SEAOC Energy Dissipation Committee

Appendix A: Guidelines for Buildings Using Passive Energy Dissipation Systems

by

Structural Engineers Association of California

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APPENDIX A
BUILDINGS USING
PASSIVE ENERGY DISSIPATION SYSTEMS

A1. GENERAL. These provisions provide minimum design requirements for the incorporation of passive energy dissipation devices in buildings.

Energy dissipation devices (also termed *damping* devices) reduce global and interstory seismic displacement response of structural systems, but may either increase or decrease seismic stresses and accelerations within structural systems. They provide a controlled increase in structural damping, and may also result in an increase in structural stiffness or change in participating mass. Passive energy dissipation systems do not require active control by electrical, pneumatic or hydraulic systems.

Buildings designed in conformance with these provisions must also be designed in accordance with all other applicable provisions of the Uniform Building Code, except as specifically defined in this appendix. Design must consider the combined behavior of all elements of both the Lateral Force Resisting System (LFRS) and the Energy Dissipation System (EDS). Energy dissipation devices must not form part of the gravity load-resisting system.

Buildings employing both energy dissipation and base-isolation devices shall be designed using the provisions for the design of base-isolated buildings.

A2. DEFINITIONS

Design Basis Ground Motion. Defined in (UBC) Section 1627.

Maximum Capable Earthquake. Defined in (UBC) Section 1655.

Lateral Force Resisting System (LFRS) - defined in (UBC) Section 1629.6.

Energy Dissipation Devices (EDDs) are supplemental devices used to reduce seismic deformations and displacements. EDD types may be classified as any combination of Displacement-Dependent or Velocity-Dependent, and may be designed or configured to act in either a linear or non linear manner.

Energy Dissipation System (EDS) consists of Energy Dissipation Devices (EDDs) plus any structural framing or bracing used to transfer forces between components of the Lateral Force Resisting System and the EDDs.

Displacement-Dependent Device. The force response of a displacement-dependent device is primarily a function of the relative displacement, between each end of the device. The response is substantially independent of the relative velocity between each end of the device, and/or the excitation frequency.

Velocity-Dependent Device. The force-displacement relation for a velocity-dependent device is a function of the relative velocity between each end of the device, and may also be a function of the relative displacement between each end of the device.

A3. SYMBOLS and NOTATIONS

The following symbols and notations apply to the provisions of this section:

B	=	Damping modification factor given in Table A-2.
C	=	Damping coefficient of a velocity-dependent energy dissipation device.
C_0, C_1	=	Coefficients defined in Section A6.3.1.
D_{Dn}	=	Maximum displacement of building at level n (roof) relative to the base.
D_{Di}	=	Maximum displacement of building at level i relative to the base.
E_{Dj}	=	Total energy dissipated by one device j during one complete cycle of response, see Equation (A6-2).
E_{EDS}	=	Earthquake forces calculated in components of the EDS, see Section A8.5.3.
E_m	=	Earthquake design force defined in Equation (A8-3).
E_S	=	The strain energy stored in the building at the maximum displacement, see Equation (A6-3).
k_{eff}		the effective stiffness of a damping device
M_M	=	Numerical coefficient related to maximum capable earthquake response as set forth in (UBC) Table A-16-D.
T_1	=	Elastic fundamental period of vibration, in seconds, in the direction under consideration, based on either a dynamic analysis of the building or Method B per (UBC) Section 1630.2.2, including the elastic stiffness of all energy dissipation devices and the provisions of (UBC) Section 1630.1.2.
T_E	=	Effective elastic building period = 1.15 T_1.
T_D	=	Secant (maximum) fundamental period of the building at the maximum displacement.
T_S, T_0	=	Response spectrum control periods, defined in (UBC) Figure 16-3.
W_D	=	Energy dissipated per cycle, calculated as the area within each cycle of a force-displacement hystereseis loop.
W, T, Ω_o	=	Terms defined in (UBC) Section 1628.
β	=	Inherent damping provided by the LFRS at the point of maximum displacement.
β_S	=	Damping provided by the EDDs and at the point of maximum displacement.
δ_{Dj}	=	Maximum relative displacement of damping device j.
δ_{Di}	=	Maximum interstory drift of floor level i relative to floor level i - 1.
$\dot{\delta}_{Dj}$	=	Maximum relative velocity of device j.
Δ_{Si}	=	Elastic building displacements defined in (UBC) Section 1630.9.1 and calculated using period T_1, relative to the base.
ω	=	Angular frequency equal to $2\pi/T$
ρ_D	=	Redundancy/Reliability Factor defined in Section A8.5.1.

α = Velocity exponent for a nonlinear velocity-dependent damping device.

A4. GENERAL REQUIREMENTS.

A4.1 Classification of Structural Behavior. Energy Dissipation Devices shall be classed as nonlinear if:

a) Displacement-Dependent Devices: the applied displacements exceed the yield or slip displacement of the device.

b) Velocity-Dependent Devices: the exponent α in Equation (A5-4) is either greater than 1.1 or less 0.9, and/or the device demonstrates stiffness in the frequency range of interest that is nonlinear with displacement.

All other devices shall be classed as linear devices.

A4.2 Selection of Analysis Procedure. Structure forces and deformations shall be determined by either of the following two procedures:

A4.2.1 Static Force Procedure. The Static Procedure presented in Section A6 may be used for buildings which conform with each of the following requirements:

a) Regular buildings not more than 5 stories nor 65 feet in height.
b) At least two EDDs shall be provided at each level (excluding penthouses) and in each direction of the building. At each level, the number of devices shall be equally distributed about the center of rigidity. No out-of-plane offsets between adjacent story levels shall be permitted in the placement of damping devices.
c) The horizontal damping forces in adjacent stories shall not differ by more than 20 percent.
d) The effective damping, β_{eff}, calculated using Equation (A4-1) shall not exceed 30 percent.
e) All velocity-dependent devices shall be linear.
f) The elastic stiffness of devices shall be included in the structure analysis.
g) Damping in displacement-dependent devices shall be ignored.
h) The LFRS shall meet both the strength and drift requirements of (UBC) Section 1630.

A4.2.2 Time-History Analysis Procedure. Any building may be designed using the Time History Analysis Method presented in Section A7. The LFRS shall meet the strength requirements of (UBC) Section 1630.

A4.3 Lateral Force Resisting System. Buildings which contain energy dissipation devices are required to contain a complete lateral force resisting system independent of the energy dissipation devices (termed herein as *Lateral Force Resisting System* or LFRS) of a type defined in (UBC) Section 1629.6.

> EXCEPTION: Displacement-dependent energy dissipation devices which operate by yielding of steel components may be utilized as part of the Lateral Force Resisting System, provided that:
>
> (i) the LFRS including the pre-yield stiffness contributed by all EDDs is designed to resist wind forces defined in (UBC) Chapter 16, Division III.
>
> (ii) the LFRS including the pre-yield stiffness contributed by all EDDs is designed to resist earthquake forces defined in (UBC) Section 1630 calculated using a maximum value of R equal to 6.0.
>
> (iii) structure forces and displacements are determined according to Section A7.
>
> (iv) the design meets all other applicable requirements of this Appendix.

The LFRS shall be designed and detailed to meet all strength and detailing requirements defined by the (UBC). Building lateral deformations shall meet the drift limitations presented in Section A8.3. Minimum strength requirements for components subjected to forces from energy dissipation devices shall meet the additional requirements of Section A8.4.

A4.4 Structure Height Limitations. Buildings containing EDDs shall not exceed the height limitations for the LFRS system set forth in (UBC) Table 16-N.

A4.5 Total and Inherent Structural Damping. Total effective damping at the point of maximum displacement, β_{eff}, shall be calculated as the sum of the damping which is provided by energy dissipation devices, β_S, and the inherent damping in the LFRS, β:

$$\beta_{eff} = \beta + \beta_S \qquad \text{(A4-1)}$$

The maximum value of β used for any mode of vibration shall not exceed 5 percent. The value of β_{eff} calculated using Equation A4-1 shall be used to determine the damping modification factor, B, in Table A-2.

A5 MATHEMATICAL REPRESENTATION OF DAMPING DEVICES.

A5.1 Displacement-Dependent Devices. Displacement-dependent devices are limited to either metallic-yielding or friction elements. The force-displacement response of such a device is primarily a function of the relative displacement between each end of the device, and is substantially independent of the relative velocity between each end of the device, and/or the frequency of excitation.

The energy dissipation characteristics of displacement-dependent devices may only be considered in conjunction with the nonlinear time-history analysis procedures presented in Section A7.

A5.2 Velocity-Dependent Devices.

