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PASSIVE VISCOUS FLUID DEVICES FOR SEISMIC ENERGY DISSIPATION

BY

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Abstract. The conventional seismic design, based on a combination of strength, ductility and energy dissipation of principal structural members, understands the strong motions, such as earthquakes, as loads at which the structure must resist and remain functional, accepting a certain level of structural degradations. While this method based on strength-ductility-energy dissipation can prevent big damages, it is difficult to rehabilitate plastic hinges developed in structural members during a strong seismic action. On the contrary, the concept of a structure with supplemental viscous fluid dampers assumes that the most dissipation energy demand is absorbed by these devices, not by the structure itself, and the damages are mainly localized and concentrated on the devices during earthquakes. The main objective of this paper is to present some of passive viscous fluid dampers and numerical results of a single degree of freedom (SDOF) system protected with such supplemental energy dissipation devices.

Keywords: passive damper; vibration control; damping; energy dissipation.

1. Hysteresis Loops of Viscous Fluid Dampers

Sinusoid load is applied to the material and the corresponding force-displacement points are drawn for several load cycles. Since the area within the

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hysteresis loops represents the amount of energy dissipated during one complete load cycle it is obvious that only simple elastic does not provide any energy dissipation capacity (Fig. 1 *a*). A rigid-plastic, in Fig. 1 *b*, material provides more energy dissipation capacity (Olteanu *et al.*, 2011). The elastoplastic material represented in Fig. 1.c results from the superposition of Fig. 1 *a* and 1 *b* (Dobre *et al.*, 2013; Pastia *et al.*, 2012). The ellipse in the force-displacement plane represents viscous damping behaviour (Fig. 1 *d*). The viscoelastic material behavior is represented by a rotation of the ellipse around the centre caused by the superposition of the linear elastic part Fig. 1 *a* and the viscous part Fig. 1 *d*. Similarly viscoplastic (Fig. 1 *e*) and viscoelastoplastic (Fig. 1 *f*) material behaviour is represented by the superposition of Fig. 1 *d* with Fig. 1 *b* and Fig. 1 *c*, respectively. Knowing the hysteretis properties of the idealised materiel model makes it possible to choose or develop the material model best suited for the actual material or system behaviour obtained from experiments (Olteanu *et al.*, 2015; Pastia *et al.*, 2005).

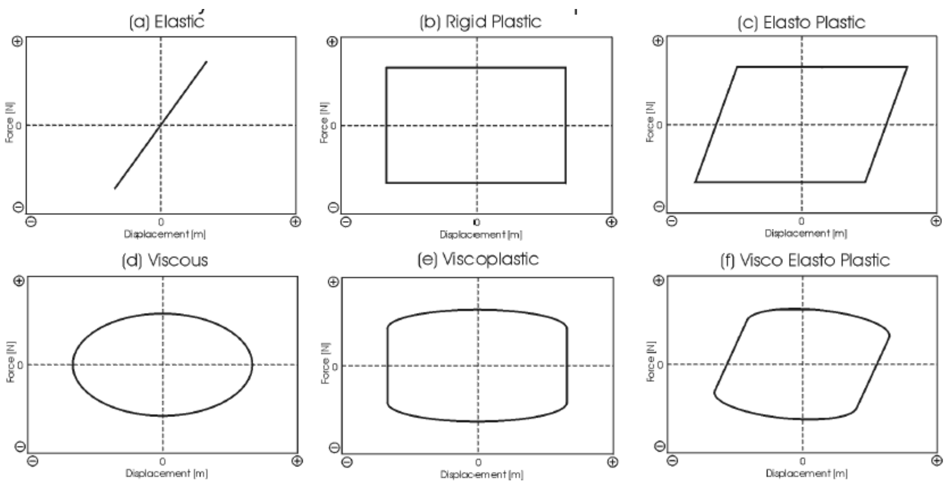


Fig. 1 – Idealised hysteresis loops (Pastia, 2004).

