the degree of reliability and the range of applicability of these values are not known to the designer. Besides this, it seems that the above relationship is not valid at each range of velocities, as also highlighted by the experimental tests carried out and presented in the following sections.

2 Fluid Viscous Dampers

Different parameters affect the performance of fluid viscous dampers (FVD) used for seismic protection of structures. During working condition a steel piston travels in a cylinder filled with silicone oil (Figure 1). Oil is forced to pass from a chamber to another one through annular orifices. The kinetic energy of the piston is transformed in heat and dissipated across the cylinder. Damping capacity depends on viscous properties of the silicon oil and on the number and dimension of the orifices. More details on the working scheme of viscous dampers can be found in the literature [Symans *et al.*, 1998, Taylor *et al.*, Constantinou *et al.*].
Different typologies of tests can be performed in order to evaluate mechanical properties of a FVD. Constant velocity tests are generally used to estimate the main characteristics of the dampers at different velocities, different amplitude of displacements and different temperatures. Cyclic tests are instead used to evaluate the durability and the stability. Energy dissipation capacity is evaluated with sinusoidal cyclic tests, while friction resistance is determined with tests at very slow force-control. In addition to these fundamental tests it is desirable to perform tests with a seismic displacement input to evaluate the behaviour in a real case [Aiken and Kelly, 1996].
The tests described above generally provide a relationship between the force applied to the piston and the relative velocity between the piston and the cylinder whose form is

$$F = C\left|\dot{x}\right|^{\alpha} sgn\left(\dot{x}\right) \tag{1}$$

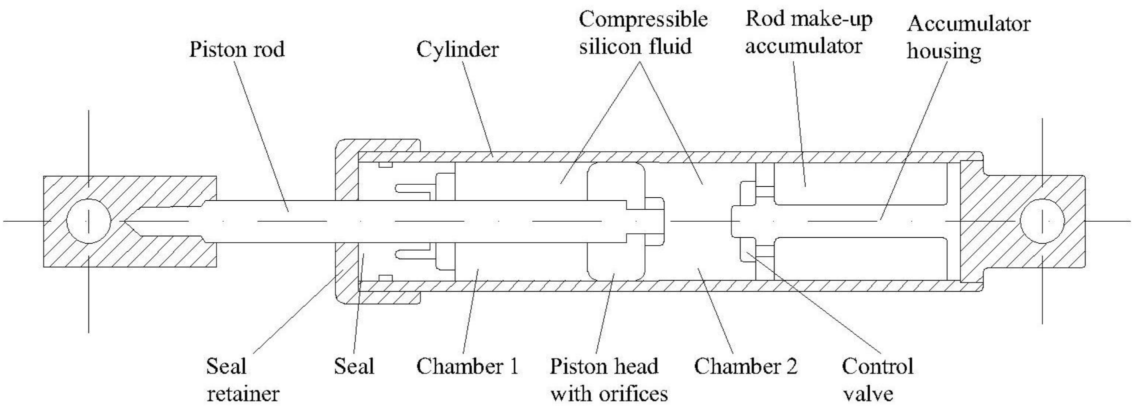


Figure 1 –*Longitudinal section of a typical fluid viscous damper*

In Eq.(1) *F* is the damper force, $|\dot{x}|$ is the velocity of the piston in the cylinder, *C* is a constant mainly depending on the orifice areas, on the diameter of the piston and on the fluid properties. When the fluid temperature increases the constant *C* changes because of the changing of fluid properties. It is possible to obtain a more stable device using a different material for the piston and the cylinder in order to counterbalance thermal effects [Symans and Constantinou, 1998]. The exponent α is a constant which generally assumes values in the range 0.15-1.95 and depends on the shape of the piston head. For civil applications the values of α are generally not greater than 1. The force-displacement curves resulting from Eq. (1) for a damper subject to a sinusoidal history of displacements have the typical shapes illustrated in Figs. 2-4. In Figure 2 it is possible to observe the typical force-displacement cycle with for different values of *C*. It should be noted that an increment of the parameter *C* results in an increase of the area described by the force-displacement curve with a consequent increase of the dissipation capacity.