A5.2.1 Viscoelastic Devices. The force F in a viscoelastic device may be expressed by the following:

$$F = k_{eff}\delta_D + C\dot{\delta}_D \qquad \text{(A5-1)}$$

The effective stiffness, k_{eff}, of a solid viscoelastic device shall be calculated as:

$$k_{eff} = \frac{|F^+| + |F^-|}{|\delta_D^{\,+}| + |\delta_D^{\,-}|} \qquad \text{(A5-2)}$$

where the forces F^+ and F^- are evaluated at device displacements δ_D^+ and δ_D^-, respectively. The damping coefficient shall be calculated as:

$$C = \frac{W_D}{\pi\omega(\delta_D)_{avg}} \qquad \text{(A5-3)}$$

where $(\delta_D)_{avg}$ is the average of the absolute values of device displacements δ_D^+ and δ_D^-, ω is the effective angular excitation frequency occurring at displacement $(\delta_D)_{avg}$, and W_D is the area enclosed by one complete cycle of the force-displacement response of the device at displacement $(\delta_D)_{avg}$.

If the cyclic response of the device cannot be defined throughout the range of operating conditions by single values of these constants, multiple analyses shall be undertaken to bound the response of the building.

A5.2.2 Fluid Viscous Devices.

In the absence of stiffness, the force in a fluid viscous device may be expressed as:

$$F = C|\dot{\delta}_D|^{\alpha} \qquad \text{(A5-4)}$$

If the cyclic response of a fluid viscous device cannot be defined throughout the range of operating conditions by single values of these constants, multiple analyses shall be undertaken to bound the response of the building.

A5.3 Other Types of Devices. Energy dissipation devices not classified as either displacement-dependent or velocity-dependent should be modeled using established principles of mechanics. Such models should accurately describe the force-velocity-displacement response of the device under all appropriate sources of loading (gravity, seismic, thermal).

A6. STATIC FORCE PROCEDURE.

A6.1 General.

The stiffness of each damping device, whether velocity-dependent or displacement-dependent, shall be included in the mathematical model of the DSS. Where velocity-dependent EDDs are used, the damping modification factor, B, must be calculated at the point of maximum displacement assuming device motion at period T_D. For displacement-dependent EDDs, B shall be set equal to 1.0.

A6.2 Damping Provided by Energy Dissipation Devices. The damping ratio provided by EDDs for buildings containing velocity-dependent devices shall be determined from the following:

$$\beta_S = \frac{\sum_j E_{Dj}}{4\pi E_S} \qquad \text{(A6-1)}$$

where the summation of E_{Dj} is the energy dissipated by all devices in the EDS during one complete cycle of response to building displacement, D_{Dn}; and E_S is defined by Equation (A6-3). E_{Dj} shall be determined from the following:

$$E_{Dj} = \frac{2\pi^2}{T_D} C_j \delta_{Di}^2 \cos^2\theta_j \qquad \text{(A6-2)}$$

where C_j is the damping coefficient of device j, δ_{Di} is the interstory displacement which occurs at device j due to building displacement D_{Di} and θ_j is the angle of the inclination of device j to the horizontal. E_S shall be determined from the following:

$$E_S = \frac{1}{2}\sum_i F_{Mi} D_{Di} \qquad \text{(A6-3)}$$

where F_{Mi} is the maximum inertial force at level i corresponding to the maximum displacement, D_{Di}, at level i.

F_{Mi} may be taken as:

$$F_{Mi} = \Omega_o F_i + \sum_j k_{eff} \delta_{Di} \cos\theta_j \qquad \text{(A6-4)}$$

where Ω_o is the value given in (UBC) Table 16-N for the LFRS, F_i is the design seismic force at level i calculated in accordance with (UBC) Section 1630.5, and the deformations of members supporting the devices is negligible.

A6.3 Minimum Lateral Displacements.

A6.3.1 Design Displacements. Design displacements at roof level n, D_{Dn}, shall be calculated as:

$$D_{Dn} = \left(\frac{g}{4\pi^2}\right)\frac{C_0 C_1 T_E^2 S_a}{B} \qquad \text{(A6-5)}$$

where:

- B = Damping displacement reduction factor given in Table A-2, calculated using Equations (A4-1) and (A6-1).
- C_0 = This factor may be calculated as the first mode participation factor at the roof level, or taken as the value given in Table A-1.
- C_1 = 1.0 for $T_E > T_S$
  = 2.0 for $T_E \le 0.10$ second
  Linear interpolation may be used to calculate C_1 for $0.10 \le T_E \le T_S$.
- S_a = Design spectrum acceleration at Period, T_E.
  = $2.5\, C_a$ for $T_E < T_S$
  = C_v / T_E for $T_E \ge T_S$
- C_a = Seismic coefficient set forth in (UBC) Table 16-Q.
- C_v = Seismic coefficient set forth in (UBC) Table 16-R.
- g = gravity constant = 386.4 in/sec^2.

The design displacement D_{Di} at level i shall be calculated using either the first mode or deformed shape of the building, scaled so that the roof displacement equals D_{Dn} per Equation A6-5. Interstory displacements δ_{Di} may be calculated as the difference between the displacements D_D at adjacent floor levels.

A6.3.2 Secant Period at Maximum Displacement. T_D shall be calculated as:

$$T_D = T_1\sqrt{\frac{V}{V_M}\frac{D_{Dn}}{\Delta_{Sn}}} \qquad \text{(A6-6)}$$

where Δ_{Sn} is the lateral displacement at level n resulting from application of the design static lateral forces F_i, V is the base shear corresponding to Δ_{Sn}, and V_M is the expected maximum base shear equal to:

$$V_M = \sum_{i=1}^{n} F_{Mi} \qquad \text{(A6-7)}$$

A6.3.3 Device Displacements and Velocities.

Device displacements δ_{Dj} shall be determined using the interstory displacements δ_{Di}. If the horizontal deformation of framing elements supporting the devices is less than 1/15 of the interstory displacement, the deformations of the supporting elements may be neglected. Device velocities may then be determined using the interstory velocities calculated as:

$$\dot{\delta}_{Dj} = \frac{2\pi\delta_{Di}}{T_D}\cos\theta_j \qquad \text{(A6-8)}$$

A7. TIME-HISTORY ANALYSIS.

A7.1 Time Histories. Ground motion time-histories used for analysis shall be selected in accordance with criteria defined in (UBC) Section 1631.6.1. In addition, motions shall be scaled such that the average value of the SRSS spectrum does not fall below 1.3 times the 5 percent-damped spectrum of the design-basis earthquake for periods from $0.2T_1$ second to $1.1T_D$ seconds.

A7.2 Analysis Procedures. Time-history analysis shall be conducted in accordance with the criteria of (UBC) Section 1631.6.3. Alternatively, if the calculated demand-to-capacity of all structural components is less than 2.0, linear time-history analysis procedures in accordance with approved national standards may be used.

A8. DETAILED DESIGN REQUIREMENTS.

A8.1 Environmental Conditions. The design, construction and installation of EDDs shall consider:

a) high-cycle, small-displacement degradation due to wind, thermal or other cyclic loads;
b) forces or displacements due to gravity loads;
c) freezing or adhesion of element components;
d) corrosion or abrasion;
e) biodegradation, moisture or chemical exposure; and
f) ultraviolet exposure.

The fatigue or wear life of EDDs shall be investigated and shown to be adequate by test for the expected design life of the devices.

EDDs subject to failure by low-cycle fatigue should resist design wind forces without slip or yielding.

The mathematical representations of device behavior defined in Section A5 shall consider the range of thermal conditions, device wear, manufacturing tolerances, and other device characteristics which may cause the device behavior to vary with time.

A8.2 Multi-Axis Movement. Connection points of EDDs shall provide sufficient articulation to accommodate simultaneous longitudinal, lateral, and vertical displacements of all components of the structure.

A8.3 Story Drift Limitation. Calculated interstory displacements δ_{Di} shall comply with (UBC) Section 1630.10, or the design performance level of the building (Blue Book Table AppB-1).

A8.4 Minimum Strength of EDDs and Related EDS Components.
A8.4.1 Reliability/Redundancy Factor, ρ_D. A reliability/redundancy factor ρ_D equal to 1.4 shall be used if fewer than four damping devices are provided at each story, distributed equally about each story's center of gravity. Otherwise, a value of 1.0 may be used for ρ_D.

A8.4.2 Determination of Design Forces in the EDS. If the Static Force Procedure of Section A6 is used, design forces shall be calculated at the Stage of Maximum Displacement (for a building incorporating displacement-dependent devices) and at the Stages of Maximum Displacement, Velocity, and Acceleration (for a building incorporating velocity-dependent devices), as follows:

a) Stage of Maximum Displacement. Design forces in the EDS shall be estimated from displacements calculated using Equation (A6-5). These displacements and forces shall be applied to the EDS to determine the design forces for structural members of the LFRS and EDS.

b) Stage of Maximum Velocity. Design forces in components of the EDS shall be determined by imposing the maximum device forces associated with the design velocity determined in Section A6.3.3, as static forces against the points of attachment of the devices to the EDS. These forces shall be applied in directions consistent with the deformed shape of the building. The horizontal component of velocity-dependent forces shall be applied at each floor level *i*, concurrent with inertial forces of equal but opposite sign, so that the horizontal displacement at each floor level is zero.

c) Stage of Maximum Acceleration. Design forces in EDDs and other EDS components shall be taken as the sum of the forces determined at the stage of maximum displacement multiplied by factor CF_1, plus the forces determined at the stage of maximum velocity multiplied by factor CF_2, where:

$$CF_1 = \cos\left[\tan^{-1}\left(2\beta_{eff}\right)\right] \qquad \text{(A8-1)}$$

$$CF_2 = \sin\left[\tan^{-1}\left(2\beta_{eff}\right)\right] \qquad \text{(A8-2)}$$

If the Time-History Analysis procedure of Section A7 is used, responses shall be calculated at each time step, and the maximum response shall be used for design.

