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Seismic Response of Hybrid Systems with Metallic and Viscous Dampers

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Summary

Metallic dampers can enhance structural performance by reducing seismically induced lateral displacements, and by reducing inelastic behavior of beams and columns. Limiting story drift also indirectly allows for mitigation of damage to nonstructural components that are sensitive to lateral deformations. However, many nonstructural elements and components are vulnerable to excessive accelerations. Therefore, in order to protect these components, floor accelerations in buildings should be kept below certain limits. In this perspective, this paper investigates the seismic performance of single-degree-of-freedom (SDOF) systems with metallic and viscous dampers installed in parallel, to determine the effectiveness or appropriateness of using metallic dampers to mitigate lateral displacements, simultaneously with viscous dampers to reduce acceleration demands. Parametric analyses investigate the effectiveness of adding various levels of viscous damping on the equivalent hysteretic damping and on the spectral floor acceleration for short, intermediate, and long period structures.

Introduction

Metallic dampers (a.k.a. hysteretic dampers), especially designed to behave as passive energy dissipation (PED) devices, have been thoroughly studied in the past to enhance structural performance by reducing seismically induced structural damage. In this sense, metallic dampers have been implemented primarily in flexible framing systems (e.g., moment frames) to reduce interstory drifts, and eliminate (or at least reduce) inelastic behavior in beams and columns (Bruneau et al., 1998). Limiting story drift allows mitigation of damage to nonstructural components that are sensitive to lateral deformations (i.e., elements that are generally attached to consecutive floors). However, many nonstructural elements and equipment are attached to a single floor, and can lose their functionality due to excessive sliding, overturning, or damage to their internal components due to severe floor vibrations.

Although metallic dampers have been shown to be effective in reducing interstory drifts, some studies have found that, in many cases, the use of metallic dampers may cause increases in floor accelerations due to the added stiffness, which may negatively affect seismic behavior of nonstructural components (e.g., Iwata, 2004; Mayes et al., 2004; Tong et al., 2004, to name a few). This suggests that it may be desirable to use metallic dampers to mitigate lateral displacements, along with viscous dampers to reduce acceleration demands. In this perspective, this paper investigates the seismic performance of single-degree-of-freedom (SDOF) systems with metallic and viscous dampers installed in parallel.

Equivalent Viscous Damping (Hysteretic Damping)

In many structural analyses such as the Nonlinear Static Procedure (FEMA 356), the dynamic characteristics of a structure having metallic dampers are transformed to an effective period, T_{eff}, which is obtained from the secant or effective stiffness, K_{eff}, of the combined system (i.e., bare frame plus dampers) to the point of maximum displacement as illustrated in Figure 1a, and an equivalent viscous damping (a.k.a. hysteretic damping), ξ_h, also determined from specific hysteresis loops at the point of maximum displacement. Generally, the hysteretic damping for a metallic damper is obtained by setting the area within a hysteresis loop equal to the area within a viscous damper cycle, provided that the area contained within one cycle of motion is the energy dissipated per cycle (Hanson and Soong, 2001).