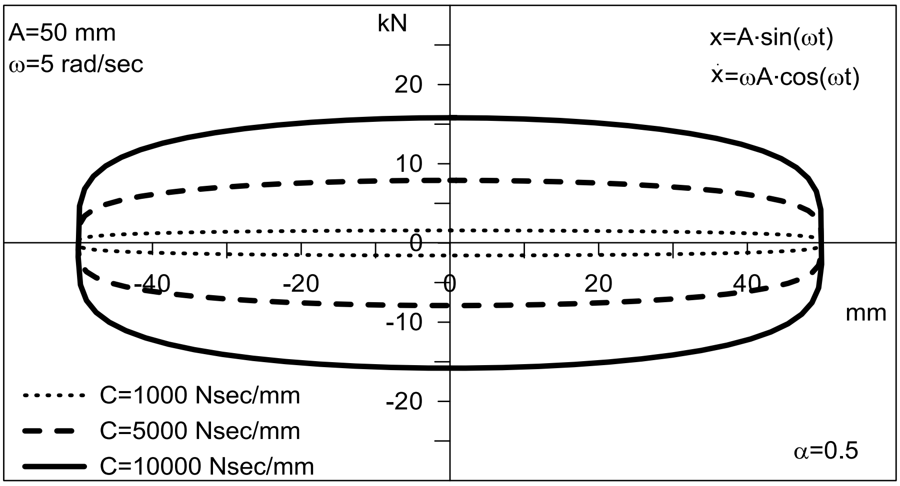


Figure 2 - *Force-displacements curves for different values of C (Nsec/m), ω=5 rad/sec, α=0.5*

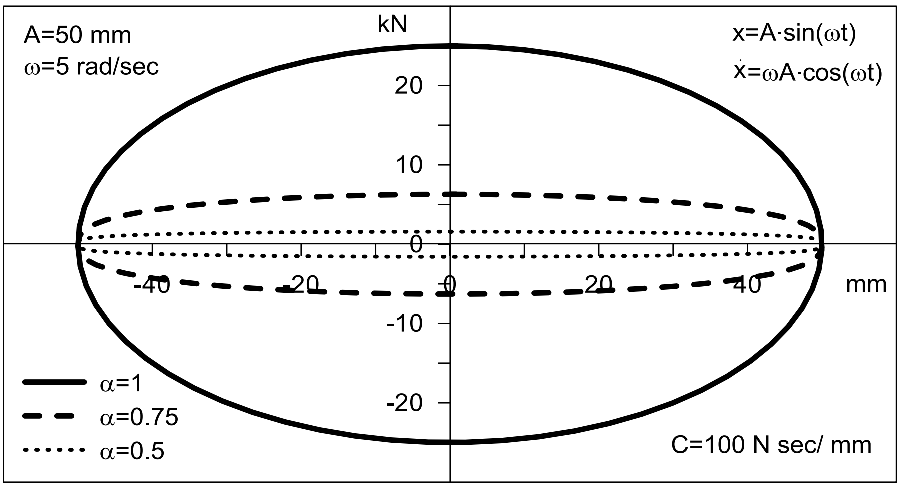


Figure 3 - *Force-displacements curves for different values of α, ω=5 rad/sec, C=100 Nsec/mm*

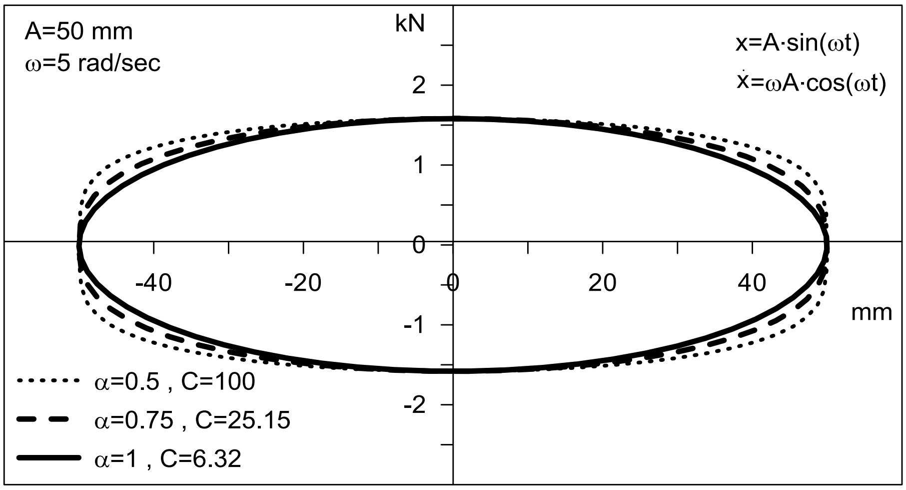


Figure 4 - *Force-displacements curves for different values of α, ω=5 rad/sec, C=100 Nsec/mm*