The characteristics of viscous damping devices can best be seen in a force-displacement plot over several load cycles as shown in Fig. 2. The shape of the loop characterizes the response behaviour of the damper and the area of the hysteretis loops represent the energy dissipation potential of the damper always at a given load frequency and amplitude.

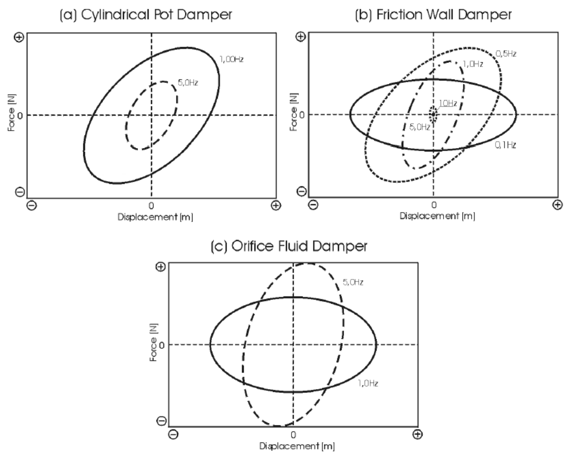


Fig. 2 – Hysteresis loops for different viscous damper types (Pastia, 2004).

1.1. Cylindrical Pot Fluid Dampers

Makris and Constantinou (1990) describes a model for cylindrical pot fluid dampers as the shown in Fig. 3, as a component of seismic base isolation systems. They consist of a cylindrical damper housing filled with a viscous fluid such as oil or silicone and a piston capable of moving within the viscous fluid filling. The damper can be used on its own or can be coupled in parallel with spring elements, see Fig. 3. This set-up is capable of reducing the dynamic system response of in plane loading, but also vertical motions can be mitigated.

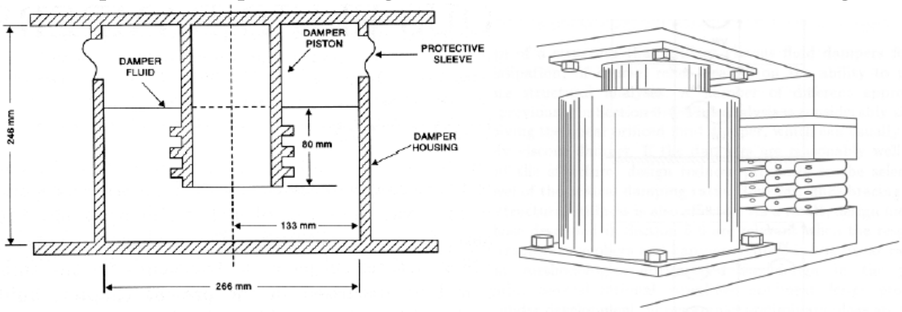


Fig. 3 – Cylindrical pot viscous damper (Makris and Constantinou, 1990).

The dynamic behaviour of this damper type is characterized by elliptical hysteresis loops rotated around the origin as shown in Fig. 2 *a* representing a classic viscoelastic damper element. For increasing excitation frequencies the viscoelastic behaviour remains almost unchanged but the energy dissipation capacity decreases rapidly. The suitable application range of this damper is below 5 Hz.

1.2. Viscous Damping Walls

Viscous damping walls as shown in Fig. 4 consist of a plate connected to the upper floor of the structure moving in a wall shaped container filled with viscous fluid attached to the lower floor. During dynamic horizontal loading the plate element moves within the viscous fluid transferring the kinetic energy via shear forces into the fluid. The shape of the damper makes it easy to integrate into buildings. An application is the seismic protection of the SUT-Building in Shizuka, Japan in 1992.