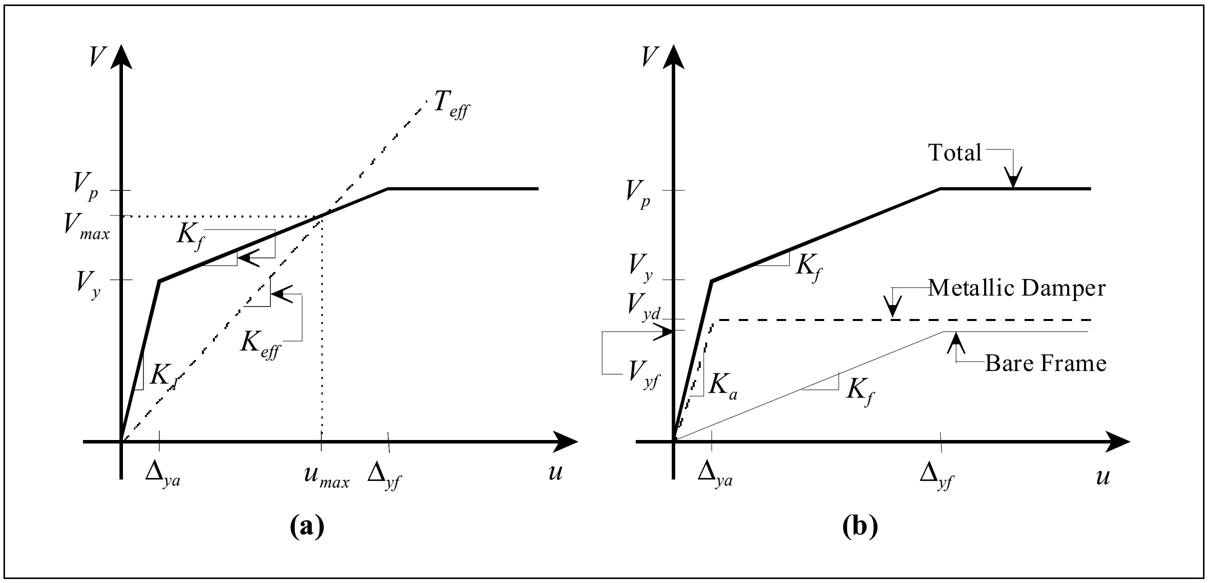

Figure 1. General pushover curve: (a) Effective stiffness and period; (b) Bare frame and metallic damper contribution to the total base shear capacity

The set of parameters used in this study are obtained from Figure 1b: the stiffness ratio, α, the maximum displacement ductility, μ_{max}, and the strength-ratio, η. The stiffness ratio, α, is the relation between the frame stiffness, K_f, and the total initial stiffness, K_1 which can be calculated as:

$$\alpha = \frac{1}{1 + K_a / K_f} < 1.0 \tag{1}$$

The maximum displacement ductility is the maximum displacement ductility that the structure experiences before the frame undergoes inelastic deformations. This parameter can be written as:

$$\mu_{\max} = \frac{\Delta_{yf}}{\Delta_{ya}} > 1.0 \tag{2}$$

where Δ_{ya} and Δ_{yf} are the yield displacement of the metallic dampers, and the yield displacement of the frame, respectively. The strength-ratio, η, is determined as the relation between the yield strength, V_y, and the maximum ground force applied during the motion, defined as:

$$\eta = \frac{V_y}{m\ddot{u}_{g\max}} \tag{3}$$

where m is the system mass and $\ddot{u}_{g\max}$ is the peak ground acceleration. Consequently, the hysteretic damping, ξ_h, may be determined from the following expression, adapted from Ramirez et al. (2000):

$$\xi_h = \left(\frac{2}{\pi}\right)\left[\frac{\left(1-1/\mu_f\right)+\dfrac{(1-\alpha)}{\alpha\mu_{\max}}(1-1/\mu)}{1+\dfrac{(1-\alpha)}{\alpha\mu_{\max}}}\right] \geq 0 \tag{4}$$

where μ and μ_f are the global and frame ductility determined as u_{max} / Δ_{ya} and u_{max} / Δ_{yf}, respectively (see Figure 1b), and u_{max} is the system maximum lateral displacement. Note that for $\mu < 0$ (and therefore, $\mu_f < 0$), the system remains elastic, which translates into no dissipation of energy through hysteretic behavior and, therefore, no hysteretic damping is developed (i.e., $\xi_h = 0$).

Hysteretic Response

As previously mentioned, the main purpose of this paper is to investigate whether using viscous fluid dampers in parallel with metallic dampers can simultaneously reduce lateral displacements and floor accelerations. Although lateral displacement always decreases when using metallic, viscous, or both kinds of dampers acting together, it was found that floor acceleration increases in most of the considered cases, even for systems designed with large viscous damping (Vargas and Bruneau, 2005). This section focuses on studying the hysteretic response of short, intermediate, and long period systems, using the lowest and highest values of η from the set of analyses (i.e., $\eta = 0.2$ and $\eta = 1.0$), along with several levels of viscous damping (i.e., 5%, 10%, 20%, and 30%), to understand the reason for these observed increases in acceleration.

