9. Seismic Isolation and Energy Dissipation (Systematic Rehabilitation)

Chapter 9 includes detailed guidelines for building rehabilitation with seismic (and base) isolation and passive energy dissipation systems, and limited guidance for other systems such as active energy dissipation devices.

The basic form and formulation of guidelines for seismic isolation and energy dissipation systems have been established and coordinated with the Rehabilitation Objectives, Performance Levels, and seismic ground shaking hazard criteria of Chapter 2 and the linear and nonlinear procedures of Chapter 3.

Criteria for modeling the stiffness, strength, and deformation capacities of conventional structural components of buildings with seismic isolation or energy dissipation systems are given in Chapters 5 through 8 and Chapter 10.

Seismic Isolation and Energy Dissipation as Rehabilitation Strategies

Seismic isolation and energy dissipation systems are viable design strategies that have already been used for seismic rehabilitation of a number of buildings. Other special seismic protective systems—including active control, hybrid combinations of active and passive energy devices, and tuned mass and liquid dampers—may also provide practical solutions in the near future. These systems are similar in that they enhance performance during an earthquake by modifying the building's response characteristics.

Seismic isolation and energy dissipation systems will not be appropriate design strategies for most buildings, particularly buildings that have only Limited Rehabilitation Objectives. In general, these systems will be most applicable to the rehabilitation of buildings whose owners desire superior earthquake performance and can afford the special costs associated with the design, fabrication, and installation of seismic isolators and/or energy dissipation devices. These costs are typically offset by the reduced need for stiffening and strengthening measures that would otherwise be required to meet Rehabilitation Objectives.

Seismic isolation and energy dissipation systems are relatively new and sophisticated concepts that require more extensive design and detailed analysis than do most conventional rehabilitation schemes. Similarly, design (peer) review is required for all rehabilitation schemes that use either seismic isolation or energy dissipation systems.

9.1 Introduction

This chapter provides guidelines for the application of special seismic protective systems to building rehabilitation. Specific guidance is provided for seismic (base) isolation systems in Section 9.2 and for passive energy dissipation systems in Section 9.3. Section 9.4 provides additional, limited guidance for other special seismic systems, including active control systems, hybrid active and passive systems, and tuned mass and liquid dampers.

Special seismic protective systems should be evaluated as possible rehabilitation strategies based on the Rehabilitation Objectives established for the building. Prior to implementation of the guidelines of this chapter, the user should establish the following criteria as presented in Chapter 2:

- The Rehabilitation Objective for the building
  - Performance Level
  - Seismic Ground Shaking Hazard

Seismic isolation and energy dissipation systems include a wide variety of concepts and devices. In most cases, these systems and devices will be implemented with some additional conventional strengthening of the structure; in all cases they will require evaluation of existing building elements. As such, this chapter supplements the guidelines of other chapters of this document with additional criteria and methods of analysis that are appropriate for buildings rehabilitated with seismic isolators and/or energy dissipation devices.

Seismic isolation is increasingly becoming considered for historic buildings that are free-standing and have a basement or bottom space of no particular historic significance. In selecting such a solution, special consideration should be given to the possibility that historic or archaeological resources may be present at the site. If that is determined, the guidance of the State Historic Preservation Officer should be obtained in a timely manner. Isolation is also often considered for essential facilities, to protect valuable contents, and on buildings with a complete, but insufficiently strong lateral-force-resisting system.

9.2 Seismic Isolation Systems

This section specifies analysis methods and design criteria for seismic isolation systems that are based on the Rehabilitation Objectives, Performance Levels, and Seismic Ground Shaking Hazard criteria of Chapter 2.

The methods described in this section augment the analysis requirements of Chapter 3. The analysis methods and other criteria of this section are based largely on the 1994 *NEHRP Provisions* (BSSC, 1995) for new buildings, augmented with changes proposed by Technical Subcommittee 12 of the Provisions Update Committee of the Building Seismic Safety Council for the 1997 *NEHRP Provisions* (BSSC, 1997).

9.2.1 Background

Buildings rehabilitated with a seismic isolation system may be thought of as composed of three distinct segments: the structure above the isolation system, the isolation system itself, and the foundation and other structural elements below the isolation system.

The isolation system includes wind-restraint and tie-down systems, if such systems are required by these *Guidelines*. The isolation system also includes supplemental energy dissipation devices, if such devices are used to transmit force between the structure above the isolation system and the structure below the isolation system.

This section provides guidance primarily for the design, analysis, and testing of the isolation system and for determination of seismic load on structural elements and nonstructural components. Criteria for rehabilitation of structural elements other than the isolation system, and criteria for rehabilitation of nonstructural components, should follow the applicable guidelines of other chapters of this document, using loads and deformations determined by the procedures of this section.

Seismic Isolation Performance Objectives

Seismic isolation has typically been used as a Rehabilitation Strategy that enhances the performance of the building above that afforded by conventional stiffening and strengthening schemes. Seismic isolation rehabilitation projects have targeted performance at least equal to, and commonly exceeding, the Basic Safety Objective of these *Guidelines*, effectively achieving Immediate Occupancy or better performance.

A number of buildings rehabilitated with seismic isolators have been historic. For these projects, seismic isolation reduced the extent and intrusion of seismic modifications on the historical fabric of the building that would otherwise be required to meet desired Performance Levels.

See the *Commentary* for detailed discussions on the development of isolation provisions for new buildings (Section C9.2.1.1) and the design philosophy on which the provisions are based (Section C9.2.1.2). The *Commentary* also provides an overview of seismic isolation rehabilitation projects (Section C9.2.1.3) and goals (Section C9.2.1.4).

9.2.2 Mechanical Properties and Modeling of Seismic Isolation Systems

9.2.2.1 General

A seismic isolation system is the collection of all individual seismic isolators (and separate wind restraint and tie-down devices, if such devices are used to meet the requirements of these *Guidelines*). Seismic isolation systems may be composed entirely of one type of seismic isolator, a combination of different types of seismic isolators, or a combination of seismic isolators acting in parallel with energy dissipation devices (i.e., a hybrid system).

Seismic isolators are classified as either elastomeric, sliding, or other isolators. Elastomeric isolators are typically made of layers of rubber separated by steel shims. Elastomeric isolators may be any one of the following: high-damping rubber bearings (HDR), low-damping rubber bearings (RB) or low-damping rubber bearings with a lead core (LRB). Sliding isolators may be flat assemblies or have a curved surface, such as the friction-pendulum system (FPS). Rolling systems may be characterized as a subset of sliding systems. Rolling isolators may be flat assemblies or have a curved or conical surface, such as the ball and cone system (BNC). Other isolators are not discussed.

This section provides guidance for modeling of elastomeric isolators and sliding isolators. Guidance for modeling of energy dissipation devices may be found in Section 9.3. Information on hybrid systems is provided in the *Commentary* (Section C9.2.2.2C)

9.2.2.2 Mechanical Properties of Seismic Isolators

A. Elastomeric Isolators

The mechanical characteristics of elastomeric isolators should be known in sufficient detail to establish force-deformation response properties and their dependence, if any, on axial-shear interaction, bilateral deformation, load history (including the effects of “scragging” of virgin elastomeric isolators; that is, the process of subjecting an elastomeric bearing to one or more cycles of large amplitude displacement), temperature, and other environmental loads and aging effects (over the design life of the isolator).

For the purpose of mathematical modeling of isolators, mechanical characteristics may be based on analysis and available material test properties, but verification of isolator properties used for design should be based on tests of isolator prototypes, as described in Section 9.2.9.

B. Sliding Isolators

The mechanical characteristics of sliding isolators should be known in sufficient detail to establish force-deformation response properties and their dependence, if any, on contact pressure, rate of loading (velocity), bilateral deformation, temperature, contamination, and other environmental loads and aging effects (over the design life of the isolator).

For the purpose of mathematical modeling of isolators, mechanical characteristics may be based on analysis and available material test properties, but verification of isolator properties used for design should be based on tests of isolator prototypes, as described in Section 9.2.9.

9.2.2.3 Modeling of Isolators

A. General

If the mechanical characteristics of a seismic isolator are dependent on design parameters such as axial load (due to gravity, earthquake overturning effects, and vertical earthquake shaking), rate of loading (velocity), bilateral deformation, temperature, or aging, then upper- and lower-bound values of stiffness and damping should be used to determine the range and sensitivity of response to design parameters.

B. Linear Models

Linear procedures use effective stiffness, k_{eff}, and effective damping, β_{eff}, to characterize nonlinear properties of isolators. The restoring force of an isolator is calculated as the product of effective stiffness, k_{eff}, and response displacement, D:

$$F = k_{eff}D \tag{9-1}$$

The effective stiffness, k_{eff}, of an isolator is calculated from test data using Equation 9-12. Similarly, the area enclosed by the force-displacement hysteresis loop is used to calculate the effective damping, β_{eff}, of an isolator using Equation 9-13. Both effective stiffness and effective damping are, in general, amplitude-dependent and should be evaluated at all response displacements of design interest.

C. Nonlinear Models

Nonlinear procedures should explicitly model the nonlinear force-deflection properties of isolators.

Damping should be modeled explicitly by inelastic (hysteretic) response of isolators. Additional viscous damping should not be included in the model unless supported by rate-dependent tests of isolators.

9.2.2.4 Isolation System and Superstructure Modeling

A. General

Mathematical models of the isolated building—including the isolation system, the lateral-force-resisting system and other structural components and elements, and connections between the isolation system and the structure above and below the isolation system—should conform to the requirements of Chapters 2 and 3 and the guidelines given below.

B. Isolation System Model

The isolation system should be modeled using deformational characteristics developed and verified by test in accordance with the requirements of Section 9.2.9.

The isolation system should be modeled with sufficient detail to:

1. Account for the spatial distribution of isolator units
2. Calculate translation, in both horizontal directions, and torsion of the structure above the isolation interface, considering the most disadvantageous location of mass eccentricity
3. Assess overturning/uplift forces on individual isolators
4. Account for the effects of vertical load, bilateral load, and/or the rate of loading, if the force deflection properties of the isolation system are dependent on one or more of these factors
5. Assess forces due to P-Δ moments

C. Superstructure Model

The maximum displacement of each floor, and the total design displacement and total maximum displacement across the isolation system, should be calculated using a model of the isolated building that incorporates the force-deflection characteristics of nonlinear components, and elements of the isolation system and the superstructure.

