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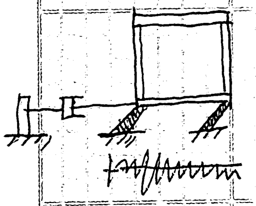
Basic Analysis and Design Concepts for Seismically Isolated Structures

Introduction

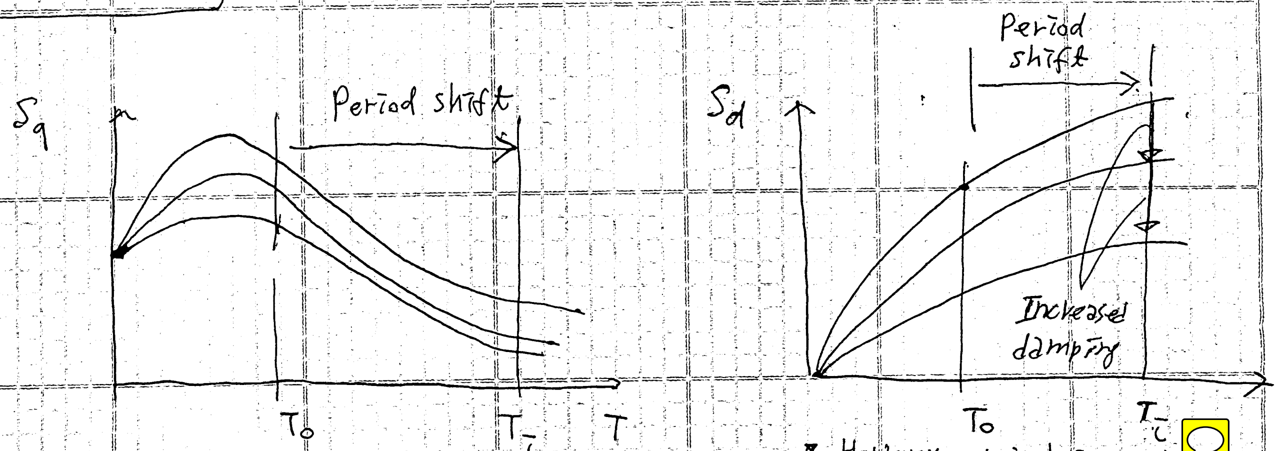
- The isolators, having much lower lateral stiffness than the lateral stiffness of the structure, seperate it from the ground motion
  - ↳ limits the seismic energy transfer to the structure
- The principle of all seismic isolation systems : the same



① An isolator : shifts the lateral period of the structure beyond the most predominant periods of typical EQs.

② An energy dissipation mechanism (damper) that dissipates the residual input energy by increased damping.

See Fig. 1

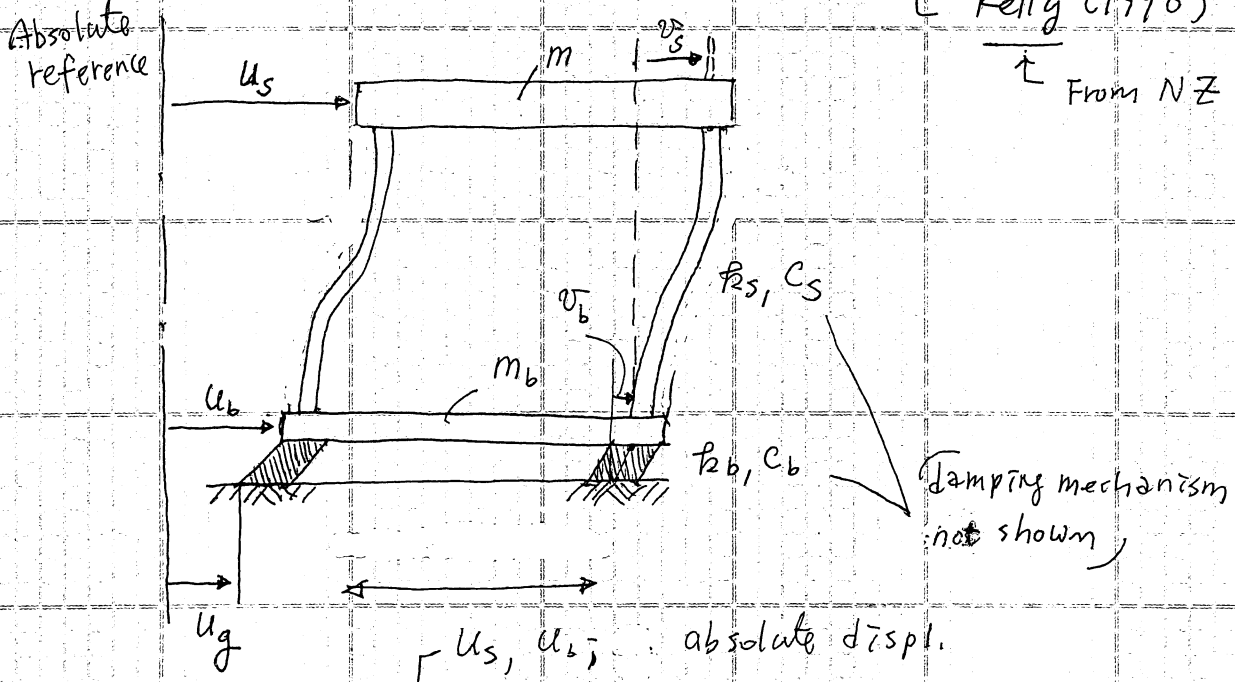


* However, this deformation is concentrated in the isolation system, accompanied by only small deformations in the structure.

: Figure 1

2. Theory of "Linear" Seismically Isolated Systems.

← Kelly (1990)
← From NZ



u_s, u_b ; absolute displ.
v_s, v_b ; relative displ.

Applying (dynamic equilibrium equation) to both masses,

$$m\boxed{\ddot{u}_s} + c_s(\dot{u}_s - \dot{u}_b) + k_s(u_s - u_b) = 0 \quad --- (1)$$

$$m\boxed{\ddot{u}_s} + m_b\boxed{\ddot{u}_b} + c_b(\dot{u}_b - \dot{u}_g) + k_b(u_b - u_g) = 0 \quad --- (2)$$

Re-writing above Eqs (1) and (2) in terms of relative displacements, v_s and v_b :

$$\left.\begin{array}{l} u_s - u_b = v_s \\ u_b - u_g = v_b \end{array}\right\} \quad ------ (3)$$

$$u_s = u_b + v_s = (v_b + u_g) + v_s \quad --- (3)'$$

$$\left.\begin{array}{l} \ddot{u}_s = \ddot{v}_b + \ddot{u}_g + \ddot{v}_s \\ \ddot{u}_b = \ddot{u}_g + \ddot{v}_b \end{array}\right\}$$

(3) & $(3)' \longrightarrow (1)$ & (2) :

(1)식에 대응

$$\underline{m(\ddot{v}_b+\ddot{u}_g+\ddot{v}_s)}+c_s\dot{v}_s+k_s v_s=0$$

$$m\ddot{v}_b+m\ddot{v}_s+c_s\dot{v}_s+k_s v_s=-m\ddot{u}_g \quad --- (4)$$

(2)식에 대응

$$m(\underline{\ddot{v}_b}+\ddot{u}_g+\ddot{v}_s)+\underbrace{m_b(\ddot{u}_g+\ddot{v}_b)}+c_b\dot{v}_b+k_b v_b=0$$

2개 연립 상미방에 불과

$$\underbrace{(m+m_b)}_{M}\ddot{v}_b+m\ddot{v}_s+c_b\dot{v}_b+k_b v_b=-\underbrace{(m+m_b)}_{M}\ddot{u}_g \quad --- (5)$$

Note : i) 상부 구조물이 "강체"라면 (즉 $v_s=0$), (5)식은

$$\underline{M\ddot{v}_b+c_b\dot{v}_b+k_b v_b=-M\ddot{u}_g} \quad --- (6)$$

↳ 단순히 "면진 장치" 상에 지지된 질량 M인 구조물의 운동방정식에 불과.

ii) 만일 고정기반이라면 (즉 $v_b=0$), (4)식은

$$\underline{m\ddot{v}_s+c_s\dot{v}_s+k_s v_s=-m\ddot{u}_g} \quad -- (7)$$

The usual equation for a fixed-base SDOF system.

In matrix form,

$$\cancel{\begin{bmatrix}\ \end{bmatrix}\begin{bmatrix}\ \end{bmatrix}+\begin{bmatrix}\ \end{bmatrix}\begin{bmatrix}\ \end{bmatrix}+\begin{bmatrix}\ \end{bmatrix}\begin{bmatrix}\ \end{bmatrix}}$$

$$\underset{2\times2}{\underline{M}}\,\underset{2\times1}{\underline{\ddot{v}}}+\underset{2\times2}{\underline{c}}\,\underset{2\times1}{\underline{\dot{v}}}+\underset{2\times2}{\underline{k}}\,\underset{2\times1}{\underline{v}}=-\underline{M}\,\underline{r}\,\ddot{u}_g$$

$$\begin{bmatrix} M & m \\ m & m \end{bmatrix} \begin{bmatrix} \ddot{v}_b \\ \ddot{v}_s \end{bmatrix} + \begin{bmatrix} c_b & 0 \\ 0 & c_s \end{bmatrix} \begin{bmatrix} \dot{v}_b \\ \dot{v}_s \end{bmatrix} + \begin{bmatrix} k_b & 0 \\ 0 & k_s \end{bmatrix} \begin{bmatrix} v_b \\ v_s \end{bmatrix} = -\begin{bmatrix} M & m \\ m & m \end{bmatrix} \begin{bmatrix} 1 \\ 0 \end{bmatrix} \times \ddot{u}_g$$

{일반적으로 non-classical damping, $\underline{\phi}_1^T \underline{c}\, \underline{\phi}_2 = c_{12} = c_{21} \neq 0$ in general}

Considering the properties of the isolation system and of the structure, we can make the following order of magnitude estimates;

- $m_b < m$, but of the same order of magnitude;
- $\omega_s = \sqrt{\frac{k_s}{m}} \gg \omega_b = \sqrt{\frac{k_b}{M}}$ and $\varepsilon = \left(\frac{\omega_b}{\omega_s}\right)^2$ is assumed to be of the order of 10^{-2}
- $\xi_s = \frac{c_s}{2m\omega_s}$ and $\xi_b = \frac{c_b}{2M\omega_b}$ are both the same order of magnitude as ε.

$\frac{1}{100} \times (1 \sim 9)$

The natural frequencies of the system;

$$\left| K - \omega^2 M \right| = 0$$

or

$$\begin{vmatrix} k_b - \omega^2 M & -\omega^2 m \\ -\omega^2 m & k_s - \omega^2 m \end{vmatrix} = 0$$

(HW# 이하 11쪽까지의 모든 수식 유도 확인)

or

$$(1-\gamma)\omega^4 - (\omega_b^2 + \omega_s^2)\omega^2 + \omega_b^2 \omega_s^2 = 0$$

where $\gamma = m/M$

$$\omega_1^2, \omega_2^2 = \frac{1}{2(1-\gamma)}\left\{(\omega_s^2+\omega_b^2) \pm \sqrt{(\omega_s^2+\omega_b^2)^2 - 4(1-\gamma)(\omega_s^2\omega_b^2)}\right\}$$

$$(\omega_s^2-\omega_b^2)\sqrt{1 + 4\gamma\frac{\omega_b^2\omega_s^2}{(\omega_s^2-\omega_b^2)^2}}$$

$\omega_s \gg \omega_b$ 이므로 1보다 매우 작음

$$\doteqdot (\omega_s^2-\omega_b^2)\left\{1 + \frac{1}{2}(4\gamma)\frac{\omega_b^2\omega_s^2}{(\omega_s^2-\omega_b^2)^2}\right\}$$

$$= (\omega_s^2-\omega_b^2) + \frac{2\gamma\,\omega_b^2\omega_s^2}{(\omega_s^2-\omega_b^2)}$$

$$\therefore \omega_1^2, \omega_2^2 = \frac{1}{2(1-\gamma)}\left[(\omega_s^2+\omega_b^2) \pm \left\{(\omega_s^2-\omega_b^2) + \frac{2\gamma\,\omega_b^2\omega_s^2}{(\omega_s^2-\omega_b^2)}\right\}\right]$$

$$\omega_1^2 = \frac{1}{\cancel{2}(1-\gamma)}\left[\cancel{2}\omega_b^2 - \frac{\cancel{2}\gamma\,\omega_b^2\omega_s^2}{(\omega_s^2-\omega_b^2)}\right]$$

$$= \frac{\omega_b^2}{(1-\gamma)}\left[1 - \frac{\gamma\omega_s^2}{(\omega_s^2-\omega_b^2)}\right]$$

$$= \frac{\omega_b^2}{(1-\gamma)}\left[1 - \frac{\gamma}{\left\{1-\left(\frac{\omega_b}{\omega_s}\right)^2\right\}}\right] \simeq \frac{\omega_b^2}{(1-\gamma)}(1-\gamma) = \omega_b^2$$

