SEISMIC RESPONSE OF BUILDING STRUCTURES WITH PASSIVE FLUID DAMPERS

CRISTIAN PASTIA, SEPTIMIU-GEORGE LUCA, FIDELIU PAULET- CRAINICEANU, GEORGE TARANU, FLORENTINA LUCA, IONUT-OVIDIU TOMA

"Gheorghe Asachi" Technical University of Iasi (Romania), Faculty of Civil Engineering and Building Services, Dimitrie Mangeron Blvd, pastiacristian@yahoo.com

This paper presents the numerical results of several passive viscous fluid dampers implemented to a real three-storey building to improve the seismic structural performance. For strong earthquakes, a large amount of input energy will be dissipated by inelastic deformation which means structural damages take the form of localized plastic hinges. Energy dissipation demand of the main building elements can be reduced by transferring this energy dissipation demand to the viscous fluid dampers. These devices operate on the principle of the flow of special compressible fluids through orifices and are characterized by a high cycle-fatigue life. Some examples of experimental studies to understand the principles of the operation of the fluid devices for seismic energy dissipation are briefly described. A common mathematical model for describing the linear or nonlinear behavior of viscous fluid dampers in terms of force-velocity curves is presented. Numerical simulations have been performed in order to assess the performance of a structure protected with such devices. The additional of passive viscous fluid dampers demonstrates a reduction of the input energy and of the deformation in structure, this way improving the structural seismic protection.

Keywords: viscous fluid damper, seismic protection, energy dissipation

INTRODUCTION

The traditional approach of decreasing vibrations due to earthquake and wind loads is applied in building structures with enough resistance and capacity of deformation in a ductile way. This approach, based on insuring a combination resistance-ductility of principal elements of a structure, understands the strong seismic action as a load at which the structure must resist and remain functional, accepting a certain level of structural and non-structural degradations.

In seismic design, the input energy of an earthquake is typically dissipated through hysteretic behaviour of main structural elements, which allows the structure to undergo inelastic deformations without compromising the stability of the structure (Banu *et al.*, 2012). Furthermore, inelastic behaviour translates into some level of damage on these elements. This damage leads to high cost for repair works, in the cases when repairs are possible. Sometimes, the damage is so large that repairs are not viable, even though the structure has not collapsed, and the building must be demolished.

The passive dampers dissipate energy on principles as phase transformation in metals, deformation of viscoelastic solids, flow of special compressible fluids through orifices and sliding friction (Budescu *et al.*, 2010; Olteanu *et al.*, 2011; Pastia and Luca, 2012; Stefancu *et al.*, 2011). In this paper, passive viscous fluid dampers are designed such that the most dissipation energy demand is concentrated on these devices. The concept is described in this study in a mathematical relationship for linear or non-linear behaviour of viscous fluid dampers in terms of force-velocity curves. Numerical simulations have been performed in order to assess the performance of the three-degree of freedom lumped mass structure protected with such devices.

Viscous damping devices and tuned mass dampers were used in London Millennium Bridge in order to reduce vertical and horizontal vibrations due to pedestrian induced forces. This reduction corresponds to increasing the basic damping ratio of the structure at 20% for the assumed loads. 8 TMDs were used to provide secondarily additional damping in horizontal direction and a total of 26 pairs of TMDs were installed to supplement primarily the damping in vertical direction. Horizontal and vertical damping is provided by 37 viscous dampers, of 7 different types (Taylor, 2002). Only 4 supplemental viscous damping devices were used to decrease resonant deflections in vertical direction. All viscous dampers increase damping primarily for the lateral and lateral-torsional structural modes. One of viscous damping devices is illustrated in Figure 1, during installation (Dallard *et al.*, 2001).

Figure 1. Installation of viscous dampers beneath the deck of the London Millennium Bridge

MATHEMATICAL MODELING OF VISCOUS FLUID DAMPER BEHAVIOUR

These dampers operate on the principle of the flow of special compressible fluids through orifices and are characterized by a high cycle-fatigue life. Construction of a device is shown in Figure 2 (Symans and Constantinou,1995).

