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SUPPLEMENTAL DAMPING FOR NEW AND RETROFIT CONSTRUCTION*

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ABSTRACT

Supplemental damping (energy dissipation) hardware are being employed in the United States to provide enhanced protection for new and retrofit building and bridge construction. Such hardware includes displacement- and velocity-dependent dampers. The types of dampers being implemented in the United States at this time are presented in the paper. Guidelines and commentary to aid in the implementation of passive supplemental dampers in existing construction are included in the new resource documents FEMA 273 and 274: *Guidelines for the Seismic Rehabilitation of Buildings* (FEMA, 1997). This paper introduces the FEMA 273 analysis procedures and outlines the modeling and analysis procedures developed for implementing supplemental dampers. Two new developments in the field of supplemental damping that will facilitate their application to stiff structural framing systems are the toggle-brace and scissor-jack damper configurations. These configurations are presented in the paper and their utility is demonstrated by comparison with conventional configurations for a sample single-story, single-bay frame.

1. INTRODUCTION

In conventional construction, earthquake-induced energy is dissipated in components of the gravity-load-resisting system. The action of dissipating energy in framing such as beams in a moment-resisting frame produces damage in those components. Repair of such damage after an earthquake is typically expensive and often requires evacuation of the building while repair work on the gravity system is undertaken.

The objective of adding damping hardware to new and existing construction is to dissipate much of the earthquake-induced energy in *disposable* elements not forming part of the gravity framing system. Key to this philosophy is limiting or eliminating damage to the gravity-load-resisting system. Although testing and perhaps replacement of all

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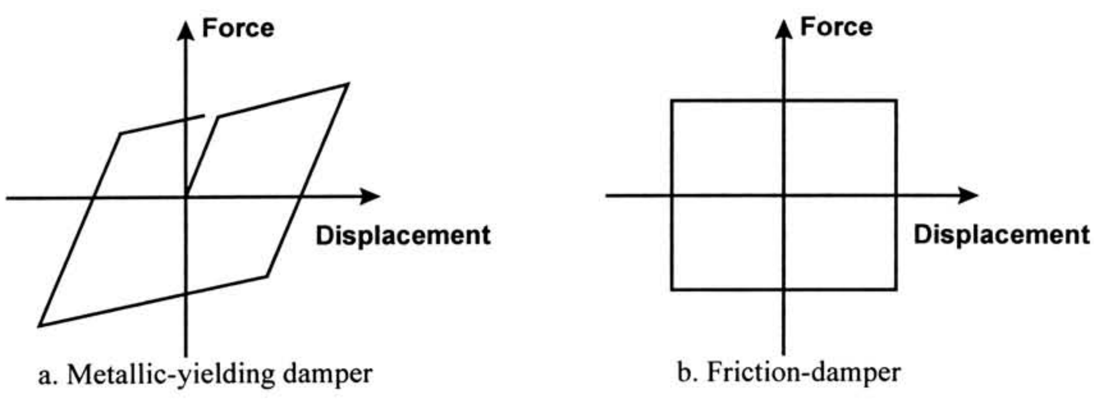
supplemental damping devices in a building should be anticipated after a design earthquake, evacuation of the building for repair might not be necessary and the total repair cost will likely be minor compared with the costs associated with repair and business interruption in a conventional building.

This paper introduces the different types of supplemental damping hardware being used or considered for use in the United States at this time (Section 2), describes the new analysis procedures for supplemental dampers in FEMA 273 that were developed in part by the authors (Section 3), and presents two new damper configurations that will facilitate the use of damping technologies in stiff structural framing systems (Section 4).

2. SUPPLEMENTAL DAMPING HARDWARE

2.1 General

Supplemental damping hardware are divided into three categories: hysteretic, velocity-dependent, and other. Examples of hysteretic systems include devices based on yielding of metal and friction. Figure 1 presents 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 that cannot be classified by one of the basic types depicted in Figures 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), Constantinou et al. (1998), EERI (1993), Soong and Constantinou (1994), and Soong and Dargush (1997). Only hysteretic and velocity-dependent dampers are discussed in this paper.



a. Metallic-yielding damper

b. Friction-damper

Fig 1. Force-displacement relations for hysteretic dampers

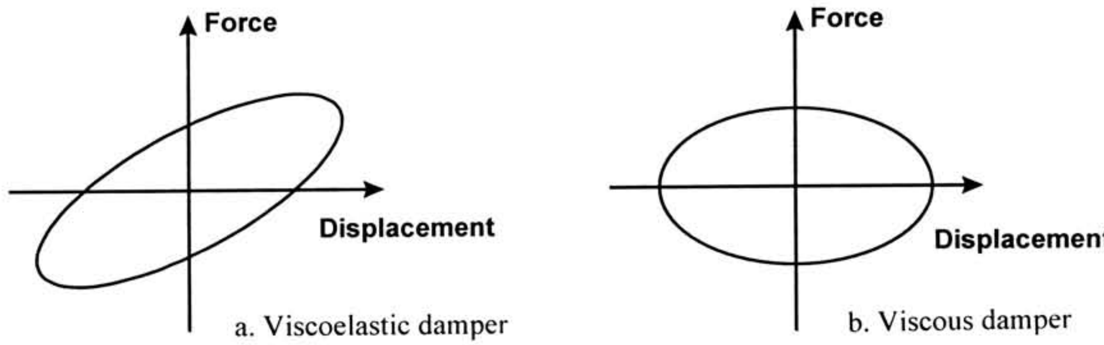


Fig 2. Force-displacement relations for velocity-dependent dampers

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 Figure 3 for metallic yielding, friction, and viscoelastic dampers. Note that these figures are schematic only and that the force-displacement relation for the right-hand figure assumes that the framing supporting the friction dampers is rigid. Viscous damping systems will generally not substantially change the pseudo-static force-displacement response of a building. The analysis procedures described in the following section account for these effects on framing-system response.