This damper shows a more complex dynamic behaviour than the viscous pot damper. At a very low excitation frequency of 0.1 Hz it shows pure viscous damping behaviour characterised by the elliptical hysteretic loop shown in Fig. 2 *b* with good energy dissipation capacity. Increasing the load frequency to 0.5 Hz changes the response to a viscoelastic behaviour, rotating the elliptical hysteretic loop about 45 degrees around the origin. A further increase of the load frequency to 1.0 Hz results in an additional rotation of the ellipse characterizing the stiffening of the damper and the area shrinks representing a decrease in energy dissipation capacity. An excitation frequency of 5.0 Hz leads to a very stiff almost rigid viscoelastic damping behaviour with very small energy dissipation. At 10 Hz there is no damper response the element acts as a rigid connection.

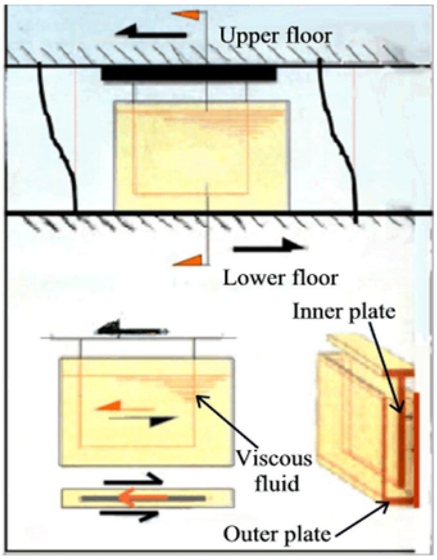


Fig. 4 – Viscous damping wall (Pastia, 2004).

1.3. Orifice Fluid Dampers and Mathematical Model

They have been used in the vehicle and machinery industries for a long time, and there are also examples of civil engineering applications in worldwide. These dampers operate on the principle of the flow of special compressible fluids through orifices and are characterized by a high cycle-fatigue life. The construction of the device is shown in Fig. 5.

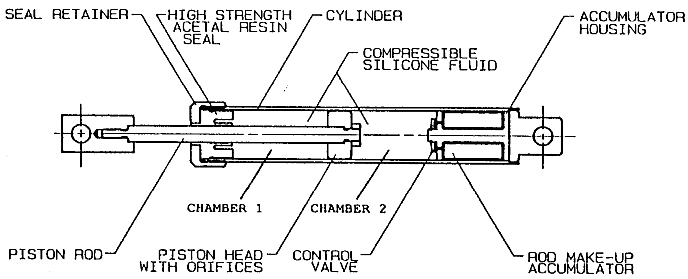


Fig. 5 – Description of passive fluid viscous damper (Symans *et al.*, 2008).

It consists of a stainless steel piston rod, with a bronze orifice head and a piston rod make-up accumulator. The device is filled with a thin silicone oil (kinematic viscosity = 100 cSt, specific weight = 9.78 KN/m^3). The force generated by the fluid damper is due to a pressure differential across the piston head. When the damper is subjected to a compressive force, the fluid volume is reduced by the product of travel and piston rod area. This change in fluid volume is accompanied by the development of a restoring force. This is prevented by use of an accumulator and a control valve. An alternative construction of this device is with a balanced piston rod. A balanced piston rod is one in which the rod enters the damper, is connected to a piston head, and then continues out through the opposite end of the device. The orifice flow around the piston head is compensated by a passive bi-metallic thermostat that allows operation of the device over a wide temperature range (–40^{o}C to 70^{o}C). The elliptical hysteresis loops shown in Fig. 2 *c* shows the viscous behaviour of the device at low excitation frequencies of 1 Hz and the increasing stiffness of the damper at higher frequencies of 4 Hz with viscoelastic behaviour, but still good energy dissipation capability. The cyclic response of fluid viscous devices is generally dependent on the deformation frequency and can be formulated mathematically by the use of a classical Maxwell model in which dashpot and spring are joined in series. The tested device demonstrated that, below a cut-off frequency less than about 4 Hz, the storage stiffness was negligible while the damping coefficient was nearly constant (Symans *et al.*, 2008). This cut-off frequency depends on the accumulator design. Hence, it's well that the device to provide supplemental damping to the natural modes of vibration of the structure which have an important contribution to the structural response. These natural modes must have the frequency less than the cut-off frequency. Also, it's well that the higher modes of vibration do not contribute significantly to the structural response because the damper provides both supplemental damping and stiffness.