A8.4.3 Minimum Strength and Stiffness of EDS Components (Static Procedure). Components of the EDS shall have sufficient strength and stiffness to resist the earthquake design forces defined below, where E_h and E_{EDS} are determined at the same stage of response.

a) Columns. Columns which comprise part of either the LFRS or EDS shall have the strength to resist the axial loads resulting from the load combinations specified in (UBC) Sections 1612.4 and either 2211.4 Part 6.1 or 2213.5.1, where:

$$E_m = \Omega_0 E_h + E_{EDS} \quad \text{(A8-3)}$$

E_{EDS} = $1.3\rho_D M_M$ times the forces determined from Section A8.5.2, if the Static Force Procedure of Section A6 is used.

b) Beams. EDS-induced stresses in beams which form part of the lateral-force resisting system shall not exceed 0.3 F_y. Other beams shall be designed to resist earthquake forces defined in Equation A8-3.

c) Braces. Bracing members used as a part of the EDS shall be designed to resist earthquake forces defined in Equation A8-3. The stress reduction factors defined in (UBC) Sections 2213.8.2.2 and 2214.6.2.1, as well as the brace force multipliers defined in (UBC) Sections 2213.8.4, 2213.8.5, 2214.6.4 and 2214.6.5, need not be considered when checking this requirement.

d) Diaphragms and Struts. Diaphragms or struts shall be designed to resist the earthquake forces given by Equation A8-3.

e) Foundations. Foundations which comprise a part of the EDS shall have sufficient strength, uplift and sliding resistance to withstand the earthquake forces defined in Equation A8-3.

A8.5 Inspection and Periodic Testing.

Means of access for inspection and removal of all EDDs shall be provided.

The engineer-of-record shall establish an appropriate inspection and testing schedule for each type of energy dissipation devices used to ensure that the devices respond in a dependable manner throughout the device design life. The degree of inspection and testing should reflect the established in-service history of each type (and internal design) of device, and the likelihood of change in mechanical characteristics over the design life of the device.

A8.6 Manufacturing Quality Control. A quality control plan for the manufacture of energy dissipation devices should be provided by the device manufacturer.

A9. DESIGN REVIEW.

Review of the design of the energy dissipation system and related test programs shall be performed by an independent engineering panel including persons licensed in the appropriate disciplines and experienced in seismic analysis including the theory and application of energy dissipation methods. The design review shall include, but not be limited to, the following:

1. Review of the earthquake ground motion characterizations used for design.
2. Review of design parameters of energy dissipation devices, including device test requirements, device production quality assurance, and scheduled maintenance and inspection requirements
3. Review of the preliminary design of the LFRS and the EDS.
4. Review of the final design of the LFRS and EDS and all supporting analysis.

A10 TESTING *of* ENERGY DISSIPATION DEVICES

A10.1 General. The force-displacement relations and damping values assumed in the design of the passive energy dissipation system should be confirmed by the following tests of a selected sample of devices prior to production of devices for construction. Alternately, if these tests precede the design phase of a project, the results of this testing program should be used for the design.

The tests specified in this section are intended to: (1) confirm the force-displacement properties of-the passive energy dissipation devices assumed for design, and (2) demonstrate the robustness of individual devices to extreme seismic excitation. These tests should not be considered as satisfying the requirements of a manufacturing quality control (production) plan. The tests also do not address tests that maybe required to demonstrate adequate long-term performance for non-seismic loads such as wind and thermal effects.

The engineer-of-record should provide explicit acceptance criteria for the effective stiffness and damping values established by the prototype tests. These criteria should reflect the values assumed in design, account for likely variations in material properties, and provide limiting response values outside of which devices will be rejected.

The engineer-of-record should also establish appropriate criteria to evaluate the amount of travel that a device will be subjected to under wind excitation. These criteria will likely vary considerably, and are a function of the stiffness of the device.

The engineer-of-record should provide explicit acceptance criteria for effective stiffness and damping values for the production EDDs. The results of the prototype tests should form the basis of the acceptance criteria for the production tests, unless an alternate basis is established by the engineer-of-record. Such acceptance criteria should recognize the influence of loading history on the response of individual devices by requiring production testing of devices prior to prototype testing.

The fabrication and quality control procedures used for all prototype and production devices should be identical. These procedures should be approved by the engineer-of-record prior to the fabrication of prototype devices.

A10.2 Prototype Tests.

A10.2.1 General. The following prototype tests should be performed separately on two full-size devices of each type and size used in the design. If approved by the engineer-of-record, representative sizes of each type of device may be selected for prototype testing, rather than each type and size, provided the fabrication, and quality control procedures are identical for each type and size of devices used in the rehabilitated building. Test specimens should not be used for construction unless approved in writing by the engineer-of-record.

A10.2.2 Data Recording. The force-deflection relationship for each cycle of each test should be digitally recorded.

A10.2.3 Sequences and Cycles of Testing. Energy dissipation devices should not form part of the gravity load-resisting system, but may be required to support some gravity load. For the following minimum test sequences, each dissipation device should be loaded to simulate the gravity loads on the device loads on the device as installed in the building, at the extreme ambient temperatures anticipated (if the response of the energy dissipation devices is dependent on temperature). In the following sequence, the design displacement for the EDD, δ_D, shall be calculated using information from Section A6.3.3, or from time-history analysis.

a) Each device should be loaded with the number of cycles expected in the design wind storm, but not less than 200 fully-reversed cycles of load (displacement-dependent and viscoelastic devices) or displacement (viscous devices) at amplitudes expected in the design wind storm, at a frequency equal to the inverse of the fundamental period of the building ($f_1 = 1/T_1$).

   EXCEPTION: Devices need not be subjected to these tests if they are not subjected to wind-induced forces or displacements, or if the design wind force is less than the device yield or slip force.

b) Each device should be loaded with 5 fully reversed cycles at a displacement in the EDD corresponding to $1.5\delta_D$ at a frequency equal to $1/T_D$ calculated in Section A6.2.1. Where the device characteristics may vary with temperature, these tests shall be conducted at a minimum of 3 temperatures which extend through and beyond the expected temperature range.

EXCEPTION: Energy dissipation devices may be tested by other methods than those noted above provided that: equivalency between the proposed method and cyclic testing can be demonstrated; the proposed method, captures the dependence of the energy dissipation device response on ambient temperature, frequency of loading, and temperature rise during testing; and the proposed method is approved by the engineer-of-record.

c) If the force-deformation properties of the EDDs at any displacement less than or equal to $1.5\delta_D$, change by more than 15 percent for changes in testing frequency from $0.5 f_l$, to $2.0 f_l$, the preceding tests should be performed at frequencies equal to f_l and $2.0 f_l$.

EXCEPTION: If reduced-scale prototypes are used to qualify the rate dependent properties of energy dissipation devices, the reduced-scale prototypes should be of the same type and materials, and manufactured with the same processes and quality control procedures, as full-scale prototypes, and tested at a similitude-scaled frequency that represents the full-scale loading rates.

d) If the EDDs are subjected to substantial bilateral deformation, the preceding tests should also be performed at the maximum bilateral displacement expected in the design earthquake.

EXCEPTION : If reduced-scale prototypes are used to quantify the bilateral displacement properties of the energy dissipation devices, the reduced scale prototypes should be of the same type and materials, and manufactured with the same processes and quality control procedures, as full-scale prototypes, and tested at similitude-scaled displacements that represent the full-scale displacements.

A10.2.4. Testing Similar Devices. Energy dissipation devices that are (1) of similar size, and identical materials, internal construction, and static and dynamic internal pressures (if any), and (2) fabricated with identical internal processes and manufacturing quality control procedures, that have been previously tested by an independent laboratory, in the manner described above, may not need to be tested provided that:

a) Such a waiver is included by the engineer-of-record.

b) All pertinent testing data are made available to, and approved by the engineer-of-record.

c) The manufacturer can substantiate the similarity of the previously-tested devices, to the satisfaction of the engineer-of-record.

d) The submission of data from a previous testing program is approved in writing by the engineer-of-record.

A10.2.5 Determination of Force-Velocity-Displacement Characteristics. The force-velocity displacement characteristics of an energy dissipation device should be based on the cyclic load and displacement tests of prototype devices specified above.