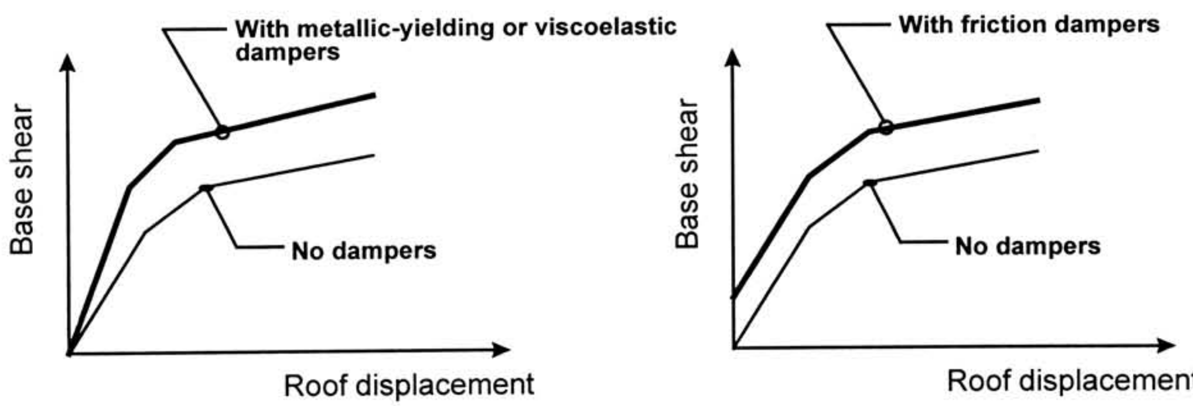
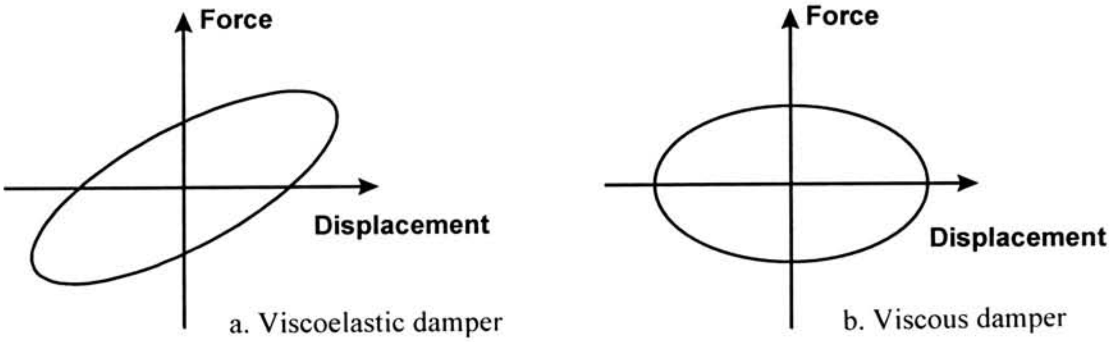


Fig 3. Influence of dampers on building response

2.2 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 *et al.* (1989); the steel dampers described by Whittaker exhibit stable force-displacement response and no temperature dependence. Aiken *et al.* (1990) and Nims *et al.* (1993) describe friction devices. Two metallic-yielding dampers, ADAS and TADAS, are shown in Figures 4a and 4b, respectively. Added Damping and Stiffness (ADAS)



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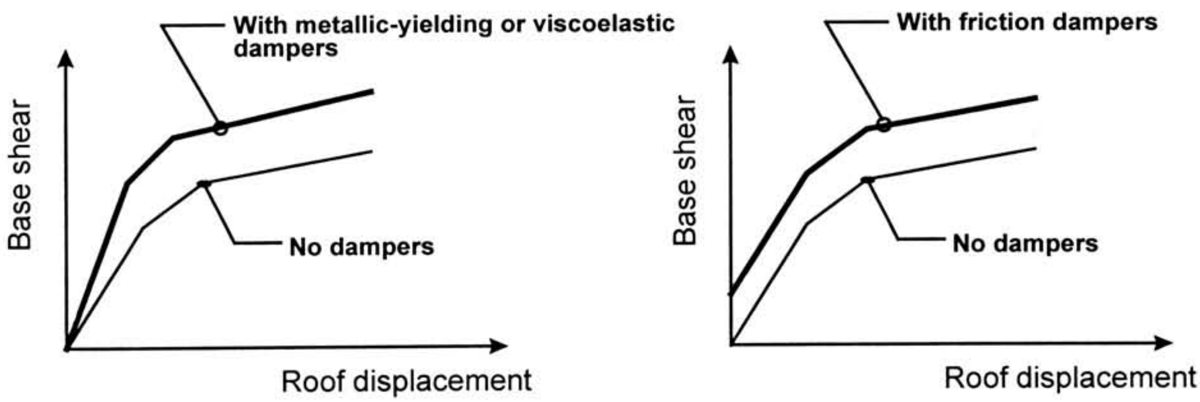

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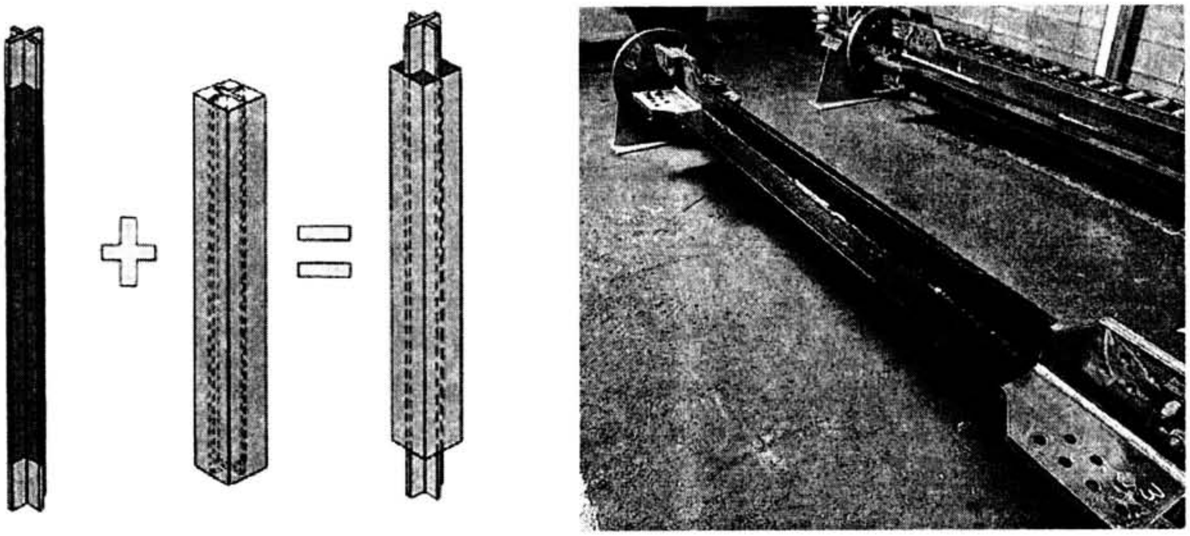


