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SEISMIC REHABILITATION USING SUPPLEMENTAL DAMPING SYSTEMS

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ABSTRACT

Recent earthquakes in the United States (1989 Loma Prieta and 1994 Northridge) and Japan (1995 Hyogo-ken-Nanbu) have clearly demonstrated the need to rehabilitate (retrofit) vulnerable buildings. On the West Coast of the United States, vulnerable construction generally predates the mid 1970's, although there exist many more modern buildings requiring retrofit. Such rehabilitation in the United States has been hampered by the lack of guidelines and commentary for design professionals and building officials.

Guidelines and commentary for the seismic rehabilitation of buildings are now being developed in the United States with funding from the Federal Emergency Management Agency (FEMA). The project will be completed in 1997. One key component of the project is incorporating provisions for supplemental damping systems. This effort is timely because damping hardware is now being proposed for seismic rehabilitation.

This paper describes the means by which energy dissipation hardware is classified for analysis purposes, and outlines modeling and analysis procedures being developed for use with energy dissipation systems. Recommendations for further study are also described.

KEYWORDS

analysis; damping; energy; nonlinear; pushover; rehabilitation; seismic.

INTRODUCTION

Seismic framing systems must be capable of absorbing and dissipating energy in a non-degrading manner for many cycles of substantial deformation. In modern conventional construction, energy dissipation occurs in plastic hinge zones in members of the structural frame that routinely form part of the gravity load resisting system. Such energy dissipation is accompanied by substantial nonlinear response (characterized by ductility) and constitutes damage to the seismic framing system. As evinced by experiences following the 1994 Northridge earthquake, structural damage is often difficult and expensive to repair following an earthquake. Older construction is generally characterized by little to no ductility, rapid stiffness and strength degradation following yielding, and poor energy dissipation characteristics.

Recent earthquakes in the United States (1989 Loma Prieta and 1994 Northridge) and Japan (1995 Hyogo-ken-Nanbu) have clearly demonstrated the need to retrofit vulnerable buildings. On the West Coast of the United States, vulnerable construction generally predates the mid 1970's, although there exist many more modern buildings requiring retrofit.

One major goal of seismic rehabilitation is to limit deformations to protect the older construction from damage, that is, to prevent substantial nonlinear response in the older, nonductile framing elements. The designer, using conventional construction such as reinforced concrete shear walls and steel braced frames, has the objective of forcing the seismic energy dissipation (damage) into the new, ductile elements. The drawback to this strategy is that many of the new elements may be substantially damaged following an earthquake. This damage may be difficult and expensive to repair.

The objective of adding damping hardware to existing construction is to dissipate much of the earthquake-induced energy in *disposable* elements not forming part of the gravity framing system — thus permitting easy, and relatively inexpensive, replacement (if necessary) following an earthquake. As such, the implementation of damping hardware is conceptually attractive for seismic rehabilitation. However, the absence of guidance and resource material has hindered the use of such hardware.

Widespread seismic rehabilitation of older construction in the United States has been hampered by the lack of guidelines for design professionals and building officials. This lack of resource material is being rectified by the preparation of guidelines and commentary for seismic rehabilitation — a project widely known as ATC-33. This national project is being funded by the Federal Emergency management Agency. One key component of Project ATC-33 is to develop procedures for the implementation of supplemental damping systems.

This paper is loosely based on the commentary to the guidelines that the authors developed for the 75 percent submittal for Project ATC-33. The paper describes the means by which damping (energy dissipation) hardware is classified for analysis purposes, and outlines modeling and analysis procedures being developed for use with damping systems. Gaps in current knowledge are identified at the end of the paper.