For EDDs with stiffness, the effective stiffness should be calculated for each cycle of deformation using Equation (A5-3). For all EDDs, the area of the hysteresis loop (W_D) should be calculated for each cycle of deformation.

A10.2.6 System Adequacy. The performance of a prototype device may be assessed as being adequate if all of the following conditions are satisfied:

a) The force-displacement curves for the tests specified in Section A10.2 have non-negative incremental stiffness.

   EXCEPTION. Energy dissipation devices that exhibit velocity-dependent behavior need not comply with this requirement.

b) Within each test of Section A10.2, the effective stiffness of a prototype energy dissipation device for any one cycle does not differ by more than plus or minus 15 percent from the average effective stiffness as calculated from all cycles in that test.

   EXCEPTIONS: (1) The 15 percent limit may be increased by the engineer-of-record, provided that the increased limit has been demonstrated by analysis to not have a deleterious effect on the response of the building. (2) Fluid viscous energy dissipation devices need not comply with this requirement.

c) Within each test of Section A10.2, the maximum force and minimum force at zero displacement for a prototype device for any one cycle does not differ by more than plus or minus 15 percent from the average maximum and minimum forces as calculated from all cycles in that test.

   EXCEPTION: The 15 percent limit may be increased by the engineer-of-record, provided that the increased limit has been demonstrated by analysis to not have a deleterious effect on the response of the building.

d) Within each test of Section A10.2, the area of hysteresis loop (W_D) of a prototype energy dissipation device for any one cycle does not differ by more than plus or minus 15 percent from the average area of the hysteresis curve as calculated from all cycles in that test.

EXCEPTION: The 15 percent limit may be increased by the engineer-of-record, provided that the increased limit has been demonstrated by analysis to not have a deleterious effect on the response of the building.

e) For displacement-dependent devices, the average effective stiffness, average maximum and minimum force at zero displacement, and average area of the hysteresis loop (W_D), calculated for each test in the sequence described in Section A10.2, shall fall within the limits set by the engineer-of-record.

f) For velocity-dependent devices, the average maximum and minimum force at zero displacement, effective stiffness (for viscoelastic devices only), and average area of the hysteresis loop (W_D) calculated for each test in the sequence described in Section A10.2, shall fall within the limits set by the engineer-of-record.

A10.3 Production Testing. Prior to installation in a building, each energy dissipation device shall be tested to ensure that its force-velocity-displacement characteristics fall within the limits set by the engineer-of-record.

Table A-1

Factors of Coefficient C_0 versus Building Story Height

Stories	C_0
1	1.0
2	1.2
3	1.3
4	1.35
5	1.4

Table A-2

Modification Factor for Increased Damping

Effective Damping Ratio, β_{eff} (% of critical)	Damping Modification Factor, B	
	Short Period Range, $T_e < T_S$	Long Period Range $T_e > T_S$
5	1.0	1.0
10	1.3	1.2
20	1.8	1.5
30	2.3	1.7

Notes:

1. $T_S = C_v / 2.5\, C_a$

COMMENTARY TO SEAOC ENERGY DISSIPATION GUIDELINES

SECTION CA.1 GENERAL

The guidelines presented in the Blue Book for implementing *passive* energy dissipation devices (also termed dampers in the commentary below) in buildings assume that the dampers are being added to the lateral-force-resisting system primarily to reduce displacements in the building during earthquake shaking. The lateral-force-resisting system, independent of the dampers and the damper-support framing, is required to be complete per UBC Section 1629.6 and to comply with all strength, drift, and detailing provisions of the UBC.

The Blue Book guidelines are based on the guidelines and commentary set forth in Chapter 9 of FEMA 273 (FEMA, 1997). Two of the three authors of Chapter 9 of FEMA 273 are members of SEAOC. The third author, Professor Michael Constantinou of SUNY Buffalo, is herewith acknowledged as a key contributor to the development of analysis, design, and implementation procedures for passive energy dissipation devices.

The primary reason for introducing dampers into a building frame is to reduce displacements during earthquake shaking. A reduction in displacement is achieved by adding either stiffness or energy dissipation (also termed damping) to the frame. Metallic yielding, friction, and viscoelastic dampers add both stiffness and damping; viscous dampers generally only add damping to a building frame. The force-displacement relations of Figure CA-1 schematically illustrate the effect of adding different types of dampers to a building frame. The addition of viscous dampers to a building frame will not alter the building's pseudo-static force-displacement relation.

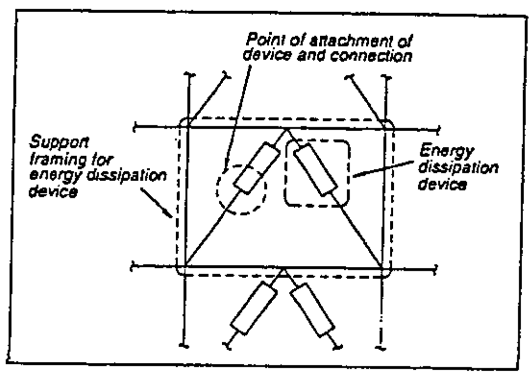

Figure CA-1 Effect of dampers on the force-displacement response of a building (FEMA, 1997)

The addition of either stiffness or damping to a yielding building frame will reduce displacements in the building, but may increase maximum accelerations in the building. If damage to the contents of a building is to be avoided during design earthquake shaking, the addition of dampers may be detrimental in terms of the acceleration response of the building. (Noting however that the adding dampers to the building frame will typically reduce the degree of damage to the building frame in design earthquake shaking and may eliminate damage to structural and nonstructural components in earthquakes smaller than the design earthquake.) The engineer must be cognizant of the relations between acceleration and displacement in highly damped yielding frames before attempting to implement dampers in a building using these provisions.

In conventional seismic framing systems, the lateral-force-resisting system inevitably includes components of the gravity-load-resisting system (e.g., beams and columns in a moment-resisting frame). In a design earthquake, components of the gravity-load-resisting system dissipate energy by inelastic response; such inelastic response produces permanent damage —damage that may be extremely expensive to repair. This observation led the writers of the SEAONC draft guidelines for implementing energy dissipation devices (see Whittaker et al., 1993) to treat energy dissipation devices as disposable structural components that did not form part of the gravity-load-resisting system. This strategy was adopted in an attempt to further uncouple the gravity-load- and lateral-force-resisting- systems and to minimize earthquake-induced damage in the gravity-load-resisting system.

These Blue Book guidelines do not apply to the implementation of energy dissipation devices in seismic isolation systems because the displacement-calculation procedures are not applicable to buildings with low yield strength (equal to the yield strength of the isolation system in this instance). The reader is referred to the Blue Book guidelines for seismic isolation for information on how to calculate displacements and implement dampers in an isolation system.

> The analysis and design procedures set forth in the Blue Book guidelines are preliminary and mutable, and must be used with great caution. At the time of this writing, case studies have not been undertaken to validate these procedures.

SECTION CA.2 DEFINITIONS

Figure CA-2 defines terms used throughout the guidelines. The dashed line enclosing the one-story, one-bay of framing defines part of the energy dissipation system. Other bays of framing that include energy dissipation devices and/or structural framing that transfer force between the lateral-force-resisting system and the energy dissipation devices are also included in the energy dissipation system.

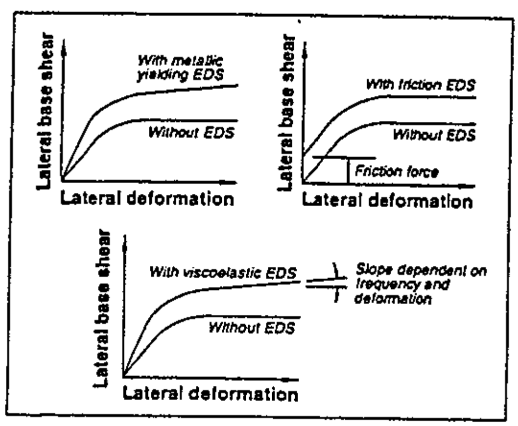

Figure CA-2 Definition of components in an energy dissipation system (FEMA 273)

SECTION CA.3 SYMBOLS AND NOTATIONS

No commentary provided for this section.

SECTION CA.4 GENERAL REQUIREMENTS

Section CA.4.1 Classification of Component Behavior

The Blue Book guidelines categorize energy dissipation devices as either linear or nonlinear. Displacement-dependent dampers (see Section A5.1) that rely on friction or yielding of metals will always be classified as nonlinear. Only linear or nearly linear viscous or viscoelastic dampers can be considered to be linear.

Section CA.4.2 Selection of Analysis Procedure

Two analysis procedures are set forth in the Guidelines: a static force procedure and two time-history (response-history) procedures.