Using d'Alembert's principle, it is possible to express the equation of motion of a SDOF system as an equation of dynamic equilibrium (Clough and Penzien, 1993). Therefore, for a SDOF subjected to ground excitation, the equation of motion may be written as:

$$F_i + F_d + F_s = 0 \tag{5}$$

where F_i is the inertial force, calculated as:

$$F_i = m\left(\ddot{u}_g + \ddot{u}\right) \tag{6}$$

where $\ddot{u}_g$ and $\ddot{u}$ are the ground acceleration, and the relative floor acceleration, respectively, F_d is the viscous damper force, and F_s is the sum of the metallic damper force and the structural frame force, called here the hysteretic force, determined according to the following expression:

$$F_s = \begin{cases} K_1 u \ , & u < \Delta_{ya} \\ V_y + \alpha K_1 (u - \Delta_{ya}) \ , & \Delta_{ya} \le u < \Delta_{yf} \\ V_p \ , & \Delta_{ya} \le u \end{cases} \tag{7}$$

where all variables are defined in Figure 1. Note that for undamped systems (i.e., $F_d = 0$), the inertial and hysteretic forces must be equal and opposite to satisfy the dynamic equilibrium of Equation (5). In damped systems, increases in viscous damping result in decreases in the lateral displacement, u, and therefore, decreases in the hysteretic force, F_s, according to Equation (7) (assuming that the system is designed such that $u < \Delta_{yf}$, which is required to prevent any inelastic behavior of the frame). Consequently, acceleration demand, $\ddot{u}$, may increase (or decrease) to satisfy dynamic equilibrium. The resultant increase or decrease in the inertial force depends on the increase in F_d value relative to the decrease in the value of F_s. For instance, if $\Delta F_d > |\Delta F_s|$ then $\Delta\ddot{u} > 0$ (i.e., acceleration increases), and if $\Delta F_d < |\Delta F_s|$ then $\Delta\ddot{u} < 0$ (i.e., acceleration decreases).

Figure 2 shows some examples of the superposed hysteresis loops for the inertial force and hysteretic force normalized with respect to the yield point (V_y, Δ_{ya}). The difference between the curves is equal to the viscous damper force, F_d. Note that when the maximum displacement is reached (i.e., $\dot{u} = 0$) the values of both curves coincide (i.e., $|F_i| = |F_s|$). Maximum difference between the curves is obtained when $u = 0$ (i.e., maximum velocity), since the hysteretic force has its minimum value at this point. For elastic systems (i.e., $u < \Delta_{ya}$), when $u = 0$, $F_s = 0$, the inertial force and the damping force are equal (i.e., $|F_i| = |F_d|$).

Note that for systems that behave inelastically and for which the frame remains elastic (i.e., $\Delta_{ya} \le u < \Delta_{yf}$), the stiffness ratio, α, has a significant influence on the acceleration demand, since $F_s = V_y + \alpha K_1 (u - \Delta_{ya})$ in this region. Since $F_s \approx V_y$ in systems with small values of α, a reduction in the hysteretic force when viscous damping is added is not significant. On the other hand, F_s may be significantly reduced in systems with large values of α, when maximum displacement decreases by the addition of viscous damping. For example, in a system with $T = 0.5$ s, $\eta = 0.2$, $\alpha = 0.05$, $\mu_{max} = 10$ (Figure 2), the hysteretic force remains almost constant (i.e., $\Delta F_s \approx 0$), and the acceleration demand consequently increases by 62%, when 25% of extra viscous damping is added. For the same system, but with $\alpha = 0.50$ instead, F_s is reduced by 40% when 25% of viscous damping is added (i.e., $\Delta F_d < |\Delta F_s|$), and accordingly, the acceleration demand decreases by 26%.