Isolation systems with nonlinear components include, but are not limited to, systems that do not meet the criteria of Section 9.2.3.3A Item (2).

Lateral-force-resisting systems with nonlinear components and elements include, but are not limited to, systems described by both of the following criteria.

1. For all deformation-controlled actions, Equation 3-18 is satisfied using a value of m equal to 1.0.
2. For all force-controlled actions, Equation 3-19 is satisfied.

Design forces and displacements in primary components of the lateral-force-resisting system may be calculated using a linearly elastic model of the isolated structure, provided the following criteria are met.

1. Pseudo-elastic properties assumed for nonlinear isolation system components are based on the maximum effective stiffness of the isolation system.
2. The lateral-force-resisting system remains essentially linearly elastic for the earthquake demand level of interest.

9.2.3 General Criteria for Seismic Isolation Design

9.2.3.1 General

Criteria for the seismic isolation of buildings are divided into two sections:

1. Rehabilitation of the building
2. Design, analysis, and testing of the isolation system

A. Basis For Design

Seismic Rehabilitation Objectives of the building should be consistent with those set forth in Chapter 2. The design, analysis, and testing of the isolation system should be based on the guidelines of this chapter.

B. Stability of the Isolation System

The stability of the vertical-load-carrying components of the isolation system should be verified by analysis and test, as required, for a lateral displacement equal to the total maximum displacement, or for the maximum displacement allowed by displacement-restraint devices, if such devices are part of the isolation system.

C. Configuration Requirements

The regularity of the isolated building should be designated as being either regular or irregular on the basis of the structural configuration of the structure above the isolation system.

9.2.3.2 Ground Shaking Criteria

Ground shaking criteria are required for the design earthquake, which is user-specified and may be chosen equal to the BSE-1, and for the Maximum Considered Earthquake (MCE), equal to the BSE-2, as described in Chapter 2.

A. User-Specified Design Earthquake

For the design earthquake, the following ground shaking criteria should be established:

1. Short period spectral response acceleration parameter, S_{DS}, and spectral response acceleration parameter at 1.0 second, S_{D1}

2. Five-percent-damped response spectrum of the design earthquake (when a response spectrum is required for linear procedures by Section 9.2.3.3A, or to define acceleration time histories)

3. At least three acceleration time histories compatible with the design earthquake spectrum (when acceleration time histories are required for nonlinear procedures by Section 9.2.3.3B)

B. Maximum Earthquake

For the BSE-2, the following ground shaking criteria should be established:

1. Short period spectral response acceleration parameter, S_{MS}, and spectral response acceleration parameter at 1.0 second, S_{M1}

2. Five-percent-damped site-specific response spectrum of the BSE-2 (when a response spectrum is required for linear procedures by Section 9.2.3.3A, or to define acceleration time histories)

3. At least three acceleration time histories compatible with the BSE-2 spectrum (when acceleration time histories are required for nonlinear procedures by Section 9.2.3.3B)

9.2.3.3 Selection of Analysis Procedure

A. Linear Procedures

Linear procedures may be used for design of seismically isolated buildings, provided the following criteria are met.

1. The building is located on Soil Profile Type A, B, C, or D; or E (if $S_1 \geq 0.6$ for BSE-2).

2. The isolation system meets all of the following criteria:

   a. The effective stiffness of the isolation system at the design displacement is greater than one-third of the effective stiffness at 20% of the design displacement.

   b. The isolation system is capable of producing a restoring force as specified in Section 9.2.7.2D.

   c. The isolation system has force-deflection properties that are essentially independent of the rate of loading.

   d. The isolation system has force-deflection properties that are independent of vertical load and bilateral load.

   e. The isolation system does not limit BSE-2 displacement to less than S_{M1}/S_{D1} times the total design displacement.

3. The structure above the isolation system remains essentially linearly elastic for the BSE-2.

Response spectrum analysis should be used for design of seismically-isolated buildings that meet any of the following criteria.

- The building is over 65 feet (19.8 meters) in height.

- The effective period of the structure, T_M, is greater than three seconds.

- The effective period of the isolated structure, T_D, is less than or equal to three times the elastic, fixed-base period of the structure above the isolation system.

- The structure above the isolation system is irregular in configuration.

B. Nonlinear Procedures

Nonlinear procedures should be used for design of seismic-isolated buildings for which the following conditions apply.

1. The structure above the isolation system is nonlinear for the BSE-2.

2. The building is located on Soil Profile Type E (if $S_1 > 0.6$ for BSE-2) or Soil Profile Type F.

3. The isolation system does not meet all of the criteria of Section 9.2.3.3A, Item (2).

Nonlinear acceleration time history analysis is required for the design of seismically isolated buildings for which conditions (1) and (2) apply.

9.2.4 Linear Procedures

9.2.4.1 General

Except as provided in Section 9.2.5, every seismically isolated building, or portion thereof, should be designed and constructed to resist the earthquake displacements and forces specified by this section.

9.2.4.2 Deformation Characteristics of the Isolation System

The deformation characteristics of the isolation system should be based on properly substantiated tests performed in accordance with Section 9.2.9.

The deformation characteristics of the isolation system should explicitly include the effects of the wind-restraint and tie-down systems, and supplemental energy-dissipation devices, if such a systems and devices are used to meet the design requirements of these guidelines.

9.2.4.3 Minimum Lateral Displacements

A. Design Displacement

The isolation system should be designed and constructed to withstand, as a minimum, lateral earthquake displacements that act in the direction of each of the main horizontal axes of the structure in accordance with the equation:

$$D_D = \left[\frac{g}{4\pi^2}\right]\frac{S_{D1}T_D}{B_{D1}} \qquad (9\text{-}2)$$

B. Effective Period at the Design Displacement

The effective period, T_D, of the isolated building at the design displacement should be determined using the deformational characteristics of the isolation system in accordance with the equation:

$$T_D = 2\pi\sqrt{\frac{W}{K_{Dmin}g}} \qquad (9\text{-}3)$$

C. Maximum Displacement

The maximum displacement of the isolation system, D_M, in the most critical direction of horizontal response should be calculated in accordance with the equation:

$$D_M = \left[\frac{g}{4\pi^2}\right]\frac{S_{M1}T_M}{B_{M1}} \qquad (9\text{-}4)$$

D. Effective Period at the Maximum Displacement

The effective period, T_M, of the isolated building at the maximum displacement should be determined using the deformational characteristics of the isolation system in accordance with the equation:

$$T_M = 2\pi\sqrt{\frac{W}{K_{Mmin}g}} \qquad (9\text{-}5)$$

E. Total Displacement

The total design displacement, D_{TD}, and the total maximum displacement, D_{TM}, of components of the isolation system should include additional displacement due to actual and accidental torsion calculated considering the spatial distribution of the effective stiffness of the isolation system at the design displacement and the most disadvantageous location of mass eccentricity.

The total design displacement, D_{TD}, and the total maximum displacement, D_{TM}, of components of an isolation system with a uniform spatial distribution of effective stiffness at the design displacement should be taken as not less than that prescribed by the equations:

$$D_{TD} = D_D\left[1 + y\frac{12e}{b^2 + d^2}\right] \qquad (9\text{-}6)$$

$$D_{TM} = D_M\left[1 + y\frac{12e}{b^2 + d^2}\right] \qquad (9\text{-}7)$$

The total maximum displacement, D_{TM}, may be taken as less than the value prescribed by Equation 9-7, but not less than 1.1 times D_M, provided the isolation system is shown by calculation to be configured to resist torsion accordingly.

9.2.4.4 Minimum Lateral Forces

A. Isolation System and Structural Components and Elements at or below the Isolation System

The isolation system, the foundation, and all other structural components and elements below the isolation system should be designed and constructed to withstand a minimum lateral seismic force, V_b, prescribed by the equation:

$$V_b = K_{Dmax} D_D \tag{9-8}$$

B. Structural Components and Elements above the Isolation System

The components and elements above the isolation system should be designed and constructed to resist a minimum lateral seismic force, V_s , taken as equal to the value of V_b, prescribed by Equation 9-8.

C. Limits on V_s

The value of V_s should be taken as not less than the following:

1. The base shear corresponding to the design wind load
2. The lateral seismic force required to fully activate the isolation system factored by 1.5 (e.g., the yield level of a softening system, the ultimate capacity of a sacrificial wind-restraint system, or the break-away friction level of a sliding system factored by 1.5)

D. Vertical Distribution of Force

The total force should be distributed over the height of the structure above the isolation interface as follows:

$$F_x = \frac{V_s w_x h_x}{\sum_i^n w_i h_i} \tag{9-9}$$

At each level designated as x, the force F_x should be applied over the area of the building in accordance with the weight, w_x, distribution at that level, h_x. Response of structural components and elements should be calculated as the effect of the force F_x applied at the appropriate levels above the base.

9.2.4.5 Response Spectrum Analysis

A. Earthquake Input

The design earthquake spectrum should be used to calculate the total design displacement of the isolation system and the lateral forces and displacements of the isolated building. The BSE-2 spectrum should be used to calculate the total maximum displacement of the isolation system.

B. Modal Damping

Response Spectrum Analysis should be performed, using a damping value for isolated modes equal to the effective damping of the isolation system, or 30% of critical, whichever is less. The damping value assigned to higher modes of response should be consistent with the material type and stress level of the superstructure.

C. Combination of Earthquake Directions

Response Spectrum Analysis used to determine the total design displacement and total maximum displacement should include simultaneous excitation of the model by 100% of the most critical direction of ground motion, and not less than 30% of the ground motion in the orthogonal axis. The maximum displacement of the isolation system should be calculated as the vector sum of the two orthogonal displacements.

D. Scaling of Results

If the total design displacement determined by Response Spectrum Analysis is found to be less than the value of D_{TD} prescribed by Equation 9-6, or if the total maximum displacement determined by response spectrum analysis is found to be less than the value of D_{TM} prescribed by Equation 9-7, then all response parameters, including components actions and deformations, should be adjusted upward proportionally to the D_{TD} value, or the D_{TM} value, and used for design.