The same effect is obtained by increasing the value of the parameter α as shown in Figure 3. However, this result does not necessarily indicate that larger values of *C* and α will be surely beneficial to the mitigation of the effects due to seismic excitation. In fact, if the characteristic curves of are plotted by imposing a fixed maximum force (Figure 4), it can be observed that the shape of the curve at α=0.5 is closer to a rectangle, while the shape of the curve at α=1.0 resembles more of an ellipse. If on the one hand smaller values of α provide lager energy dissipation, this is will simultaneously reduce the uncoupling between elastic forces and dissipative forces. It means also that a nonlinear damper force allows lower force level with respect to that of a linear damper (with α=1.0) when the same energy has to be dissipated. For what above it is clear that there is a fundamental trade-off between α and *C*. In fact, in order to achieve a certain amount of force using a smaller α, a larger C has to be chosen at the same time. This inverse relationship between α and C is also evident from Eq. (1). The value of *C*, however, is correlated to the stiffness of dampers: an excessively high stiffness of the damper would potentially create difficulties in designing structural elements connected with the dampers. Thus, selecting the appropriate α and *C* values deserve special care during preliminary design phases.

Figures 2-4 suggest also that, in order to obtain a major uncoupling between the elastic force and the damper force, a linear behaviour is needed (α=1) [Cavaleri *et al.*, 2008]. Differently, the damper force adds up to the elastic one, increasing the stress in the structural members.

It should be finally noted that some of the most recent studies have highlighted some limits of validity of Eq. (1), proposing alternative models. As example in Gusella and Terenzi, 1997 it is found that the damper force, can be more correctly described using the fractional derivative of the displacement (with an order of derivation comprised between 0 and 1) rather than the first derivative of the displacement, that is the velocity $|\dot{x}|$. On the other hand, the assumption that *C* and α remain constant (independently from the velocity experimented by the damper) is a useful, but not always reliable, idealization.

The experimental tests presented in this paper are aimed at investigating the dependence of these parameters on the velocity, in order to provide experimental references for the development of more refined models.

3 Strategies for the experimental characterization of the parameters of a FVD

The parameters C and α of a FVD can be estimated by performing monotonic tests at constant velocity. If the velocity is constant, the reaction force of the FVD is also constant. Considering that in a monotonic test the velocity does not change his signum, Eq.(1) can be rewritten as:

$$F = C\dot{x}^{\alpha} \tag{2}$$

Then by applying the log function to both sides of Eq.(2) one obtains:

$$log\,F = log\,C + \alpha\,log\,\dot{x} \tag{3}$$

If one sets

$$y = log\,F;\ \ z = log\,\dot{x} \tag{4}$$

Eq (3) becomes:

$$y = log\,C + \alpha z \tag{5}$$

which is the equation of a straight line having slope α and *y*-intercept equal to *logC*. By repeating the test for different values of the velocity some points in the plane *y-z* can be plotted and the parameters *logC* and α can be estimated after the best fitting straight line is plotted.

A different approach can be used to derive α and C in the case of variable velocity. Assuming an history of forces *F(t)* defined as:

$$F(t) = \beta t \tag{6}$$

Eq.(2) becomes:

$$C\dot{x}^{\alpha} = \beta t \tag{7}$$

By applying log function to both sides of Eq.(7) one obtains

$$log\,\beta t = log\,C + \alpha\,log\left(\dot{x}\left(t\right)\right) \tag{8}$$