$\therefore \omega_1 = \omega_b$

$\varepsilon \ll 1.0$

~~$= \frac{\omega_b^2}{(1-\gamma)}[1-\gamma(1+\varepsilon)]$ [illegible]~~

근사

$$\omega_2^2 = \frac{1}{2(1-\gamma)}\left[(\omega_s^2+\cancel{\omega_b^2}) + (\omega_s^2-\cancel{\omega_b^2}) + \frac{2\gamma\,\omega_b^2\omega_s^2}{(\omega_s^2-\omega_b^2)}\right]$$

$$= \frac{\omega_s^2}{(1-\gamma)}\left[1+\frac{\gamma\,\omega_b^2}{(\omega_s^2-\omega_b^2)}\right]$$

$$= \frac{\omega_s^2}{(1-\gamma)}\left[1+\frac{\gamma\left(\frac{\omega_b}{\omega_s}\right)^2}{1-\left(\frac{\omega_b}{\omega_s}\right)^2}\right]$$

$$= \frac{\omega_s^2}{(1-\gamma)}\left[1+\frac{\gamma\varepsilon}{1-\varepsilon}\right]$$

$$\doteq \frac{\omega_s^2}{(1-\gamma)}\left[1+\underbrace{\gamma\varepsilon(1+\varepsilon)}_{\cancel{\gamma\varepsilon+\gamma\varepsilon^2}}\right]$$

~~ΔΘ~~

$$\left(\underbrace{\omega_2 \simeq \frac{\omega_s}{\sqrt{1-\gamma}}}\ ,\quad \underline{\omega_1 = \omega_b}\right)$$

a

The second natural frequency is the structural frequency that is significantly increased by the presence of the mass of the base.

The isolation frequency that is essentially not affected by the flexibility of the structures.

Combining these two factors further increases the separation between the isolation frequency and the fixed-base structural frequency.

$$\left(\text{note}: \gamma = \frac{m}{M} = \frac{m}{m+m_b}\right)$$

The first mode shape $\underline{A}^1$: $\omega^2 \rightarrow \omega_b^2$

$$\left[\begin{array}{c|c} k_b - \omega_b^2 m & -\omega_b^2 m \\ \hline -\omega_b^2 m & k_s - \omega_b^2 m \end{array}\right] \begin{bmatrix} A_1^1 \\ \\ A_2^1 \end{bmatrix} = \underline{0}$$

; From the 2nd equation,

$$(-\omega_b^2 m) A_1^1 + (k_s - \omega_b^2 m) A_2^1 = 0$$

Setting $A_1^1 = 1.0$:

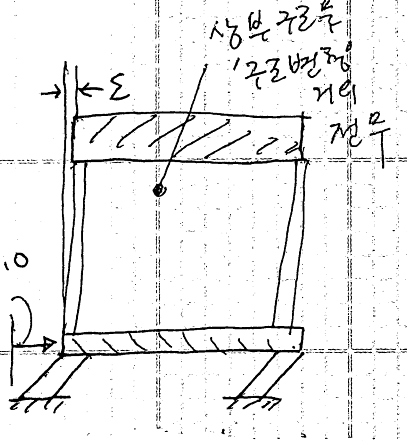
$$A_2^1 = \frac{\omega_b^2 m}{k_s - \omega_b^2 m} = \frac{\omega_b^2 (m/m)}{\underbrace{\boxed{(k_s/m)}}_{\omega_s^2} - \omega_b^2}$$

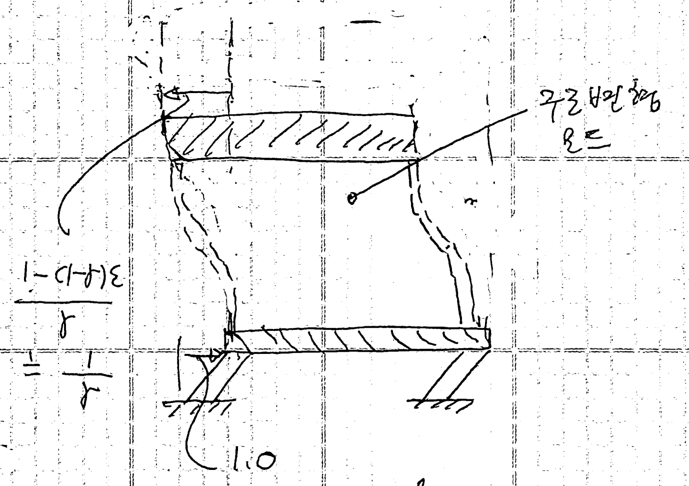
$$= \frac{\left(\frac{\omega_b}{\omega_s}\right)^2}{1 - \left(\frac{\omega_b}{\omega_s}\right)^2} = \frac{\varepsilon}{1 - \varepsilon}$$

$\therefore$ $A_2^1 \approx \varepsilon$

$$\therefore \quad \underline{A}^1 = \begin{bmatrix} 1.0 \\ \\ \varepsilon \end{bmatrix}$$

Similary, $\underline{A}^2 = \begin{bmatrix} 1.0 \\ \\ -\frac{1-(1-\gamma)\varepsilon}{\gamma} \end{bmatrix}$





$$\frac{1-(1-\gamma)\varepsilon}{\gamma} \doteq \frac{1}{\gamma}$$

○ 1st mode (면진모드)

(practically a rigid structure on a flexible base isolation)

○ 2nd mode (구조모드)

(Very close to a motion where the two masses are vibrating completely free in space about the center of the mass of the combined system.)

(The practical significance of this: "High acceleration in the 2nd mode of an isolated structure do not generate a large base shear.")

(이 부분에 대한 이해는 mode superposition 해석에 도움을 받는 것이 타당)

☆ 왜 위와 같은 mode shape이 얻어지는가? (운동방정식의 geometric coordinate를 어떻게 잡았는가에 유의)

Analysis by modal superposition

(Modal expansion of $\underline{v}$)

$$\underset{2\times1}{\underline{v}} = \begin{bmatrix} v_b(t) \\ v_s(t) \end{bmatrix} = [\underline{A}^1, \underline{A}^2] \times \begin{bmatrix} u_1(t) \\ u_2(t) \end{bmatrix}$$

Assuming the damping orthogonality, -- [illegible]

$$M_i \ddot{u}_i + C_i \dot{u}_i + K_i u_i = P_i(t)$$

$(i=1, 2)$

$$\ddot{u}_i + 2\xi_i \omega_i \dot{u}_i + \omega_i^2 u_1 = \alpha_i \ddot{u}_g \quad (i=1, 2).$$

Modal participation factor:

$$\alpha_1 = -\frac{(\underline{A}^1)^T \underline{M}\, \underline{r}}{M_1} = \boxed{1-\gamma\varepsilon}$$ — order of $\underline{\underline{1.0}}$

M_1^* (= the first modal mass) $= \alpha_1^2 M_1 \doteq M$

$$\alpha_2 = \boxed{\gamma\varepsilon}$$ — order of ε (very small) → $\frac{1}{100}$

$$M_2^* = M \times \frac{(1-\gamma)\left[1-2\varepsilon(1-\gamma)\right]}{\gamma}$$

(Why is the seismic isolation effective ?)

The modal participation factor for the 2nd mode (α_2), which is the mode involving structural deformation is order of ε and very small if ω_b and ω_s are well seperated. → [illegible] $\omega_s \gg \omega_b$ [illegible]

Furthe more, since $\overset{\frac{\omega_s}{\sqrt{1-\gamma}}}{\omega_2} >> \omega_s$, the isolated structure will be out of range of strong earthquake motions.

o.k

Moreover,

$$P_2(t) = -(\underline{A}^2)^T \underline{M}\, \underline{r}\, \ddot{u}_g(t)$$

where $\underline{r} = \begin{bmatrix} 1 \\ 0 \end{bmatrix}$

Recalling $\underline{A}^1 = \begin{bmatrix} 1 \\ \varepsilon \end{bmatrix} \doteq \begin{bmatrix} 1 \\ 0 \end{bmatrix} \doteq \underline{r}$

$$P_2(t) = -\underbrace{(\underline{A}^2)^T \underline{M}\, \underline{A}^1}\, \ddot{u}_g(t)$$

Zero due to the mass orthogonality property.

or $\underline{\underline{P_2(t) \simeq 0}}$

(Even if the ground motion contains energy at the 2nd mode frequency, it will not be transmitted into the structure.)

2nd mode 자체가 어떤 input에 대해서도 자극을 받지 않음

Energy absorption is however an important component of the behavior of an isolation system. In this simple model, energy dissipation is described by linear viscous damping.

How to select the modal damping ratios ξ_1 and ξ_2 ?

$$\xi_1 = \frac{(\underline{A}^1)^T \underline{c}\, \underline{A}^1}{2\omega_1 M_1} = \frac{\begin{bmatrix}1\\ \varepsilon\end{bmatrix}^T \begin{bmatrix}c_b & 0\\ 0 & c_s\end{bmatrix} \begin{bmatrix}1\\ \varepsilon\end{bmatrix}}{2\omega_1 (M+2m\varepsilon+m\varepsilon^2)}$$

$$= \frac{c_b + \cancel{c_s\varepsilon^2}}{2\omega_b\sqrt{1-\gamma\varepsilon}\,(M+2m\varepsilon\cancel{+m\varepsilon^2})}$$

$$\simeq \xi_b \times \left(1-\frac{3}{2}\gamma\varepsilon\right)$$

(Isolator의 변형과 상관되는 1차모드의 감쇠는 Isolator 자체의 감쇠비 ξ_b와 거의 동일) → Good news (why?)

Similarly,

$$\xi_2 \doteq \frac{\xi_s}{\sqrt{1-\gamma}} + \frac{\gamma\xi_b\sqrt{\varepsilon}}{\sqrt{1-\gamma}}$$

구조 변형과 관련되는 감쇠인 2차모드의 감쇠는 Isolation system의 감쇠에 $\sqrt{\varepsilon}$ 만큼이 곱해져서 더해지는데 ξ_s가 작을 경우 상당한 기여가 될 수 있다.

(Isolator의 높은 감쇠는 구조모드의 감쇠 증대에 크게 기여할 수 있다)

Good news also.

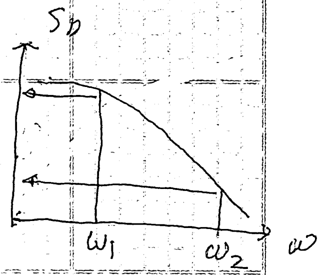
Knowing α_1, α_2, ξ_1 and ξ_2,

$$\left[\begin{array}{l} |u_1(t)|_{max} = \alpha_1 \times S_D(\omega_1, \xi_1) \\ |u_2(t)|_{max} = \alpha_2 \times S_D(\omega_2, \xi_2) \end{array}\right.$$

If SRSS combination is used,

$$|v_s(t)|_{max} = \sqrt{(A^1_2\, u_1(t)|_{max})^2 + (\quad)}$$

$$|v_b(t)|_{max} = \sqrt{(\quad)^2 + (\quad)^2}$$



$$\underline{A}^1 = \begin{bmatrix} 1 \\ \varepsilon \end{bmatrix}, \quad \underline{A}^2 = \begin{bmatrix} 1 \\ \{(1-\gamma)\varepsilon - 1\}/\gamma \end{bmatrix}$$

$$\alpha_1 = 1 - \gamma\varepsilon$$

$$\alpha_2 = \gamma\varepsilon$$

$$S_D(\omega_1) \gg S_D(\omega_2)$$

$$|v_b(t)|_{max} = \sqrt{(1-\gamma\varepsilon)^2\,[S_D(\omega_1, \xi_1)]^2 + \gamma^2 \underline{\underline{\varepsilon^2}}\,[S_D(\omega_2, \xi_2)]^2}$$

무시 가능

$$|v_s(t)|_{max} = \sqrt{\quad}$$

$$\therefore \quad |v_b(t)|_{max} \simeq (1-\gamma\varepsilon)\, S_D(\omega_1, \xi_1)$$

$$|v_s(t)|_{max} \simeq \varepsilon \sqrt{S_D(\omega_1, \xi_1)^2 + S_D(\omega_2, \xi_2)^2}$$