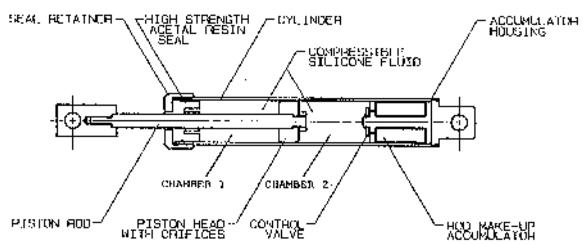


Figure 2. Description of passive viscous fluid damper

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 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 this device over a wide temperature range (-40°C to 70°C) (Symans and Constantinou, 1995).

The linear force-displacement response of a fluid viscous device has commonly been characterized by mechanical models consisting of combinations of linear springs and dashpots. The cyclic response of fluid viscous devices is generally dependent on the deformation frequency and can be mathematically formulated using a classical Maxwell model in which a dashpot and a spring are joined in series. The tested device demonstrated that, below a cut-off frequency less than about 4Hz, the storage stiffness was negligible while the damping coefficient was nearly constant. This cut-off frequency depends on the accumulator design (Symans and Constantinou, 1995). Hence, the device provides supplemental damping to the natural modes of vibration of the structure having an important contribution to the structural response. These natural modes must have frequencies less than the cut-off frequency. Also, 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 (Symans *et al.*, 2008)

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

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 which is determined by the piston head orifice design and is located in a range of approximately 0.5 to 2.0. For seismic applications the exponent α is a value from 0.5 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 (Symans *et al.*, 2008).

SEISMIC RESPONSE OF 3DOF FRAME STRUCTURE WITH PASSIVE FLUID DAMPERS

A series of numerical analyses was performed to a three-story frame structure with one degree of freedom per floor at which are attached damping devices. The dampers were placed at the first story (consisting in 2 fluid devices), at the second story (consisting in 4 fluid devices) and at the third story (consisting in 6 fluid devices).

Description of the Frame Structure

The frame structure constructed inside the ELSA (European Laboratory for Structural Assessment) has three stories. It consists of a steel frame with floors constituted by sheet metal and concrete properly connected. The inter-storey hight is 2 meters because the scale was considered 2/3 of a real structure. The structure has been tested with dynamic and pseudodynamic techniques (Marazzi, 2003). Without entering into details, the mass, stiffness and damping matrices used in the analytical model are as follows:

$$M = \begin{bmatrix} 5000 & 0 & 0 \\ 0 & 5000 & 0 \\ 0 & 0 & 5000 \end{bmatrix} (\text{Kg}), \quad K = \begin{bmatrix} 45774000 & -25936000 & 647000 \\ -25936000 & 36260000 & -17555000 \\ 647000 & -17555000 & 12600000 \end{bmatrix} (\text{N/m}),$$

$$C=\begin{bmatrix} 5854 & -3547 & 1347 \\ -3547 & 5073 & -1571 \\ 1347 & -1571 & 2273 \end{bmatrix} \text{(Ns/m)}.$$

With the above matrices, the identified natural frequencies and the damping ratios are reported in the following table:

Table 1. Frequencies and damping ratios

Frequencies	f_1 3.018 (Hz)	f_2 10.29 (Hz)	f_3 19.09 (Hz)
Damping ratios	ξ_1 0.8 %	ξ_2 0.32 %	ξ_3 0.8 %

These low damping ratio values are normal for a steel structure.

Numerical Results

The structural system has been modeled with MATLAB and several simulations have been performed using as input El Centro and Bucuresti'77 earthquake accelerations and a synthetic ground acceleration time history with a response spectrum compatible with Eurocode 8 (EC8) for stiff soils. Characteristics of the fluid device are: damping coefficient C=20000 Ns/m and exponent α=1 for the linear behavior.