Also, it may be noted in Figure 2 that for elastic systems (i.e., $F_s = K_1 u$), the displacement and acceleration demands both decrease by increasing the viscous damping, since the decrease in the hysteretic force is always larger than the increase in the viscous damper force (i.e., $\Delta F_d < |\Delta F_s|$). For example, in a system with $T = 1.50$ s, $\eta = 1.0$, $\alpha = 0.25$, $\mu_{max} = 2.5$, the hysteretic force reduces by 40% when 25% of viscous damping is added (i.e., $\Delta F_d < |\Delta F_s|$), and the acceleration demand accordingly decreases by 46%.

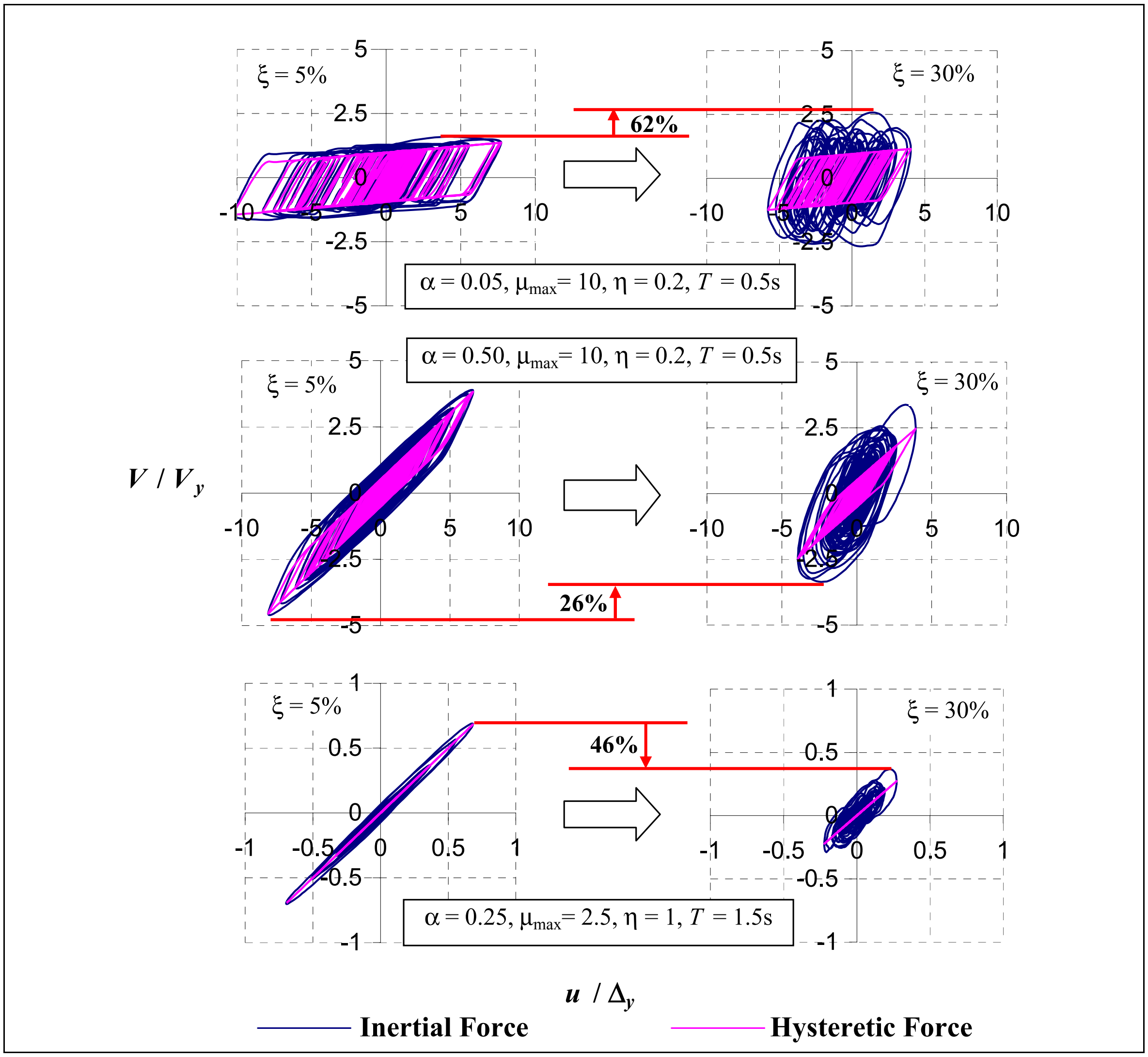

Figure 2. Normalized hysteresis loops for 5% and 30% of viscous damping

These results corroborate the fact that the addition of viscous damping is effective in reducing the displacements and acceleration demands of elastic or near-elastic (e.g., $\alpha = 0.5$) systems, but is ineffective (and in fact detrimental) for nonlinear systems. However, metallic dampers with elastic behavior are not effective, since they only provide additional stiffness to reduce lateral displacements, which is something that could be done just as well with conventional structural elements (Vargas and Bruneau, 2005).

Analysis in the Frequency Domain

Results from the previously studied systems were also analyzed in the frequency domain. Using the Fast Fourier Transform (FFT) algorithm (Cooley and Tukey, 1965), response of the systems studied parametrically here were transformed from the time domain to the frequency domain, in which inertial, viscous damper, and hysteretic forces can be represented as rotational vectors forming a closed polygon in the complex plane, as schematically