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Seismic Evaluation and Retrofit of Existing Buildings

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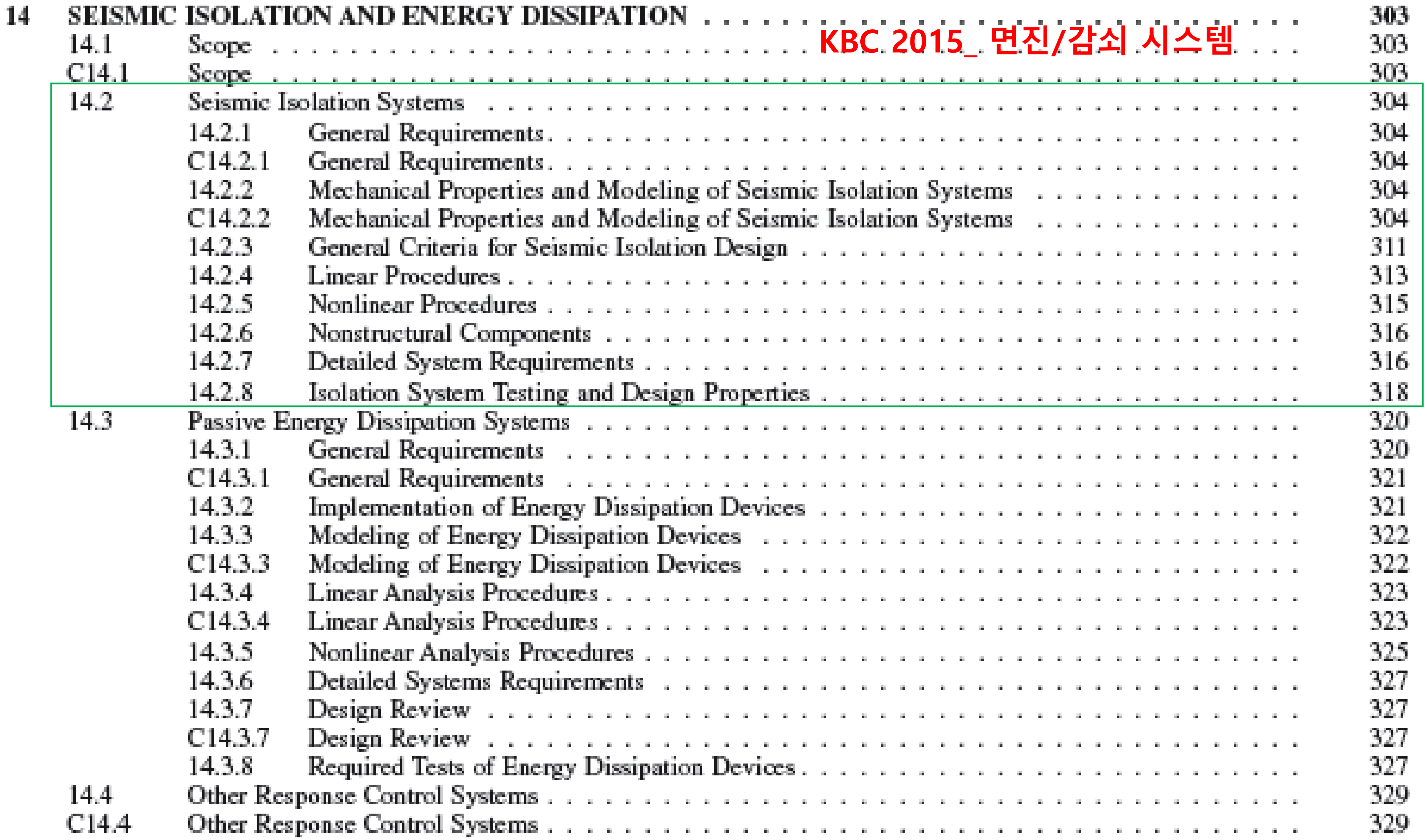


CHAPTER 14

SEISMIC ISOLATION AND ENERGY DISSIPATION

14.1 SCOPE

This chapter sets forth requirements for the systematic evaluation and retrofit of buildings using seismic isolation and energy dissipation systems. Section 14.2 provides analysis and design criteria for seismic isolation systems. Section 14.3 provides analysis and design criteria for passive energy dissipation systems. Section 14.4 provides criteria for other control systems. Any of the Performance Objectives are permitted for seismic isolation and passive energy dissipation retrofits.

Whenever either the Reduced Performance Objective of Section 2.2.3.1 or the Partial Retrofit Objective of Section 2.2.3.2 is selected, the devices must be able to achieve performance responses larger than those used for the Reduced Performance Objectives.

Components and elements in buildings with seismic isolation and passive energy dissipation systems shall also comply with the requirements of Chapters 1 through 13 of this standard, unless they are modified by the requirements of this chapter. Independent design review is required for all retrofit schemes that use either seismic isolation or energy dissipation systems.

C14.1 SCOPE

The basic form and formulation of requirements for seismic isolation and passive energy dissipation systems have been established and coordinated with the performance objectives, target Building Performance Levels, and Seismic Hazard Level criteria of Chapter 2 and the linear and nonlinear procedures of Chapter 7.

Criteria for modeling the stiffness, strength, and deformation properties of conventional structural components of buildings with seismic isolation or passive energy dissipation systems are given in Chapters 9 through 12.

Limited guidance for other special seismic protective systems, including active control systems, hybrid active and passive systems, and tuned mass and liquid dampers, is provided in this chapter. Seismic isolation and passive energy dissipation systems are viable design strategies that have been used for seismic retrofit 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 passive energy dissipation systems may not be appropriate design strategies for buildings that have only Limited Performance Objectives. In general, these systems are most applicable to the retrofit 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 passive energy dissipation devices. These costs are typically offset by the reduced need for stiffening and strengthening measures that would otherwise be required to meet Performance Objectives.

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

Conceptually, isolation reduces response of the superstructure by decoupling the building from the ground. Typical isolation systems reduce forces transmitted to the superstructure by lengthening the period of the building and adding some amount of damping.

Added damping is an inherent property of most isolators, but it may also be provided by supplemental passive energy dissipation devices installed across the isolation interface. Under favorable conditions, the isolation system can reduce drift in the superstructure by a factor of at least two—and sometimes by as much as a factor of five—from that which would occur if the building were not isolated. Accelerations are also reduced in the structure, although the amount of reduction depends on the force-deflection characteristics of the isolators and may not be as significant as the reduction of drift. Reduction of drift in the superstructure protects structural components and elements, as well as nonstructural components sensitive to drift-induced damage. Reduction of acceleration protects nonstructural components that are sensitive to acceleration-induced damage.

Passive energy dissipation devices add damping (and sometimes stiffness) to the building. A wide variety of passive energy dissipation devices are available, including viscous fluid dampers, viscoelastic materials, and hysteretic devices. Ideally, passive energy dissipation devices dampen earthquake excitation of the structure that would otherwise cause higher levels of response and damage to components of the building. Under favorable conditions, passive energy dissipation devices can reduce drift of the structure by a factor of up to three (if no stiffness is added) and by larger factors if the devices also add stiffness to the structure. Passive energy dissipation devices also reduce force in the structure—provided the structure is responding nearly elastically—but are not expected to significantly reduce force in structures that are responding beyond yield, resulting in structural damage.

Active control damping systems sense and resist building motion, either by applying an external force or by modifying structural properties of active components (e.g., so-called smart braces). Tuned mass or liquid dampers modify properties and add damping to key building modes of vibration. These systems can be complicated to model and analyze and require specialized knowledge and experience. Independent design review is necessary for the design and construction of these systems.

Special seismic systems, such as isolation or passive energy dissipation systems, should be considered early in the design process and should be based on the Performance Objectives established for the building. Whether a special seismic system is found to be the appropriate or optimum design strategy for building retrofit depends primarily on the target Building Performance Level required at the specified Seismic Hazard Level. In general, special protective seismic systems are found to be more attractive as a retrofit strategy for buildings that have higher performance objectives than for ordinary buildings (i.e., higher Building Performance Levels and/or more severe Seismic Hazard Levels).

The seismic response benefits generated from using an isolation retrofit typically are not very effective or economical for the lowest performance objectives. In general, isolation systems provide significant protection to the building structure, nonstructural components, and contents but at a cost that may not be the most feasible option where the budget and Performance Objectives are modest. The seismic response benefits generated from using energy dissipation retrofit can be effective and/or economical for the lowest Performance Objectives.

Passive energy dissipation systems have a wider range of building height applications than do isolation systems. For the tall buildings, passive energy dissipation systems should be considered as a prudent and potentially cost-effective design strategy where performance objectives include the Damage Control Structural Performance Level. Certain passive energy dissipation devices are quite economical and might be practical for retrofits that address only Limited Performance Objectives. In general, however, passive energy dissipation systems are more likely to be an appropriate design strategy where the desired performance objective is higher. Other criteria may also influence the decision to use passive energy dissipation devices, because these devices can also be useful for control of building response caused by wind or mechanical loads.

Whenever either the Reduced Performance Objective of Section 2.2.3.1 or the Partial Retrofit Objective of Section 2.2.3.2 is selected, the structural design requirements are less than those required for the potential seismic event. There is concern that response to this potential earthquake could exceed the design limits of the seismic isolation or passive energy dissipation devices, leading to device failure. Failure of these devices could result in catastrophic performance of the building. Therefore, the displacement design of these devices for these two lower Performance Objectives requires a conservative multiplier on the lower level multipliers or the use of a BSE-2E analysis to determine an appropriate device design displacement.

14.2 SEISMIC ISOLATION SYSTEMS

14.2.1 General Requirements Seismic isolation systems using seismic isolators, classified as either elastomeric or sliding, as defined in Section 14.2.2, shall comply with the requirements of Section 14.2. Properties of seismic isolation systems shall be based on Section 14.2.2. Seismic isolation systems shall be designed and analyzed in accordance with Section 14.2.3. Linear and nonlinear analyses shall be performed, as required by Section 14.2.3, in accordance with Sections 14.2.4 and 14.2.5, respectively. Nonstructural components shall be rehabilitated in accordance with Section 14.2.6. Additional requirements for seismic isolation systems as defined in Section 14.2.7 shall be met. Seismic isolation systems shall be tested in accordance with Section 14.2.8.

The seismic isolation system shall include wind-restraint and tie-down systems, if such systems are required by this standard. The isolation system also shall include 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.

For seismically isolated structures, the coefficients C_0, C_1, C_2, and J defined in Chapter 7, shall be taken as 1.0.

C14.2.1 General Requirements Analysis methods and design criteria for seismic isolation systems are based on criteria for the Performance Objectives of Chapter 2.

The methods described in this section augment the analysis requirements of Chapter 7. The analysis methods and other criteria of this section are based largely on FEMA P-750, *NEHRP Recommended Seismic Provisions for Regulations for New Buildings and Other Structures* (2009c).

Seismic isolation has typically been used as a retrofit strategy that enhances the performance of the building above that afforded by conventional stiffening and strengthening schemes. Seismic isolation retrofit projects have targeted performance at least equal to, and commonly exceeding, the Basic Performance Objective for Existing Buildings of this standard, effectively achieving a target Building Performance Level of Immediate Occupancy or better.

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.

14.2.2 Mechanical Properties and Modeling of Seismic Isolation Systems Seismic isolators shall be classified as either elastomeric or sliding. Elastomeric isolators shall include any one of the following: high-damping rubber bearings, low-damping rubber bearings, or low-damping rubber bearings with a lead core. Sliding isolators shall include flat assemblies or shall have a curved surface, such as the friction pendulum system. Rolling systems shall be characterized as a subset of sliding systems. Rolling isolators shall be flat assemblies or shall have a curved or conical surface, such as the ball and cone system. Isolators that cannot be classified as either elastomeric or sliding are not addressed in this standard.

C14.2.2 Mechanical Properties and Modeling of Seismic Isolation Systems 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 this standard). 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).

Elastomeric isolators are typically made of layers of rubber separated by steel shims.

14.2.2.1 General Design Properties Nominal design properties for each isolator size shall be established per Section 14.2.2.1.1 and upper and lower bound property variations shall be established per Section 14.2.2.1.2 through 14.2.2.1.4.

14.2.2.1.1 Nominal Design Properties Nominal design properties for each isolator size shall be established from either project-specific prototype test data or prior prototype tests on an isolator of similar size. These nominal design properties shall be modified by property variation or lambda (λ) factors to account for manufacturing tolerances, prototype test issues such as first-cycle effects and long-term environmental effects to develop upper- and lower-bound properties for the design and analysis of the isolated structure, as specified in Section 14.2.2.1.4.