which leads to

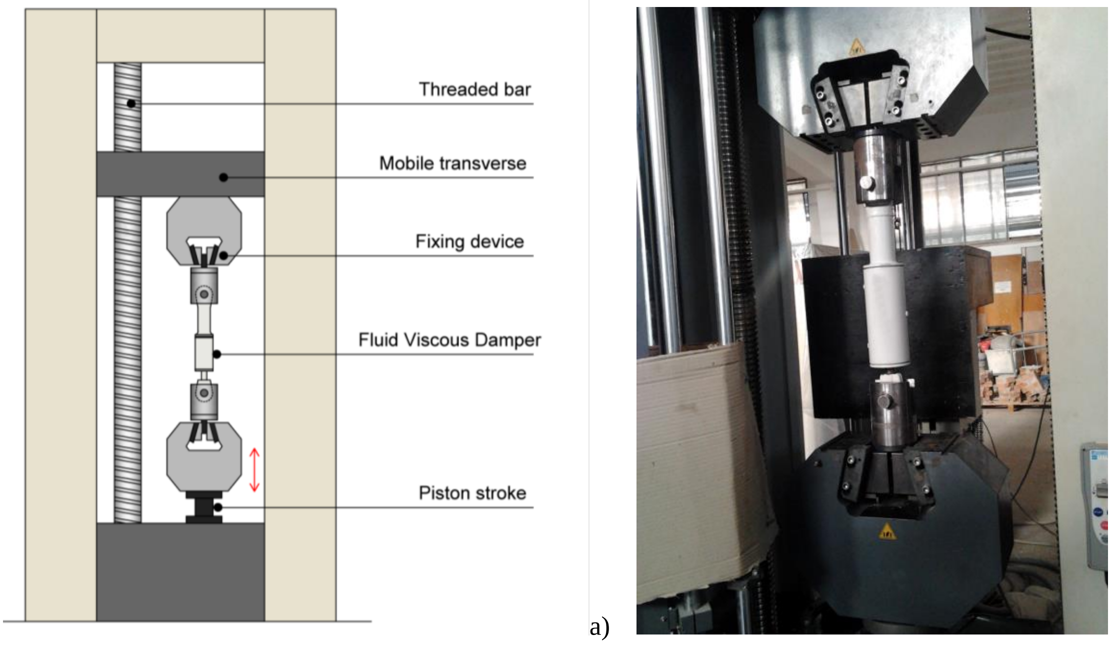
$$\alpha = \frac{log\,t_2 - log\,t_1}{log\left(\dot{x}\left(t_2\right)\right) - log\left(\dot{x}\left(t_1\right)\right)},\ t_2 > t_1 \tag{9}$$

In this case, considering that α represents the slope of the straight line described by Eq. (5), this can be obtained as

$$\alpha = \frac{log\left[F\left(t+\Delta t\right)\right] - log\left[F\left(t\right)\right]}{log\left[\dot{x}\left(t+\Delta t\right)\right] - log\left[\dot{x}\left(t\right)\right]} \tag{10}$$

4 Experimental Tests

Experimental tests have been carried out on a fluid viscous damper actually on the market. The FVD was characterized by the producer providing the following nominal parameters: C=30.53 kN/(mm/sec)$^{0.15}$; α=0.15, maximum velocity 400 mm/sec, maximum stroke 55 mm, maximum force 75 kN. The tests were carried out in a universal machine. The frequency dependent behaviour was not considered in the tests. A scheme of the test apparatus is reported in Figure 5a, while a real picture of the FVD during a test is shown in Figure 5b. Four different tests have been performed. Each test consisted in applying a progressively increasing force up to the achievement of a fixed value, which was maintained constant for about 300 sec. In consideration of Eq. (1) the velocity was variable in the first branch and constant during the 300 secs. of application of the maximum load. Four different constant load (and velocity) levels were considered. For all of them velocity was limited to low levels. The details of the test are reported in Table 1. The experimental force-time and displacement-time responses of the damper during each of the four tests are shown in Figure 6.



a) b)

Figure 1 - *Test of the FVD: a) Scheme of the test apparatus; b) FVD during the test*

Table 1- *Tests setup data*

Test	Maximum force [kN]	Maximum velocity [mm/sec]	Duration of the variable velocity branch [sec]
1	4.0	0.015	50
2	6.0	0.033	71
3	8.0	0.038	88
4	10.0	0.056	112