a. Conceptual details b. Cruciform configuration of brace

Fig 5. Nippon Steel unbonded brace

2.3 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 for a viscoelastic solid device, under sinusoidal motion of amplitude Δ_0 and frequency ω, is shown in Figure 6a. The force in the damper may be expressed as:

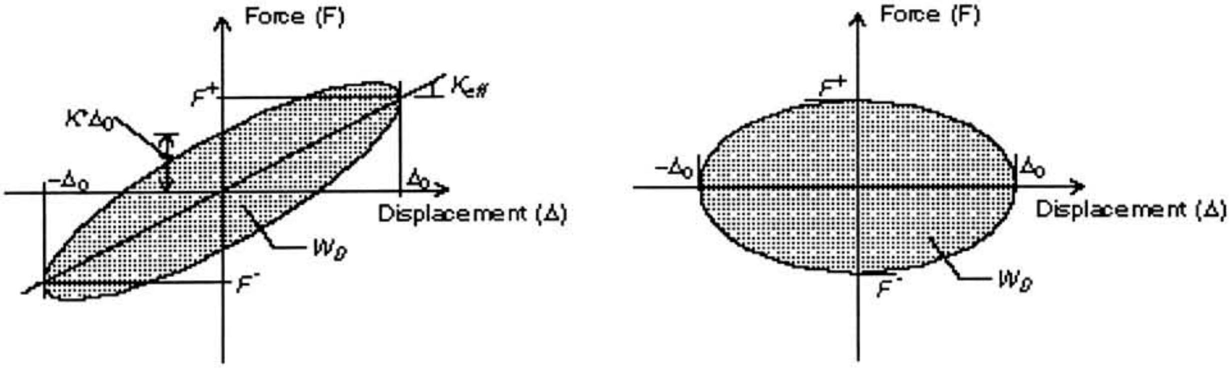
$$F = K_{eff}\Delta + C\dot{\Delta} \tag{1}$$

where K_{eff} is the effective stiffness (also termed the storage stiffness K') as defined in Figure 6a, 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 damping coefficient is calculated as:

$$C = \frac{W_D}{\pi\omega\Delta_0^2} \tag{2}$$

where W_D is the area enclosed within the hysteresis loop and ω is the angular frequency of excitation. The damping coefficient C is also equal to the loss stiffness (K'') divided by ω.

The effective stiffness and damping coefficient 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. The standard linear solid model (a spring in series with a Kelvin model), which can be implemented in commercially available structural analysis software, is capable of modeling behavior over a small range of frequencies, which will generally be satisfactory for most projects.



a. Viscoelastic damper	b. Viscous damper

Fig 6. Parameter definition for velocity-dependent dampers

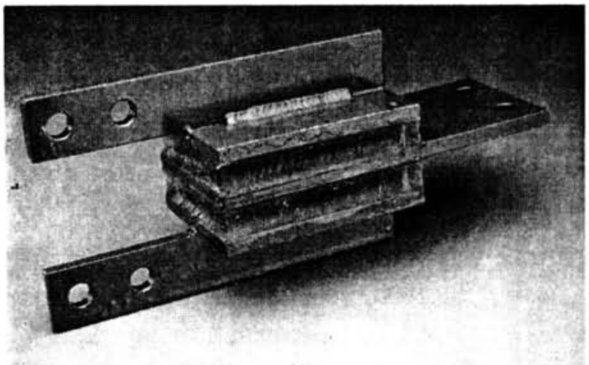
Fluid viscoelastic devices, which operate on the principle of deformation (shearing) of viscoelastic fluids, have behavior that resembles a solid viscoelastic device. However, fluid viscoelastic devices have zero effective stiffness under static loading conditions. Fluid and solid viscoelastic devices are distinguished by the ratio of the loss stiffness to the effective or storage stiffness. 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.

Figure 7 presents photographs of two viscoelastic dampers. Figure 7a is a solid viscoelastic damper manufactured by 3M Corporation. This damper configuration is similar to that employed to reduce the wind-induced vibrations of buildings. More recent configurations employ rectangular tube steel sections with copolymer bonded to all four faces of the tube. Figure 7b is a fluid viscoelastic damper that is known by many as a viscous damping wall (VDW). The VDW is composed of a cavity-precast wall that is filled with a viscous fluid and attached at its base to the floor framing. A tee-shaped paddle is inserted in the fluid and is attached to the framing above the cavity wall. Interstory drift in the building frame produces relative movement between the paddle and the cavity wall and dissipates energy.