C14.2.2.1.1 Nominal Design Properties In the early applications of base isolation technology, the design properties were obtained from prototype tests, which generally led to an extended design process. As the number of applications has increased, the prototype test data that are now available from manufacturers of the more widely used systems have increased significantly, and it is now possible to get reasonably accurate nominal design properties from the manufacturers. These nominal design properties can either be confirmed by prototype tests later in the design or construction phase of the project, or similarity may be used to accept the prototype tests on which the nominal properties are based. This enables the design process to proceed like a conventional project.

Results from testing of a small number of prototype isolators may not necessarily provide the best estimate of the nominal design properties and the associated upper- and lower-bound specification limits. This potential discrepancy occurs because a single test result may be at the upper or lower end of the range of a larger population.

14.2.2.1.2 Specification Tolerance on Nominal Design Properties Lambda factors shall be established ($\lambda_{spec,upper}$ and $\lambda_{spec,lower}$) for the permissible variation of the average of the manufacturing production test values from the nominal design value for each isolator size. This tolerance shall be the same as that used for the procurement of isolators for construction, and it is also used to establish the upper- and lower-bound properties of the isolators for use in the design and analysis process (Section 14.2.2.1.4).

C14.2.2.1.2 Specification Tolerance on Nominal Design Properties As part of the design process, it is important to recognize that there are variations in the nominal properties caused by manufacturing tolerances. This section specifies the lambda factors for the manufacturing process, and these are then used with the property modification factors in Section 14.2.2.1.3 to determine the upper- and lower-bound properties of the isolators in Section 14.2.2.1.4 for use in the design and analysis process.

Recommended values for the specification tolerance on the average properties of all isolators of a given size isolator are typically in the ±10% to ±15% range. For a ±10% specification tolerance, the corresponding lambda factors would be $\lambda_{spec,upper} =$ 1.10 and $\lambda_{spec,lower} = 0.90$. Variations in individual isolator properties may be greater than the tolerance on the average properties of all isolators of a given size, as discussed in Section 14.2.7.2.9. It is recommended that the isolator manufacturer be consulted when establishing these tolerance values.

The wider specification tolerance for individual isolators should be taken into account for isolator connection design by amplifying the upper-bound analysis forces by the ratio of the lambda factors, e.g., 1.15/1.10 for the example values here.

14.2.2.1.3 Property Variation (λ) Factors Property variation or lambda (λ) factors shall be established for each isolator type to account for both environmental and aging effects and prototype test properties such as first-cycle effects that are not accounted for in the nominal design values. Lambda (λ) factors for each significant effect shall be established that describe the expected variations above and below the nominal value (1.0) and shall be designated $\lambda_{effect,upper}$ and $\lambda_{effect,lower}$.

Upper-bound property modification factors, $\lambda_{upper,PM}$, shall be determined for each isolator type by computing the product of all the upper-bound lambda (λ) factors for environmental and testing effects to get $\lambda_{upper,PM}$, and similarly for all the lower-bound lambda (λ) factors to get $\lambda_{lower,PM}$.

The system property adjustment factor (SPAF) used to modify these values in Section 14.2.2.1.4 is 0.67 for all Performance Levels.

C14.2.2.1.3 Property Variation (λ) Factors Section 14.2.7.1 requires the isolation system to be designed with consideration given to other environmental conditions, including aging effects, creep, fatigue, and operating temperatures. Prototype tests may also indicate the need to address velocity effects, first-cycle effects, and other effects that cause the isolator test properties to vary from the nominal design properties. Lambda factors are not required for any behavior that can be directly accounted for in the analytical model of the isolator used in the analysis. This section provides the lambda factor methodology for addressing these potential variations in isolator properties from the nominal design properties. These variations are then included in the upper- and lower-bound isolator properties in Section 14.2.2.1.4.

Lambda factor values describe deviations in properties from unity. For example, if aging effects are expected to cause a 15% increase in isolator effective stiffness over the considered design life, then the corresponding lambda factor is 1.15.

For elastomeric isolators, lambda factors should address axial–shear interaction; bilateral deformation; load history, including first-cycle effects and the effects of scragging of virgin elastomeric isolators; temperature; and other environmental loads and aging effects over the design life of the isolator.

For sliding isolators, lambda factors should address contact pressure, rate of loading or velocity, bilateral deformation, temperature, contamination, and other environmental loads and aging effects over the design life of the isolator.

The system property adjustment factor (SPAF) was developed on the basis that a full and simultaneous increase in each parameter does not occur at the same time. This work originated with a report by Constantinou et al. (1999) that was then incorporated into the AASHTO *Guide Specifications for Seismic Isolation Design* (1999 and 2010) and was also included in the recommended AASHTO *LRFD Bridge Design Specifications* (2012).

14.2.2.1.4 Upper- and Lower-Bound Design and Analysis Properties Upper- and lower-bound design and analysis properties for each isolator size shall be determined for each modeling parameter as follows:

$$\begin{aligned}&\text{Upper-bound design property} =\\&\quad\text{Nominal design property}\\&\quad\times\{\lambda_{spec,upper}[1+\text{SPAF}(\lambda_{upper,PM}-1)]\}\end{aligned}\qquad(14\text{-}1a)$$

$$\begin{aligned}&\text{Upper-bound design property} > 1.3\\&\quad\times\text{Nominal design property}\end{aligned}\qquad(14\text{-}1b)$$

$$\begin{aligned}&\text{Lower-bound design property}\\&\quad=\text{Nominal design property}\\&\quad\times\{\lambda_{spec,lower}[1-(\text{SPAF}(1-\lambda_{lower,PM})]\end{aligned}\qquad(14\text{-}2a)$$

$$\begin{aligned}&\text{Lower-bound design property} < 0.85\\&\quad\times\text{Nominal design property}\end{aligned}\qquad(14\text{-}2b)$$

Table C14-1. Upper-Bound Multiplier Using AASHTO Lambda Factors

Variable	Unlubricated PTFE (μ)	Lubricated PTFE	Plain Elastomerics (K)	Lead Rubber (K2)
Aging (λ_a)	1.2	1.4	1.1	1.1
Velocity (λ_v)[a]	[b]	[b]	1	1
Contamination (λ_c)	1.1	1.1	1	1
Temperature (λ_t)	1.1	1.3	1.1	1.1
Scragging (λ_{scrag})[c]	1	1	1	1
Assumed lambda factor for first-cycle effect	1.10	1.10	1.10	1.10
Multiple of all lambda factors	1.60	2.20	1.33	1.33
Upper-bound with 0.67 SPAF	1.40	1.81	1.22	1.22
Lambda factor for specification tolerance	1.10	1.10	1.10	1.10
Upper-bound multiplier, including specification tolerance with 0.67 SPAF	1.54	1.99	1.34	1.34

[a] Sometimes first-cycle effect: Q_d for low-damping rubber bearings with a lead core.
[b] By test-design value.
[c] First-cycle effect for high-damping rubber bearings.

Upper-bound strength, stiffness, and energy dissipation shall be considered together as the upper-bound design and analysis case, and lower-bound strength, stiffness, and energy dissipation shall be considered together as the lower-bound design and analysis case. At a minimum, upper- and lower-bound properties shall be established for loads and displacements corresponding to each hazard level being evaluated.

C14.2.2.1.4 Upper- and Lower-Bound Design and Analysis Properties This section provides the methodology for combining both the specification tolerances and the environmental and prototype test property variation factors to obtain upper- and lower-bound design and analysis properties for each isolator size.

An upper- and lower-bound design and analysis property shall be established for each modeling parameter required for the selected method of analysis. For example, effective stiffness and damping are necessary for linear methods, and initial stiffness, postyield stiffness, and strength are necessary for nonlinear methods.

The AASHTO recommended lambda factors are acceptable for addressing the environmental and prototype testing effects, but other rational judgments by the licensed design professional may also be acceptable. A summary of results from using the AASHTO recommendations for the upper-bound properties is provided in Table C14-1 for a SPAF of 0.67, a first-cycle lambda factor of 1.1, and a specification tolerance of ±10%.

Temperature effects in bridge applications may be more severe than in typical building applications. In addition, some of the recommended factors in AASHTO (e.g., for the velocity effect on Q_d for lead rubber isolators or for the scragging effect for high damping rubber isolators) may be captured as first-cycle effects in prototype testing and should not be accounted for twice.

14.2.2.2 Mechanical Properties of Seismic Isolators

14.2.2.2.1 Elastomeric Isolators For mathematical modeling of isolators, mechanical characteristics based on analysis or available material test properties shall be permitted. For design, mechanical characteristics shall be based on tests of isolator prototypes in accordance with Section 14.2.8.

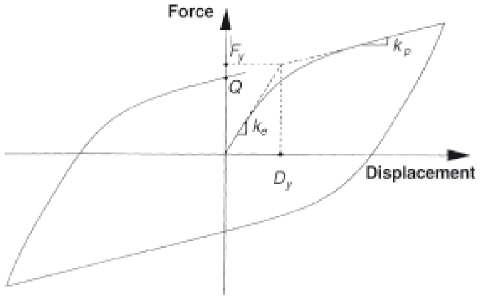


FIG. C14-1. Idealized Hysteretic Force–Displacement Relation of a Lead and Rubber Bearing

C14.2.2.2.1 Elastomeric Isolators Elastomeric bearings represent a common means for introducing flexibility into an isolated structure. They consist of thin layers of natural rubber that are vulcanized and bonded to steel plates. Natural rubber exhibits a complex mechanical behavior, which can be described simply as a combination of viscoelastic and hysteretic behavior. Low-damping natural rubber bearings exhibit essentially linearly elastic and linearly viscous behavior at large shear strains. The effective damping is typically less than 0.07 equivalent viscous damping for shear strains in the range of 0 to 2.0.

Leadrubber bearings are generally constructed of low-damping natural rubber with a preformed central hole into which a lead core is press fitted. Under lateral deformation, the lead core deforms in almost pure shear, yields at low levels of stress (approximately 8 to 10 MPa in shear at normal temperature), and produces hysteretic behavior that is stable over many cycles. Unlike mild steel, lead recrystallizes at normal temperature (about 20 °C), so that repeated yielding does not cause fatigue failure. Lead and rubber bearings generally exhibit characteristic strength that ensures rigidity under service loads. Fig. C14-1 shows an idealized force–displacement relation of a lead and rubber bearing. The characteristic strength, Q, is related to the lead plug area, A_p, and the shear yield stress of lead, σ_{YL}:

$$Q = A_p\sigma_{YL}\qquad(\text{C14-1})$$

The postyield stiffness, k_p, is typically higher than the shear stiffness of the bearing without the lead core:

$$k_p = \frac{A_r G f_L}{\sum t}\qquad(\text{C14-2})$$

where A_r = bonded rubber area;
Σt = total rubber thickness;
G = shear modulus of rubber (typically computed at shear strain of 0.5); and
f_L = a factor larger than unity.

Typically, f_L is 1.15, and the elastic stiffness ranges between 6.5 to 10 times the postyield stiffness.

The behavior of leadrubber bearings may be represented by a bilinear hysteretic model. Computer programs *3D-BASIS* (Nagarajaiah et al. 1991, Reinhorn et al. 1994, and Tsopelas et al. 1994), *ETABS* (CSI 2012a), and SAP2000 (CSI 2012b)

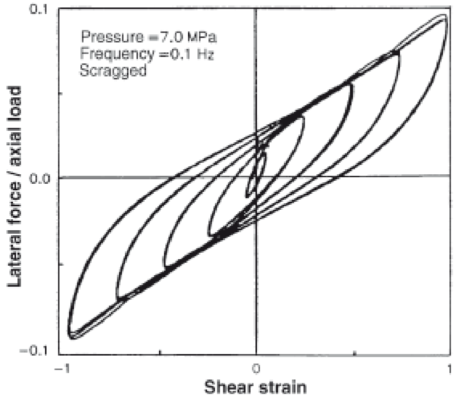


FIG. C14-2. Force–Displacement Loops of a High-Damping Rubber Bearing

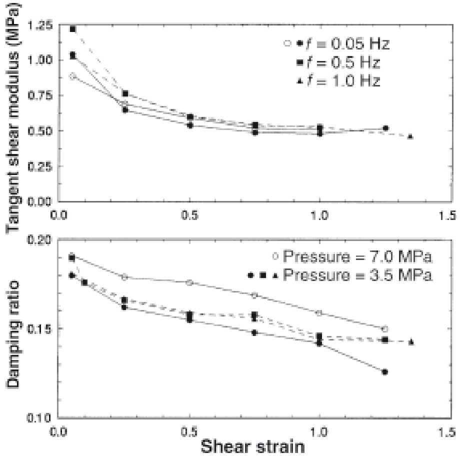


FIG. C14-3. Tangent Shear Modulus and Effective Damping Ratio of High-Damping Rubber Bearing

have the capability of modeling hysteretic behavior for isolators. These models typically require definition of three parameters, namely, the postyield stiffness k_p, the yield force F_y, and the yield displacement D_y. For leadrubber bearings in which the elastic stiffness is approximately equal to 6.5 k_p, the yield displacement can be estimated as

$$D_y = \frac{Q}{5.5k_p} \tag{C14-3}$$

The yield force is then given by

$$F_y = Q + k_p D_y \tag{C14-4}$$

High-damping rubber bearings are made of specially compounded rubber that exhibits effective damping between 0.10 and 0.20 of critical. The increase in effective damping of high-damping rubber is achieved by the addition of chemical compounds that may also affect other mechanical properties of rubber. Fig. C14-2 shows representative force–displacement loops of a high-damping rubber bearing under scragged conditions.