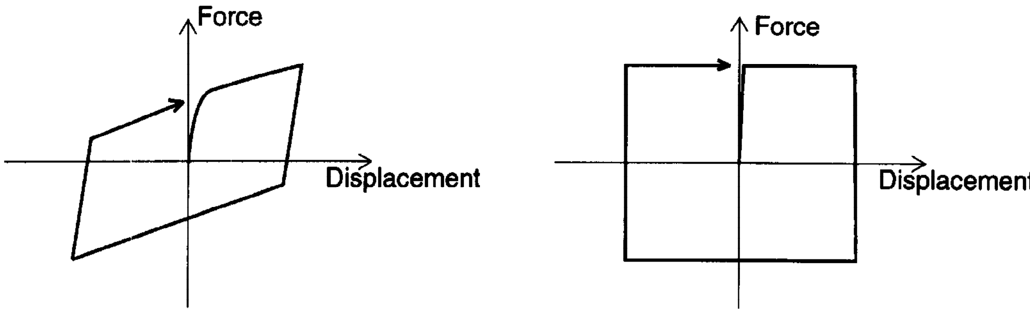
Much experimental research has been conducted on the use of supplemental damping hardware for new and retrofit seismic construction. This research is not described in the paper. The reader is referred to Aiken (1990, 1993), Bergman (1993), Chang (1991), Constantinou (1993), Reinhorn (1995), and Whittaker (1989) for detailed information.

CLASSIFICATION OF SUPPLEMENTAL DAMPING SYSTEMS

On the basis of their behavior, passive supplemental dampers are classified in the ATC-33 *Guidelines* and *Commentary* (ATC, 1995) as hysteretic, velocity-dependent, or other. Examples of hysteretic systems include devices based on yielding of metal and friction. Figure 1 shows sample force-displacement loops of hysteretic dampers. Examples of velocity-dependent systems include dampers consisting of viscoelastic solid materials, dampers operating by deformation of viscoelastic fluids (e.g., viscous shear walls), and dampers operating by forcing fluid through an orifice (e.g., viscous fluid dampers). Figure 2 illustrates the behavior of these velocity-dependent systems.

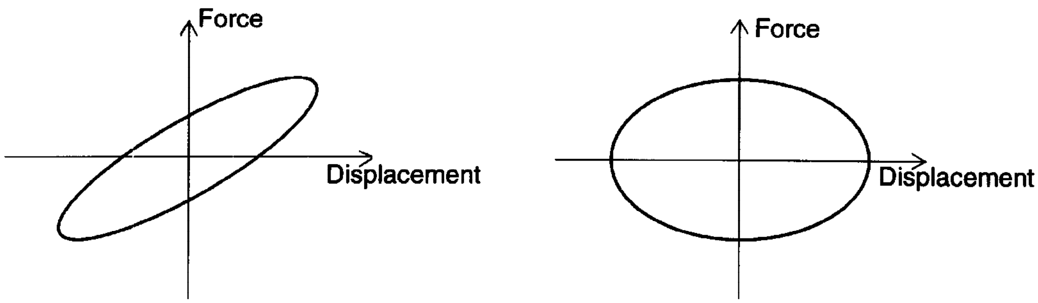
Other systems have characteristics which cannot be classified by one of the basic types depicted in either Figs. 1 or 2. Examples are dampers made of shape memory alloys, frictional-spring assemblies with recentering capabilities and fluid restoring force/damping dampers. For information on these dampers, the reader is referred to ATC (1993), EERI (1993) and Soong and Constantinou (1994). Only hysteretic and velocity-dependent dampers are discussed in this paper.

Some types of supplemental damping systems can substantially change the force-displacement response of a building by adding strength and stiffness. Such influence is demonstrated in Fig. 3 for metallic-yielding, friction, and viscoelastic dampers. Note that these figures are schematic only and that the force-displacement relation for the central figure assumes that the framing supporting the friction dampers is rigid. Viscous damping systems will generally not substantially change the force-displacement response of a building.