9.2.4.6 Design Forces and Deformations

Components and elements of the building should be designed for forces and displacements estimated by linear procedures using the acceptance criteria of Section 3.4.2.2, except that deformation-controlled components and elements should be designed using a component demand modifier no greater than 1.5.

9.2.5 Nonlinear Procedures

Isolated buildings evaluated using nonlinear procedures should be represented by three-dimensional models that incorporate both the nonlinear characteristics of the isolation system and the structure above the isolation system.

9.2.5.1 Nonlinear Static Procedure

A. General

The Nonlinear Static Procedure (NSP) for seismically isolated buildings should be based on the nonlinear procedure guidelines of Section 3.3.3, except that the target displacement and pattern of applied lateral load should be based on the criteria given in the following sections.

B. Target Displacement

In each principal direction, the building model should be pushed to the design earthquake target displacement, D'_D, and to the BSE-2 target displacement, D'_M, as defined by the following equations:

$$D'_D = \frac{D_D}{\sqrt{1 + \left(\frac{T_e}{T_D}\right)^2}} \tag{9-10}$$

$$D'_M = \frac{D_M}{\sqrt{1 + \left(\frac{T_e}{T_M}\right)^2}} \tag{9-11}$$

where T_e is the effective period of the superstructure on a fixed base as prescribed by Equation 3-10. The target displacements, D'_D and D'_M, should be evaluated at a control node that is located at the center of mass of the first floor above the isolation interface.

C. Lateral Load Pattern

The pattern of applied lateral load should be proportional to the distribution of the product of building mass and the deflected shape of the isolated mode of response at target displacement.

9.2.5.2 Nonlinear Dynamic Procedure

A. General

The Nonlinear Dynamic Procedure (NDP) for seismically isolated buildings should be based on the nonlinear procedure guidelines of Section 3.3.4, except that results should be scaled for design based on the criteria given in the following section.

B. Scaling of Results

If the design displacement determined by Time-History Analysis is found to be less than the value of D'_D prescribed by Equation 9-10, or if the maximum displacement determined by Response Spectrum Analysis is found to be less than the value of D'_M prescribed by Equation 9-11, then all response parameters, including component actions and deformations, should be adjusted upward proportionally to the D'_D value or the D'_M value, and used for design.

9.2.5.3 Design Forces and Deformations

Components and elements of the building should be designed for the forces and deformations estimated by nonlinear procedures using the acceptance criteria of Section 3.4.3.2.

9.2.6 Nonstructural Components

9.2.6.1 General

Parts or portions of a seismically isolated building, permanent nonstructural components and the attachments to them, and the attachments for permanent equipment supported by a building should be designed to resist seismic forces and displacements as given in this section and the applicable requirements of Chapter 11.

9.2.6.2 Forces and Displacements

A. Components and Elements at or above the Isolation Interface

Components and elements of seismically isolated buildings and nonstructural components, or portions thereof, that are at or above the isolation interface, should be designed to resist a total lateral seismic force equal to the maximum dynamic response of the element or component under consideration.

EXCEPTION: Elements of seismically isolated structures and nonstructural components, or portions thereof, may be designed to resist total lateral seismic force as required for conventional fixed-base buildings by Chapter 11.

B. Components and Elements That Cross the Isolation Interface

Elements of seismically isolated buildings and nonstructural components, or portions thereof, that cross the isolation interface should be designed to withstand the total maximum (horizontal) displacement and maximum vertical displacement of the isolation system at the total maximum (horizontal) displacement. Components and elements that cross the isolation interface should not restrict displacement of the isolated building or otherwise compromise the Rehabilitation Objectives of the building.

C. Components and Elements Below the Isolation Interface

Components and elements of seismically isolated buildings and nonstructural components, or portions thereof, that are below the isolation interface should be designed and constructed in accordance with the requirements of Chapter 11.

9.2.7 Detailed System Requirements

9.2.7.1 General

The isolation system and the structural system should comply with the general requirements of Chapter 2 and the requirements of Chapters 4 through 8. In addition, the isolation system and the structural system should comply with the detailed system requirements of this section.

9.2.7.2 Isolation System

A. Environmental Conditions

In addition to the requirements for vertical and lateral loads induced by wind and earthquake, the isolation system should be designed with consideration given to other environmental conditions, including aging effects, creep, fatigue, operating temperature, and exposure to moisture or damaging substances.

B. Wind Forces

Isolated buildings should resist design wind loads at all levels above the isolation interface in accordance with the applicable wind design provisions. At the isolation interface, a wind-restraint system should be provided to limit lateral displacement in the isolation system to a value equal to that required between floors of the structure above the isolation interface.

C. Fire Resistance

Fire resistance rating for the isolation system should be consistent with the requirements of columns, walls, or other such elements of the building.

D. Lateral Restoring Force

The isolation system should be configured to produce either a restoring force such that the lateral force at the total design displacement is at least $0.025W$ greater than the lateral force at 50% of the total design displacement, or a restoring force of not less than $0.05W$ at all displacements greater than 50% of the total design displacement.

EXCEPTION: The isolation system need not be configured to produce a restoring force, as required above, provided the isolation system is capable of remaining stable under full vertical load and accommodating a total maximum displacement equal to the greater of either 3.0 times the total design displacement or 36 S_{M1} inches.

E. Displacement Restraint

The isolation system may be configured to include a displacement restraint that limits lateral displacement due to the BSE-2 to less than S_{M1}/S_{D1} times the total design displacement, provided that the seismically isolated building is designed in accordance with the following criteria when more stringent than the requirements of Section 9.2.3.

1. BSE-2 response is calculated in accordance with the dynamic analysis requirements of Section 9.2.5, explicitly considering the nonlinear characteristics of the isolation system and the structure above the isolation system.

2. The ultimate capacity of the isolation system, and structural components and elements below the isolation system, should exceed the force and displacement demands of the BSE-2.

3. The structure above the isolation system is checked for stability and ductility demand of the BSE-2.

4. The displacement restraint does not become effective at a displacement less than 0.75 times the total design displacement, unless it is demonstrated by analysis that earlier engagement does not result in unsatisfactory performance.

F. Vertical Load Stability

Each component of the isolation system should be designed to be stable under the full maximum vertical load, $1.2Q_D + Q_L + |Q_E|$, and the minimum vertical load, $0.8Q_D - |Q_E|$, at a horizontal displacement equal to the total maximum displacement. The earthquake vertical load on an individual isolator unit, Q_E, should be based on peak building response due to the BSE-2.

G. Overturning

The factor of safety against global structural overturning at the isolation interface should be not less than 1.0 for required load combinations. All gravity and seismic loading conditions should be investigated. Seismic forces for overturning calculations should be based on the BSE-2, and the vertical restoring force should be based on the building's weight, *W*, above the isolation interface.

Local uplift of individual components and elements is permitted, provided the resulting deflections do not cause overstress or instability of the isolator units or other building components and elements. A tie-down system may be used to limit local uplift of individual components and elements, provided that the seismically isolated building is designed in accordance with the following criteria when more stringent than the requirements of Section 9.2.3.

1. BSE-2 response is calculated in accordance with the dynamic analysis requirements of Section 9.2.5, explicitly considering the nonlinear characteristics of the isolation system and the structure above the isolation system.

2. The ultimate capacity of the tie-down system should exceed the force and displacement demands of the BSE-2.

3. The isolation system is both designed to be stable and shown by test to be stable (Section 9.2.9.2F) for BSE-2 loads that include additional vertical load due to the tie-down system.

H. Inspection and Replacement

Access for inspection and replacement of all components and elements of the isolation system should be provided.

I. Manufacturing Quality Control

A manufacturing quality control testing program for isolator units should be established by the engineer responsible for the structural design.

9.2.7.3 Structural System

A. Horizontal Distribution of Force

A horizontal diaphragm or other structural components and elements should provide continuity above the isolation interface. The diaphragm or other structural components and elements should have adequate strength and ductility to transmit forces (due to nonuniform ground motion) from one part of the building to another, and have sufficient stiffness to effect rigid diaphragm response above the isolation interface.

B. Building Separations

Minimum separations between the isolated building and surrounding retaining walls or other fixed obstructions should be not less than the total maximum displacement.

9.2.8 Design and Construction Review

9.2.8.1 General

A review of the design of the isolation system and related test programs should be performed by an independent engineering team, including persons licensed in the appropriate disciplines, and experienced in seismic analysis methods and the theory and application of seismic isolation.

9.2.8.2 Isolation System

Isolation system design and construction review should include, but not be limited to, the following:

1. Site-specific seismic criteria, including site-specific spectra and ground motion time history, and all other design criteria developed specifically for the project

2. Preliminary design, including the determination of the total design and total maximum displacement of the isolation system, and the lateral force design level

3. Isolation system prototype testing (Section 9.2.9)

4. Final design of the isolated building and supporting analyses

5. Isolation system quality control testing (Section 9.2.7.2I)

9.2.9 Isolation System Testing and Design Properties

9.2.9.1 General

The deformation characteristics and damping values of the isolation system used in the design and analysis of seismically isolated structures should be based on the following tests of a selected sample of the components prior to construction.

The isolation system components to be tested should include isolators, and components of the wind restraint system and supplemental energy dissipation devices if such components and devices are used in the design.

The tests specified in this section establish design properties of the isolation system, and should not be considered as satisfying the manufacturing quality control testing requirements of Section 9.2.7.2I.

9.2.9.2 Prototype Tests

A. General

Prototype tests should be performed separately on two full-size specimens of each type and size of isolator of the isolation system. The test specimens should include components of the wind restraint system, as well as individual isolators, if such components are used in the design. Supplementary energy dissipation devices should be tested in accordance with Section 9.3.8 criteria. Specimens tested should not be used for construction unless approved by the engineer responsible for the structural design.

B. Record

For each cycle of tests, the force-deflection and hysteretic behavior of the test specimen should be recorded.