Scragging is the process of subjecting an elastomeric bearing to one or more cycles of large-amplitude displacement. The scragging process modifies the molecular structure of the elastomer and results in more stable hysteresis at strain levels lower than that to which the elastomer was scragged. Although it is usually assumed that the scragged properties of an elastomer remain unchanged with time, studies by Cho and Retamal (1993) and Murota et al. (1994) suggest that partial recovery of unscragged properties is likely. The extent of this recovery is dependent on the elastomer compound.

Mathematical models capable of describing the transition between virgin and scragged properties of high-damping rubber bearings are not yet available. It is appropriate in this case to perform multiple analyses with stable hysteretic models and to obtain bounds on the dynamic response. A smooth, bilinear hysteretic model that is capable of modeling the behavior depicted in Fig. C14-1 is appropriate for such analyses, as long as the peak shear strain is below the stiffening limit of approximately 1.5 to 2.0, depending on the rubber compound. Beyond this strain limit, many elastomers exhibit stiffening behavior, with tangent stiffness approximately equal to twice the tangent stiffness before initiation of stiffening. For additional information, refer to Tsopelas and Constantinou (1994).

To illustrate the calculations of parameters from test data on prototype bearings, Fig. C14-3 shows experimentally determined properties of the high-damping rubber bearings, for which loops are shown in Fig. C14-2. The properties identified are the tangent shear modulus, G, and the effective damping ratio, β_{eff} (described by Eq. C14-18), which is now defined for a single bearing (rather than the entire isolation system), under scragged conditions. With reference to Fig. C14-1, G is related to the postyielding stiffness k_p.

$$k_p = \frac{GA}{\Sigma t} \tag{C14-5}$$

where A is the bonded rubber area. The results of Fig. C14-3 demonstrate that the tangent shear modulus and equivalent damping ratio are only marginally affected by the frequency of loading and the bearing pressure, within the indicated range for the tested elastomer. Different conclusions may be drawn from the testing of other high-damping rubber compounds.

The parameters of the bilinear hysteretic model may be determined by use of the mechanical properties G and β_{eff} at a specific shear strain, such as the strain corresponding to the design displacement D. The postyield stiffness k_p is determined from Eq. (C14-5), whereas the characteristic strength, Q, can be determined as

$$Q = \frac{\pi\beta_{\mathrm{eff}} k_p D^2}{(2-\pi\beta_{\mathrm{eff}})D - 2D_y} \tag{C14-6}$$

where D_y is the yield displacement. The yield displacement is generally not known a priori. However, experimental data suggest that D_y is approximately equal to 0.05 to 0.1 times the total rubber thickness, Σt. With the yield displacement approximately determined, the model can be completely defined by

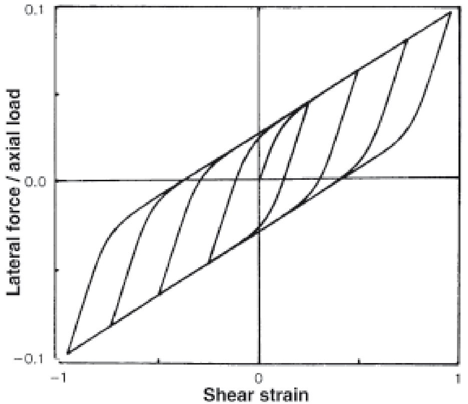


FIG. C14-4. Analytical Force–Displacement Loops of High-Damping Rubber Bearing

determining the yield force (Eq. C14-4). It should be noted that the characteristic strength may be alternatively determined from the effective stiffness, k_{eff} (Eq. C14-17), of the bearing, as follows:

$$Q = \frac{\pi\beta_{\mathrm{eff}} k_{\mathrm{eff}} D^2}{2(D - D_y)} \tag{C14-7}$$

The effective stiffness is a more readily determined property than the postyielding stiffness. The effective stiffness is commonly used to obtain the effective shear modulus, G_{eff}, defined as

$$G_{\mathrm{eff}} = \frac{k_{\mathrm{eff}} \Sigma t}{A} \tag{C14-8}$$

The behavior of the bearing for which the force–displacement loops are shown in Fig. C14-2 is now analytically constructed using the mechanical properties at a shear strain of 1.0 and a bearing pressure of 7.0 MPa. These properties are $G_{\mathrm{eff}} = 0.50$ MPa and $\beta_{\mathrm{eff}} = 0.16$. With the bonded area and total thickness of rubber known, and assuming $D_y = 0.1\Sigma t$, a bilinear hysteretic model was defined and implemented in the program *3D-BASIS*. The simulated loops are shown in Fig. C14-4, where it may be observed that the calculated hysteresis loop at shear strain of 1.0 agrees well with the corresponding experimental hysteresis loop. However, at lower peak shear strain, the analytical loops have a constant characteristic strength, whereas the experimental loops have a characteristic strength dependent on the shear strain amplitude. Nevertheless, the analytical model is likely to produce acceptable results where the design parameters are based on the mechanical properties at a strain corresponding to the design displacement.

Elastomeric bearings have finite vertical stiffness that affects the vertical response of the isolated structure. The vertical stiffness of an elastomeric bearing may be obtained from

$$k_v = \frac{E_c A}{\Sigma t} \tag{C14-9}$$

where E_c is the compression modulus. Although a number of approximate empirical relations have been proposed for the calculation of the compression modulus, the correct expression for circular bearings is the following:

$$E_c = \left(\frac{1}{6G_{\mathrm{eff}}S^2} + \frac{4}{3K}\right)^{-1} \tag{C14-10}$$

where K is the bulk modulus (typically assumed to have a value of 2,000 MPa) and S is the shape factor, which is defined as the ratio of the loaded area to the perimeter area of a single rubber layer (Kelly 1993). For a circular bearing of bonded diameter ϕ and rubber layer thickness t, the shape factor is given by

$$S = \frac{\phi}{4t} \tag{C14-11}$$

Seismic elastomeric bearings are generally designed with a large shape factor, typically 12 to 20. Considering an elastomeric bearing design with $S = 15$, $G_{\mathrm{eff}} = 1$ MPa, and $K = 2{,}000$ MPa, the ratio of vertical stiffness (Eq. C14-9) to effective horizontal stiffness (Eq. C14-8) is approximately equal to 700. Thus, the vertical period of vibration of a structure on elastomeric isolation bearings is about 26 times (i.e., $\sqrt{700}$) less than the horizontal period, on the order of 0.1 s. This value of vertical period provides potential for amplification of the vertical ground acceleration by the isolation system. The primary effect of this amplification is to change the vertical load on the bearings, which may need to be considered for certain design applications.

Another consideration in the design of seismically isolated structures with elastomeric bearings is reduction in height of a bearing with increasing lateral deformation (Kelly 1993). Whereas this reduction of height is typically small, it may be important where elastomeric bearings are combined with other isolation components that are vertically rigid (such as sliding bearings). In addition, incompatibilities in vertical displacements may lead to a redistribution of loads.

14.2.2.2.2 Sliding Isolators Mechanical characteristics for use in mathematical models shall be based on analysis and available material test properties. Verification of isolator properties used for design shall be based on tests of isolator prototypes, in accordance with Section 14.2.8.

C14.2.2.2.2 Sliding Isolators Sliding bearings limit the transmission of force to an isolated structure to a predetermined level. Although this limit is desirable, the lack of significant restoring force can result in significant variations in the peak displacement response and can result in permanent offset displacements. To avoid these undesirable features, sliding bearings are typically used in combination with a restoring force mechanism.

The lateral force developed in a sliding bearing can be defined as

$$F = \frac{N}{R}D + \mu_s N \operatorname{sgn}(\dot{D}) \tag{C14-12}$$

where D = displacement;
$\dot{D}$ = sliding velocity;
R = radius of curvature of sliding surface;
μ_s = coefficient of sliding friction;
N = normal load on the bearing; and
$\operatorname{sgn}(\dot{D})$ = sign of sliding velocity vector; +1 or −1.

The normal load consists of the gravity load, W, the effect of vertical ground acceleration, $\ddot{D}_v$, and the additional seismic force caused by overturning moment, P_s:

$$N = W\left(1 + \frac{\ddot{D}_v}{g} + \frac{P_s}{W}\right) \tag{C14-13}$$

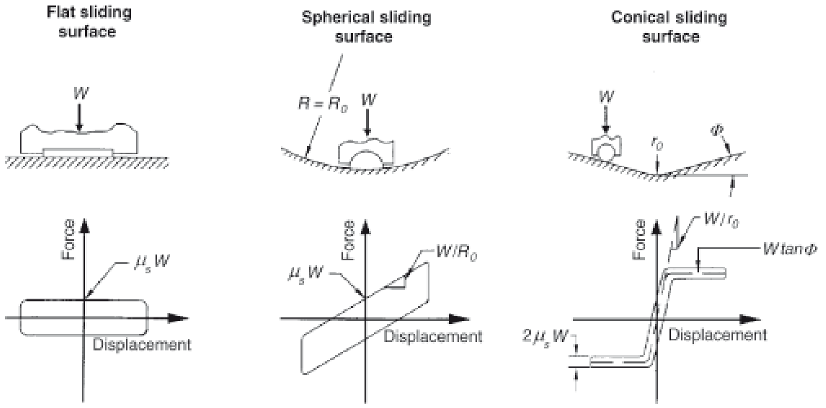


FIG. C14-5. Idealized Force–Displacement Loops of Sliding Bearings

The first term in Eq. (C14-13) denotes the restoring force component, and the second term describes the friction force. For flat sliding bearings, the radius of curvature is infinite, so the restoring force term in Eq. (C14-13) vanishes. For a spherical sliding surface (Zayas et al. 1987), the radius of curvature is constant, so the bearing exhibits a linear restoring force; that is, under constant gravity load the stiffness is equal to W/R_o, where R_o is the radius of the spherical sliding surface. Where the sliding surface takes a conical shape, the restoring force is constant. Fig. C14-5 shows idealized force–displacement loops of sliding bearings with flat, spherical, and conical surfaces.

Sliding bearings with either a flat or single curvature spherical sliding surface are typically made of polytetrafluoroethylene (PTFE) or PTFE-based composites in contact with polished stainless steel. The shape of the sliding surface allows large contact areas that, depending on the materials used, are loaded to average bearing pressures in the range of 7 to 70 MPa. For interfaces with shapes other than flat or spherical, the load needs to be transferred through a bearing, as illustrated in Fig. C14-5 for the conical sliding surface. Such an arrangement typically results in a very low coefficient of friction.

For bearings with large contact area, and in the absence of liquid lubricants, the coefficient of friction depends on several parameters, of which the three most important are the composition of the sliding interface, bearing pressure, and velocity of sliding. For interfaces composed of polished stainless steel in contact with PTFE or PTFE-based composites, the coefficient of sliding friction may be described by

$$\mu_s = f_{max} - (f_{max} - f_{min})\exp\left(-a\left|\dot{U}\right|\right) \qquad \text{(C14-14)}$$

where parameters f_{min} and f_{max} describe the coefficient of friction at small and large velocities of sliding and under constant pressure, respectively, all as depicted in Fig. C14-6. Parameters f_{max}, f_{min}, and a depend on the bearing pressure, although only the dependency of f_{max} on pressure is of practical significance.

A good approximation to the experimental data (Constantinou et al. 1993) is

$$f_{max} = f_{maxo} - (f_{maxo} - f_{maxp})\tanh \varepsilon p \qquad \text{(C14-15)}$$

where the physical significance of parameters f_{maxo} and f_{maxp} is as illustrated in Fig. C14-6. The term p is the instantaneous bearing pressure, which is equal to the normal load N computed by Eq. (C14-13), divided by the contact area; and ε is a parameter that controls the variation of f_{max} with pressure.