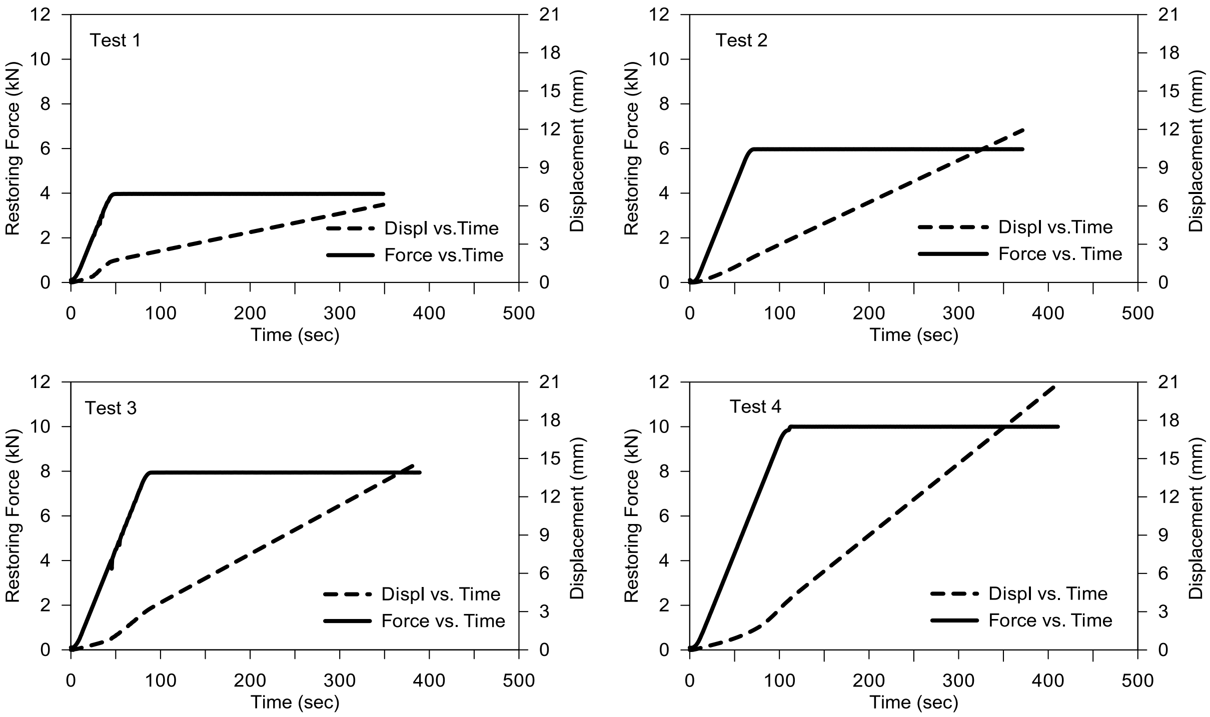


Figure 6 - *Experimental response of the FVD at the different load and velocity levels*

Referring to the constant load branch, the tests were used to determine parameters α and C in the range of velocities considered with the procedure presented in the previous section. Logarithms of forces and of the velocities were used to obtain four points in the $y = Log\, F$ / $z = Log\, \dot{x}$ plane previously described. As it can be observed in Figure 7, experimental points can be interpolated by the function

$$y = 0.67z + 1.83 \tag{10}$$

By comparing Eq.(10) with Eq.(5) one obtains:

$$\begin{aligned} &\alpha = 0.67 \\ &C = 67.6 kN / (mm / sec)^{0.67} \end{aligned} \tag{11}$$

While considering nominal values the expected straight line is:

$$y = 0.15z + 1.55 \tag{12}$$

Figure 7 shows significant differences between results obtained from experimental testing of the FVD and nominal values. In particular, in the range of velocities investigated and increment of +119% of C was found, while the increment of α was +346%. This result implies that the values of the characteristic parameters α and C of fluid viscous dampers are sensitive to the variation of velocity. Hence the constitutive model in Eq. (1) may be not appropriate to accurately describe the response of a FVD at any velocity range.

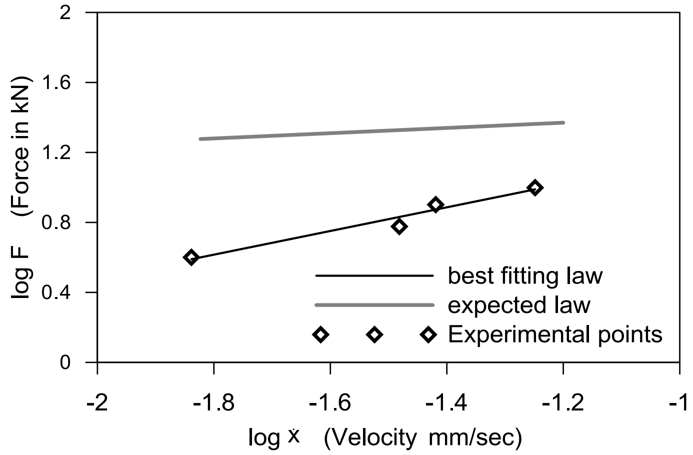


Figure 7 - *Identification of the parameters of the FVD in the constant force branch. Experimental results and nominal values*