shown in Figure 3 (a.k.a. Argand diagrams as in Clough and Penzien, 1993). Figure 3a shows a representation of the equation of motion (Equation (5)) for a system with elastic behavior at a particular time during the earthquake time history. Note that increases in the viscous damper force result in substantial decreases in the hysteretic and in the inertial forces (shown as dotted lines). On the other hand, in systems with inelastic behavior (Figure 3b) an increase in the viscous damper force may result in a substantial increase in the inertial force along with a slight decrease in the hysteretic force (shown again as dotted lines).

Note that for small viscous damping (i.e., 5%), the inertial force and the hysteretic force are almost equal (see Figure 2). On the other hand, for systems with large viscous damping (i.e., 30%), the inertial force is considerably greater than the hysteretic force. This vectorial addition shows how a greater damping force can lead to the acceleration increases described in the previous section. Incidentally, this observation has been reported by some practitioners that have considered using viscous dampers to retrofit buildings in selective case studies, and have noticed increases in the floor accelerations if the structure remains inelastic after the retrofit but could not explain why (e.g., personal communication, Dr. Chris Tokas, Manager, California Hospital Seismic Retrofit Program, State of California Office of Statewide Health Planning and Development).

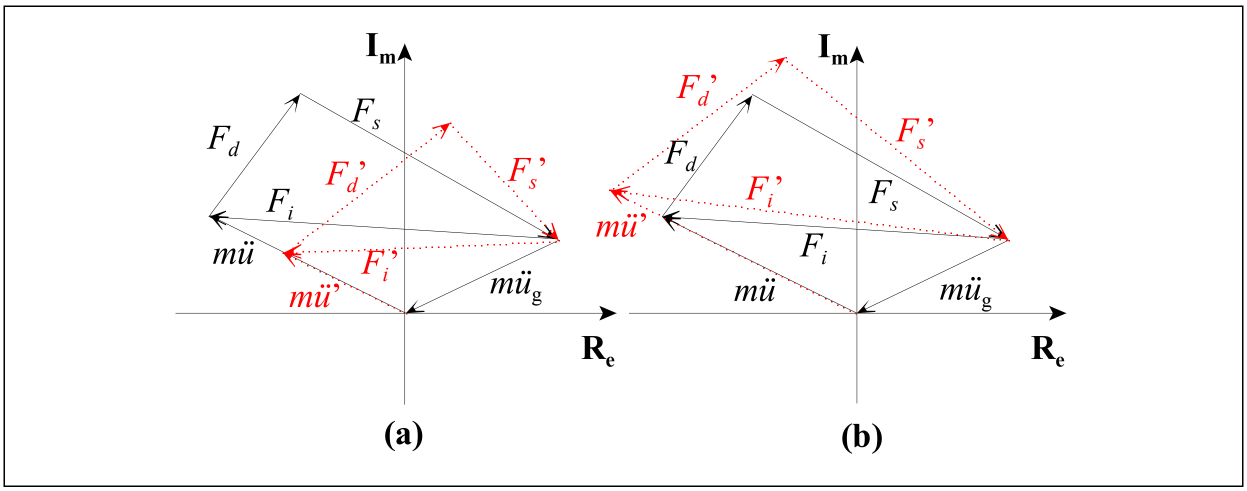

Figure 3. Schematic Representation of Inertial, Viscous Damper and Metallic Damper Forces: (a) Elastic Systems; (b) Inelastic Systems