Limitations are placed on the use of the static force procedure. The limits identified in Section A4.2.1 are based on engineering judgement. No case studies have been performed to validate the limits. Item a) is a carryover of the limit enforced on conventional framing systems because framing systems over 5 stories or 65 feet in height may experience higher mode effects, which the static force procedure cannot capture. The intent of item b) and item c) is to provide dampers in each story of a building and to eliminate a concentration of dampers in any one story. Item d) is a somewhat arbitrary limit that prevents the engineer from designing a highly damped yielding system for which the static force procedure is inappropriate (see FEMA 273 for more information). Item e) prevents the use of the static force procedure for nonlinear velocity-dependent systems because the analysis procedures of Section A.6 cannot capture the characteristics of such dampers. Item f) identifies the need to include the elastic stiffness of the dampers in the mathematical model of the building frame. Item g) restates the design philosophy of the Blue Book guidelines, namely, that the lateral-force-resisting system must satisfy all strength and stiffness requirements of the Uniform Building Code.

Fewer restrictions are placed on the use of time- (response-) history analysis to implement energy dissipation devices. Linear response-history analysis may be used if the building frame remains essentially elastic in the design earthquake. Essentially elastic response is achieved if the demand-to-capacity ratio for each component is less than 2.0. This value was chosen for a number of reasons including a) the ultimate strength of structural components generally exceed the strength determined by analysis by a wide margin and b) nominal strengths are reduced by capacity reduction factors to estimate design strengths. (The product of the ratio of the ultimate strength to the strength required by analysis and the inverse of the capacity reduction factor likely exceeds 2.0. See ATC (1995) for more information.) If the building frame remains essentially elastic, the force-based procedures of the Uniform Building Code can be used to check component demands versus expected component strengths. (See FEMA 273 for procedures to calculate expected component strengths.)

Nonlinear response-history analysis can be used to implement dampers regardless of the degree of inelastic response in the building frame. If nonlinear procedures are used, deformation demands must be checked against deformation capacities for deformation-controlled actions, and actions must be checked against lower-bound estimates of component strengths for force-controlled actions. Refer to FEMA 273 for information on deformation- and force-controlled actions, component deformation capacities, and procedures for calculating lower-bound estimates of component strengths.

Section CA.4.3 Lateral Force Resisting System

The design philosophy assumed by the Blue Book is that dampers are added primarily to reduce displacements in a building. As such, the guidelines require that a building contain a complete lateral-force-resisting system, independent of the dampers, that meets all of the strength and detailing requirements of the Uniform Building Code. The only exception to this rule is for steel yielding dampers (Whittaker et al., 1991; Tsai et al. 1993).

Steel-yielding dampers function in a manner very similar to shear links in eccentrically braced frames. Accordingly, steel-yielding dampers can be modeled as conventional structural steel components (i.e., nominal material properties and elastic stiffness) and may be included in the lateral-force-resisting system. Similar to all other components in a steel frame, the force in a steel-yielding damper must be less than its design yield strength (equal to the nominal yield strength multiplied by a capacity reduction factor of 0.75) in the design wind storm. Conservatively, buildings incorporating steel-yielding dampers in the lateral-force-resisting system must be designed for forces calculated using a maximum value of R equal to 6. (The value of 6.0 is smaller than the value of 7.0 assigned to an eccentrically braced frame in the Blue Book.) If the steel-yielding dampers are being implemented in parallel with a lateral-force-resisting system that is assigned a value of R smaller than 6.0, the smaller value must be used to analyze and design the damped lateral-force-resisting system.

Section CA.4.4 Structure Height Limitations

No commentary is provided for this section.

Section CA.4.5 Total and Inherent Structural Damping

The total effective damping of the building frame, including the effects of the dampers is given by Equation A4-1. In this equation, β is the inherent damping in the structural frame that accounts for energy dissipation in the framing system prior to significant yield. β should not be increased beyond 5 percent of critical. The term β_S is the damping provided by the energy dissipation devices at the point of maximum displacement. Values of β_S for velocity-dependent dampers are calculated in Section A.6; β_S equals 0 for displacement-dependent dampers.

If nonlinear response-history analysis is used to implement energy dissipation devices in a building frame, care must be taken to not overestimate the inherent damping at the point of maximum displacement. If the inherent damping is assumed to be equal to 5 percent of critical at the point of maximum displacement, a smaller value must be assigned to the mathematical model for analysis because the inherent damping will be increased by a factor equal to T_s / T_1, where T_s is the secant period at the point of maximum displacement, and T_1 is the fundamental period of the building as determined by eigen analysis.

SECTION CA.5 MATHEMATICAL REPRESENTATION OF DAMPING DEVICES

The Blue Book guidelines identify three types of energy dissipation devices: displacement-dependent, velocity-dependent, and other. Metallic yielding and friction devices are classed as displacement-dependent dampers. Figure CA-3 shows sample force-displacement relations for displacement-dependent devices. Velocity-dependent devices include solid and fluid viscoelastic dampers and fluid viscous dampers. Figure CA-4 shows sample force-displacement relations for velocity-dependent dampers. Other devices have characteristics that cannot be classified as one of the two basic types depicted in Figures CA-3 and CA-4. Examples of other devices include those constructed using shape-memory alloys (superelastic), friction-spring assemblies with recentering capability, and fluid dampers with restoring force. The reader is referred to ATC (1993), EERI (1993), and Soong and Constantinou (1994) for more information on this class of damper. Only displacement-dependent and velocity-dependent dampers are addressed in the Blue Book guidelines.

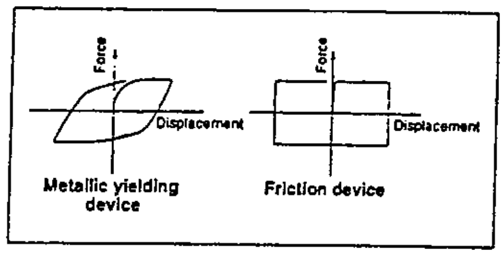

Figure CA-3 Idealized force-displacement loops for displacement-dependent EDDs

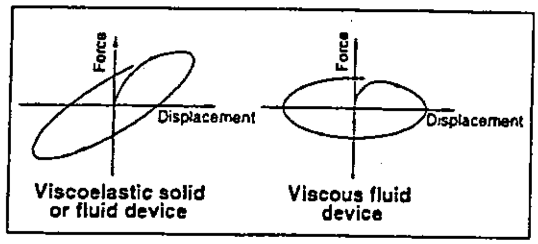

Figure CA-4 Idealized force-displacement loops for velocity-dependent EDDs

Displacement-dependent dampers exhibit bilinear or trilinear hysteretic, elasto-plastic or rigid-plastic behavior. Details on the behavior of displacement-dependent devices can be found in Whittaker et al. (1991), Aiken et al. (1993), ATC (1993), and Soong and Constantinou (1994).

Solid viscoelastic dampers are typically composed of constrained layers of acrylic coploymers. Such dampers have mechanical properties, which are dependent on the frequency, temperature, and amplitude of the imposed loading. Viscoelastic solid behavior can be modeled with the standard linear model of Figure CA-5 using Equations A5-1 through A5-3. Fluid viscoelastic dampers operate by shearing viscoelastic fluids, and have response characteristics similar to those of solid viscoelastic dampers except that the fluid dampers have zero effective stiffness (Equation A5-2) under static load. Fluid viscoelastic behavior can be modeled with the Maxwell model of Figure CA-6. Pure viscous behavior can be produced by forcing fluid through an orifice. Fluid viscous dampers may exhibit some stiffness if the excitation frequency is high (i.e., greater than 4 Hz). In the absence of stiffness, the force in a fluid viscous damper can be calculated using Equation A5-4. Derivations of Equations A5-1 through A5-4 can be found in ATC (1993) and Soong and Constantinou (1994).

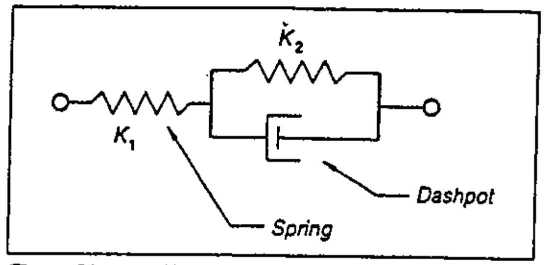

Figure CA-5 Model for Solid Viscoelastic EDD (FEMA, 1997)

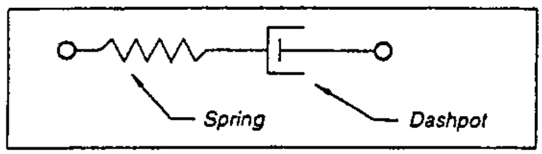

Figure CA-6 Model for Fluid Viscoelastic EDD (FEMA, 1997)

SECTION CA.6 STATIC FORCE PROCEDURE

Section CA.6.1 General

The Blue Book design provisions are based on checking component strengths with respect to component actions calculated using a design base shear (V in Equation **-**), which is reduced from the elastic spectral value by a response modification factor (R). Design displacements are calculated using elastic analysis and lateral forces based on the design base shear. Maximum inelastic displacements are calculated by increasing the design displacements by $0.7R$. Maximum inelastic displacements are not used to calculate component deformations to check whether component deformation limits are exceeded. Rather, prescriptive detailing requirements (e.g., transverse confinement in reinforced concrete beams and columns, flange and web compactness ratios in steel beams and columns) are employed, whereby it is assumed that each component has sufficient deformation capacity. Maximum inelastic displacements are only used to check interstory drifts and building separations.