The non-linear force-velocity relationship of the passive fluid damper below the cut-off frequency is expressed as (Luca *et al.*, 2009):

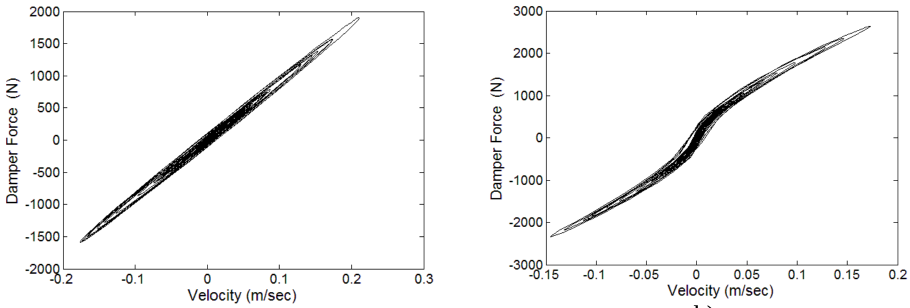
$$f_{df}(t) = C\left|\dot{x}(t)\right|^{\alpha} \operatorname{sgn}\left[\dot{x}(t)\right], \tag{1}$$

where: $\dot{x}(t)$ is the relative velocity of the piston head with respect to the damper housing, C – the damping coefficient and α – the exponent is determined by the piston head orifice design and is situated in the range of approximately 0.2 to 2.0. For seismic applications the exponent α is a value from 0.2 to 1. A design with α = 1 appears to be the most desired for earthquake engineering applications because the damper behavior becomes as an ideal linear viscous dashpot.

2. Structural Response of SDOF System with Passive Orifice Fluid Dampers

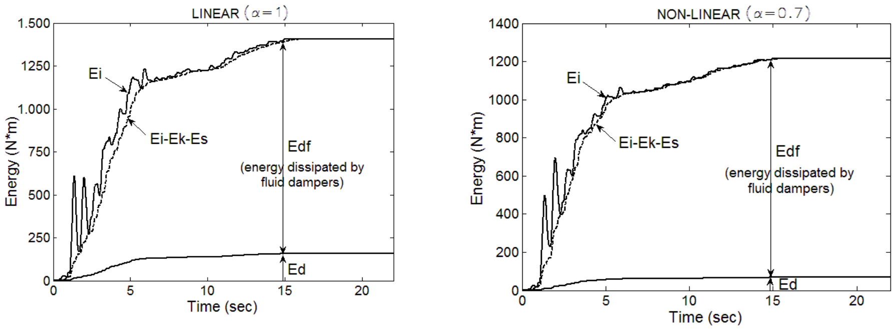
To illustrate the effects of methods for seismic energy dissipation in structures, an idealized SDOF structure will be analyzed when subjected to the historical earthquake recorded at Bucureşti'77 (Dobre *et al.*, 2014; Vacăreanu *et al.*, 2014). The corresponding dynamic characteristics are as follow: mass m = = 11,000 Kg; lateral stiffness k = 1,405,000 N/m; viscous damping c = 2,486 Ns/m; circular frequency ω = 11.302 rad/s; period T = 0.556 s; frequency f = = 1.798 Hz; damping ratio ξ = 0.01. The characteristics of the fluid orifice device are: damping coefficient C = 12,000 Ns/m, exponent α = 1 for the linear behavior and α = 0.7 for the non-linear behavior (see Fig. 6). Results are showed in Figs. 7 and 8 supposing that the structure works in elastic domain and it's equipped with two fluid dampers connected through diagonal bracings to the structure. The global damper force $f_{df}(t)$ acting on the structure is obtained by considering the angle θ = 30° of the damping element with respect to the horizontal axis. For a rigid brace the damper force can be written as

$$f_{df}(t) = C\left|\dot{x}(t)\right|^{\alpha} \operatorname{sgn}\left[\dot{x}(t)\right]\cos^2\theta\,. \tag{2}$$