C. Sequence and Cycles

The following sequence of tests should be performed for the prescribed number of cycles at a vertical load equal to the average $Q_D + 0.5Q_L$ on all isolators of a common type and size:

1. Twenty fully reversed cycles of loading at a lateral force corresponding to the wind design force
2. Three fully reversed cycles of loading at each of the following displacements: $0.25D_D$, $0.50D_D$, $1.0D_D$, and $1.0D_M$
3. Three fully reversed cycles at the total maximum displacement, $1.0D_{TM}$
4. $30S_{D1}/S_{DS}B_D$, but not less than 10, fully reversed cycles of loading at the design displacement, $1.0D_D$

If an isolator is also a vertical-load-carrying element, then Item 2 of the sequence of cyclic tests specified above should be performed for two additional vertical load cases:

1. $1.2Q_D + 0.5Q_L + |Q_E|$
2. $0.8Q_D - |Q_E|$

where D, L, and E refer to dead, live, and earthquake loads. Q_D and Q_L are as defined in Section 3.2.8. The vertical test load on an individual isolator unit should include the load increment Q_E due to earthquake overturning, and should be equal to or greater than the peak earthquake vertical force response corresponding to the test displacement being evaluated. In these tests, the combined vertical load should be taken as the typical or average downward force on all isolators of a common type and size.

D. Isolators Dependent on Loading Rates

If the force-deflection properties of the isolators are dependent on the rate of loading, then each set of tests specified in Section 9.2.9.2C should be performed dynamically at a frequency equal to the inverse of the effective period, T_D, of the isolated structure.

EXCEPTION: If reduced-scale prototype specimens are used to quantify rate-dependent properties of isolators, the reduced-scale prototype specimens should be of the same type and material and be manufactured with the same processes and quality as full-scale prototypes, and should be tested at a frequency that represents full-scale prototype loading rates.

The force-deflection properties of an isolator should be considered to be dependent on the rate of loading if there is greater than a plus or minus 10% difference in the effective stiffness at the design displacement (1) when tested at a frequency equal to the inverse of the effective period of the isolated structure and (2) when tested at any frequency in the range of 0.1 to 2.0 times the inverse of the effective period of the isolated structure.

E. Isolators Dependent on Bilateral Load

If the force-deflection properties of the isolators are dependent on bilateral load, then the tests specified in Sections 9.2.9.2C and 9.2.9.2D should be augmented to include bilateral load at the following increments of the total design displacement: 0.25 and 1.0; 0.50 and 1.0; 0.75 and 1.0; and 1.0 and 1.0.

EXCEPTION: If reduced-scale prototype specimens are used to quantify bilateral-load-dependent properties, then such scaled specimens should be of the same type and material, and manufactured with the same processes and quality as full-scale prototypes.

The force-deflection properties of an isolator should be considered to be dependent on bilateral load, if the bilateral and unilateral force-deflection properties have greater than a plus or minus 15% difference in effective stiffness at the design displacement.

F. Maximum and Minimum Vertical Load

Isolators that carry vertical load should be statically tested for the maximum and minimum vertical load, at the total maximum displacement. In these tests, the combined vertical loads of $1.2Q_D + 1.0Q_L + |Q_E|$ should be taken as the maximum vertical force, and the combined vertical load of $0.8Q_D - |Q_E|$ should be taken as the minimum vertical force, on any one isolator of a common type and size. The earthquake vertical load on an individual isolator, Q_E, should be based on peak building response due to the BSE-2.

G. Sacrificial Wind-Restraint Systems

If a sacrificial wind-restraint system is part of the isolation system, then the ultimate capacity should be established by test.

H. Testing Similar Units

Prototype tests are not required if an isolator unit is:

1. Of similar dimensional characteristics
2. Of the same type and materials, and
3. Fabricated using identical manufacturing and quality control procedures

9.2.9.3 Determination of Force-Deflection Characteristics

The force-deflection characteristics of the isolation system should be based on the cyclic load testing of isolator prototypes specified in Section 9.2.9.2C.

As required, the effective stiffness of an isolator unit, k_{eff}, should be calculated for each cycle of deformation by the equation:

$$k_{eff} = \frac{|F^+| + |F^-|}{|\Delta^+| + |\Delta^-|} \tag{9-12}$$

where F^+ and F^- are the positive and negative forces at positive and negative test displacements, Δ^+ and Δ^-, respectively.

As required, the effective damping of an isolator unit, β_{eff}, should be calculated for each cycle of deformation by the equation:

$$\beta_{eff} = \frac{2}{\pi}\left[\frac{E_{Loop}}{k_{eff}(|\Delta^+| + |\Delta^-|)^2}\right] \tag{9-13}$$

where the energy dissipated per cycle of loading, E_{Loop}, and the effective stiffness, k_{eff}, are based on test displacements, Δ^+ and Δ^-.

9.2.9.4 System Adequacy

The performance of the test specimens should be assessed as adequate if the following conditions are satisfied.

1. The force-deflection plots of all tests specified in Section 9.2.9.2 have a nonnegative incremental force-carrying capacity.
2. For each increment of test displacement specified in Section 9.2.9.2C, Item (2), and for each vertical load case specified in Section 9.2.9.2C the following criteria are met.

   a. There is no greater than a plus or minus 15% difference between the effective stiffness at each of the three cycles of test and the average value of effective stiffness for each test specimen.

b. There is no greater than a 15% difference in the average value of effective stiffness of the two test specimens of a common type and size of the isolator unit over the required three cycles of test.

3. For each specimen there is no greater than a plus or minus 20% change in the initial effective stiffness of each test specimen over the $30S_{D1}/S_{DS}B_D$, but not less than 10, cycles of the test specified in Section 9.2.9.2C, Item (3).

4. For each specimen there is no greater than a 20% decrease in the initial effective damping over the $30S_{D1}/S_{DS}B_D$, but not less than 10, cycles of the test specified in Section 9.2.9.2C, Item (4).

5. All specimens of vertical-load-carrying elements of the isolation system remain stable at the total maximum displacement for static load as prescribed in Section 9.2.9.2F.

6. The effective stiffness and effective damping of test specimens fall within the limits specified by the engineer responsible for structural design.

9.2.9.5 Design Properties of the Isolation System

A. Maximum and Minimum Effective Stiffness

At the design displacement, the maximum and minimum effective stiffness of the isolation system, K_{Dmax} and K_{Dmin}, should be based on the cyclic tests of Section 9.2.9.2 and calculated by the formulas:

$$K_{Dmax} = \frac{\sum\left|F_D^+\right|_{max} + \sum\left|F_D^-\right|_{max}}{2D_D} \qquad (9\text{-}14)$$

$$K_{Dmin} = \frac{\sum\left|F_D^+\right|_{min} + \sum\left|F_D^-\right|_{min}}{2D_D} \qquad (9\text{-}15)$$

At the maximum displacement, the maximum and minimum effective stiffness of the isolation system should be based on cyclic tests of Section 9.2.9.2 and calculated by the formulas:

$$K_{Mmax} = \frac{\sum\left|F_M^+\right|_{max} + \sum\left|F_M^-\right|_{max}}{2D_M} \qquad (9\text{-}16)$$

$$K_{Mmin} = \frac{\sum\left|F_M^+\right|_{min} + \sum\left|F_M^-\right|_{min}}{2D_M} \qquad (9\text{-}17)$$

For isolators that are found by the tests of Sections 9.2.9.2C, 9.2.9.2D, and 9.2.9.2E to have force-deflection characteristics that vary with vertical load, rate of loading, or bilateral load, respectively, the values of K_{Dmax} and K_{Mmax} should be increased and the values of K_{Dmin} and K_{Mmin} should be decreased, as necessary, to bound the effects of the measured variation in effective stiffness.

B. Effective Damping

At the design displacement, the effective damping of the isolation system, β_D, should be based on the cyclic tests of Section 9.2.9.2 and calculated by the formula:

$$\beta_D = \frac{1}{2\pi}\left[\frac{\sum E_D}{K_{Dmax}D_D^2}\right] \qquad (9\text{-}18)$$

In Equation 9-18, the total energy dissipated in the isolation system per displacement cycle, ΣE_D, should be taken as the sum of the energy dissipated per cycle in all isolators measured at test displacements, Δ^+ and Δ^-, that are equal in magnitude to the design displacement, D_D.

At the maximum displacement, the effective damping of the isolation system, β_M, should be based on the cyclic tests of Section 9.2.9.2 and calculated by the formula:

$$\beta_M = \frac{1}{2\pi}\left[\frac{\sum E_M}{K_{Mmax}D_M^2}\right] \qquad (9\text{-}19)$$

In Equation 9-19, the total energy dissipated in the isolation system per displacement cycle, ΣE_M, should be taken as the sum of the energy dissipated per cycle in all isolators measured at test displacements, Δ^+ and Δ^-, that are equal in magnitude to the maximum displacement, D_M.

9.3 Passive Energy Dissipation Systems

This section specifies analysis methods and design criteria for energy dissipation systems that are based on the Rehabilitation Objectives, Performance Levels, and Seismic Ground Shaking Hazard criteria of Chapter 2.

9.3.1 General Requirements

This section provides guidelines for the implementation of passive energy dissipation devices in the seismic rehabilitation of buildings. In addition to the requirements provided herein, every rehabilitated building incorporating energy dissipation devices should be designed in accordance with the applicable provisions of the remainder of the *Guidelines* unless modified by the requirements of this section.

The energy dissipation devices should be designed with consideration given to other environmental conditions including wind, aging effects, creep, fatigue, ambient temperature, operating temperature, and exposure to moisture or damaging substances.

The building height limitations should not exceed the values for the structural system into which the energy dissipation devices are implemented.

The mathematical model of a rehabilitated building should include the plan and vertical distribution of the energy dissipation devices. Analysis of the mathematical model should account for the dependence of the devices on excitation frequency, ambient and operating temperature, velocity, sustained loads, and bilateral loads. Multiple analyses of the building may be necessary to capture the effects of varying mechanical characteristics of the devices.

Energy dissipation devices shall be capable of sustaining larger displacements (and velocities for velocity-dependent devices) than the maxima calculated in the BSE-2. The increase in displacement (and velocity) capacity is dependent on the level of redundancy in the supplemental damping system as follows:

1. If four or more energy dissipation devices are provided in a given story of a building, in one principal direction of the building, with a minimum of two devices located on each side of the center of stiffness of the story in the direction under consideration, all energy dissipation devices shall be capable of sustaining displacements equal to 130% of the maximum calculated displacement in the device in the BSE-2. A velocity-dependent device (see Section 9.3.3) shall also be capable of sustaining the force associated with a velocity equal to 130% of the maximum calculated velocity for that device in the BSE-2.