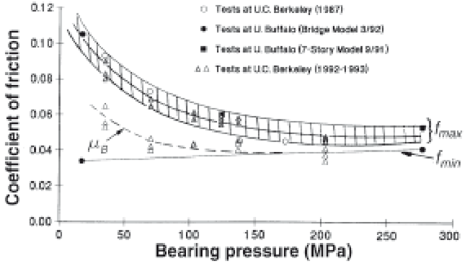


FIG. C14-6. Coefficient of Friction of PTFE-Based Composite in Contact with Polished Stainless Steel at Normal Temperature

Fig. C14-6 illustrates another feature of sliding bearings. On initiation of motion, the coefficient of friction exhibits a static or breakaway value, μ_B, which is typically higher than the minimum value f_{min}. To demonstrate frictional properties, Fig. C14-6 shows the relation between bearing pressure and the friction coefficients f_{max}, μ_B, and f_{min} of a PTFE-based composite material in contact with polished stainless steel at normal temperature. These data were compiled from testing of bearings in four different testing programs (Soong and Constantinou 1994).

Combined elastomeric and sliding isolation systems have been used in buildings in the United States. Japanese engineers have also used elastomeric bearings in combination with mild steel components that are designed to yield in strong earthquakes and enhance the energy dissipation capability of the isolation system (Kelly 1988). These mild steel components exhibit either elastoplastic behavior or bilinear hysteretic behavior with low postyielding stiffness. Moreover, fluid viscous energy dissipation devices have been used in combination with elastomeric bearings. The behavior of fluid viscous devices is described in Section 14.3.3.2.3.

Hybrid seismic isolation systems composed of elastomeric and sliding bearings should be modeled taking into account the likely significant differences in the relationships between vertical displacement as a function of horizontal displacement. The use of elastomeric and sliding isolators close to one another under vertically stiff structural framing elements (e.g., reinforced concrete shear walls) may be problematic and could result in significant redistributions of gravity loads.

14.2.2.3 Modeling of Isolators

14.2.2.3.1 General The upper- and lower-bound values of stiffness and damping defined in Section 14.2.2.1.4 shall be used in multiple analyses of the model to determine the range and sensitivity of response to design parameters.

14.2.2.3.2 Linear Models The restoring force, F, of an isolator shall be calculated as the product of effective stiffness, k_{eff}, and response displacement, D:

$$F = k_{eff}D \qquad \text{(14-3)}$$

The effective stiffness, k_{eff}, of an isolator shall be calculated from test data using Eq. (14-17). The area enclosed by the force–displacement hysteresis loop shall be used to calculate the effective damping, β_{eff}, of an isolator using Eq. (14-18). Effective stiffness and effective damping shall be evaluated at all response displacements of design interest.

C14.2.2.3.2 Linear Models Linear procedures use effective stiffness, k_{eff}, and effective damping, β_{eff}, to characterize nonlinear properties of isolators.

For linear procedures (see FEMA 274, Section C14.2.3 [FEMA 1997b]), the seismic isolation system can be represented by an equivalent linearly elastic model. The force in a seismic isolation device is calculated as

$$F = k_{eff}D \qquad \text{(C14-16)}$$

where all terms are as defined in Section 14.2.2.3.2 of this standard. The effective stiffness of the seismic isolation device may be calculated from test data as follows:

$$k_{eff} = \frac{\left|F^+\right| + \left|F^-\right|}{\left|\Delta^+\right| + \left|\Delta^-\right|} \qquad \text{(C14-17)}$$

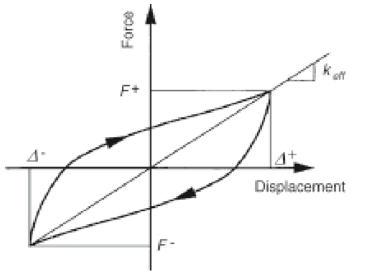
Fig. C14-7 illustrates the physical significance of the effective stiffness.

Analysis by a linear method requires that either each seismic isolator or groups of seismic isolators be represented by linear springs of either stiffness, k_{eff}, or the combined effective stiffness of each group. The energy dissipation capability of an isolation system is generally represented by effective damping. Effective damping is amplitude dependent and calculated at each displacement amplitude, as follows:

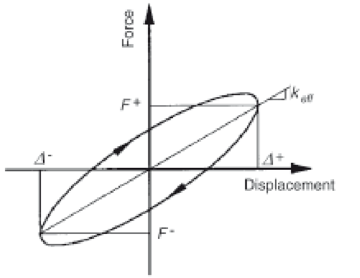
$$\beta_{eff} = \frac{1}{2\pi}\left(\frac{\Sigma E_D}{k_{eff}D^2}\right) \qquad \text{(C14-18)}$$

where ΣE is the sum of the areas of the hysteresis loops of all isolators, and k_{eff} is the sum of the effective stiffnesses of all seismic isolation devices.

The application of Eq. (C14-16) through Eq. (C14-18) to the design of isolation systems is complicated if the effective stiffness and loop area depend on axial load. Multiple analyses are then required to establish bounds on the properties and response of the isolators. For example, sliding isolation systems exhibit such dependencies as described in Section C14.2.2.2.2. To account for these effects, the following procedure is proposed.



Hysteretic behavior



Viscoelastic behavior

FIG. C14-7. Definition of Effective Stiffness of Seismic Isolation Devices

1. In sliding isolation systems, the relation between horizontal force and vertical load is substantially linear (see Eq. [C14-16]). Accordingly, the net effect of overturning moment on the mechanical behavior of a group of bearings is small and can be neglected.

   Al-Hussaini et al. (1994) provided experimental results that demonstrate this behavior up to the point of imminent bearing uplift. Similar results are likely for elastomeric bearings.
2. The effect of vertical ground acceleration is to modify the load on the isolators. If it is assumed that the building is rigid in the vertical direction, and axial forces caused by overturning moments are absent, the axial loads can vary between $W\left(1-\ddot{U}/g\right)$ and $W\left(1+\ddot{U}/g\right)$, where $\ddot{U}$ is the peak vertical ground acceleration. However, recognizing that horizontal and vertical ground motion components are likely not correlated unless in the near field, it is appropriate to use a combination rule that uses only a fraction of the peak vertical ground acceleration. Based on the use of 50% of the peak vertical ground acceleration, maximum and minimum axial loads on a given isolator may be defined as

   $$N_C = W(1 \pm 0.20S_{XS}) \qquad \text{(C14-19)}$$

   where the plus sign gives the maximum value and the minus sign gives the minimum value. Equation (C14-19) is based on the assumption that the short-period spectral response parameter, S_{XS}, is 2.5 times the peak value of the vertical ground acceleration. For analysis for the maximum considered earthquake, the axial load should be determined from

$$N_C = W(1 \pm 0.20 S_{MS}) \tag{C14-20}$$

Eqs. (C14-19) and (C14-20) should be used with caution if the building is located in the near field of a major active fault. In this instance, expert advice should be sought regarding correlation of horizontal and vertical ground motion components.

Load N_C represents a constant load on isolators, which can be used for determining the effective stiffness and area of the hysteresis loop. To obtain these properties, the characteristic strength Q (see Fig. C14-7) is needed. For sliding isolators, Q can be taken as equal to $f_{max}N_C$, where f_{max} is determined at the bearing pressure corresponding to load N_C. For example, for a sliding bearing with spherical sliding surface of radius R_0 (see Fig. C14-5), the effective stiffness and area of the loop at the design displacement D are

$$k_{eff} = \left(\frac{1}{R_0} + \frac{f_{max}}{D}\right) N_C \tag{C14-21}$$

$$\text{Loop area} = 4 f_{max} N_C D \tag{C14-22}$$

14.2.2.3.3 Nonlinear Models The nonlinear upper- and lower-bound force-deflection properties of isolators shall be explicitly modeled if nonlinear analysis procedures are used.

The inelastic (hysteretic) model of the isolators shall represent damping in the devices. Additional viscous damping shall not be included in the model of the isolators unless it is supported by rate-dependent tests of isolators. Viscous damping in the structural modes shall be separately considered.

C14.2.2.3.3 Nonlinear Models For dynamic nonlinear time-history analysis, the seismic isolation components should be explicitly modeled. FEMA 274, in Sections C14.2.2.2 through C14.2.2.4 (FEMA 1997b), presents relevant information. Where uncertainties exist and where aspects of behavior cannot be modeled, multiple analyses should be performed with appropriate lambda factors, as described in Section 14.2.2.1.3.

Inherent damping in isolated structures must be considered separately for the isolated and superstructure modes. For example, whereas a value of 5% may be appropriate for the superstructure, a value of 2% or less may be appropriate for the isolated modes. This issue may be further complicated where coupled isolated and superstructure modes occur.

For simplified nonlinear analysis, each seismic isolation component can be modeled by an appropriate rate-independent hysteretic model. Elastomeric bearings may be modeled as bilinear hysteretic components, as described in FEMA 274, Section C14.2.2.2 (1997b). Sliding bearings may also be modeled as bilinear hysteretic components with characteristic strength (see Fig. C14-5), given by

$$Q = f_{max} N_C \tag{C14-23}$$

where N_C is determined by either Eq. (C14-19) or Eq. (C14-20), and f_{max} is the coefficient of sliding friction at the appropriate sliding velocity. The postyield stiffness can then be determined as

$$k_p = \frac{N_C}{R} \tag{C14-24}$$

where R is as defined in FEMA 274, Section C14.2.2.2.B (1997b). The yield displacement D_y in a bilinear hysteretic model of a sliding bearing should be very small, perhaps on the order of 2 mm. Alternatively, a bilinear hysteretic model for sliding bearings may be defined to have an elastic stiffness that is at least 100 times larger than the postyield stiffness, k_p.

Isolation devices that exhibit viscoelastic behavior as shown in Fig. C14-7 should be modeled as linearly elastic components with effective stiffness k_{eff}, as determined by Eq. (C14-21).

14.2.2.4 Isolation System and Superstructure Modeling

14.2.2.4.1 General Mathematical models of the isolated building, including the isolation system, the seismic-force-resisting system of the superstructure, other structural components and elements, and connections between the isolation system and the structure, shall meet the requirements of Chapter 7 and Sections 14.2.2.4.2 and 14.2.2.4.3.

14.2.2.4.2 Isolation System Model The isolation system shall be modeled using upper- and lower-bound deformation characteristics developed and verified by test in accordance with the requirements of Section 14.2.2.1.4.

The isolation system shall 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 and/or 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 caused by P-delta moments; and
6. Account for nonlinear components. Isolation systems with nonlinear components include systems that do not meet the criteria of Section 14.2.3.3.1, Item 2.

14.2.2.4.3 Superstructure Model The maximum displacement of each floor, the total design displacement, and the total maximum displacement across the isolation system shall be calculated using a model of the isolated building that incorporates the force–deformation characteristics of nonlinear components.

Calculation of design forces and displacements in primary components of the seismic-force-resisting system using linearly elastic models of the isolated structure above the isolation system shall be permitted if both of the following criteria are met:

1. Pseudo-elastic properties assumed for nonlinear isolation system components are based on the upper-bound effective stiffness of the isolation system; and
2. The seismic-force-resisting system remains linearly elastic for the earthquake demand level of interest.

A seismic-force-resisting system that meets both of the following criteria may be classified as linearly elastic:

1. For all deformation-controlled actions, Eq. (7-36) is satisfied using an m-factor equal to the lesser of the following: those specified for the component or Performance Level, 1.5 for the Immediate Occupancy and Life Safety Performance Level and 2.0 for the Collapse Prevention Performance Level; and
2. For all force-controlled actions, Eq. (7-37) is satisfied.

14.2.3 General Criteria for Seismic Isolation Design

14.2.3.1 General The design, analysis, and testing of the isolation system shall be based on the requirements of this section.

C14.2.3.1 General Criteria for the seismic isolation of buildings are divided into two sections:

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

14.2.3.1.1 Stability of the Isolation System The stability of the vertical-load-carrying components of the isolation system shall be verified by analysis and test, as required by Section 14.2.8, for a lateral displacement equal to the total maximum displacement computed in accordance with Section 14.2.4.3.5 or Section 14.2.5.1.2, or for the maximum displacement allowed by displacement-restraint devices, if such devices are part of the isolation system.

14.2.3.1.2 Configuration Requirements The isolated building shall be classified as regular or irregular, as defined in Section 7.3.1.1, based on the structural configuration of the structure above the isolation system.