A comparison of peak responses (relative displacement and absolute acceleration at each floors) are shown in Table 2 supposing that the structure works in linear elastic domain and it is equipped with fluid dampers connected through diagonal bracings to the structure. The damper force $f_{df}(t)$ acting on the structure is obtained by considering an angle θ=30^{o} of the damping element with respect to the horizontal axis. For a rigid brace the damper force can be written as

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

Table 2. Peak relative displacements and peak absolute accelerations

Excitation	No. Dampers	d1 (cm)	d2 (cm)	d3 (cm)	a1 (m/s^2)	a2 (m/s^2)	a3 (m/s^2)
El Centro	0	0.9473	2.4811	3.4862	5.3126	9.8528	13.910
El Centro	2	0.8510	2.2892	3.2419	3.4284	7.8442	11.234
El Centro	4	0.6531	1.7724	2.5316	2.9957	5.9727	7.7222
El Centro	6	0.5470	1.4851	2.1233	2.2269	4.6444	6.1147
Buc'77	0	0.3523	0.9140	1.2748	1.4565	3.4807	4.5943
Buc'77	2	0.3269	0.7749	1.0339	1.2054	2.9085	3.8114
Buc'77	4	0.3041	0.7520	1.0235	0.8112	1.9162	2.5047
Buc'77	6	0.2968	0.7354	1.0025	0.6453	1.5654	2.1093
EC8	0	1.4372	3.5653	4.8242	8.3443	14.792	18.006
EC8	2	1.0395	2.6071	3.5607	3.9973	9.5597	12.526
EC8	4	0.7563	1.9075	2.6216	3.2745	6.7703	8.9416
EC8	6	0.5831	1.4684	2.0127	2.7919	5.5471	7.6382

Figure 3 shows a comparison among the time histories of displacement response of the structure's third floor, with and without the 6 fluid dampers.

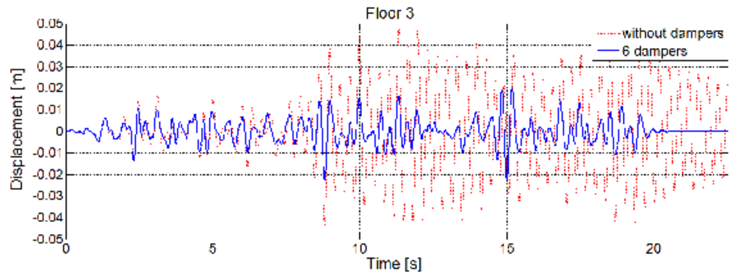


Figure 3. Time histories of displacement response of structural models to EC8 earthquake motion without and with 6 fluid dampers

In all analyzed cases, the effect of fluid dampers is to reduce the response of the 3DOF structural model from 10% (case of 2 dampers) to 65% (case of 6 dampers). The placement of the viscous fluid devices at first story did not have any adverse behavior. In general, the effect of fluid dampers is improved by placing them at those stories where the largest interstory velocities are expected.

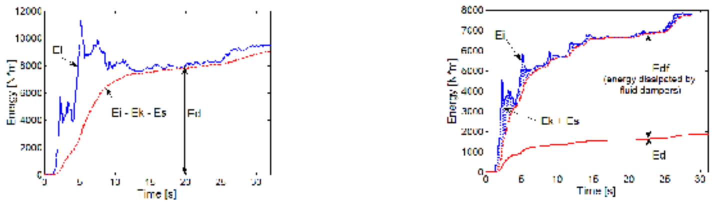
From view point of energy balance, the work done by external forces acting on a system is equal to the sum of the mechanical energy temporarily stored in the structure (kinetic and recoverable strain energies) and the energy transformed to another form, through either viscous damping energy or irrecoverable hysteretic energy. The relative energy balance equation takes the following time-dependent conservation of energy form (Symans, et al., 2008):

$$E_i = E_k + E_s + E_d + E_h + E_{df} \quad (3)$$

where, at time t, E_i is input energy in structure by the earthquake motion, E_k - kinetic energy stored in the mass, E_s - recoverable strain energy stored by the structure, E_d - viscous damping energy dissipated by the principal elements of the structure, E_h - hysteretic energy dissipated by the principal elements of the structure, E_{df} – viscous energy dissipated by the supplemental fluid dampers.

The sum of kinetic and recoverable strain energies indicates the level of deformation in the structure while the hysteretic energy dissipated by the principal elements of the structure shows the level of the structural inelastic action. However, due to the use of additional fluid viscous dampers, the structure is expected to deform into the linear elastic range.