The use of an amplification factor of $0.7R$ will likely produce non-conservative estimates of maximum displacements, because the displacements so calculated will be less than the elastic displacements (displacements calculated using unreduced forces). Displacements are more correctly estimated using the procedures set forth in FEMA 273 (FEMA, 1997), wherein maximum inelastic displacements equal or exceed elastic displacements.

Energy dissipation devices (also termed dampers) are used to reduce displacements (and therefore damage) in a building to values smaller than the limits set forth in Section *.* of the Blue Book. Because the energy dissipation provisions are intended to facilitate the correct implementation of dampers, the provisions must include procedures that will enable the engineer to calculate improved estimates of maximum inelastic displacements. As such, the static force procedure of Section A.6 is based on one of the displacement-oriented design procedures of FEMA 273: the nonlinear static procedure.

The equation used to calculate maximum inelastic displacements with the static lateral force procedure is based on the assumption that mean elastic displacements equal mean inelastic displacements for non-degrading framing systems with fundamental periods greater than 0.5 second and significant post-yield stiffness. FEMA 273 writes that the maximum inelastic displacement (termed δ_t) can be calculated as:

$$\delta_t = \prod_{i=1,4} C_i \frac{S_a}{B} \frac{T_e^2}{4\pi^2} \qquad \text{(CA6-1)}$$

where C_i are coefficients to relate expected inelastic displacements to elastic displacements (all greater than 1.0), T_e is the effective fundamental period of the building (an improved measure of the fundamental period of the building up to first significant yielding), S_a is the 5-percent damped spectral acceleration at period T_e, and B is a reduction factor for values of viscous damping different from five percent of critical. The effective period is calculated using an estimate of the effective elastic stiffness (K_e), where the effective stiffness is defined in Figure CA-7:

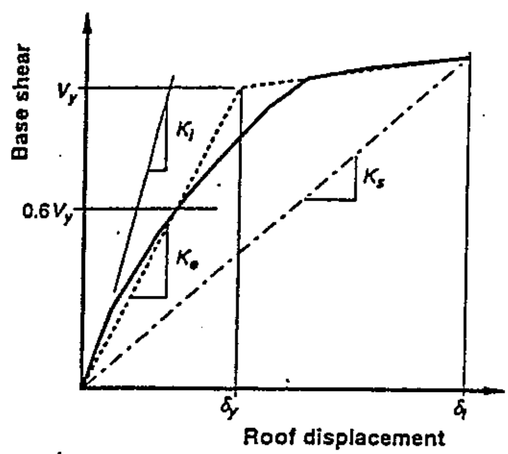

Figure CA-7 Force-displacement relation for a building (FEMA, 1997)

In Figure CA-7, the multi-linear force-displacement relation (solid line) is approximated by a bilinear relation (dashed line). The elastic stiffness of the bilinear relation is termed the effective stiffness.

The FEMA 273 provisions recognize that the primary benefit of adding displacement-dependent dampers to a building frame is that of added stiffness. As such, there is no calculation of added damping for displacement-dependent devices. Adding stiffness to a framing system reduces the effective period and displacements of the building frame. See Equation CA6-1, wherein a reduction in the effective period will generally reduce the maximum inelastic displacement (termed the target displacement in FEMA 273).

The addition of velocity-dependent dampers to a building frame will reduce displacements through a combination of added damping and added stiffness. Some velocity-dependent dampers exhibit little or no stiffness (e.g., fluid viscous devices operating at frequencies below 5 Hertz) and the primary benefit of such devices is added damping.

The Blue Book provisions for calculating displacements in framing systems that include energy dissipation devices mirror those set forth in FEMA 273 for use with the nonlinear static procedure. Namely, displacements are reduced with displacement-dependent dampers through added stiffness only, and with velocity-dependent dampers through added stiffness (if any) and added damping.

The Blue Book calculation of the maximum inelastic displacement in a building frame incorporating displacement-dependent dampers is straightforward. The calculation requires the engineer to estimate the effective elastic period (T_e) of the building frame using an eigen analysis of a mathematical model that includes the elastic stiffness of the dampers. Because the Blue Book procedures are based on elastic analysis, it is not possible to develop the multi-linear and bilinear force-displacement relations of Figure 1. Therefore, it is assumed that $T_e = 1.15T_1$ where T_1 is the fundamental period of the mathematical model of the building frame that includes the elastic stiffness properties of the dampers.

The viscous damping added by velocity-dependent dampers is calculated in the Blue Book using the equations of Section A.6.2. The corresponding reduction in displacement is estimated using the effective damping ratio of the building frame (including the dampers). The effective damping ratio is converted to a displacement reduction factor (B in Equation CA6-1), which is used to reduce the maximum inelastic displacement below that value associated with 5-percent damping that is generally assigned to the building frame exclusive of the dampers. The calculation of maximum inelastic displacement is iterative, because the estimates of secant period at maximum displacement and effective damping ratio require a priori knowledge of the maximum inelastic displacement. When the assumed and calculated values of the maximum inelastic displacement are sufficiently close for a given configuration of dampers, the solution has converged.

Section CA.6.2 Damping Provided by Energy Dissipation Devices

Section A.6.2 presents equations for calculating the added damping provided by velocity-dependent dampers. Equation A6-1 is the well-established relation for viscoelastic systems (Constantinou and Symans, 1993; Constantinou et al., 1996). In this equation, $\sum E_{Dj}$ is the energy dissipated by all dampers in the building at displacements corresponding to the maximum inelastic displacement. Individual damper displacements should be calculated using estimates of interstory displacements that correspond to the maximum inelastic displacement. These displacements must be resolved into the axis of the damper, and the deformations of the framing supporting the dampers must be accounted for. The work done in one cycle of loading for one damper is calculated as

$$E_{Dj} = \pi(F_D \delta_D) \quad \text{(CA6-2)}$$

In this equation, the damper force (F_D) is equal to $C\dot{\delta}_D$, where C is the damping coefficient and $\dot{\delta}_D$ is the relative velocity between the two ends of the damper. Assuming that the relative displacement history is harmonic with amplitude δ_D and frequency ω_D, the maximum velocity is equal to:

$$\dot{\delta}_D = \omega_D \delta_D = \frac{2\pi}{T_D}\delta_D \quad \text{(CA6-3)}$$

In Equation A6-1, E_s is the elastic strain energy in the building frame at the point of maximum inelastic displacement, which can be calculated using Equation A6-3.

Equation A6-4 represents a crude estimate of the inertial force at floor level i, where F_{Mi} is the design lateral force at level i, and Ω_o is an estimate of the ratio of the maximum story shear strength at level *i* and the design lateral force at level *i*. The second term on the right-hand side of the equation is the contribution of the dampers to the inertial force at floor level *i*.

Section CA.6.3 Minimum Lateral Displacements

Equation A6-5 provides an estimate of the maximum displacement of a yielding system subject to earthquake shaking characterized by an earthquake with a 5-percent damped spectral acceleration ordinate equal to S_a at an effective elastic period of T_e. The maximum displacement is that of the control node of the building where the control node is typically the node associated with the center of mass at the roof. The equation assumes a relation between mean elastic and mean inelastic displacements.

The coefficient C_0 serves to extrapolate the displacement of the generalized first modal mass to the roof level. Either the first mode participation factor or an approximate value from Table A-1 should be used for C_0.

The coefficient C_1 accounts for the difference between the maximum inelastic and elastic displacements in buildings with full and stable hysteresis loops. The values are loosely based on the studies of Miranda (1991) and Nassar and Krawinkler (1991). For buildings either designed using large values of *R* (greater than 5) or located in the near field to a major active fault, the values assigned to C_1 may not be conservative (Whittaker et al., 1998).

Interstory displacements are estimated using the estimate of the maximum inelastic displacement (D_{Dn} in these provisions). Floor displacements are calculated by multiplying the maximum inelastic displacement by the normalized ordinates of the first mode shape. Interstory displacements are estimated to be the difference between the floor displacements. This procedure is approximate at best because an elastic mode shape is used to estimate interstory displacements in a yielding system wherein displacements will tend to concentrate in one or two stories. Interstory displacements so calculated should be assumed to be lower bound values.