2. If fewer than four energy dissipation devices are provided in a given story of a building, in one principal direction of the building, or fewer than two devices are located on each side of the center of stiffness of the story in the direction under consideration, all energy dissipation devices shall be capable of sustaining displacements equal to 200% of the maximum calculated displacement in the device in the BSE-2. A velocity-dependent device shall also be capable of sustaining the force associated with a velocity equal to 200% of the maximum calculated velocity for that device in the BSE-2.

Energy Dissipation Performance Levels

Passive energy dissipation is an emerging technology that enhances the performance of the building by adding damping (and in some cases stiffness) to the building. The primary use of energy dissipation devices is to reduce earthquake displacement of the structure. Energy dissipation devices will also reduce force in the structure—provided the structure is responding elastically—but would not be expected to reduce force in structures that are responding beyond yield.

For most applications, energy dissipation provides an alternative approach to conventional stiffening and strengthening schemes, and would be expected to achieve comparable Performance Levels. In general, these devices would be expected to be good candidates for projects that have a Performance Level of Life Safety, or perhaps Immediate Occupancy, but would be expected to have only limited applicability to projects with a Performance Level of Collapse Prevention.

Other objectives may also influence the decision to use energy dissipation devices, since these devices can also be useful for control of building response due to small earthquakes, wind, or mechanical loads.

The components and connections transferring forces between the energy dissipation devices shall be designed to remain linearly elastic for the forces described in items 1 or 2 above—dependent upon the degree of redundancy in the supplemental damping system.

9.3.2 Implementation of Energy Dissipation Devices

The following subsections of Section 9.3 provide guidance to the design professional to aid in the implementation of energy dissipation devices. Guidelines and criteria for analysis procedures and component acceptance can be found in other chapters of the *Guidelines*.

Restrictions on the use of linear procedures are established in Chapter 2. These restrictions also apply to the linear procedures of Section 9.3.4. Restrictions on the use of nonlinear procedures, established in Chapter 2, also apply to the nonlinear procedures of Section 9.3.5. Example applications of linear and nonlinear procedures are provided in the *Commentary,* Section C9.3.9 (there is no corresponding section in the *Guidelines*).

9.3.3 Modeling of Energy Dissipation Devices

Energy dissipation devices are classified in this section as either displacement-dependent, velocity-dependent, or other. Displacement-dependent devices may exhibit either rigid-plastic (friction devices), bilinear (metallic yielding devices), or trilinear hysteresis. The response of displacement-dependent devices should be independent of velocity and/or frequency of excitation. Velocity-dependent devices include solid and fluid viscoelastic devices, and fluid viscous devices. The third classification (other) includes all devices that cannot be classified as either displacement- or velocity-dependent. Examples of “other” devices include shape-memory alloys (superelastic effect), friction-spring assemblies with recentering capability, and fluid restoring force-damping devices.

Models of the energy dissipation system should include the stiffness of structural components that are part of the load path between energy dissipation devices and the ground, if the flexibility of these components is significant enough to affect the performance of the energy dissipation system. Structural components whose flexibility could affect the performance of the energy dissipation system include components of the foundation, braces that work in series with the energy dissipation devices, and connections between braces and the energy dissipation devices.

Energy dissipation devices should be modeled as described in the following subsections, unless more advanced methods or phenomenological models are used.

9.3.3.1 Displacement-Dependent Devices

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

Displacement-dependent devices should be modeled in sufficient detail so as to capture their force-displacement response adequately, and their dependence, if any, on axial-shear-flexure interaction, or bilateral deformation response.

For the purposes of evaluating the response of a displacement-dependent device from testing data, the force in a displacement-dependent device may be expressed as:

$$F = k_{eff} D \tag{9-20}$$

where the effective stiffness k_{eff} of the device is calculated as:

$$k_{eff} = \frac{|F^+| + |F^-|}{|D^+| + |D^-|} \tag{9-21}$$

and where forces in the device, F^+ and F^-, are evaluated at displacements D^+ and D^-, respectively.

9.3.3.2 Velocity-Dependent Devices

The force-displacement response of a velocity-dependent device is primarily a function of the relative velocity between each end of the device.

A. Solid Viscoelastic Devices

The cyclic response of viscoelastic solids is generally dependent on the frequency and amplitude of the motion, and the operating temperature (including temperature rise due to excitation).

Solid viscoelastic devices may be modeled using a spring and dashpot in parallel (Kelvin model). The spring and dashpot constants selected should adequately capture the frequency and temperature dependence of the device consistent with fundamental frequency of the rehabilitated building (f_1), and the operating temperature range. If the cyclic response of a viscoelastic solid device cannot be adequately captured by single estimates of the spring and dashpot constants, the response of the rehabilitated building should be estimated by multiple analyses of the building frame, using limited values for the spring and dashpot constants.

The force in a viscoelastic device may be expressed as:

$$F = k_{eff} D + C\dot{D} \tag{9-22}$$

where C is the damping coefficient for the viscoelastic device, D is the relative displacement between each end of the device, $\dot{D}$ is the relative velocity between each end of the device, and k_{eff} is the effective stiffness of the device calculated as:

$$k_{eff} = \frac{|F^+| + |F^-|}{|D^+| + |D^-|} = K' \tag{9-23}$$

where K' is the so-called storage stiffness.

The damping coefficient for the device should be calculated as:

$$C = \frac{W_D}{\pi \omega_1 D_{ave}^2} = \frac{K''}{\omega_1} \tag{9-24}$$

where K'' is the loss stiffness, the angular frequency ω_1 is equal to $2\pi f_1$, D_{ave} is the average of the absolute values of displacements D^+ and D^-, and W_D is the area enclosed by one complete cycle of the force-displacement response of the device.

B. Fluid Viscoelastic Devices

The cyclic response of viscoelastic fluid devices is generally dependent on the frequency and amplitude of the motion, and the operating temperature (including temperature rise due to excitation).

Fluid viscoelastic devices may be modeled using a spring and dashpot in series (Maxwell model). The spring and dashpot constants selected should adequately capture the frequency and temperature dependence of the device consistent with fundamental frequency of the rehabilitated building (f_1), and the operating temperature range. If the cyclic response of a viscoelastic fluid device cannot be adequately captured by single estimates of the spring and dashpot constants, the response of the rehabilitated building should be estimated by multiple analyses of the building frame, using limiting values for the spring and dashpot constants.

C. Fluid Viscous Devices

The cyclic response of a fluid viscous device is dependent on the velocity of motion; may be dependent on the frequency and amplitude of the motion; and is generally dependent on the operating temperature (including temperature rise due to excitation). Fluid viscous devices may exhibit some stiffness at high frequencies of cyclic loading. Linear fluid viscous dampers exhibiting stiffness in the frequency range 0.5 f_1 to 2.0 f_1 should be modeled as a fluid viscoelastic device.

In the absence of stiffness in the frequency range 0.5 f_1 to 2.0 f_1, the force in the fluid viscous device may be expressed as:

$$F = C_0 |\dot{D}|^{\alpha} \operatorname{sgn}(\dot{D}) \tag{9-25}$$

where C_0 is the damping coefficient for the device, α is the velocity exponent for the device, $\dot{D}$ is the relative velocity between each end of the device, and sgn is the signum function that, in this case, defines the sign of the relative velocity term.

9.3.3.3 Other Types of Devices

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

9.3.4 Linear Procedures

Linear procedures are only permitted if it can be demonstrated that the framing system exclusive of the energy dissipation devices remains essentially linearly elastic for the level of earthquake demand of interest after the effects of added damping are considered. Further, the effective damping afforded by the energy dissipation shall not exceed 30% of critical in the fundamental mode. Other limits on the use of linear procedures are presented below.

The secant stiffness of each energy dissipation device, calculated at the maximum displacement in the device, shall be included in the mathematical model of the rehabilitated building. For the purpose of evaluating the regularity of a building, the energy dissipation devices shall be included in the mathematical model.

9.3.4.1 Linear Static Procedure

A. Displacement-Dependent Devices

The Linear Static Procedure (LSP) may be used to implement displacement-dependent energy dissipation devices, provided that the following requirements are satisfied:

1. The ratio of the maximum resistance in each story, in the direction under consideration, to the story shear demand calculated using Equations 3-7 and 3-8, shall range between 80% and 120% of the average value of the ratio for all stories. The maximum story resistance shall include the contributions from all components, elements, and energy dissipation devices.

2. The maximum resistance of all energy dissipation devices in a story, in the direction under consideration, shall not exceed 50% of the resistance of the remainder of the framing where said resistance is calculated at the displacements anticipated in the BSE-2. Aging and environmental effects shall be considered in calculating the maximum resistance of the energy dissipation devices.

   The pseudo lateral load of Equation 3-6 should be reduced by the damping modification factors of Table 2-15 to account for the energy dissipation (damping) afforded by the energy dissipation devices. The calculation of the damping effect should be estimated as:

$$\beta_{eff} = \beta + \frac{\sum_j W_j}{4\pi W_k} \tag{9-26}$$

where β is the damping in the framing system and is set equal to 0.05 unless modified in Section 2.6.1.5, W_j is work done by device j in one complete cycle corresponding to floor displacements δ_i, the summation extends over all devices j, and W_k is the maximum strain energy in the frame, determined using Equation 9-27:

$$W_k = \frac{1}{2}\sum_i F_i \delta_i \tag{9-27}$$

where F_i is the inertia force at floor level i and the summation extends over all floor levels.

B. Velocity-Dependent Devices

The LSP may be used to implement velocity-dependent energy dissipation devices provided that the following requirements are satisfied:

- The maximum resistance of all energy dissipation devices in a story, in the direction under consideration, shall not exceed 50% of the resistance of the remainder of the framing where said resistance is calculated at the displacements anticipated in the BSE-2. Aging and environmental effects shall be considered in calculating the maximum resistance of the energy dissipation devices.