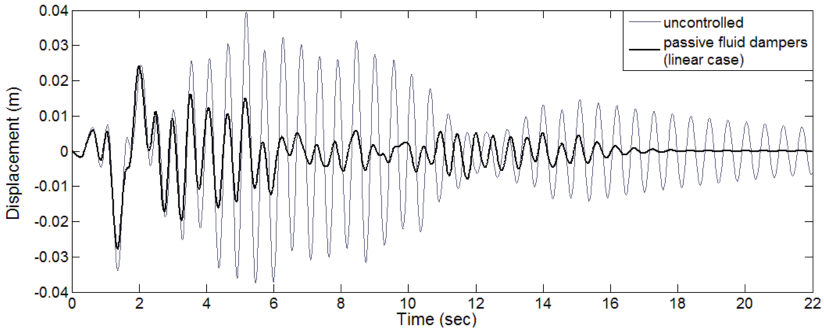
a) b)

Fig. 6 – Force-displacement curves of the passive control dampers:
a) linear (α = 1); b) non-linear (α = 0.7).

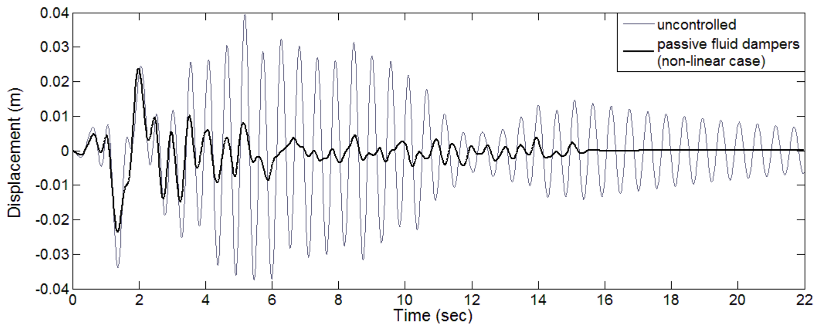


a) b)

Fig. 7 – Time history of energy dissipation in structure with passive fluid dampers:
a) linear (α = 1); b) non-linear (α = 0.7).



a)



b)

Fig. 8 – Comparison of relative displacement response of structure without and with passive fluid dampers: a) linear(α = 1); b) non-linear (α = 0.7).

In this case the demand of energy absorption capacity on the main structural members and the relative displacement response of the system are reduced. Thus, the possibility of structural damage is minimized.

3. Conclusions

The approach using energy dissipation mechanisms is to transfer as much energy as possible from the primary structural members to the device attached to structure. The additional of passive orifice fluid devices demonstrates a reduction of the input energy and of the deformation in structure and thus improves the seismic performance of the structure.

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DISPOZITIVE PASIVE CU FLUID VASCOS PENTRU DISIPAREA ENERGIEI SEISMICE

(Rezumat)

În proiectarea seismică convențională, bazată pe legătura dintre rezistență, ductilitate şi disiparea energiei seismice de către elementele structurale principale, cutremurele si vânturile puternice sunt modelate ca încărcări la care structura trebuie să reziste şi să rămână funcțională, acceptând un anumit nivel de degradări structurale. Deşi această metodă bazată pe rezistență - ductilitate - energie disipată poate preveni avariile mari, este dificilă reabilitarea articulațiilor plastice dezvoltate în elementele structurale în timpul unei acțiunii seismice puternice. Conceptul unei structuri cu disipatori suplimentari cu fluid vâscos presupune că cea mai mare cantitate de energie disipată este absorbită de aceste dispozitive, nu de structura însăşi, iar pagubele sunt în principal localizate şi concentrate pe dispozitive în timpul cutremurelor. Obiectivul principal al acestei lucrări constă în prezentarea unor disipatori pasivi cu fluid vâscos şi a unor rezultate numerice ale unui sistem cu un grad de libertate dinamică protejată cu astfel de disipatori de energie suplimentari.