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Seismic Retrofitting of Buildings Using Fluid Viscous Dampers. Case Study

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1. Introduction

The classical methods for seismic rehabilitation of buildings imply the increase of the strength capacity and stiffness and also a shortening of the fundamental vibration period or an increase of displacement capacity with an increase of the fundamental period too. An extension of the second solution that implies a stiffness reduction and deformation build-up in a single plane is known as base-isolation. Another method for building damage limitation, cheaper than the base isolation, but with not so spectacular results, is the increase of building damping. The increase of damping may be realized for structures with base isolation for diminishing the displacement, but also for moment resisting frame structures with ductile behaviour able to develop large displacements.

If in the case of classical design the energy dissipation is made through plastic hinges, in the case of added fluid viscous dampers, a part of the seismic input energy will be dissipated by the forced flow of a liquid through damper interior orifices; in this way, the building damage will be limited.

The use of viscous dampers has the advantage of the phase delay that exists between damper force and damper displacement, the last one being in phase with the maximum inertia force that exists in structures.

2. Analytical Modeling of Viscous Dampers

Equation (1) governs the force/velocity relation for a fluid viscous damper:

$$F = C \cdot v^{\alpha} \qquad (1)$$

where:
F – damper force
v – relative velocity between piston ends
C – damping coefficient function of damper diameter and orifice area
α - exponential constant, with values between 0.20 and 1.95 (for usual seismic applications, the values are between 0.2 and 1.0). For α=1 the damping is considered linear while for $\alpha \neq 1$ the damping is nonlinear.

Two models for visco-elastic damper modeling are given in literature: Kelvin model and Maxwell model. The Kelvin model (Fig. 1), for which the viscous component is connected in parallel with the elastic (stiffness) one may be used for modeling the dampers together with a framing system or for the base isolation system with dampers. The Maxwell Model (Fig.2), for which the viscous component is connected in series with the elastic one, may be used for modeling the damper together with the brace it belongs to.

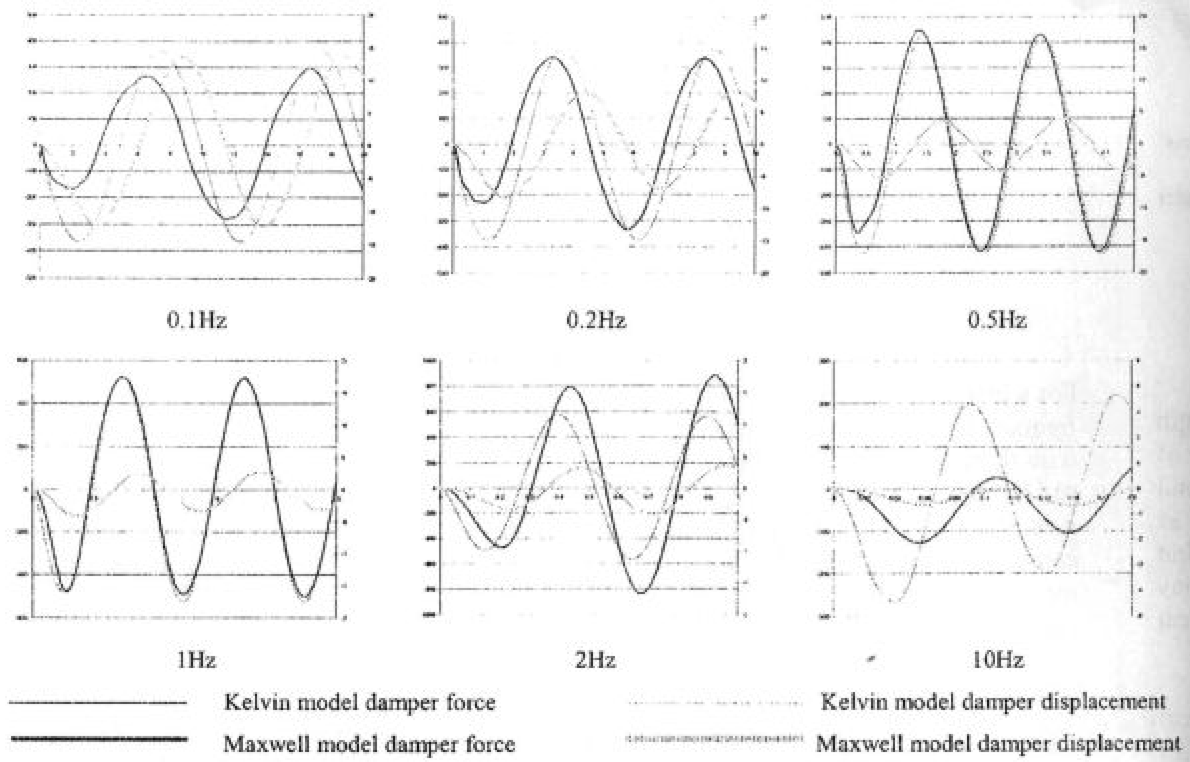

Fig. 4 Forces and displacements in Kelvin and Maxwell models for dampers

3. Effective Damping Ratio of Structures with Linear Viscous Dampers

Consider a single degree of freedom system equipped with a linear viscous damper under an imposed sinusoidal displacement time history:

$$u = u_0 \sin \omega t \tag{2}$$

where u is the displacement of the system and of the damper; u_0 is the amplitude of the displacement; ω is the excitation circular frequency. The force response is:

$$P = P_0 \sin(\omega t + \varphi) \tag{3}$$

where P is the force response of the system; P_0 is the force amplitude; and φ is the phase delay. The energy dissipated by the damper, W_D, is:

$$W_D = \oint F_D du \tag{4}$$

where F_D is the damper force equal to $C\dot{u}$; C is the damping constant of the damper; and $\dot{u}$ is the velocity of the system and of the damper. Therefore,

$$W_D = \oint C\dot{u}du = \int_0^{2\pi/\omega} C\dot{u}^2 dt = Cu_0^2\omega^2 \int_0^{2\pi} \cos^2 \omega t \, d(\omega t) = \pi C u_0^2 \omega \tag{5}$$

Considering that the damping ratio contributed by the damper can be expressed as $\xi_d = C / C_{cr}$, the following equation is obtained:

$$W_D = \pi C u_0^2 \omega = \pi \xi_d C_{cr} u_0^2 \omega = 2\pi \xi_d \sqrt{Km} u_0^2 \omega = 2\pi \xi_d K u_0^2 \frac{\omega}{\omega_0} = 2\pi \xi_d W_s \frac{\omega}{\omega_0} \tag{6}$$

where C_{cr} is the critical damping coefficient, K is the system stiffness, m mass of the system, ω_0 circular frequency and W_S is the elastic strain energy of the system. The damping ratio attributed to the damper may be expressed as:

$$\xi_d = \frac{W_D}{2\pi W_s}\frac{\omega_0}{\omega} \tag{7}$$

where W_D and W_S are represented in Figure 5. For seismic excitations, $\omega = \omega_0$ so equation (7) becomes:

$$\xi_d = \frac{W_D}{2\pi W_s} \tag{8}$$

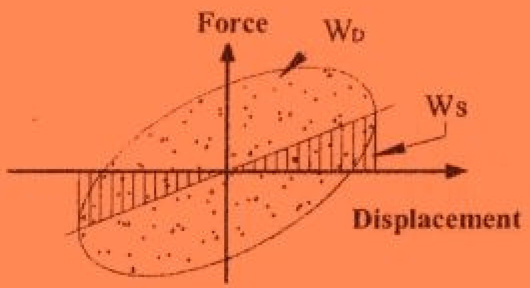

Fig 5 Definition of dissipated energy per cycle - W_D and of elastic strain energy– W_S for a SDOF system with viscous damping

Considering an MDOF system; the total effective damping of the system may be defined as:

$$\xi_{ef} = \xi_0 + \xi_d \tag{9}$$

where ξ_0 is the damping ratio of the MDOF system without dampers and ξ_d is the damping ratio of the added dampers. Extending the concept of SDOF system for MDOF ones:

$$\xi_d = \frac{\sum W_j}{2\pi W_k} \tag{10}$$

where $\sum W_j$ is the sum of the energy dissipated by the "j" damper of the system in one cycle and W_K is the elastic strain energy of the structure that equals to:

$$W_k = \sum F_i \Delta_i \tag{11}$$

where F_i is the story shear force, Δ_i is the "i"th storey relative displacement. Now, the energy dissipated by viscous dampers may be expressed as:

$$\sum_j W_j = \sum_j \pi C_j u_j^2 \omega_0 = \frac{2\pi^2}{T}\sum_j C_j u_j^2 \tag{12}$$

where u_j is the relative axial displacement of the "j" damper between the two ends.