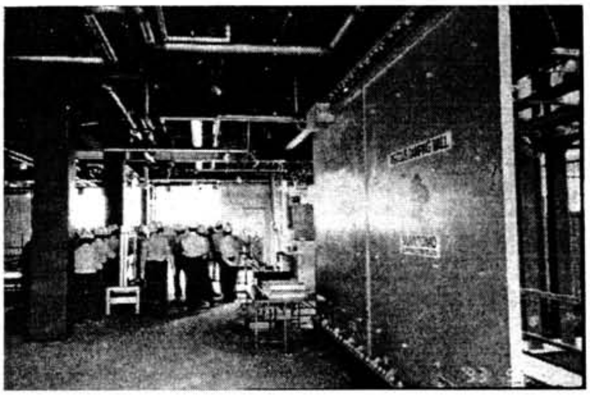
Pure viscous behavior may be produced by forcing fluid through an orifice (Constantinou and Symans, 1993; Soong and Constantinou, 1994). The force output of a viscous damper (Figure 6b) has the general form:

$$F = C_0 |\Delta|^{\alpha} \operatorname{sgn}(\dot{\Delta}) \tag{3}$$

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 1.0. In this paper, the discussion on fluid viscous devices is limited to linear fluid dampers; for a detailed treatment of nonlinear fluid viscous dampers, the reader is referred to Soong and Constantinou (1994).



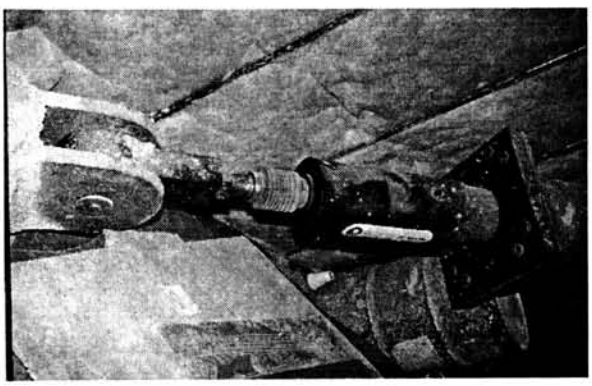
a. Solid viscoelastic damper



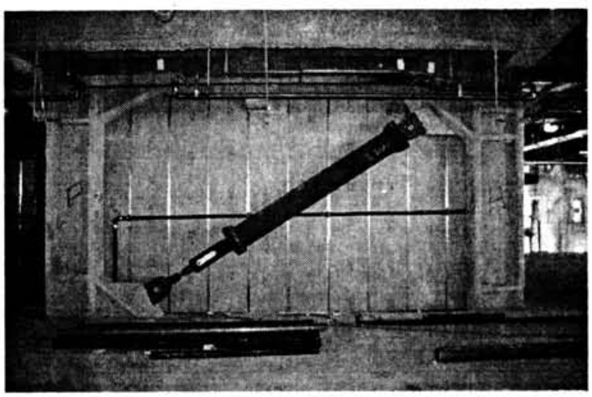
b. Fluid viscoelastic damper

Fig 7. Solid and fluid viscoelastic dampers

Fluid viscous dampers are widely used in the United States at this time. Much of the technology used in this type of damper was developed for military, aerospace, and energy applications. Figure 8 shows photographs of double acting, nonlinear fluid viscous dampers used in a new 14-story building in San Francisco. Such dampers are often compact because the pressure drop across the damper piston head generally ranges between 5000 and 1000 psi (35 to 70 MPa).



a. Fluid viscous damper



b. Diagonal damper configuration

Fig 8. Fluid viscous dampers

3. ANALYSIS PROCEDURES FOR SUPPLEMENTAL DAMPERS

3.1 Introduction

The lack of analysis methods, guidelines and commentary has been the key impediment to the widespread application of supplemental dampers in buildings and bridges. Prior to 1997, seismic design codes and guidelines in the United States focused on designing structures for strength alone, where the design forces were set equal to the elastic forces divided by a response reduction factor (for buildings). Component deformations, which are indicators of damage and performance, were not checked.

FEMA 273, entitled *Guidelines for the Seismic Rehabilitation of Buildings*, was published in 1997 after more than five years of development. FEMA 273 represented a paradigm shift is the practice of earthquake engineering in the United States because deformations and not forces were used as the basis for the design of ductile components. Performance and damage were characterized in terms of component deformation capacity.

Four new methods of seismic analysis are presented in FEMA 273: Linear Static Procedure (LSP), Linear Dynamic Procedure (LDP), Nonlinear Static Procedure (NSP), and Nonlinear Dynamic Procedure (NDP). All four procedures can be used to implement supplemental dampers in buildings although the limitations on the use of the linear procedures likely will limit their widespread use. Of the four, only the NDP can explicitly capture nonlinear deformations and strain- and load-history effects. The other three procedures are considered to be less precise than the NDP, although given the additional uncertainties associated with nonlinear analysis, the loss of accuracy might be small. The two nonlinear procedures lend themselves to component checking using deformations and displacements; component deformation limits are given in FEMA 273, but most are based on engineering judgment and evaluation of test data. The two static methods are described below. Much additional information on these procedures and the two dynamic procedures are available in FEMA 273 and 274.

3.2 Linear Static Procedure: General

In any linear procedure, there is a direct relation between internal deformations and internal forces. Component checking involves comparing actions with capacities. In building design codes such as the Uniform Building Code (ICBO, 1997), component actions due to earthquake effects are calculated using elastic spectral forces divided by a response modification factor. Although inelastic response is implied by the use of values of the factor greater than 1, component deformation capacity is not checked.

The LSP of FEMA 273 is substantially different from the static lateral force procedures adopted in modern seismic codes. A pseudo lateral force (V) is applied to a linear elastic model of the building frame such that its maximum displacement is approximately equal to the expected displacement of the *yielding* building frame. The objective is to estimate displacements in a yielding building using a linear procedure. As such, the pseudo lateral force may be much greater than the yielding strength of the building, and component demands may exceed component capacities by a significant margin. However, the LSP acceptance criteria accommodate this situation by permitting demand-to-capacity ratios (denoted *m* in FEMA 273) greater than 1.0, where the values assigned to *m* vary as a function of the nonlinear deformation capacity of the component. The FEMA 273 equation for the pseudo lateral force is

$$V = C_1 C_2 C_3 S_a W \tag{4}$$

where C_1 is a modification factor to relate maximum inelastic displacements to displacements calculated assuming linear elastic response, C_2 is a modification factor to represent the effect of stiffness and strength degradation on the maximum displacement response, C_3 is a modification factor to account for dynamic second-order effects, S_a is the response-spectrum acceleration at the fundamental period and damping ratio of the building frame, and W is the total dead load and anticipated live load. The spectral acceleration and displacement are calculated as shown in Figure 9 below.