14.2.3.2 Seismic Hazard Criteria Seismic hazard criteria for the design earthquake, BSE-1X, and the maximum considered earthquake, BSE-2X, shall be established in accordance with Section 2.4 as modified by this section. The design Seismic Hazard Level shall be user specified and shall be permitted to be chosen equal to the BSE-1E or BSE-1N Seismic Hazard Level. The maximum considered earthquake, BSE-2X, shall be taken equal to the BSE-2E or the BSE-2N Seismic Hazard Level, depending on whether the BSE-1E or BSE-1N, respectively, is chosen for the design earthquake.

14.2.3.2.1 User-Specified Design Earthquake: BSE-1X For the design earthquake, BSE-1X, the following seismic hazard criteria shall be established:

1. Short-period spectral response acceleration parameter, S_{XS}, and spectral response acceleration parameter at 1.0 s, S_{X1}, in accordance with Section 2.4.1 or 2.4.2;
2. Five-percent-damped response spectrum of the design earthquake (where a response spectrum is required for linear procedures by Section 14.2.3.3.2, or to define ground motion acceleration histories); and
3. Ground motion acceleration histories compatible with the design earthquake spectrum, as specified in Section 2.4.2.2 (where ground motion acceleration histories are required for nonlinear procedures by Section 14.2.3.3.3).

14.2.3.2.2 Maximum Considered Earthquake: BSE-2X For the maximum considered earthquake, BSE-2X, the following seismic hazard criteria shall be established:

1. Short-period spectral response acceleration parameter, S_{XS}, and spectral response acceleration parameter at 1 s, S_{X1}, in accordance with Section 2.4.1 or 2.4.2;
2. Five-percent-damped site-specific response spectrum of the BSE-2E or BSE-2N (where a response spectrum is required for linear procedures by Section 14.2.3.3.2, or to define ground motion acceleration histories); and
3. Ground motion acceleration histories compatible with the BSE-2E or BSE-2N spectrum, as specified in Section 2.4.2.2 (where ground motion acceleration histories are required for nonlinear procedures by Section 14.2.3.3.3).

14.2.3.3 Selection of Analysis Procedure A linear or nonlinear analysis procedure in Sections 14.2.3.3.1 through 14.2.3.3.3 shall be used.

C14.2.3.3 Selection of Analysis Procedure Linear static and linear response spectrum procedures include prescriptive formulas and response spectrum analysis. Linear procedures based on formulas (similar to the seismic-coefficient equation required for design of fixed-base buildings) prescribe peak lateral displacement of the isolation system and define minimum design criteria that may be used for design of a limited class of isolated structures (without confirmatory dynamic analyses). These simple formulas are useful for preliminary design and provide a means of expeditious review of more complex calculations.

Response spectrum analysis is recommended for design of isolated structures that have either (1) a tall or otherwise flexible superstructure or (2) an irregular superstructure. For most buildings, response spectrum analysis does not predict significantly different displacements of the isolation system than those calculated by prescriptive formulas, provided that both calculations are based on the same effective stiffness and damping properties of the isolation system. The real benefit of response spectrum analysis is not in the prediction of isolation system response but, rather, in the calculation and distribution of forces in the superstructure. Response spectrum analysis permits the use of more detailed models of the superstructure that better estimate forces and deformations of components and elements considering flexibility and irregularity of the structural system.

Nonlinear procedures include the nonlinear static procedure (NSP) and the nonlinear dynamic procedure (NDP). The NSP is a static pushover procedure, and the NDP is based on nonlinear time-history analysis. The NSP or the NDP is required for isolated structures that do not have essentially linearly elastic superstructures (during BSE-2X demand). In this case, the superstructure would be modeled with nonlinear components.

Time-history analysis is required for isolated structures on very soft soil (i.e., Soil Profile Type E where shaking is strong, or Soil Profile Type F) that could shake the building with a large number of cycles of long-period motion, and for buildings with isolation systems that are best characterized by nonlinear models. Such isolation systems include the following:

1. Systems with more than about 30% effective damping (because high levels of damping can significantly affect higher mode response of the superstructure);
2. Systems that lack significant restoring force (because these systems may not stay centered during earthquake shaking);
3. Systems that are expected to exceed the sway-space clearance with adjacent structures (because impact with adjacent structures could impose large demands on the superstructure); and
4. Systems that are rate or load dependent (because their properties vary during earthquake shaking).

For the types of isolation systems described above, appropriate nonlinear properties must be used to model isolators. Linear properties could be used to model the superstructure, provided that the superstructure's response is essentially linearly elastic for BSE-2X demand.

The restrictions placed on the use of linear procedures effectively suggest that nonlinear procedures should be used for virtually all isolated buildings. However, lower-bound limits on isolation system design displacement and force are specified by this standard as a percentage of the demand prescribed by the linear formulas, even where dynamic analysis is used as the basis for design. These lower-bound limits on key design attributes ensure consistency in the design of isolated structures and serve as a "safety net" against gross underdesign.

14.2.3.3.1 Linear Procedures Linear static and linear response spectrum procedures shall be permitted 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 $S1 \le 0.6$ for BSE-2X;
2. The isolation system meets all of the following criteria:
   - 2.1. 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;
   - 2.2. The isolation system is capable of producing a restoring force as specified in Section 14.2.7.2.4;
   - 2.3. Where considering analysis procedures, for the BSE-2X, the isolation system does not limit BSE-2X displacement to less than the ratio of the design spectral response acceleration at 1 s (S_{X1}) for the BSE-2X to that for the design earthquake times the total design displacement; and
3. The structure above the isolation system exhibits linear elastic behavior for the earthquake motions under consideration.

14.2.3.3.2 Response Spectrum Analysis Response spectrum analysis shall be used for design of seismically isolated buildings that meet any of the following criteria:

1. The building is more than 65 ft (19.8 m) in height above the isolation plane;
2. The effective period of the structure, T, is greater than 3 s, when evaluated for nominal isolator properties corresponding to BSE-2X demands;
3. The effective period of the isolated structure, T, is less than or equal to three times the elastic, fixed-base period of the structure above the isolation system when evaluated for nominal isolator properties corresponding to BSE-1X demands; or
4. The structure above the isolation plane is irregular in configuration as defined in Section 7.3.1.1.

14.2.3.3.3 Nonlinear Procedures Nonlinear static or response history analysis procedures shall be used for design of seismic-isolated buildings for which either of the following conditions apply:

1. The structure above the isolation plane cannot be classified linearly elastic as defined in Section 14.2.2.4.3 for the earthquake motions under consideration; and
2. The isolation system does not meet all of the criteria of Section 14.2.3.3.1.

Nonlinear acceleration response history analysis shall be performed for the design of seismically isolated buildings when both conditions (1) and (2) apply.

14.2.4 Linear Procedures

14.2.4.1 General Seismically isolated buildings for which linear analysis procedures are selected based on the criteria of Section 14.2.3.3 shall be designed and constructed to resist the earthquake displacements and forces specified in this section, at a minimum.

14.2.4.2 Deformation Characteristics of the Isolation System The deformation characteristics of the isolation system shall be based on upper- and lower-bound properties as defined in Section 14.2.2.1.4.

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

14.2.4.3 Minimum Lateral Displacements Isolation system displacements shall be checked at the BSE-1X and BSE-2X hazard levels using the following formula and the lower-bound isolator properties established in Section 14.2.2.1.4. If a Limited Performance Objective (LPO) is selected and a BSE-2X analysis is not performed, then the maximum displacements shall be 200% of the calculated BSE-1X displacement.

14.2.4.3.1 Design Displacement The isolation system shall be designed and constructed to withstand, as a minimum, lateral earthquake displacements, D_D, that act in the direction of each of the main horizontal axes of the structure in accordance with Eq. (14-4):

$$D_D = \left(\frac{g}{4\pi^2}\right)\frac{S_{X1}T_D}{B_{D1}} \tag{14-4}$$

where S_{X1} is evaluated for the BSE-1X;

T_D = the effective period, in seconds, of the seismic-isolated structure at the design displacement in the direction under consideration;

B_{D1} = a numerical damping coefficient equalt to the value of B_1 per Section 2.4.1.7.1 at the value β_D; and

β_D = Isolation system equivalent viscous damping at the displacement for the hazard level under consideration, determined separately for upper- and lower-bound properties

14.2.4.3.2 Effective Period at the Design Displacement The effective period, T_D, of the isolated building at the design displacement for the BSE-1X hazard shall be determined using the lower-bound deformation characteristics of the isolation system in accordance with Eq. (14-5):

$$T_D = 2\pi\sqrt{\frac{W}{K_D g}} \tag{14-5}$$

where W = effective seismic weight; and
K_D is effective stiffness of the isolation system at the design displacement in the horizontal direction under consideration.

14.2.4.3.3 Maximum Displacement The maximum displacement of the isolation system, D_M, in the most critical direction of horizontal response shall be calculated in accordance with Eq. (14-6), unless governed by Section 14.2.4.3.

$$D_M = \left(\frac{g}{4\pi^2}\right)\frac{S_{X1}T_M}{B_{M1}} \tag{14-6}$$

where S_{X1} is evaluated for the BSE-2X;

T_M = the effective period, in seconds, of the seismic-isolated structure at the design displacement in the direction under consideration;

B_{M1} = a numerical damping coefficient equalt to the value of B_1 per Section 2.4.1.7.1 at the value β_M; and

β_M = Isolation system equivalent viscous damping at the displacement for the hazard level under consideration, determined separately for upper- and lower-bound properties.

14.2.4.3.4 Effective Period at the Maximum Displacement The effective period, T_M, of the isolated building at the maximum displacement for the BSE-2X event shall be determined using the lower-bound deformation characteristics of the isolation system in accordance with Eq. (14-7):

$$T_M = 2\pi\sqrt{\frac{W}{K_M g}} \tag{14-7}$$

where W = effective seismic weight; and
K_M is effective stiffness of the isolation system at the design displacement in the horizontal direction under consideration.

14.2.4.3.5 Total Displacement The total design displacement, D_{TD}, and the total maximum displacement, D_{TM}, of components of the isolation system shall include additional displacement caused by 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 shall be taken as not less than that prescribed by Eqs. (14-8) and (14-9):

$$D_{TD} = D_D\left(1 + y\frac{12e}{b^2 + d^2}\right) \tag{14-8}$$

$$D_{TM} = D_M\left(1 + y\frac{12e}{b^2 + d^2}\right) \tag{14-9}$$

where y = the distance 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;

e = actual eccentricity 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 taken as 5% of the maximum building dimension perpendicular to the direction of force under consideration;

d = the longest plan dimension of the building;

b = the shortest plan dimension of the building, measured perpendicular to d;

D_D = the design displacement, at the center of rigidity of the isolation system in the direction under consideration per Eq. (14-4); and

D_M = the maximum displacement at the center of rigidity of the isolation system in the direction under consideration per Eq. (14-6).

A value for the total maximum displacement, D_{TM}, less than the value prescribed by Eq. (14-9), but not less than 1.1 times D_M, shall be permitted, provided the NDP or NSP analysis method is used.

14.2.4.4 Minimum Lateral Seismic Forces

14.2.4.4.1 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 at or below the isolation system shall be designed and constructed to withstand a minimum lateral seismic force, V_b, using the upper-bound properties of the isolation system and BSE-1X as prescribed by Eq. (14-10):

$$V_b = K_{UB}D_D \tag{14-10}$$

14.2.4.4.2 Structural Components and Elements Above the Isolation System The components and elements above the isolation system shall be designed and constructed to resist a minimum lateral seismic force equal to the maximum value of V_b, prescribed by Eq. (14-10).

14.2.4.4.3 Limits on V_b The value of V_b shall be taken as not less than the following:

1. The base shear corresponding to the design wind load; and
2. The lateral seismic force required to fully activate the isolation system factored by 1.5 when considering nominal isolator properties, or factored by 1.0 when considering upper-bound properties.

C14.2.4.4.3 Limits on V_b Examples of lateral seismic forces required to fully activate the isolation system include the yield level of a softening system, the ultimate capacity of a sacrificial wind-restraint system, or the breakaway friction level of a sliding system.

14.2.4.4.4 Vertical Distribution of Force The level immediately above the isolation plane is defined as the isolation base level. The lateral seismic force apportioned to the superstructure above the isolation base level, V_{st}, shall be determined in accordance with Eq. (14-11):

$$V_{st} = V_b\left(\frac{W_s}{W}\right)^{(1-2.2\beta_D)} \tag{14-11}$$

where W_s = effective seismic weight of the structure above the isolation base level (kip or kN).