Equations A6-6 and A6-7 present an approximate means by which to calculate the secant period at the maximum inelastic displacement of the building. Using the force-displacement relation of Figure 1, the secant period at the maximum inelastic displacements can be calculated as:

$$T_s = T_e \sqrt{\frac{K_e}{K_s}} \qquad \text{(CA6-4)}$$

Because it is not possible to directly measure the base shear corresponding to the maximum inelastic displacement, equation A6-7 is used. This estimate for V_M is approximate at best. The engineer is urged to investigate the design and performance implications of using different values for V_M.

As noted above, an estimate of the secant period at maximum displacement is needed to establish the effective damping ratio of a building frame incorporating velocity-dependent dampers. The calculation of the effective damping ratio is based on the energy dissipated by all velocity-dependent dampers assuming that the building is subjected to harmonic loading with a maximum displacement of D_{Dn} at a period of T_D. If the deformation of the framing supporting a damper is small, such deformation can be ignored in the calculation of the relative displacements between the ends of the damper (estimated using interstory drifts) and the relative velocities between the ends of the damper (estimated assuming harmonic motion with an amplitude equal to the relative displacement and periodicity T_D).

SECTION CA.7 TIME-HISTORY ANALYSIS

Section CA.7.1 Time Histories

The earthquake ground motion histories proposed for the analysis of building frames incorporating energy dissipation devices must conform with the criteria set forth in Section 1631.6.3 of the Uniform Building Code. The Blue Book guidelines further require that the histories be amplitude and frequency scaled such that the ordinates of the SRSS spectrum do not fall below 130% of the ordinates of the target spectrum. These requirements are virtually identical to those of the seismic isolation provisions. The period range of $(0.2T_I, 1.1T_D)$ is intended to bracket the second-mode elastic period and the secant period at maximum displacement.

Section CA.7.2 Analysis Procedures

Procedures for time- (response-) history analysis are given in Section 1631.6.3 of the Uniform Building Code. Nonlinear response-history analysis must be used if substantial yielding is expected in the building frame; for these guidelines, substantial yielding corresponds to demand-capacity ratios greater than 2.0. Many additional guidance and acceptance criteria for nonlinear response-history analysis is given in FEMA 273. Additional information on linear response-history analysis is given in Section CA4.2 above.

SECTION CA.8 DETAILED DESIGN REQUIREMENTS

Section CA.8.1 Environmental Conditions

Apart from corrosion, little consideration has been given to environmental effects on traditional structural engineering materials (e.g., reinforced concrete and steel) when those materials have been placed in buildings. The use of non-traditional materials (e.g., acrylic copolymers) and mechanical devices (e.g., fluid viscous dampers, friction dampers), which are substantially affected by temperature, creep, corrosion, and UV exposure, present the engineer with new and additional challenges. Before specifying a damper for a project, the engineer must consider the environmental factors listed in Section CA.8.1 in order to either correctly bound the likely response characteristics of the damper over its design life or take special measures to mitigate the environmental factor(s).

Dampers are added to a building to dissipate earthquake-induced energy and must not form part of the gravity-load-resisting system. (Such dampers may also be used to mitigate the effects of wind, but such discussion is beyond the purview of the Blue Book guidelines.) Although earthquake-related forces and displacements will generally drive the design of a damper, adequate attention must be paid to the effects of wind forces on the damper. Consider two examples: a steel-yielding damper and a fluid viscous damper. For a steel-yielding damper subject to failure by low-cycle fatigue, the force in the damper produced by the design windstorm must be substantially less than the yield strength of the damper. For a fluid viscous damper, wind forces on a building will introduce displacements in the damper; the seals of the damper must have a travel life in excess of the expected travel of the damper piston due to all wind effects for its design life.

The engineer must characterize the likely changes in the response of a damper due to environmental effects over the design life of the damper. The maximum and minimum values of damper response must be carefully evaluated prior to final analysis and design. The change in building response as a function of the maximum, target, and minimum values of damper response should each be evaluated by analysis prior to final design. Consider the idealized force-velocity response of a linear viscous damper of Figure CA-8. Line C represents the relation assumed in design. Lines B and D define the limiting values of the constitutive relation for the damper as determined by prototype testing (typically taken as ± 15% of the design relation). Lines A and E define the limiting values of the constitutive relation after accounting for the effects of aging, temperature, corrosion, etc. In addition to designing for the force-velocity relation of Line C, the engineer must evaluate the response of the building for the force-velocity relations given by Lines A and E. Line A will characterize the minimum energy dissipation of the damper (for a given displacement) and Line E will characterize the maximum force delivered to the energy dissipation system by the damper.

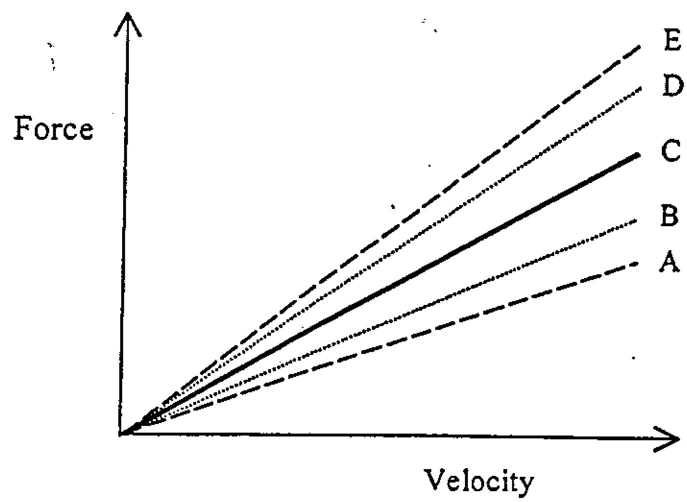

Figure CA-8 Variations in damper response

Section CA.8.2 Multi-Axis Movement

Some types of energy dissipation devices are not capable of sustaining significant displacements perpendicular to their longitudinal axis. For these types of devices, articulated connections (e.g., spherical bearings) must be used at each end of the damper.

Section CA.8.3 Story Drift Limitation

No commentary provided for this section.

Section CA.8.4 Minimum Strength of EDDs and Related EDS Components

Section CA.8.5.1 Reliability and Redundancy Factor

The factor ρ_D for reliability and redundancy shall be set equal to 1.4 if less than four dampers total are provided in each story of the building. If three or fewer dampers are used in any one story of a building, ρ_D shall be set equal to 1.4 regardless of the number and location of the dampers in any other story. The value of 1.4 is preliminary and mutable at the time of this writing, and is based solely on the judgement of the authors of the guidelines. The intent of the provision is to encourage engineers to use a large number of small force-capacity dampers rather than a small number of large force-capacity dampers.

Section CA.8.5.2 Determination of Design Forces in the EDS

Component actions and deformations can be estimated using either the static lateral force procedure of Section A4.2.1 or response-history analysis per Section A4.2.2. If response-history analysis is used, forces and deformations in each component, at each time step, must be checked against the limiting values defined by the engineer. If the static lateral force procedure is used, forces must be checked as follows:

In a building incorporating displacement-dependent dampers, the maximum forces in the building frame and the dampers are realized at the point of maximum displacement. In this case, structural components and dampers need only be checked at the point of maximum displacement, as is the case with conventionally framed buildings.

In a building incorporating velocity-dependent dampers, the viscous forces associated with the dampers must be considered. Maximum forces in individual components may occur at one of three stages: maximum displacement, maximum velocity, and maximum acceleration. Consider the base shear-roof displacement relation of Figure CA-9 that approximates the behavior of a building in which velocity-dependent dampers have been implemented.

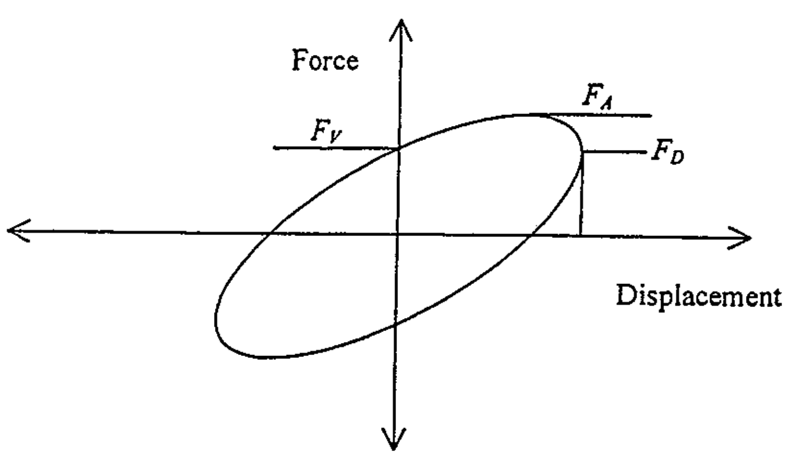

Figure CA-9 Base shear-roof displacement relation for a building

The base shear F_D corresponds to the point of maximum displacement, F_A corresponds to the point of maximum acceleration, and F_V corresponds to the point of maximum velocity. Checking for forces at the point of maximum displacement is no different for displacement-dependent and velocity-dependent dampers.