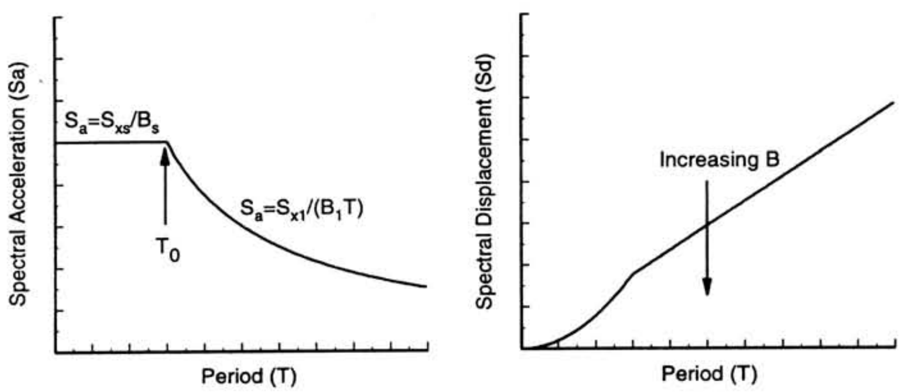


Fig 9. Spectral accelerations and displacements

In this figure, B is a damping coefficient, which is used to reduce the elastic spectral demands for increases in damping above 5 percent of critical, and T_o is the period at which the constant acceleration and constant velocity regions of the design spectrum intersect. Table 1 presents the values assigned in FEMA 273 to the damping coefficients B_s (periods less than T_o) and B_1 (other periods). It is evident from analysis of Figure 9 and Table 1 that displacements (and deformations) can be reduced by either (a) adding damping to the framing system or (b) adding stiffness to the framing system. A supplemental damper will add stiffness and/or damping to a seismic framing system depending upon its mechanical characteristics.

Table 1. Damping coefficients as a function of effective damping

Effective damping, β (% of critical)	B_s	B_1
<2	0.8	0.8
5	1.0	1.0
10	1.3	1.2
20	1.8	1.5
30	2.3	1.7
40	2.7	1.9
>50	3.0	2.0

3.3 Nonlinear Static Procedure: General

The Nonlinear Static Procedure is a displacement-based method of analysis. Structural components are modeled using nonlinear force-deformation relations and the stiffness of the supplemental dampers is included in the model. Lateral loads are applied in a predetermined pattern to the model, which is incrementally *pushed* to a target displacement thereby establishing a force (base shear) versus displacement (roof) relation for the building. Component deformations are calculated at the target displacement. Component evaluation involves checking the maximum deformation versus the deformation capacity; force-based checking is not used for deformation-controlled components. Deformation capacities are given in FEMA 273 for different components, materials, and performance levels. Because higher-mode loading patterns are not considered, FEMA 273 limits the use of the NSP unless an LDP evaluation is also performed.

The target displacement is established in FEMA 273 by either the *coefficient method* or the *capacity-spectrum method.* Both methods are equally accurate if the yield strength of the building exceeds 20 percent of the required elastic strength (Whittaker *et al.,* 1998). Only the coefficient method is described below. For information on the capacity-spectrum method, refer to FEMA 274 (FEMA, 1997).

Calculation of the target displacement by the coefficient method 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, the mean elastic displacements are approximately equal to the mean inelastic displacements. (Note that the degree of scatter in the ratio of elastic and inelastic displacements may be substantial, and that this assumption is not conservative for buildings with low strength.) The general form of the target displacement (δ_t) equation is:

$$\delta_t = C_0 C_1 C_2 C_3 S_a \frac{T_e^2}{4\pi^2} \qquad (5)$$

where T_e is the effective fundamental period of the building, C_0 is a coefficient relating roof displacement and spectral displacement, and all remaining terms are defined below equation 4.

3.4 Linear Static Procedure: Supplemental Dampers

Limits are placed on the use of the Linear Static Procedure (LSP) for implementing dampers in buildings. The LSP can only be used if the framing system exclusive of the dampers remains essentially linearly elastic in the design earthquake after the effects of the added damping are considered. Further, the level of effective damping must not exceed 30 percent of critical in the fundamental mode. Dampers are modeled using their secant stiffness at the point of maximum displacement. The stiffness of each damper must be included in the mathematical model. Specific requirements for displacement- and velocity-dependent dampers follow.

Displacement-Dependent Dampers

Additional restrictions to those noted above are placed on the use of the LSP. Specifically, the maximum resistance in each story must vary uniformly over the height of the building and the maximum resistance (strength) of the supplemental dampers cannot exceed 50 percent of the resistance of the remainder of the framing.

For use with the LSP, displacement-dependent dampers (see Figure 1a) are modeled as viscoelastic dampers (see Figure 6a). The effective damping of the frame (see Table 1) is calculated as:

$$\beta_{eff} = \beta + \frac{\sum_j W_j}{4\pi W_k} \tag{6}$$

where β is the damping in the building frame exclusive of the dampers, W_j is the work done by device j in one complete cycle corresponding to floor displacements δ_i and the summation extends over all devices. W_k is the maximum strain energy in the frame that can be calculated as

$$W_k = \frac{1}{2}\sum_i F_i \delta_i \tag{7}$$

where F_i is the inertial force at floor level i; and δ_i is the displacement of floor level i, and the summation extends over all floor levels i.

The value of β_{eff} is used to calculate a value of B from Table 1. The spectral acceleration for use in equation 4 is calculated using the fundamental period of the framing system whose model includes the secant stiffness of the displacement-dependant dampers. Component actions and deformations are checked at the stage of maximum displacement.

Velocity-Dependent Dampers

One additional restriction to those noted in the introduction is placed on the use of the LSP, namely, that the maximum resistance (strength) of the velocity-dependent supplemental dampers in any story cannot exceed 50 percent of the resistance of the remainder of the framing in that story. This restriction will only apply to viscoelastic dampers.