Using the modal strain energy method, the energy dissipated by the dampers and the elastic strain energy provided by the primary frame may be rewritten as:

$$\sum_j W_j = \frac{2\pi^2}{T}\sum_j C_j \phi_{rj}^2 \cos^2\theta_j \tag{13}$$

and

$$W_K = \Phi_1^T[K]\Phi_1 = \Phi_1^T \omega^2 [m]\Phi_1 = \sum_i \omega^2 m_i \phi_i^2 = \frac{4\pi^2}{T^2}\sum_i m_i \phi_i^2 \qquad (14)$$

where $[K]$ is the stiffness matrix of the system, $[m]$ lumped mass matrix and Φ_1 first mode shape of the system; ϕ_{rj} is the relative horizontal displacement of the damper "j" corresponding to first mode shape, ϕ_i is the first mode displacement at level "i"; m_i is mass of floor "i" and θ_j is the inclined angle of the damper j. By substituting equations (13), (14) in equation (10) and the last one in equation (9), the effective damping ratio of a structure results, with linear viscous dampers is given by:

$$\xi_{ef} = \xi_0 + \frac{\frac{2\pi^2}{T}\sum_j C_j \phi_{rj}^2 \cos^2\theta_j}{2\pi \frac{4\pi^2}{T^2}\sum_i m_i \phi_i^2} = \xi_0 + \frac{T\sum_j C_j \phi_{rj}^2 \cos^2\theta_j}{4\pi \sum_i m_i \phi_i^2} \qquad (15)$$

In the design codes there is no suggestion for a procedure to distribute the values of C along the height of a building so when designing a structure with viscous damping it may be convenient to distribute the C values equally on each floor. Hence, an efficient distribution of the C values of the dampers may be to size the horizontal damper force in proportion to the storey shear forces of the primary frame.

4. Case Study

4.1 Improvement of structural seismic response by increasing damping ratio

The possibility of improving the response of a structure (section A of the building of Technical University of Civil Engineering of Bucharest) using viscous dampers such as to reduce the large displacements expected during a strong earthquake was studied.

The building with basement, ground floor and 3 stories dissipates too little energy through plastic hinges (lack of ductility) and it is characterized by a high risk of extended damage in case of an incidence of a major earthquake.

The structural system is made of reinforced concrete orthogonal frames in the longitudinal and transversal direction, with cast in place reinforced concrete slabs. For this building, the possibility of improving the seismic response in the transversal direction (Fig. 6, Fig. 7) was studied by using added fluid viscous dampers.

4.2 Structural Analysis

In order to determine the structure deformation and strength capacity, a static - non-linear (push-over) analysis using ETABS 8.15 was completed. The structure was loaded with imposed displacements keeping a constant distribution of the lateral forces proportional to the first mode shape.

Fig. 8 presents the variation of the base shear P versus displacement Δ, the P-Δ curve, for the transversal direction of section A. The structure capacity for an ultimate displacement of 28 cm is around 470kN.

As input time-history acceleration for the base of the building, the N-S component of the record of March 4th, 1977 Vrancea earthquake recorded at INCERC site was used. Figure 9 presents the displacement response spectrum of the previous mentioned record obtained by using the software SeismoSignal v3.1.0. The results of the analysis show excessively large drift demands.

The rehabilitation proposal using viscous dampers came up from the idea of introducing less force in the initial structure by adding these devices, so that at the maximum relative story displacement, the indirect force in the column from the maximum vertical component of the force developed by

The use of viscous dampers for seismic rehabilitation is efficient for displacement reduction but not as efficient for inertia force reduction if the structure undergoes large inelastic displacements.

The use of viscous dampers for seismic rehabilitation of moment resisting frames requires special attention to be paid to their contribution to columns axial forces and avoidance, as much as possible, of time overlapping of beam maximum shear forces with maximum damper forces.

Renforcement parasismique des immeubles avec amortisseurs à fluide visqueux. Etude de cas

Résumé

Le renforcement parasismique des immeubles en utilisant des méthodes classiques présente certains inconvénients pour les résidents/utilisateurs à cause des travaux impliqués. En comparaison avec les méthodes traditionelles, dans le cas d'utilisation des amortisseurs à fluide visqueux, l'immeuble peut être utilisé tout au long de la période des travaux. Dans ce cas il faut également noter le décalage en phase entre le maximum des forces d'inertie dans la structure et le maximum de ces forces dans les amortisseurs. Dans le présent article est presenté le projet préliminaire de renforcement parasismique d'un imeuble avec amortisseurs linéaires à fluide visqueux. L'article contient également des détails sur: l'influence de l'amortissement dans le comportement de la structure sans aucune intervention, le déplacement spectral et le déplacement au sommet de la structure pour la structure analysée en domaine linéaire et non-linéaire, en utilisant des différents pourcentages de l'amortissement critique et les amortisseurs qui lui correspondent. Finalement sont présentées les caractéristiques techniques des amortisseurs et leurs disposition dans la structure, afin d'atteindre le pourcentage d'amortissement critique ciblé/nécessaire.

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