a. Metallic-yielding damper b. Friction damper

Fig. 1. Force-displacement relations for hysteretic dampers



a. Viscoelastic damper b. Viscous damper

Fig. 2. Force-displacement relations for velocity-dependent dampers

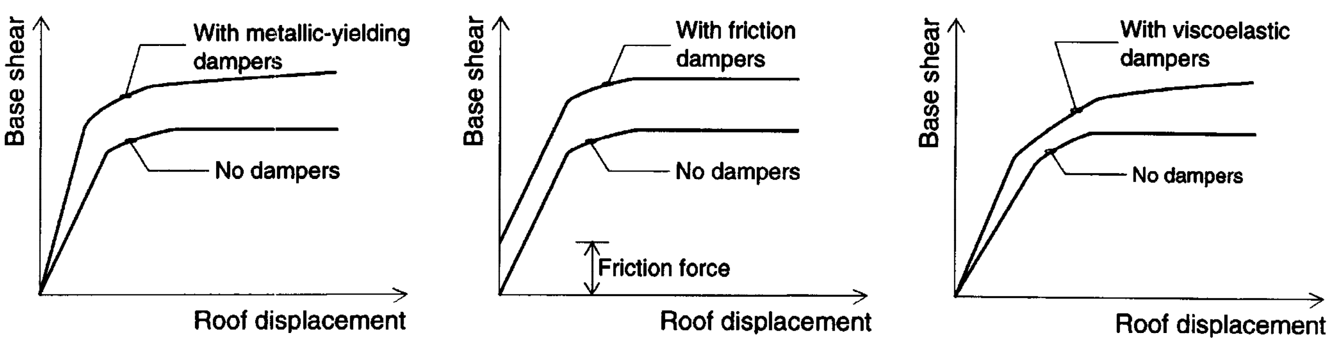


Fig. 3. Influence of selected supplemental dampers on the force-displacement relation of a building

CHARACTERIZATION OF SUPPLEMENTAL DAMPING SYSTEMS

For the purpose of this discussion, damping systems are classified as either hysteretic or velocity-dependent. The following discussion provides information on the characterization of individual dampers for use in modeling and nonlinear analysis.

Hysteretic Dampers

Hysteretic dampers exhibit bilinear or trilinear hysteretic, elasto-plastic or rigid-plastic (frictional) behavior, which can be easily captured with structural analysis software currently in the marketplace. Details on the modeling of metallic-yielding dampers may be found in Whittaker (1989); the steel dampers described by Whittaker exhibit stable force-displacement response and no temperature dependence. Friction devices are described by Aiken (1990) and Nims (1993); the devices tested by Aiken and Nims responded with box-like hysteresis and no temperature dependence.

Velocity-Dependent Dampers

Solid viscoelastic dampers typically consist of constrained layers of viscoelastic polymers. They exhibit viscoelastic solid behavior with mechanical properties dependent on frequency, temperature and amplitude of motion. A force-displacement loop of a viscoelastic solid device under sinusoidal motion of amplitude Δ_0 and frequency ω is shown in Fig. 4a. The force in the damper may be expressed as:

$$F = K_{eff}\Delta + C\dot{\Delta} \quad (1)$$

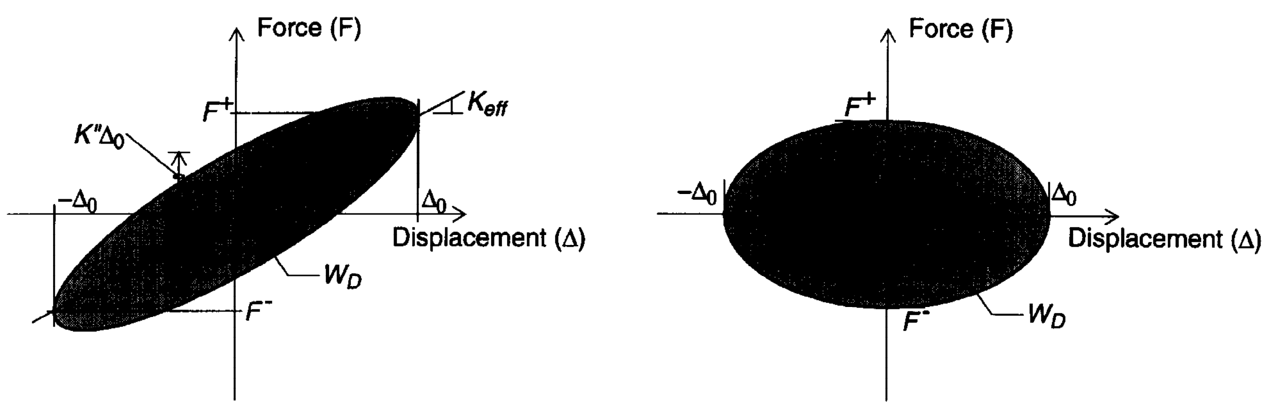
where K_{eff} is the effective stiffness, C is the damping coefficient, and Δ and $\dot{\Delta}$ are the relative displacement and relative velocity between the ends of the damper, respectively. The effective stiffness of the damper is calculated as:

$$K_{eff} = \frac{|F^+| + |F^-|}{|\Delta_0^+| + |\Delta_0^-|} \quad (2)$$

where F^+ and F^- are the forces in the damper at damper displacements Δ_0^+ and Δ_0^-, respectively. The damping coefficient (C) is calculated as:

$$C = \frac{W_D}{\pi\omega\Delta_0^2} \quad (3)$$

where W_D is the area enclosed within the hysteresis loop. The effective stiffness is also termed the storage stiffness (K'). The damping coefficient C is often defined in terms of the loss stiffness (K'') as follows:



a. Viscoelastic damper

b. Viscous damper

Fig. 4. Parameter definition for velocity-dependent dampers

$$C = \frac{K''}{\omega} \quad (4)$$

Parameters K_{eff} and C are dependent on the frequency, temperature and amplitude of motion; the frequency and temperature dependence of viscoelastic polymers generally vary as a function of the composition of the polymer (Bergman, 1993). Modeling of viscoelastic solid behavior over a wide range of frequencies is possible by use of advanced models of viscoelasticity (Kasai, 1993). Simpler models such as the standard linear solid model (a spring in series with a Kelvin model), which can be implemented in commercially-available structural analysis software, are capable of modeling behavior over a small range of frequencies, which will generally be satisfactory for most rehabilitation projects.

Fluid viscoelastic devices which operate on the principle of deformation (shearing) of viscoelastic fluids (ATC, 1993) have behavior which resembles that of solid viscoelastic devices. However, fluid viscoelastic devices have zero effective stiffness under static loading conditions. Fluid and solid viscoelastic devices are distinguished by the ratio of the loss stiffness (K'') to the effective or storage stiffness (K'). This ratio approaches infinity for fluid devices and zero for solid viscoelastic devices as the loading frequency approaches zero. Fluid viscoelastic behavior may be modeled with advanced models of viscoelasticity (Makris, 1993). However, for most practical purposes, the Maxwell model (a spring in series with a dashpot) can be used to model fluid viscoelastic devices.

Pure viscous behavior may be produced by forcing fluid through an orifice (Soong and Constantinou, 1994; Constantinou, 1993). The force output of these devices (Fig. 4b) has the general form:

$$F = C_0|\dot{\Delta}|^{\alpha}\,\mathrm{sgn}\,(\dot{\Delta}) \tag{5}$$

where $\dot{\Delta}$ is the velocity, α is an exponent in the range of 0.1 to 2.0, and sgn is the signum function. The simplest form is the linear fluid damper for which the exponent is equal to 1. In this paper, discussion on fluid viscous devices is limited to linear fluid dampers; for a detailed treatment of nonlinear fluid dampers, the reader is referred to Soong and Constantinou (1994)

ANALYSIS AND MODELING PROCEDURES

Two analysis procedures have been developed for the implementation of supplemental damping systems. To date, only procedures for simplified nonlinear analysis (also known as *pushover* analysis) and nonlinear dynamic analysis have been drafted for Project ATC-33. Simplified elastic analysis procedures are not yet available. The application of the nonlinear static analysis procedure, to the design of different damping systems for the seismic rehabilitation of buildings, is described below. The reader is referred to the list of references at the end of this paper, and the literature in general for information on nonlinear dynamic analysis.