The effective damping is calculated using equations 6 and 7. For linear viscous dampers, the work done by damper *j* can be calculated as:

$$W_j = \pi(C_j\dot{\delta}_{rj})\delta_{rj} = \frac{2\pi^2}{T}C_j\delta_{rj}^2 \tag{8}$$

where C_j is the damper coefficient for device *j*, δ_{rj} is the relative displacement between the ends of device *j* measured *along the axis* of the damper, and *T* is the fundamental period of the framing system whose model includes the stiffness of the dampers. This equation assumes harmonic motion of amplitude δ_{rj} and periodicity *T*. As such, it may not be applicable if near-field (non-harmonic) ground motions are being used for design. FEMA 273 provides an alternative equation for calculating the effective damping provided by linear viscous devices using first mode information:

$$\beta_{eff} = \beta + \frac{T\sum_j C_j\cos^2\theta_j\varphi_{rj}^2}{4\pi\sum_i m_i\varphi_i^2} \tag{9}$$

where φ_i is the first mode displacement of floor level *i*, m_i is the mass of floor level *i*, θ_j is the angle of device *j* to the horizontal, φ_{rj} is first mode relative horizontal displacement between the ends of device *j*, and all other terms are described above. (Equation 9, with minor modification, can be used to calculate modal damping ratios for buildings incorporating linear viscous dampers.)

Design actions in components of buildings incorporating velocity-dependent dampers must be checked at three stages. Component checking is more onerous for velocity-dependent dampers than displacement-dependent dampers because component actions must be checked at three stages: maximum displacement, maximum velocity, and maximum acceleration. Information on the calculation of component actions at the stages of maximum velocity and maximum acceleration can be found in FEMA 273 and 274 (FEMA, 1997).

3.5 Nonlinear Static Procedure: Supplemental Dampers

Two methods of nonlinear static analysis are provided in FEMA 273 for implementing supplemental dampers: Method 1 (known as the coefficient method), and Method 2 (known as the capacity-spectrum method). The two methods are equally precise. The use of the coefficient method to implement dampers is described below. The reader is encouraged to read Tsopelas *et al.* (1997) and Section C9.3.5 of FEMA 274 (FEMA, 1997) for key information on the use of the capacity-spectrum method.

Regardless of which method is used to calculate the target displacement and the associated component deformations, the nonlinear mathematical model of the building frame must include the nonlinear force-velocity-displacement relations for the dampers and the mechanical characteristics of the framing supporting the dampers. If the stiffness of a damper is dependent upon amplitude, frequency, or velocity, the stiffness value used for analysis should be consistent with deformations corresponding to the target displacement and frequencies corresponding to the inverse of the effective period T_e.

Displacement-Dependent Dampers

The benefit of adding displacement-dependent dampers to a building frame is recognized in FEMA 273 by the increase in building stiffness afforded by the dampers. The increase in stiffness will reduce the effective period T_e in equation 5 thereby reducing the maximum displacement ($=\delta_t$). The spectral acceleration in this equation should be calculated using the effective period of the mathematical model that includes the stiffness of the dampers and the value of B assigned to the building frame exclusive of the dampers.

Velocity-Dependent Dampers

The benefits of adding velocity-dependent dampers to a building frame are recognized in FEMA 273 by (a) the increase in viscous damping and (b) the increase in building stiffness, afforded by the dampers. The increase in damping will reduce the spectral acceleration. The increase in stiffness will reduce the effective period and the spectral displacement as noted in the second-to-last paragraph.

The effective damping in the building frame at the point of maximum displacement is calculated iteratively using equations 6, 7, 8, and 9. In these equations, the floor displacements δ_i are those that correspond to the target displacement, the forces F_i are the lateral forces that correspond to the target displacement, and T_e is replaced by the secant period ($=T_s$) at the point of maximum displacement. Using the force-displacement relation of Figure 10, the secant period can be calculated as:

$$T_s = T_e\sqrt{\frac{K_e}{K_s}} \tag{10}$$

An estimate of target displacement is needed to calculate the effective damping and secant stiffness, which in turn are used to calculate a revised estimate of the target displacement. When the assumed and calculated values of the target displacement are sufficiently close, the solution has converged.

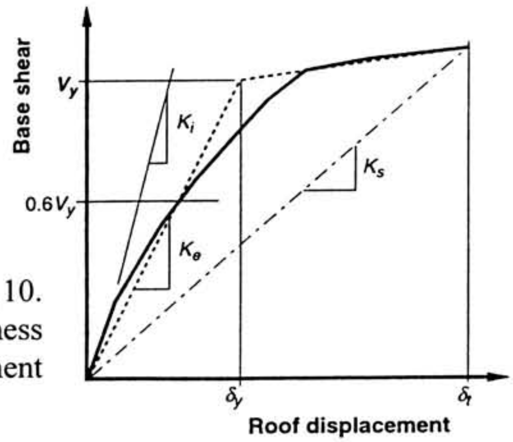


Fig 10.
Calculation of secant stiffness
at maximum displacement

As described above, the component actions in a framing system incorporating velocity-dependent dampers must be checked at the stages of maximum drift, maximum velocity, and maximum acceleration. The procedures for such checking are presented in FEMA 273 and 274. Higher-mode damping forces must be considered if velocity-dependent dampers are being implemented using the NSP. The magnitude of these forces may be similar to those damping forces calculated using the procedure described above. An example of how higher mode forces can be calculated is presented in FEMA 274 (FEMA, 1997).

4. SUPPLEMENTAL DAMPING FOR STIFF SEISMIC FRAMING SYSTEMS

Small interstory drifts and velocities characterize stiff seismic framing systems. One could assume that such systems are not candidates for the addition of dampers because significant drifts and velocities are needed to dissipate substantial energy, although the values listed in Table 1 indicate that damping is most effective in the short-period (constant acceleration) range of the spectrum. FEMA (1995) writes

> ... structural systems best suited for implementation of energy dissipation devices are the moment-resisting frame and the flexible dual system, in either structural steel or reinforced concrete. The interstory response of a stiff lateral load-resisting system, such as a reinforced concrete shear wall system or a steel-braced dual system, is generally characterized by both small relative velocities and small relative displacements. As such it may not be feasible to implement supplemental energy dissipation...