The pseudo lateral load of Equation 3-6 should be reduced by the damping modification factors of Table 2-15 to account for the energy dissipation (damping) afforded by the energy dissipation devices. The calculation of the damping effect should be estimated as:

$$\beta_{eff} = \beta + \frac{\sum_j W_j}{4\pi W_k} \tag{9-28}$$

where β is the damping in the structural frame and is set equal to 0.05 unless modified in Section 2.6.1.5, W_j is work done by device j in one complete cycle corresponding to floor displacements δ_i, the summation extends over all devices j, and W_k is the maximum strain energy in the frame, determined using Equation 9-27.

The work done by linear viscous device j in one complete cycle of loading may be calculated as:

$$W_j = \frac{2\pi^2}{T} C_j \delta_{rj}^2 \tag{9-29}$$

where T is the fundamental period of the rehabilitated building including the stiffness of the velocity-dependent devices, C_j is the damping constant for device j, and δ_{rj} is the relative displacement between the ends of device j along the axis of device j. An alternative equation for calculating the effective damping of Equation 9-28 is:

$$\beta_{eff} = \beta + \frac{T \sum_j C_j \cos^2 \theta_j \, \phi_{rj}^2}{\pi \sum_i \left(\frac{w_i}{g}\right) \phi_i^2} \tag{9-30}$$

where θ_j is the angle of inclination of device j to the horizontal, ϕ_{rj} is the first mode relative displacement between the ends of device j in the horizontal direction, w_i is the reactive weight of floor level i, ϕ_i is the first mode displacement at floor level i, and other terms are as defined above. Equation 9-30 applies to linear viscous devices only.

The design actions for components of the rehabilitated building should be calculated in three distinct stages of deformation as follows. The maximum action should be used for design.

1. **At the stage of maximum drift.** The lateral forces at each level of the building should be calculated using Equations 3-7 and 3-8, where V is the modified equivalent base shear.

2. **At the stage of maximum velocity and zero drift.** The viscous component of force in each energy dissipation device should be calculated by Equations 9-22 or 9-25, where the relative velocity $\dot{D}$ is given by $2\pi f_1 D$, where D is the relative displacement between the ends of the device calculated at the stage of maximum drift. The calculated viscous forces should be applied to the mathematical model of the building at the points of attachment of the devices and in directions consistent with the deformed shape of the building at maximum drift. The horizontal inertia forces at each floor level of the building should be applied concurrently with the viscous forces so that the horizontal displacement of each floor level is zero.

3. **At the stage of maximum floor acceleration.** Design actions in components of the rehabilitated building should be determined as the sum of [actions determined at the stage of maximum drift] times [CF_1] and [actions determined at the stage of maximum velocity] times [CF_2], where

$$CF_1 = \cos[\tan^{-1}(2\beta_{eff})] \tag{9-31}$$

$$CF_2 = \sin[\tan^{-1}(2\beta_{eff})] \tag{9-32}$$

in which β_{eff} is defined by either Equation 9-28 or Equation 9-30.

9.3.4.2 Linear Dynamic Procedure

The Linear Dynamic Procedures (LDP) of Section 3.3.2.2 should be followed unless explicitly modified by this section.

The response spectrum method of the LDP may by used when the effective damping in the fundamental mode of the rehabilitated building, in each principal direction, does not exceed 30% of critical.

A. Displacement-Dependent Devices

Application of the LDP for the analysis of rehabilitated buildings incorporating displacement-dependent devices is subject to the restrictions set forth in Section 9.3.4.1A.

For analysis by the Response Spectrum Method, the 5%-damped response spectrum may be modified to account for the damping afforded by the displacement-dependent energy dissipation devices. The 5%-damped acceleration spectrum should be reduced by the modal-dependent damping modification factor, B, either B_s or B_1, for periods in the vicinity of the mode under consideration; note that the value of B will be different for each mode of vibration. The damping modification factor in each significant mode should be determined using Table 2-15 and the calculated effective damping in that mode. The effective damping should be determined using a procedure similar to that described in Section 9.3.4.1A.

If the maximum base shear force calculated by dynamic analysis is less than 80% of the modified equivalent base shear of Section 9.3.4.1, component and element actions and deformations shall be proportionally increased to correspond to 80% of the modified equivalent base shear.

B. Velocity-Dependent Devices

For analysis by the Response Spectrum Method, the 5%-damped response spectrum may be modified to account for the damping afforded by the velocity-dependent energy dissipation devices. The 5%-damped acceleration spectrum should be reduced by the modal-dependent damping modification factor, B, either B_s or B_1, for periods in the vicinity of the mode under consideration; note that the value of B will be different for each mode of vibration. The damping modification factor in each significant mode should be determined using Table 2-15 and the calculated effective damping in that mode.

The effective damping in the m-th mode of vibration (β_{eff-m}) shall be calculated as:

$$\beta_{eff-m} = \beta_m + \frac{\sum_j W_{mj}}{4\pi W_{mk}} \tag{9-33}$$

where β_m is the m-th mode damping in the building frame, W_{mj} is work done by device j in one complete cycle corresponding to modal floor displacements δ_{mi}, and W_{mk} is the maximum strain energy in the frame in the m-th mode, determined using Equation 9-34:

$$W_{mk} = \frac{1}{2}\sum_i F_{mi}\delta_{mi} \tag{9-34}$$

where F_{mi} is the m-th mode horizontal inertia force at floor level i and δ_{mi} is the m-th mode horizontal displacement at floor level i. The work done by linear viscous device j in one complete cycle of loading in the m-th mode may be calculated as:

$$W_{mj} = \frac{2\pi^2}{T_m} C_j \delta_{mrj}^2 \tag{9-35}$$

where T_m is the m-th mode period of the rehabilitated building including the stiffness of the velocity-dependent devices, C_j is the damping constant for device j, and δ_{mrj} is the m-th mode relative displacement between the ends of device j along the axis of device j.

Direct application of the Response Spectrum Method will result in member actions at maximum drift. Member actions at maximum velocity and maximum acceleration in each significant mode should be determined using the procedure described in Section 9.3.4.1B. The combination factors CF_1 and CF_2 should be determined from Equations 9-31 and 9-32 using β_{eff-m} for the m-th mode.

If the maximum base shear force calculated by dynamic analysis is less than 80% of the modified equivalent base shear of Section 9.3.4.2, component and element actions and deformations shall be proportionally increased to correspond to 80% of the modified equivalent base shear.

9.3.5 Nonlinear Procedures

Subject to the limits set forth in Chapter 2, the nonlinear procedures of Section 3.3.3 may be used to implement passive energy dissipation devices without restriction.

9.3.5.1 Nonlinear Static Procedure

The Nonlinear Static Procedure (NSP) of Section 3.3.3 should be followed unless explicitly modified by this section.

The nonlinear mathematical model of the rehabilitated building should explicitly include the nonlinear force-velocity-displacement characteristics of the energy dissipation devices, and the mechanical characteristics of the components supporting the devices. Stiffness characteristics should be consistent with the deformations corresponding to the target displacement and a frequency equal to the inverse of period T_e as defined in Section 3.3.3.2.

The nonlinear mathematical model of the rehabilitated building shall include the nonlinear force-velocity-displacement characteristics of the energy dissipation

Benefits of Adding Energy Dissipation Devices

The benefit of adding *displacement-dependent* energy dissipation devices is recognized in the *Guidelines* by the increase in building stiffness afforded by such devices, and the reduction in target displacement associated with the reduction in T_e. The alternative Nonlinear Static Procedure, denoted in the *Commentary* as Method 2, uses a different strategy to calculate the target displacement and explicitly recognizes the added damping provided by the energy dissipation devices.

The benefits of adding *velocity-dependent* energy dissipation devices are recognized by the increases in stiffness and equivalent viscous damping in the building frame. For most velocity-dependent devices, the primary benefit will be due to the added viscous damping. Higher-mode damping forces in the energy dissipation devices must be evaluated regardless of the Nonlinear Static Procedure used—refer to the *Commentary* for additional information.

devices, and the mechanical characteristics of the components supporting the devices. Energy dissipation devices with stiffness and damping characteristics that are dependent on excitation frequency and/or temperature shall be modeled with characteristics consistent with (1) the deformations expected at the target displacement, and (2) a frequency equal to the inverse of the effective period.

Equation 3-11 should be used to calculate the target displacement. For velocity-dependent energy dissipation devices, the spectral acceleration in Equation 3-11 should be reduced to account for the damping afforded by the viscous dampers.

A. Displacement-Dependent Devices

Equation 3-11 should be used to calculate the target displacement. The stiffness characteristics of the energy dissipation devices should be included in the mathematical model.

B. Velocity-Dependent Devices

The target displacement of Equation 3-11 should be reduced to account for the damping added by the velocity-dependent energy dissipation devices. The calculation of the damping effect should be estimated as:

$$\beta_{eff} = \beta + \frac{\sum_j W_j}{4\pi W_k} \qquad (9\text{-}36)$$

where β is the damping in the structural frame and is set equal to 0.05 unless modified in Section 2.6.1.5, W_j is work done by device *j* in one complete cycle corresponding to floor displacements δ_i, the summation extends over all devices *j*, and W_k is the maximum strain energy in the frame, determined using Equation 9-27.

The work done by device *j* in one complete cycle of loading may be calculated as:

$$W_j = \frac{2\pi^2}{T_s} C_j \delta_j^2 \qquad (9\text{-}37)$$

where T_s is the secant fundamental period of the rehabilitated building including the stiffness of the velocity-dependent devices (if any), calculated using Equation 3-10 but replacing the effective stiffness (K_e) with the secant stiffness (K_s) at the target displacement (see Figure 9-1); C_j is the damping constant for device *j*; and δ_{rj} is the relative displacement between the ends of device *j* along the axis of device *j* at a roof displacement corresponding to the target displacement.

The acceptance criteria of Section 3.4.3 apply to buildings incorporating energy dissipation devices. The use of Equation 9-36 will generally capture the maximum displacement of the building. Checking for displacement-controlled actions should use deformations corresponding to the target displacement. Checking for force-controlled actions should use component actions calculated for three limit states: maximum drift, maximum velocity, and maximum acceleration. Maximum actions shall be used for design. Higher-mode effects should be explicitly evaluated.