Figure 4 shows time histories of the energy dissipated at third story by viscous damping and kinetic plus strain energies for the linear structural models without and with 6 fluid dampers under El Centro motion. The demand of energy absorption capacity on the main structural members is reduced. When the maximum response of the system is achieved, the peak of input energy is decreased by 50% approximately.



(a) (b)

Figure 4. Time histories of energy dissipation: (a) linear system without fluid dampers, (b) linear system with fluid dampers

CONCLUSION

The response of a 3DOF structural system with conventional and added 2-4-6 passive viscous fluid dampers was analyzed and interpreted. Linear time-history analyses were presented to assess the effect of adding viscous damping devices. Simulation results showed that the addition of 2-4-6 devices is beneficial for reducing the seismic response of the 3DOF frame structure.

The approach using energy dissipation mechanisms consists in transferring as much energy as possible from the primary structural members to the devices attached to structure. It is clearly observed that the increasing of damping ratios of the dominant modes of vibration by supplemental fluid dampers reduces the input energy, the kinetic plus strain energy and the energy dissipated by the principal elements of the structure, this way improving seismic protection of structures.

REFERENCES

Banu, O.M., Olteanu, I., Alistar, A., Budescu, M. (2012), “Vulnerability Assessment. An Efficient Approach to Improve Structural Safety of Locally Damaged Reinforced Concrete Frame Structures”, *Proc. of the 4th Int. on Advanced Materials and Systems*, ICAMS Bucharest, Romania, ISSN 2068-0783, 537-542.

Budescu, M., Taranu, G., Plesu, G. and Taranu, N. (2010), “An Innovative Hybrid Solution to Improve the Seismic Behaviour of a Shear Wall Building Module”, *Proc. of the 3rd International Conference on Advanced Materials and Systems*, ICAMS Bucharest, Romania, ISBN 978-86-904721-6-1, 477-482.

Dallard, P., Fitzpatrick, A.J., Flint, A., Le Bourva, S., Low, A., Ridsdill Smith, R.M., and Willford, M. (2001), “The London Millennium Footbridge”, *The Structural Engineer*, 79(22), 17-33.

Marazzi, F. (2003), *Semi-active Control of Civil Structures: Implementation Aspects*, Ph.D. Dissertation, University of Pavia, Structural Mechanics Department, Italy.

Olteanu, I., Alistar, A., Budescu, M. (2011), “Nonlinear Analysis of Reinforced Concrete Frames in Atena 3D”, *Bul. of the Polytech. Inst. of Jassy*, Romania, Tomme: LVII, Fasc. 2, ISSN: 1224-3884, 93-103.

Pastia, C. and Luca, S.G. (2012), “Seismic Protection of a Realistic Bridge Structure using Passive Friction Devices”, *Bul. of the Polytechnic Inst. of Jassy*, Romania, Tomme: LVIII (LXII), fasc. 1, 77-84.

Stefancu, A.I., Budescu, M. and Paulet-Crainiceanu, F. (2011), “Time-History Analysis of Frictionally Damped Structures”, *Bul. of the Polytech Inst. of Jassy*, Romania, Tomme: LVII (LXI), fasc. 4, 65-74.

Symans, M.D. and Constantinou, M.C. (1995), “Development and Experimental Study of Semi-active Fluid Damping Devices for Seismic Protection of Structures”, *Technical Report* NCEER-95-011, National Centre for Earthquake Engineering Research, Buffalo, New York.

Symans, M.D., Charney, F.A., Whittaker, A.S., Constantinou, M.C., Kircher, C.A., Johnson, M.W. and McNamara, R.J. (2008), “Energy Dissipation Systems for Seismic Applications: Current Practice and Recent Developments”, *Journal of Structural Engineering - ASCE*, USA, vol. 134 (1), 3-21.

Taylor, D.P. (2002), “Damper retrofit of the London Millennium Footbridge – A Case Study in Biodynamic Design”, *Proceedings of the 73d Shock and Vibration Symposium*, Newport, USA, 10.