This observation is correct for conventional damper configurations involving diagonal (in-line) or chevron installations. For example, interstory displacements in a stiff code-compliant building will likely not exceed 15 mm (0.6 inch) in the design earthquake. Large damper forces are needed to develop moderate levels of supplemental damping.

Damper displacements in conventionally configured systems will be less than or equal to the interstory displacements. For small-stroke fluid viscous dampers, special details are required that increase the volume and cost of the damper.

Recent work at the State University of New York at Buffalo (Constantinou et al., 1997) has sought to expand the utility of fluid viscous damping devices to the short-period range through the use of mechanisms that magnify the damper displacement for a given interstory drift. Such magnification permits the use of dampers with smaller force outputs (smaller damper volume), larger strokes, and reduced cost. Two configurations are the *toggle-brace* and the *scissor-jack*. These configurations can be used for stiff and flexible framing systems.

A toggle-brace configuration (Constantinou et al., 1997) is shown in Figure 11 and Figure 12a. The supplemental framing consists of toggles AB and BC that are configured as a shallow truss. The damper is placed perpendicular to toggle AB. The most effective damper site is number 2. Displacement of point C with respect to point A, equal to interstory drift u, causes toggle AB to rotate. The resulting changes in distance between points B and D, and B and E are the damper displacements u_{D1} and u_{D2}, respectively. These displacements are related to the interstory drift, u, through simple equations.

Damping forces in the toggle-brace system are small, but are magnified in the shallow truss and delivered to the framing system by axial forces in the braces. The absence of flexure in the toggle-brace assembly facilitates the use of small structural sections and standard connection details. The assembly is compact and can be installed in a square space with a side length equal to the column height.

For small rotations and damper location number 1, the damper displacement is related to the interstory drift, u, as follows:

$$u_D = fu \tag{11}$$

For damper location number 2, the relation is:

$$u_D = (f + \sin\theta_1)u = f_u u \tag{12}$$

where,

$$f = \frac{\sin\theta_2}{\cos(\theta_1 + \theta_2)} \tag{13}$$

The displacement magnification factors f and f_u depend only on the inclination of the toggle braces. High displacement magnifications can be achieved although values are sensitive to small changes in θ_1 and θ_2. Magnification factors of between 2 and 3 can be easily achieved and are insensitive to small variations in changes in θ_1 and θ_2.

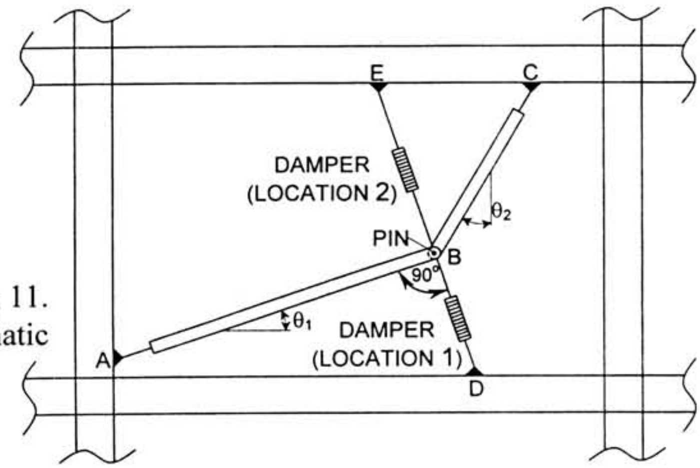
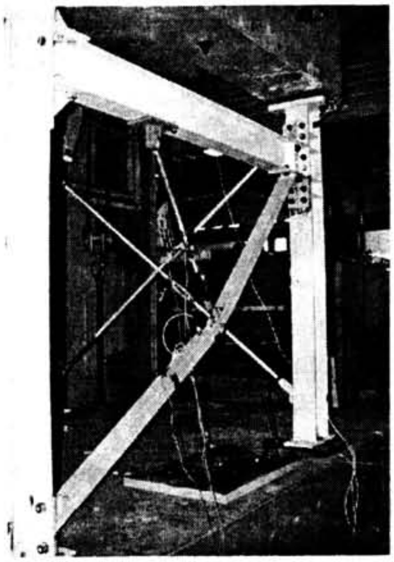
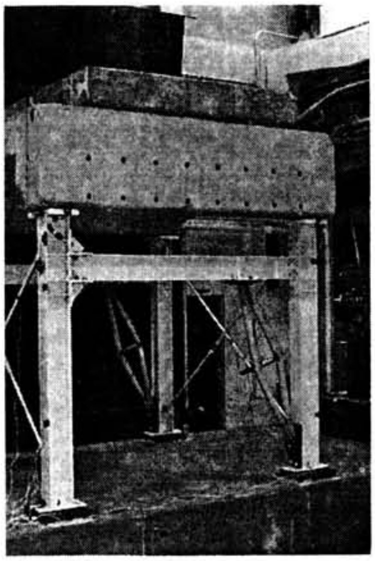


Fig 11.
Toggle-brace assembly schematic



a. Toggle-brace



b. Scissor-jack

Fig 12. Toggle-brace and scissor-jack damper assemblies on the Buffalo earthquake simulator

For small rotations, the relation between the damper force output, F_D, and the force exerted by the toggle-brace assembly on the structural frame, F, is:

$$F = fF_D \tag{14}$$

for location number 1 (see Figure 10), and:

$$F = f_u F_D \tag{15}$$

for location number 2. Equations 11 through 15 have the same form as those equations written for dampers installed in diagonal or in-line braces and dampers atop chevron braces.

The scissor-jack assembly of Figure 12b is a variant of the toggle-brace assembly. Equations similar to those presented above for the toggle-brace assemblies have been developed for the scissor-jack assembly. See Figure 13 for details.