Conclusions

Seismic response of hybrid systems having metallic and viscous dampers has been studied in this paper through parametric analyses. It was found that increases in viscous damping reduce the effectiveness of metallic dampers, since the amplitude of motion (and thus ductility demand) is reduced. In some cases, when the amplitude of motion decreases to the point where the system behaves elastically, metallic dampers only work to provide additional stiffness to the system, which may be achieved by other conventional methods (e.g., steel braces as apposed to special ductile devices).

Although viscous dampers are known to decrease both displacements and acceleration demands in structures with elastic behavior, for structural systems where metallic dampers are designed to behave inelastically (i.e., $\Delta_{ya} \leq u < \Delta_{yf}$), the floor accelerations are likely to increase if viscous dampers are added in parallel to metallic dampers, especially for systems with small stiffness ratio (i.e., α < 0.25). Adding such viscous dampers in parallel is therefore not only ineffective but detrimental to the seismic performance of acceleration sensitive equipment and nonstructural components. This observation would also be true for buildings that have been retrofitted with viscous dampers and whose original frame still behaves inelastically under major earthquakes. Argand diagrams in the frequency domain are successfully used to explain these observations.

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References

Bruneau M, Uang CM, Whittaker A (1998): *Ductile Design of Steel Structures*. McGraw Hill, New York

Clough RW, Penzien J (1993): *Dynamics of Structures*. Second Edition. McGraw Hill, New York.

Cooley JW, Tukey JW (1965): An Algorithm for Machine Calculation of Complex Fourier Series. *Mathematics of Computation*, American Mathematical Society, Volume 9, No. 90, pp. 297-301.

Hanson RD, Soong TT (2001): Seismic Design with Supplemental Energy Dissipation Devices. *Monograph No. MNO-8*, Earthquake Engineering Research Institute, Oakland, California.

Iwata M (2004): Applications-Design of Buckling Restrained Braces in Japan. *13th World Conference on Earthquake Engineering*, Vancouver, Canada, 2004. Paper No.3208.

Mayes R, Goings C, Naguib W, Harris S, Lovejoy J, Fanucci J, Bystricky P, Hayes J (2004): Comparative Performance of Buckling-Restrained Braces and Moment Frames. *13th World Conference on Earthquake Engineering*, Vancouver, Canada, 2004. Paper No.2287.

Ramirez OM, Constantinou MC, Kircher CA, Whittaker AS, Johnson MW, Gomez JD, Chrysostomou CZ (2000): Development and Evaluation of Simplified Procedures for Analysis and Design of Buildings with Passive Energy Dissipation Systems. *Report No. MCEER-00-0010, Revision 1*, Multidisciplinary Center for Earthquake Engineering Research, University at Buffalo, State University of New York, Buffalo, NY.

Tokas C (2005): Personal Communication. Manager, California Hospital Seismic Retrofit Program, State of California Office of Statewide Health Planning and Development (OSHPD).

Tong M, Lee GC, Rzhevsky V, Qi J, Shinozuka M, Middleton J (2004): A Comparison of Seismic Risk of Non-structural Systems in a Hospital before and after a Major Structural Retrofit. *ATC-29-2 Seminar on Seismic Design, Retrofit, and Performance of Nonstructural Components in Critical Facilities*. Newport Beach, CA.

Vargas R, Bruneau M (2005): Investigation of the Structural Fuse Concept. *Draft Report*, Multidisciplinary Center for Earthquake Engineering Research, State University of New York at Buffalo.