The experimental evaluation of the parameter α was also done referring to ascending branch of the experimental force-time curve of the FVD. In this branch the velocity is variable, hence the estimation of α can be performed by using Eq.(9). Figure 8 shows a sequence of estimations of α carried out by using Eq.(9). Even in this case the values of α were larger than the nominal ones and more than double of those evaluated in the constant velocity branch.

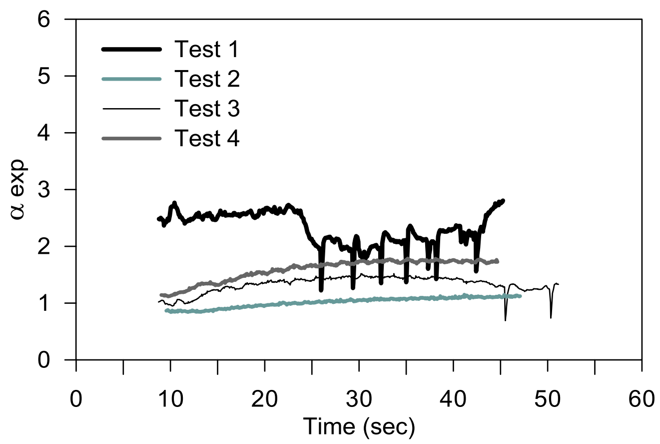


Figure 8 - *Identification of the parameter α of an FVD subject to a linear increase of force*

5 Conclusions

The paper presented the results of experimental tests carried out on a fluid viscous damper (FVD) aimed at determining parameters α and C in the range of low velocities. The tests provided the achievement of a constant load (and velocity) which was maintained for 300 secs. From the results obtained the following conclusions can be drawn:

- FVDs subject to low velocity behave differently to what expected in the range of high velocities;

- Parameters α and *C* resulted to be sensitive to the velocity experimented by the FVD. Significant increments with respect to the nominal values were found in the range of low velocities;
- Eq. (1) has shown to be not reliable for any range of velocity, hence the use of more refined constitutive models is desirable;
- Seismic assessment and design phases should be carried out considering this potential variability of parameters α and *C*.

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DETERMINAZIONE SPERIMENTALE DEI PARAMETRI DI DISSIPATORI VISCOSI A BASSE VELOCITA'

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SUMMARY: *Negli ultimi decenni sono state sviluppate molte strategie per la mitigazione delle vulnerabilità sismica attraverso studi analitici e test sperimentali. Tra questi, la dissipazione energetica per mezzo di dispositivi esterni assume una grande rilevanza per la relativa semplicità di progettazione, anche se applicata a strutture complesse, e l'efficacia nel ridurre la domanda sismica. In particolare, l'utilizzo di dissipatori viscosi rappresenta una soluzione molto efficace, a causa del loro comportamento dipendente dalla velocità e dei costi relativamente bassi. L'applicazione sulle strutture richiede uno studio specifico sotto l'eccitazione sismica e una particolare cura dei dettagli strutturali. In questo contesto, l'utilizzo di adeguati modelli costitutivi per i dissipatori, assume un ruolo fondamentale. Le normative sismiche, così come i modelli di letteratura, si basano generalmente una relazione dipendente dalla velocità e caratterizzata da due costanti che definiscono la forma della curva di forza-spostamento.*
In questo articolo viene presentata una campagna sperimentale finalizzata alla determinazione delle costanti di un dissipatore viscoso in regime di basse velocità. I test sono condotti impiegando funzioni rampa a diverse soglie di velocità. I risultati mostrano che l'ipotesi di indipendenza dalla velocità, delle costanti del dissipatore, non è affidabile nel caso di basse velocità, ponendo nuove questioni circa il limite di validità dei modelli costitutivi generalmente impiegati per i dissipatori viscosi.

KEYWORDS: *Dissipatori viscosi, Dissipazione, bassa velocità, Protezione sismica, Test sperimentali.*

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