A discussion on modeling supplemental dampers for the purpose of nonlinear static analysis follows the description of the nonlinear static analysis procedure.

Nonlinear Static Analysis Procedure

The purpose of this procedure is to evaluate the response of a rehabilitated building by a procedure which is simpler than nonlinear response history analysis but more realistic and comprehensive than linear elastic analysis. The simplified nonlinear analysis procedure may be used for the analysis of rehabilitated buildings incorporating supplemental dampers provided (a) the building with the energy dissipation devices is classified as regular in plan, (b) biaxial effects in framing members that resist seismic forces in orthogonal directions are appropriately accounted for, and (c) the fundamental modal mass in each principle translational direction exceeds 80 percent of the total mass in that direction.

In the nonlinear static analysis procedure the structure is represented by a two-or-three-dimensional mathematical model which accounts for all important response characteristics, including those of the supplemental damping system. (The supplemental damping system is composed of the dampers and the structural members that transfer forces between the dampers and the remainder of the seismic framing system.) Lateral loads are applied in a predetermined pattern and the structure is incrementally pushed to a target displacement (D). A force-displacement relation for the building is thereby developed. Typically, the force variable is base shear and the displacement variable is roof displacement. The target displacement is established by analysis of the seismic hazard. In Project ATC-33, the seismic hazard is characterized by a 5-percent damped response spectrum. Further, the calculation of the target displacement is based on the assumption that for periods greater than approximately 0.5 second (for a rock site), displacements are preserved in a mean sense, that is, mean elastic displacements are approximately equal to mean inelastic displacements. (Note that the degree of scatter in the ratio of elastic and inelastic displacements may be substantial.)

The reader is referred to ATC (1995) and the literature for additional information on nonlinear static analysis.

Modeling Supplemental Dampers

Hysteretic Dampers. Hysteretic energy dissipation devices should be explicitly modeled by bilinear, elasto-plastic or rigid-plastic elements for nonlinear static analysis. There are no rigorous procedures for the linearization of hysteretic dampers. The mathematical model of the rehabilitated building should include all important characteristics of the hysteretic dampers and their supporting framing. The fundamental period of this model should be used to estimate the target displacement.

Velocity-dependent Dampers. The only velocity-dependent dampers currently considered for seismic rehabilitation applications are viscoelastic and viscous dampers. Accordingly, only these types of velocity-dependent dampers are discussed in this section.

Viscoelastic dampers exhibit effective stiffness which is generally dependent on frequency of motion, amplitude of motion, and temperature. Viscoelastic devices should be modeled for the purpose of nonlinear analysis as either linear or nonlinear springs representing the effective stiffness of the device at a fixed temperature and frequency. Multiple analyses using different temperature-based effective stiffnesses should be undertaken to address the temperature dependence of the viscoelastic material. The effective stiffness calculation should be based on an excitation frequency equal to the inverse of the effective period of the rehabilitated building (including the viscoelastic dampers) at the target displacement.

The mathematical model of the rehabilitated building must include the stiffness characteristics of the viscoelastic dampers and their supporting framing. The fundamental period of this model should be used to estimate the target displacement from a response spectrum that is modified from the 5-percent spectrum to account for the viscous damping provided by the dampers.