9.3.5.2 Nonlinear Dynamic Procedure

Nonlinear Time History Analysis should be undertaken as in the requirements of Section 3.3.4.2, except as modified by this section. The mathematical model should account for both the plan and vertical spatial

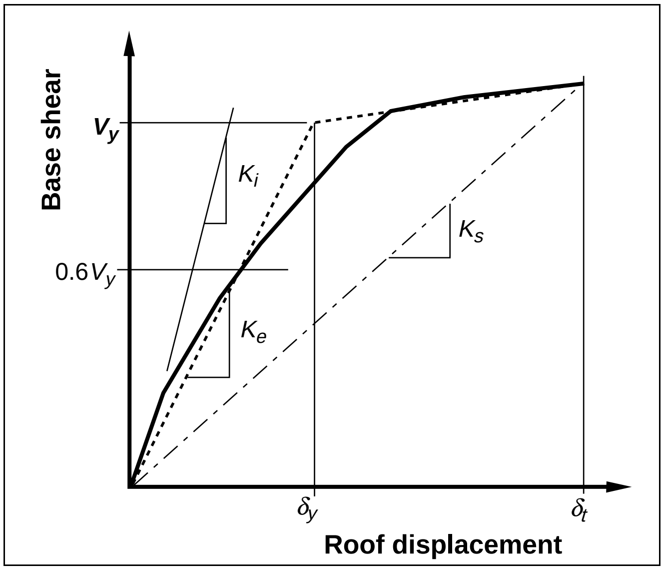

Figure 9-1 Calculation of Secant Stiffness, K_s

distribution of the energy dissipation devices in the rehabilitated building. If the energy dissipation devices are dependent on excitation frequency, operating temperature (including temperature rise due to excitation), deformation (or strain), velocity, sustained loads, and bilateral loads, such dependence should be accounted for in the analysis.

The viscous forces in velocity-dependent energy dissipation devices should be included in the calculation of design actions and deformations. Substitution of viscous effects in energy dissipation devices by global structural damping for nonlinear Time History Analysis is not permitted.

9.3.6 Detailed Systems Requirements

9.3.6.1 General

The energy dissipation system and the remainder of the lateral-force-resisting system should comply with all of the requirements of the *Guidelines*.

9.3.6.2 Operating Temperature

The force-displacement response of an energy dissipation device will generally be dependent on ambient temperature and temperature rise due to cyclic or earthquake excitation. The analysis of a rehabilitated building should account for likely variations in the force-displacement response of the energy dissipation devices to bound the seismic response of the building during the design earthquake, and develop limits for defining the acceptable response of the prototype (Section 9.3.8) and production (Section 9.3.6.6) devices.

9.3.6.3 Environmental Conditions

In addition to the requirements for vertical and lateral loads induced by wind and earthquake actions, the energy dissipation devices should be designed with consideration given to other environmental conditions, including aging effects, creep, fatigue, ambient temperature, and exposure to moisture and damaging substances.

9.3.6.4 Wind Forces

The fatigue life of energy dissipation devices, or components thereof (e.g., seals in a fluid viscous device), should be investigated and shown to be adequate for the design life of the devices. Devices subject to failure by low-cycle fatigue should resist wind forces in the linearly elastic range.

9.3.6.5 Inspection and Replacement

Access for inspection and replacement of the energy dissipation devices should be provided.

9.3.6.6 Manufacturing Quality Control

A quality control plan for manufacturing energy dissipation devices should be established by the engineer of record. This plan should include descriptions of the manufacturing processes, inspection procedures, and testing necessary to ensure quality device production.

9.3.6.7 Maintenance

The engineer of record should establish a maintenance and testing schedule for energy dissipation devices to ensure reliable response of said devices over the design life of the damper hardware. The degree of maintenance and testing should reflect the established in-service history of the devices.

9.3.7 Design and Construction Review

9.3.7.1 General

Design and construction review of all rehabilitated buildings incorporating energy dissipation devices should be performed in accordance with the requirements of Section 2.12, unless modified by the requirements of this section. Design review of the energy dissipation system and related test programs should be performed by an independent engineering review 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 should include, but should not necessarily be limited to the following:

- Preliminary design including sizing of the devices
- Prototype testing (Section 9.3.8.2)
- Final design of the rehabilitated building and supporting analyses
- Manufacturing quality control program for the energy dissipation devices

9.3.8 Required Tests of Energy Dissipation Devices

9.3.8.1 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. Alternatively, 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 manufacturing quality control (production) plan of Section 9.3.6.6.

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 provide explicit acceptance criteria for the effective stiffness and damping values established by the production tests of Section 9.3.6.6. 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 in the specification. 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.

9.3.8.2 Prototype Tests

A. 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 that 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.

B. Data Recording

The force-deflection relationship for each cycle of each test should be electronically recorded.

C. Sequence 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 sequence, each energy dissipation device should be loaded to simulate the gravity loads on the device as installed in the building, and the extreme ambient temperatures anticipated.

1. Each device should be loaded with the number of cycles expected in the design wind storm, but not less than 2000 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 rehabilitated building.

EXCEPTION: Devices not subject to wind-induced forces or displacements need not be subjected to these tests.

2. Each device should be loaded with 20 fully reversed cycles at the displacement in the energy dissipation device corresponding to the BSE-2, at a frequency equal to the inverse of the fundamental period of the rehabilitated building.

EXCEPTION: Energy dissipation devices may be tested by other methods than those noted above, provided that: (1) equivalency between the proposed method and cyclic testing can be demonstrated; (2) the proposed method captures the dependence of the energy dissipation device response to ambient temperature, frequency of loading, and (3) temperature rise during testing; and the proposed method is approved by the engineer of record.

D. Devices Dependent on Velocity and/or Frequency of Excitation

If the force-deformation properties of the energy dissipation devices at any displacement less than or equal to the total design displacement change by more than 15% for changes in testing frequency from 0.5 f_1 to 2.0 f_1, the preceding tests should be performed at frequencies equal to 0.5 f_1, f_1, and 2.0 f_1.

EXCEPTION: If reduced-scale prototypes are used to quantify 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.

E. Devices Dependent on Bilateral Displacement

If the energy dissipation devices are subjected to substantial bilateral deformation, the preceding tests should be made at both zero bilateral displacement, and peak lateral displacement in the BSE-2.

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.

F. 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 be tested, provided that:

1. All pertinent testing data are made available to, and approved by the engineer of record.
2. The manufacturer can substantiate the similarity of the previously tested devices to the satisfaction of the engineer of record.
3. The submission of data from a previous testing program is approved in writing by the engineer of record.

9.3.8.3 Determination of Force-Displacement Characteristics

The force-displacement characteristics of an energy dissipation device should be based on the cyclic load and displacement tests of prototype devices specified in Section 9.3.8.2.

As required, the effective stiffness (k_{eff}) of an energy dissipation device with stiffness should be calculated for each cycle of deformation as follows:

$$k_{eff} = \frac{|F^-| + |F^+|}{|\Delta^-| + |\Delta^+|} \tag{9-38}$$

where forces F^+ and F^- are calculated at displacements Δ^+ and Δ^-, respectively. The effective stiffness of an energy dissipation device should be established at the test displacements in Section 9.3.8.2C.

The equivalent viscous damping of an energy dissipation device (β_{eff}) exhibiting stiffness should be calculated for each cycle of deformation as:

$$\beta_{eff} = \frac{1}{2\pi}\frac{W_D}{k_{eff}\Delta_{ave}^2} \qquad (9\text{-}39)$$

where k_{eff} is established in Equation 9-38, and W_D is the area enclosed by one complete cycle of the force-displacement response for a single energy dissipation device at a prototype test displacement (Δ_{ave}) equal to the average of the absolute values of displacements Δ^+ and Δ^-.

9.3.8.4 System Adequacy

The performance of a prototype device may be assessed as adequate if all of the following conditions are satisfied:

1. The force-displacement curves for the tests in Section 9.3.8.2C have nonnegative incremental force-carrying capacities.

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

2. Within each test of Section 9.3.8.2C, the effective stiffness (k_{eff}) of a prototype energy dissipation device for any one cycle does not differ by more than plus or minus 15% from the average effective stiffness as calculated from all cycles in that test.

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

3. Within each test of Section 9.3.8.2C, 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% from the average maximum and minimum forces as calculated from all cycles in that test.

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

4. Within each test of Section 9.3.8.2C, the area of the hysteresis loop (W_D) of a prototype energy dissipation device for any one cycle does not differ by more than plus or minus 15% from the average area of the hysteresis curve as calculated from all cycles in that test.

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

5. 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 9.3.8.2C, shall fall within the limits set by the engineer-of-record in the specification. The area of the hysteresis loop at the end of cyclic testing should not differ by more than plus or minus 15% from the average area of the 20 test cycles.

6. 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 9.3.8.2C, shall fall within the limits set by the engineer of record in the specification.

9.4 Other Response Control Systems

Response control strategies other than base isolation (Section 9.2) and passive energy dissipation (Section 9.3) systems have been proposed. Dynamic vibration absorption and active control systems are two such response control strategies. Although both dynamic vibration absorption and active control systems have been implemented to control the wind-induced vibration of buildings, the technology is not sufficiently mature, and the necessary hardware is not sufficiently robust, to warrant the preparation of general guidelines for the implementation of other response control systems. However, *Commentary* Section C9.4 provides a more detailed discussion of two other systems: dynamic vibration absorbers and active control systems.

The analysis and design of other response control systems should be reviewed by an independent engineering review panel per the requirements of Section 9.3.7. This review panel should include persons expert in the theory and application of the response control strategies being considered, and should be impaneled by the owner prior to the development of the preliminary design.

9.5 Definitions

BSE-1: Basic Safety Earthquake-1, which is the lesser of the ground shaking at a site for a 10%/50 year earthquake or two thirds of the MCE earthquake at the site.

BSE-2: Basic Safety Earthquake-2, which is the ground shaking at a site for an MCE earthquake.

Design displacement: The design earthquake displacement of an isolation or energy dissipation system, or elements thereof, excluding additional displacement due to actual and accidental torsion.

Design earthquake: A user-specified earthquake for the design of an isolated building, having ground shaking criteria described in Chapter 2.