Viscous forces are maximized at the time of maximum velocity, which occurs approximately at the time of zero displacement. At this time, inertial forces at each floor level balance the horizontal components of the viscous forces, such that the lateral displacements at each floor level are zero. The viscous forces will introduce axial forces into collectors and drag struts at each floor level and axial forces into columns supporting the dampers (see Figure CA-2). The magnitude of these forces will depend on the amount of damping added to the building frame, and the size and location of the dampers within the building frame.

Component actions at the point of maximum acceleration can be calculated using information on the forces at the points of maximum displacement (F_D) and velocity (F_V). Assuming that the building frame is a viscoelastic system undergoing harmonic displacement at a frequency f_D ($=1/T_D$, where T_D is the secant period at maximum displacement), the forces at maximum acceleration (F_A) can be calculated to be equal to:

$$F_A = CF_1 \times F_D + CF_2 \times F_V \qquad \text{(CA8-1)}$$

The forces at maximum acceleration can be conservatively estimated by setting CF_1 and CF_2 equal to 1.0.

Section CA.8.5.3 *Minimum Strength and Stiffness of EDS Components*

This section defines rules for combining the design force components from the LFRS, which have been determined using R factors, with force components resulting from energy dissipation devices.

Structure members of the EDS should resist forces in the elastic stress range to provide stable and predictable movements at dissipation devices. In order to achieve this, EDDs should generally not be connected directly to elements of the LFRS (such as beams in moment frames) which are designed to resist seismic forces in the inelastic range. Beams intended for inelastic behavior may still be required to transmit some secondary EDS forces as collector elements, therefore stress limitations are provided to establish reasonable limits for EDS stress components. Other beams, as well as columns, braces, diaphragms, struts and foundations, should be designed using the earthquake design force multipliers specified.

Because bracing members which transmit only EDS forces are designed to resist transmitted forces in the elastic stress range, normal code multipliers intended to correct for less ductile performance are not considered to be applicable.

Section CA.8.5 Inspection and Periodic Testing

Structural components of conventional steel, reinforced concrete, and timber are infrequently or never inspected following construction. However, most energy dissipation devices on the market at the time of this writing are mechanical and not structural components.

Industries that have implemented mechanical damping components in the past (e.g., defense, power generation, and aerospace) have relied upon regular inspection and periodic testing of damping devices to ensure that the devices remain fully functional. There is no technical reason to support a change in this philosophy for mechanical damping components.

Dampers that are not mechanical components (e.g., having no moving parts, seals, internal fluid, etc.) such as devices that rely upon the yielding of metals should be inspected on a regular basis (e.g., to guard against corrosion) but likely do not need periodic testing. Dampers that dissipate energy by deforming solid and fluid viscoelastic materials should be both regularly inspected and tested if the properties of such materials change with time or environmental effects.

The engineer-of-record and not the vendor should establish the criteria for inspection and periodic testing. The criteria should be sufficiently rigorous to ensure that the dampers will respond as intended at any time over their design life. The scope of the inspection and testing program should be based upon the in-service history of the damper(s) under consideration and the likelihood that the properties of the damper(s) will change due to aging or environmental effects.

Section CA.8.6 Manufacturing Quality Control

To ensure effective control over product quality, the vendor should establish and maintain a manufacturing/processing control system, including written process specifications and procedures. It is strongly recommended that the quality control program be designed to ensure that manufacturing, processing inspection, and testing be accomplished in accordance with a recognized quality assurance system, such as International Standards Organization (ISO) 9001.

The extent and detail of a suitable quality control program will likely vary depending on the complexity of the energy dissipation devices. For example, relatively simple metallic yielding devices may only require some controls for metallurgy and cutting and/or welding processes, while devices which are complex assemblages of many sub-components should have more detailed programs.

SECTION CA.9 DESIGN REVIEW

Analysis, design and construction issues associated with the use of energy dissipation devices are not well understood by most design professionals and building officials at the time of this writing. Accordingly, all phases of the analysis, design, and construction of buildings incorporating energy dissipation devices should be reviewed by an independent engineering panel that is comprised of person(s) experienced in seismic analysis and the theory and application of energy dissipation devices. (Such review is required for the analysis, design, and construction of seismic isolation systems.)

The design or peer review should commence during the preliminary design phase of the project and continue through to the testing and installation of the energy dissipation devices in the building.

SECTION CA.10 TESTING OF ENERGY DISSIPATION DEVICES

CA.10.1 General.

Two separate programs of testing are to be conducted for each type of energy dissipation device used in the structure. First, prototype testing is intended to establish that the device operating characteristics conform to the assumptions made in the design. Second, production testing of the devices to be installed in the structure may be required to verify correct operation. Production testing is not intended as a substitute for manufacturing quality control procedures.

CA.10.2 Prototype Tests.

CA.10.2.1 General. Although reduced-scale devices are permitted for certain prototype tests, full-scale devices should be tested wherever possible. Failure or ultimate load characteristics of devices should not be determined by reduced-scale testing.

CA.10.2.2 Data Recording. To adequately capture the force-displacement or force-velocity response of the device, at least 100 data points per cycle of loading should be recorded.

CA.10.2.3 Sequences and Cycles of Testing. Energy dissipation devices are not permitted to support structure gravity loads, but nonetheless may still be required to support their self-weight and the weight of attached braces or components, which could in some instances have a detrimental effect on their performance.

a) For short-period structures the number of cycles of low-amplitude testing may need to be increased to adequately represent the possible number of cycles of wind motion during the building life.

   Devices that do not exhibit a significant stiffness component are likely to be subjected to cyclic displacements from slowly applied actions such as wind or thermal movements. For these types of devices, high-cycle, low-amplitude testing is necessary to confirm resistance to wear or similar deterioration under these types of loads.

   Devices which have a significant stiffness component, and which are designed to resist wind, thermal, or similar actions without yield or slip, or for which the installation is designed to ensure that the device is not subjected to such actions, need not be tested for resistance to these actions.

b) All devices should be tested to confirm acceptable behavior under large earthquake loading. The physical limitations of available testing equipment may prevent large devices from being cyclically tested at real-time rates of loading. For such devices, and in particular for fluid viscous velocity-dependent devices, impact tests of full-size units, combined with both cyclic testing and impact testing of reduced-scale units may provide a reasonable alternative.

   The energy demand on devices that are subjected to real-time testing should be carefully assessed. The 20-cycle test may subject the device to considerably more energy than what would be associated with an actual large earthquake loading, and may even overload the device. In such cases, the number of cycles and/or the amplitude of testing should be carefully determined to ensure that the device is subjected to a realistic, but not unreasonable or implausible, total energy demand.

c) The rules given for evaluating frequency dependence are based on similar rules developed for testing seismic isolation devices. The frequency range of $0.5 f_1$ to $2.0 f_1$ should bound the frequency response of a building. The frequency of $2.0 f_1$ corresponds to a fourfold increase in building stiffness (perhaps due to nonstructural components, etc.); the frequency of $0.5 f_1$ corresponds to a fourfold decrease in stiffness due to the effects of earthquake shaking - likely an upper bound for the inelastic building response.

d) If the properties of an energy dissipation device are influenced by building displacements in the direction perpendicular to the longitudinal axis of the device (termed bilateral displacement), such influence should be investigated by testing. The importance of bilateral displacements may be a consequence of either (i) the fundamental design characteristics of the device, or (ii) the as-designed installation configuration for the device.

CA.10.2.4. Testing Similar Devices. A custom, or one-off, energy dissipation device design with specific mathematical behavior will require unique prototype testing for each device type. However, manufacturers may be able to produce standardized energy dissipation device designs, in terms of design strength and operating behavior. A standard set of prototype tests could then be used to meet prototype testing requirements. The adequacy of such a standard set of tests for any particular project should be determined by the engineer-of-record.

CA.10.2.5 Determination of Force-Velocity-Displacement Characteristics.

The determination of energy dissipation device properties and subsequent evaluation of adequacy should use consistent definitions for properties and parameters.

CA.10.2.6 System Adequacy.

Negative incremental stiffness is ordinarily assumed to be indicative of unstable behavior in displacement dependent devices. It should be recognized that in some cases for these devices, and for all velocity-dependent devices, negative incremental stiffness is an implicit feature of their behavior and is not detrimental.

The 15 percent tolerance range is generally regarded as a maximum acceptable range to meet design assumptions without significant deviation of actual versus modeled behavior. A different tolerance range may be more appropriate for a particular type of device, or may be acceptable in specific project instances. In such cases, the acceptable range of device properties should be appropriately incorporated in the design process, either by utilizing more sophisticated modeling techniques, or by performing multiple analyses to account for the actual range of device properties.

CA.10.3 Production Testing.

As part of the manufacturing quality control processes, each production device should be subjected to testing and inspection. Upon completion of manufacture, additional testing may be appropriate to confirm the behavior of the final assembled device. The need for and extent of for final production testing should be reviewed and established by the engineer-of-record.

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