Modification of the spectral displacement demand is a key step in the analysis process. The first mode damping (ξ) provided by the viscoelastic dampers can be estimated as follows. The energy dissipated (W_D) in one cycle of loading to the target displacement can be estimated as:

$$W_D = \frac{2\pi^2}{T_{eff}}\sum C_j \Delta_{rj}^2 (\cos\theta_j)^2 \tag{6}$$

where C_j is the damping coefficient of damper j, θ_j is the angle of inclination of damper j to the horizontal, Δ_{rj} is the relative axial displacement of the ends of damper j at the target displacement (D), T_{eff} is the effective fundamental period of building at the target displacement, and the summation extends over all dampers. This calculation is iterative because the target displacement is a function of the damping provided by the viscoelastic energy dissipators.

The first mode damping provided by the viscoelastic dampers can be estimated as:

$$\xi = \frac{1}{2\pi}\left(\frac{W_D}{KD^2}\right) \tag{7}$$

where W_D is calculated per eq. (6), and K is the effective stiffness of the rehabilitated building at the target displacement (D). The modal damping ratio used to calculate the target displacement is then calculated by adding (a) the first mode damping provided by the viscoelastic dampers, and (b) the structural damping in the building frame — typically assumed to be 5 percent of critical. This iterative procedure is complete when the modal damping ratio used to calculate W_D is approximately equal to the modal damping ratio calculated following the subsequent evaluation of eq. (7).

The member forces calculated from the nonlinear static analysis do not include the viscous forces developed in the viscoelastic dampers. Separate analysis should be performed to capture the viscous forces. The reader is referred to ATC (1995) for further information.

Fluid viscous dampers do not exhibit stiffness unless the excitation frequency is high. As such, the model of the rehabilitated building need not include such dampers for the purpose of nonlinear static analysis — the viscous dampers serve only to improve the energy dissipation characteristics of the rehabilitated building. The fundamental period of the mathematical model should be used to estimate the target displacement from a response spectrum that is modified from the 5-percent spectrum to account for the damping provided by the viscous dampers. If the response of the viscous dampers is temperature dependent, multiple analyses will be required to capture the maximum force output and minimum energy dissipation of the dampers.

Modification of the spectral displacement demand is a key step in the analysis process. The first mode damping ratio (ξ) provided by the viscous dampers can be estimated by calculation of the energy dissipated (W_D) by all of the dampers in the building, in one cycle of loading to the target displacement, as follows:

$$W_D = \frac{2\pi^2}{T_{eff}} \sum C_{0j} \Delta_{rj}^2 (\cos\theta_j)^2 \tag{8}$$

where C_{0j} is the damping coefficient of damper j, the summation extends over all dampers, and all other terms are as defined above. This calculation is iterative because the target displacement is a function of the damping provided by the viscous dampers.

The remainder of the procedure for viscous dampers is virtually identical to that described above for viscoelastic dampers and is not repeated here. Following convergence of the procedure, the effects of forces in the viscous dampers must be included in the calculation of the maximum frame forces. The reader is referred to ATC (1995) for more information.

SUMMARY AND CONCLUSIONS

Recent damaging earthquakes have demonstrated that substantial earthquake risk mitigation can only be realized in the United States through rehabilitation of the vulnerable building stock. This effort will be made easier by the publication and promulgation of the ATC-33 Guidelines and Commentary (ATC, 1995). A key component of the ATC-33 project is the development of guidelines for the implementation of hysteretic and velocity-dependent damping hardware. This paper has been based in part on the authors' work on the ATC-33 project. Background information on selected types of damping hardware, and guidance on modeling dampers and the use of nonlinear static analysis for seismic rehabilitation has been presented. Similar procedures can be used for new construction.

The authors' research work in the field of supplemental damping, and activities associated with Project ATC-33, have identified substantial gaps in the knowledge base. Such gaps include (a) a poor understanding of the interaction between hysteretic and velocity-dependent damping, (b) the lack of simplified elastic procedures for the implementation of supplemental dampers in new and retrofit construction, (c) inadequate verification of the nonlinear static analysis procedure, and (d) a paucity of information on optimal distributions of supplemental dampers. It is recommended that these gaps in our knowledge be the subject of focused research in the near future.

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