Displacement-dependent energy dissipation devices: Devices having mechanical properties such that the force in the device is related to the relative displacement in the device.

Displacement restraint system: Collection of structural components and elements that limit lateral displacement of seismically-isolated buildings during the BSE-2.

Effective damping: The value of equivalent viscous damping corresponding to the energy dissipated by the building, or element thereof, during a cycle of response.

Effective stiffness: The value of the lateral force in the building, or an element thereof, divided by the corresponding lateral displacement.

Energy dissipation device (EDD): Non-gravity-load-supporting element designed to dissipate energy in a stable manner during repeated cycles of earthquake demand.

Energy dissipation system (EDS): Complete collection of all energy dissipation devices, their supporting framing, and connections.

Isolation interface: The boundary between the upper portion of the structure (superstructure), which is isolated, and the lower portion of the structure, which moves rigidly with the ground.

Isolation system: The collection of structural elements that includes all individual isolator units, all structural elements that transfer force between elements of the isolation system, and all connections to other structural elements. The isolation system also includes the wind-restraint system, if such a system is used to meet the design requirements of this section.

Isolator unit: A horizontally flexible and vertically stiff structural element of the isolation system that permits large lateral deformations under seismic load. An isolator unit may be used either as part of or in addition to the weight-supporting system of the building.

Maximum displacement: The maximum earthquake displacement of an isolation or energy dissipation system, or elements thereof, excluding additional displacement due to actual or accidental torsion.

Tie-down system: The collection of structural connections, components, and elements that provide restraint against uplift of the structure above the isolation system.

Total design displacement: The BSE-1 displacement of an isolation or energy dissipation system, or elements thereof, including additional displacement due to actual and accidental torsion.

Total maximum displacement: The maximum earthquake displacement of an isolation or energy dissipation system, or elements thereof, including additional displacement due to actual and accidental torsion.

Velocity-dependent energy dissipation devices: Devices having mechanical characteristics such that the force in the device is dependent on the relative velocity in the device.

Wind-restraint system: The collection of structural elements that provides restraint of the seismic-isolated structure for wind loads. The wind-restraint system may be either an integral part of isolator units or a separate device.

9.6 Symbols

This list may not contain symbols defined at their first use if not used thereafter.

B_{D1}	Numerical coefficient taken equal to the value of β_1, as set forth in Table 2-15, at effective damping equal to the value of β_D
B_{M1}	Numerical coefficient taken equal to the value of β_1, as set forth in Table 2-15, at effective damping equal to the value of β_M
C or C_j	Damping coefficient
CF_i	State combination factors for use with velocity-dependent energy dissipation devices
D	Target spectral displacement
D	Displacement of an energy dissipation unit
D_{ave}	Average displacement of an energy dissipation unit, equal to $(\lvert D^+\rvert + \lvert D^-\rvert)/2$
D^-	Maximum negative displacement of an energy dissipation unit
D^+	Maximum positive displacement of an energy dissipation unit
$\dot{D}$	Relative velocity of an energy dissipation unit
D_D	Design displacement, in in. (mm), at the center of rigidity of the isolation system in the direction under consideration, as prescribed by Equation 9-2
D'_D	BSE-1 displacement, in in. (mm), at the center of rigidity of the isolation system in the direction under consideration, as prescribed by Equation 9-10
D_M	Maximum displacement, in in. (mm), at the center of rigidity of the isolation system in the direction under consideration, as prescribed by Equation 9-4
D'_M	Maximum displacement, in in. (mm), at the center of rigidity of the isolation system in the direction under consideration, as prescribed by Equation 9-11
D_{TD}	Total design displacement, in in. (mm), of an element of the isolation system, including both translational displacement at the center of rigidity and the component of torsional displacement in the direction under consideration, as specified by Equation 9-6
D_{TM}	Total maximum displacement, in in. (mm), of an element of the isolation system, including both translational displacement at the center of rigidity and the component of torsional displacement in the direction under consideration, as specified by Equation 9-7
E_{Loop}	Energy dissipated, in kip-inches (kN-mm), in an isolator unit during a full cycle of reversible load over a test displacement range from Δ^+ to Δ^-, as measured by the area enclosed by the loop of the force-deflection curve
F	Force in an energy dissipation unit
F^-	Negative force, in k, in an isolator or energy dissipation unit during a single cycle of prototype testing at a displacement amplitude of Δ^-
F^+	Positive force, in k, in an isolator or energy dissipation unit during a single cycle of prototype testing at a displacement amplitude of Δ^+
K_{Dmax}	Maximum effective stiffness, in k/in., of the isolation system at the design displacement in the horizontal direction under consideration, as prescribed by Equation 9-14
K_{Dmin}	Minimum effective stiffness, in k/in., of the isolation system at the design displacement in the horizontal direction under consideration, as prescribed by Equation 9-15
K'	Storage stiffness
K''	Loss stiffness

K_{Mmax} Maximum effective stiffness, in k/in., of the isolation system at the maximum displacement in the horizontal direction under consideration, as prescribed by Equation 9-16

K_{Mmin} Minimum effective stiffness, in k/in., of the isolation system at the maximum displacement in the horizontal direction under consideration, as prescribed by Equation 9-17

S_{D1} One-second, 5%-damped spectral acceleration for the design earthquake, as set forth in Chapter 2

S_{DS} Short-period, 5%-damped spectral acceleration for the design earthquake, as set forth in Chapter 2

S_{M1} One-second, 5%-damped spectral acceleration, as set forth in Chapter 2 for the BSE-2

S_{MS} Short-period, 5%-damped spectral acceleration, as set forth in Chapter 2 for the BSE-2

T_D Effective period, in seconds, of the seismic-isolated structure at the design displacement in the direction under consideration, as prescribed by Equation 9-3

T_e Effective fundamental-mode period, in seconds, of the building in the direction under consideration

T_M Effective period, in seconds, of the seismic-isolated structure at the maximum displacement in the direction under consideration, as prescribed by Equation 9-5

T_s Secant fundamental period of a rehabilitated building calculated using Equation 3-10 but replacing the effective stiffness (K_e) with the secant stiffness (K_s) at the target displacement

V^* Modified equivalent base shear

V_b The total lateral seismic design force or shear on elements of the isolation system or elements below the isolation system, as prescribed by Equation 9-8

V_s The total lateral seismic design force or shear on elements above the isolation system, as prescribed by Section 9.2.4.4B

V_t Total base shear determined by Time-History Analysis

W The total seismic dead load. For design of the isolation system, W is the total seismic dead load weight of the structure above the isolation interface

W_D Energy dissipated, in in.-k, in a building or element thereof during a full cycle of displacement

b The shortest plan dimension of the rehabilitated building, in ft (mm), measured perpendicular to d

d The longest plan dimension of the rehabilitated building, in ft (mm)

e Actual eccentricity, ft (mm), measured in plan between the center of mass of the structure above the isolation interface and the center of rigidity of the isolation system, plus accidental eccentricity, ft (mm), taken as 5% of the maximum building dimension perpendicular to the direction of force under consideration

f_1 Fundamental frequency of the building

g Acceleration of gravity (386.1 in/sec.^{2}, or 9,800 mm/sec.^{2} for SI units)

k_{eff} Effective stiffness of an isolator unit, as prescribed by Equation 9-12, or an energy dissipation unit, as prescribed by Equation 9-38

m Mass (k-sec^2/in.)

q Coefficient, less than one, equal to the ratio of actual hysteresis loop area to idealized bilinear hysteresis loop area

y The distance, in ft (mm), between the center of rigidity of the isolation system rigidity and the element of interest, measured perpendicular to the direction of seismic loading under consideration

Δ_{ave} Average displacement of an energy dissipation unit during a cycle of prototype testing, equal to $(|\Delta^+| + |\Delta^-|)/2$

Δ^+ Positive displacement amplitude, in in. (mm), of an isolator or energy dissipation unit during a cycle of prototype testing

Δ^- Negative displacement amplitude, in in. (mm), of an isolator or energy dissipation unit during a cycle of prototype testing

ΣE_D Total energy dissipated, in in.-k, in the isolation system during a full cycle of response at the design displacement, D_D

ΣE_M Total energy dissipated, in in.-k, in the isolation system during a full cycle of response at the maximum displacement, D_M

$\Sigma|F_D^+|_{max}$ Sum, for all isolator units, of the maximum absolute value of force, k, at a positive displacement equal to D_D

$\Sigma|F_D^+|_{min}$ Sum, for all isolator units, of the minimum absolute value of force, k, at a positive displacement equal to D_D

$\Sigma|F_D^-|_{max}$ Sum, for all isolator units, of the maximum absolute value of force, k, at a negative displacement equal to D_D

$\Sigma|F_D^-|_{min}$ Sum, for all isolator units, of the minimum absolute value of force, k, at a negative displacement equal to D_D

$\Sigma|F_M^+|_{max}$ Sum, for all isolator units, of the maximum absolute value of force, k, at a positive displacement equal to D_M

$\Sigma|F_M^+|_{min}$ Sum, for all isolator units, of the minimum absolute value of force, k, at a positive displacement equal to D_M

$\Sigma|F_M^-|_{max}$ Sum, for all isolator units, of the maximum absolute value of force, k, at a negative displacement equal to D_M

$\Sigma|F_M^-|_{min}$ Sum, for all isolator units, of the minimum absolute value of force, k, at a negative displacement equal to D_M

β Damping inherent in the building frame (typically equal to 0.05)

β_b Equivalent viscous damping of a bilinear system

β_{eff} Effective damping of isolator unit, as prescribed by Equation 9-13, or an energy dissipation unit, as prescribed by Equation 9-39; also used for the effective damping of the building, as prescribed by Equations 9-26, 9-30, and 9-36

β_D Effective damping of the isolation system at the design displacement, as prescribed by Equation 9-18

β_M Effective damping of the isolation system at the maximum displacement, as prescribed by Equation 9-19

δ_i Floor displacement

θ_j Angle of inclination of energy dissipation device

ϕ_i Modal displacement of floor i

ϕ_{rj} Relative modal displacement in horizontal direction of energy dissipation device j

ω_1 $2\pi f_1$

9.7 References

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