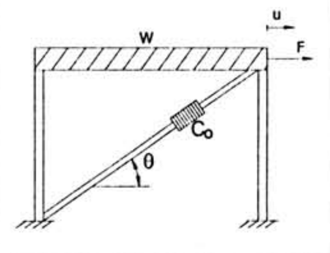
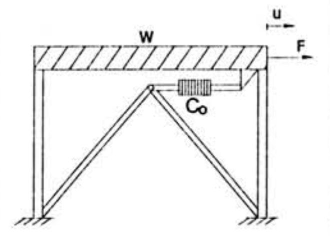
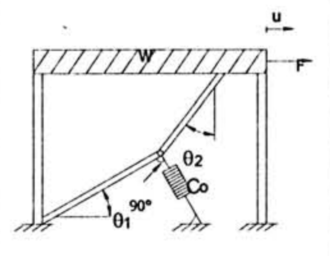
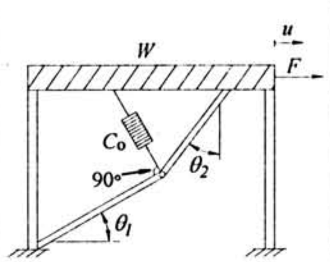
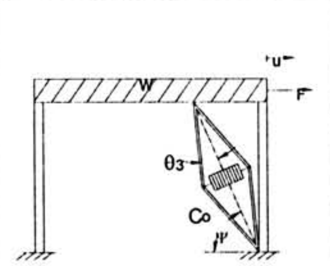
Diagonal		$f = \cos\theta$	$f = 0.799$ $\beta = 0.017$
Chevron		$f = 1$	$f = 1.00$ $\beta = 0.027$
Lower Toggle		$f = \dfrac{\sin\theta_2}{\cos(\theta_1 + \theta_2)}$	$f = 2.662$ $\beta = 0.194$
Upper Toggle		$f = \dfrac{\sin\theta_2}{\cos(\theta_1 + \theta_2)} + \sin\theta_1$	$f = 3.191$ $\beta = 0.279$
Scissor Jack		$f = \dfrac{\cos\psi}{\tan\theta_3}$	$f = 2.159$ $\beta = 0.126$

Fig 13. Effectiveness of damper configurations in framing systems

To illustrate the effectiveness of the toggle-brace and scissor-jack assemblies for short-period framing systems consider the five damper configurations presented in Figure 13. The diagonal (in-line) and chevron brace configurations represent conventional damper assemblies. For the purpose of comparison, assume that (1) the elastic single-bay, single-story frame has a fundamental period of 0.3 second, (2) the damper is a linear fluid viscous device with a damping constant, C_0, equal to 160 kNs/m, (3) the weight of the frame is 1370 kN, and (4) angles, θ, θ_1, θ_2, θ_3, and ψ are equal to 37.0, 31.9, 43.2, 9.0, and 70.0 degrees, respectively.

The force output of the damper, F_D, is given by:

$$F_D = C_0 \dot{u}_D \tag{16}$$

where $\dot{u}_D$ is the relative velocity between the ends of the damper along the axis of the damper. The damping force exerted on the frame by the damper assemblies, F, is given by

$$F = C_0 f^2 \dot{u} \tag{17}$$

where $\dot{u}$ is the interstory velocity and f is equal to f_u if the damper is placed in location 2 of the toggle brace in Figure 11. The damping ratio of the single-story frame of Figure 13, with weight, W, and fundamental period, T, is:

$$\beta = \frac{C_0 f^2 gT}{4\pi W} \quad \text{or} \quad \beta = \frac{C_0 f_u{}^2 gT}{4\pi W} \tag{18}$$

Figure 13 provides a comparison of various configurations of dampers in a short-period, single-story, single-bay frame. The damping ratios for the conventional diagonal and chevron-brace configurations are less than 3 percent of critical, and greater than 19 percent for the toggle-brace and scissor-jack assemblies. The displacement magnification factors for the toggle-brace and scissor-jack assemblies exceed 2.1. These new damper configurations will facilitate the use of dampers in stiff framing systems provided that the cost of the toggle-brace- or scissor-jack-support framing is not substantially greater than the cost of the framing that would be required to support the dampers in conventional configurations.

5. SUMMARY AND CONCLUSIONS

Two types of supplemental damping hardware were described: displacement-dependent and velocity-dependent dampers. Examples of each type of hardware, including metallic yielding ADAS, TADAS, and unbonded-brace, solid and fluid viscoelastic, and fluid viscous dampers were presented.

New procedures for the analysis and design of buildings incorporating displacement- and velocity-dependent dampers were discussed. Linear and nonlinear static methods of analysis were described. These analysis methods are displacement oriented and as such represent a paradigm shift in the analysis of buildings for the effects of earthquakes. For implementing dampers, the linear procedures can be used only if the building is regular, the response of the framing system is essentially elastic in the design earthquake, and the effective damping ratio is 30 percent of critical or less. Displacement- and velocity-dependent dampers are modeled using their secant stiffness at the maximum displacement and their damping is assumed to be equivalent viscous. The nonlinear analysis procedures of FEMA 273 are displacement-based; component checking focuses on deformations rather than forces. The force-displacement relations for displacement-dependent dampers are modeled explicitly and the key benefit of such dampers is the stiffness they add to the building frame. Velocity-dependent dampers are modeled using their secant stiffness at the stage of maximum displacement, and the primary benefit of such dampers is added viscous damping.

Up to the time of this writing, supplemental damping has generally been considered appropriate for flexible framing systems only although the greatest benefit of viscous damping, measured as a percentage reduction in displacement, is typically realized for stiff framing systems. Two new damper configurations, toggle-brace and scissor-jack, were described. The efficacy of these configurations was demonstrated by application to a stiff framing system with a period of 0.3 second. Fourfold to tenfold increases in damping ratio with respect to that provided by conventional damper configurations were shown to be possible with the toggle-brace and scissor-jack configurations.

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