The shear force V_b shall be distributed over the height of the structure above the isolation interface in accordance with the following equations:

At the isolation base level, the force shall be

$$F_1 = V_b - V_{st} \tag{14-12}$$

For the superstructure above the isolation base level, the forces shall be

$$F_x = \frac{V_{st}w_x h_x^{k_{DI}}}{\sum_{i=1}^{n} w_i h_i^{k_{DI}}} \tag{14-13}$$

The inertia force distribution exponent shall be

$$k_{DI} = 14\beta_D T_S \le 4 \tag{14-14}$$

where V_{st} = Total lateral seismic design force or shear on elements above the isolation base level as prescribed by Eq. (14-11);

W_x = Portion of W that is located at or assigned to level i, n, or x, respectively;

h_x = Height above the isolation base level i, n, or x, respectively;

w_i = Portion of W that is located at or assigned to level i, n, or x, respectively;

At each level designated as x, the force F_i or F_x shall 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 shall be calculated as the effect of the force F_x applied at the appropriate levels above the base.

C14.2.4.4.4 Vertical Distribution of Force In previous provisions, the vertical distribution included the weight of the slab level directly above the isolators when proportioning story forces. In this section, the vertical distribution of forces calculates the force at the base level immediately above the isolation plane then distributes the remainder of the base shear among the levels above based on York and Ryan (2008). The vertical distribution of forces is based on the effective damping and superstructure period and aligns more closely with distributions found by a nonlinear response history analysis of a representative set of isolated buildings.

14.2.4.5 Response Spectrum Analysis

14.2.4.5.1 Earthquake Input The BSE-1X spectrum shall be used to calculate the total design displacement of the isolation system and the seismic forces and displacements of the isolated building. The BSE-2X spectrum shall be used to calculate the total maximum displacement of the isolation system, unless an LPO is selected. The analyses shall be performed for both upper- and lower-bound isolator properties.

14.2.4.5.2 Modal Damping Response spectrum analysis shall 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 shall be consistent with the value required for fixed-base analysis of the same structure. Separate modal damping ratios shall be computed for analyses performed using upper- and lower-bound isolator properties.

14.2.4.5.3 Combination of Earthquake Directions Response spectrum analysis used to determine the total design displacement and total maximum displacement shall 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 shall be calculated as the vector sum of the two orthogonal displacements.

14.2.4.5.4 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 Eq. (14-8), or if the total maximum displacement determined by response spectrum analysis is found to be less than the value of D_{TM} prescribed by Eq. (14-9), then all response parameters, including component actions and deformations, shall be adjusted by the greater of the following:

1. D_{TD} / displacement determined by response spectrum analysis for BSE-1X, or
2. D_{TM} / displacement determined by response spectrum analysis for BSE-2X.

The shear at any story shall not be less than that resulting from the application of the story forces calculated using Section 14.2.4.4.4 and a value of V_s equal to the base shear obtained from the response spectrum analysis in the direction of interest.

14.2.4.6 Design Forces and Deformations Components and elements of the building shall be designed for forces and displacements estimated by linear procedures using the acceptance criteria of Section 7.5.2.2, using appropriate m-values as specified in Chapters 8 through 12. For all deformation-controlled actions, Eq. (7-36) is satisfied using an m-factor equal to the lesser of the following: those specified for the component at the selected Performance Level or 1.5 for the Immediate Occupancy or Life Safety Performance Levels and 2.0 for the Collapse Prevention Performance Level.

Components and elements shall be separately checked for the demands corresponding to analyses performed with upper- and lower-bound isolator properties.

14.2.5 Nonlinear Procedures Seismically isolated buildings evaluated using nonlinear procedures shall be represented by three-dimensional models that incorporate the nonlinear characteristics of both the isolation system and the structure above the isolation system.

14.2.5.1 Nonlinear Static Procedure

14.2.5.1.1 General The nonlinear static procedure (NSP) for seismically isolated buildings shall be based on the criteria of Section 7.4.3, except that the target displacement and pattern of applied seismic forces shall be based on the criteria given in Sections 14.2.5.1.2 and 14.2.5.1.3, respectively.

14.2.5.1.2 Target Displacement In each principal direction, the building model shall be pushed to the BSE-1X target displacement, D'_D, and to the BSE-2X target displacement, D'_M, as defined by Eqs. (14-15) and (14-16):

$$D'_D = \frac{D_D}{\sqrt{1+\left(\frac{T_e}{T_D}\right)^2}} \qquad (14\text{-}15)$$

$$D'_M = \frac{D_M}{\sqrt{1+\left(\frac{T_e}{T_M}\right)^2}} \qquad (14\text{-}16)$$

where T_e is the effective period of the structure above the isolation interface on a fixed base, as prescribed by Eq. (7-27). The target displacements, D'_D and D'_M, shall be evaluated at a control node that is located at the center of mass of the first floor above the isolation interface.

14.2.5.1.3 Seismic Force Pattern The pattern of applied seismic forces shall be as required by Section 14.2.4.4.4.

14.2.5.1.4 Design Forces and Deformations Components and elements of the building shall be designed for the forces and deformations estimated by nonlinear procedures and using the acceptance criteria of Section 7.5.3.2.

14.2.5.2 Nonlinear Dynamic Procedure

14.2.5.2.1 General The nonlinear dynamic procedure (NDP) for seismically isolated buildings shall be based on the nonlinear procedure requirements of Section 7.4.4, except that results shall be scaled for design based on the criteria given in the following section.

14.2.5.2.2 Scaling of Results If the design displacement determined by nonlinear response history analysis is less than 80% of the D'_D value prescribed by Eq. (14-15), or if the maximum displacement determined by response spectrum analysis is found to be less than 80% of the value of D'_M prescribed by Eq. (14-16), then all response parameters, including component actions and deformations, shall be adjusted by the greater of the following:

1. $0.80D'_D$ / displacement determined by time-history analysis for BSE-1X, or
2. $0.80D'_M$ / displacement determined by time-history analysis for BSE-2X.

Table C14-2. Analysis Cases for Evaluation of Effect of Accidental Eccentricity

Case	Isolator Properties	Accidental Eccentricity
I	Lower bound	No
IIa	Lower bound	Yes, X direction
IIb	Lower bound	Yes, Y direction

14.2.5.3 Torsion In lieu of performing analyses with mass shifted along each principal axis in turn to account for accidental eccentricity, it is permitted to establish amplification factors on forces, drifts, and deformations that allow results determined using a center-of-mass analysis to bound the results of all the mass-eccentric cases.

A mass eccentricity of not less than 2% is acceptable for use in all seismically isolated structures for which an NDP analysis is performed.

C14.2.5.3 Torsion To avoid the need to perform a large number of nonlinear response history analyses that include the suites of ground motion acceleration histories for both BSE-1X and BSE-2X events, the upper and lower isolator properties, and five or more locations of the center of mass, this change has been made so that the center of mass results can be scaled and used to account for the mass eccentricity in different quadrants.

The following procedure is one acceptable method of developing appropriate amplification factors for deformations and forces for use with center-of-mass NDP analyses, to account for the effects of accidental torsion. The use of other rationally based amplification factors is permitted.

The most critical directions for moving the calculated center of mass are such that the accidental eccentricity adds to the inherent eccentricity in each principal direction at each level. For each of these two eccentric mass cases, and with lower-bound isolator properties, the suite of nonlinear response history analyses should be run, and the results should be processed. The analysis cases are defined in Table C14-2.

The results from Cases IIa and IIb are then compared with those from Case I. The following amplification factors (ratio of Case IIa or IIb response to Case I response) are computed:

1. The amplification of story drift in the structure at the plan location with the highest drift, enveloped over all stories.
2. The amplification of frame-line shear forces at each story for the frame subjected to the maximum drift.

The larger of the two resulting scalars on drift should be used as the deformation amplifier, and the larger of the two resulting scalars on force should be used as the force amplifier. If both of these scalars are less than 1.1, the effects of accidental torsion need not be considered. If either scalar is greater than or equal to 1.1, the effects of accidental eccentricity should be considered as follows: NDP analyses for the inherent mass eccentricity case should be run, considering the variation of isolator properties. Response quantities should be computed per Section 7.2.3. For each isolator property variation, all deformation response quantities should be increased by the deformation amplifier and all force quantities should be increased by the force amplifier, before being used for evaluation or design.

14.2.5.4 Design Forces and Deformations Components and elements of the building shall be designed for the forces and deformations estimated by nonlinear procedures using the acceptance criteria of Section 7.5.3.2.

14.2.6 Nonstructural Components

14.2.6.1 General Permanent nonstructural components and the attachments to them shall be designed to resist seismic forces and displacements as given in this section and the applicable requirements of Chapter 13.

14.2.6.2 Forces and Displacements

14.2.6.2.1 Components and Elements at or Above the Isolation Interface Nonstructural components, or portions thereof, that are at or above the isolation interface shall be designed to resist a total lateral seismic force equal to the maximum dynamic response of the element or component under consideration.

> **EXCEPTION:** Design of elements of seismically isolated structures and nonstructural components, or portions thereof, to resist the total lateral seismic force as required for conventional fixed-base buildings by Chapter 13 shall be permitted.

14.2.6.2.2 Components and Elements that Cross the Isolation Interface Nonstructural components, or portions thereof, that cross the isolation interface shall 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 shall not restrict displacement of the isolated building or otherwise compromise the Performance Objectives of the building.

14.2.6.2.3 Components and Elements Below the Isolation Interface Nonstructural components, or portions thereof, that are below the isolation interface shall be designed and constructed in accordance with the requirements of Chapter 13.

14.2.7 Detailed System Requirements The isolation system and the structural system shall comply with the detailed system requirements specified in Section 14.2.7.1, 14.2.7.2, and 14.2.7.3.

14.2.7.1 Design Review A review of the design of a structure with an isolation system and related test programs shall be performed by an independent engineer (or engineers) experienced in design and analysis of structures incorporating isolation systems, in accordance with the requirements of Section 1.5.10.

As a minimum, the following items shall be included in the design review:

1. Project design criteria;
2. Device selection;
3. Preliminary design, including the determination of the structure lateral displacements and the isolation system displacement and force demands;
4. Review of a prototype testing program to be conducted in accordance with Section 14.2.8.2, or of the basis for use of data from similar isolators;
5. Final design of the building, incorporating the isolation system and the supporting analyses; and
6. Review of the manufacturing quality control testing program.

C14.2.7.1 Design Review In the early applications of isolation, many design review panels included three individuals to cover the range of expertise required in the design review, including the site-specific seismic and other criteria and witnessing prototype testing of the devices. Design review may now be performed by just one individual. On more significant structures, a local jurisdiction may require a design review panel with two or three individuals, but for many structures incorporating an isolation system, one well qualified and experienced design reviewer is adequate.

Review of the seismic and other dynamic input is still required because this review should be a part of the project design criteria. Whereas review of the prototype test program is mandated, the design reviewer is no longer required to witness the prototype tests.

14.2.7.2 Isolation System

14.2.7.2.1 Environmental Conditions In addition to the requirements for vertical loads and lateral forces induced by wind and earthquake, the isolation system shall be designed with consideration given to other environmental conditions, including aging effects, creep, fatigue, operating temperature, and exposure to moisture or damaging substances. Design for isolator property variation is addressed in Section 14.2.2.1.3.

14.2.7.2.2 Wind Forces Isolated buildings shall 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 shall 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.

14.2.7.2.3 Fire Resistance Fire resistance rating for the isolation system shall be consistent with the requirements of columns, walls, or other such components of the building.

14.2.7.2.4 Lateral Restoring Force The isolation system shall be configured to produce either a restoring force such that the seismic force at the total design displacement is at least $0.025W$ greater than the seismic 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 that 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 $36S_{X1}$ in., where S_{X1} is calculated for the BSE-2X or where NDP is used.

14.2.7.2.5 Displacement Restraint Configuration of the isolation system to include a displacement restraint that limits lateral displacement caused by the BSE-2X to less than the ratio of the design spectral response acceleration parameter at 1 s (S_{X1}) for the BSE-2X to that for the design earthquake times the total design displacement shall be permitted, provided that the seismically isolated building is designed in accordance with the following criteria where they are more stringent than the requirements of Section 14.2.3:

1. BSE-2X response is calculated in accordance with the dynamic analysis requirements of Section 14.2.5, 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, shall exceed the force and displacement demands of the BSE-2X;
3. The structure above the isolation system is checked for stability and ductility demand of the BSE-2X; and
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.

14.2.7.2.6 Vertical Load Stability Each component of the isolation system shall 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 force on an individual isolator unit, Q_E, shall be based on peak building response caused by the BSE-2X. The maximum vertical loads and maximum displacements may be the envelope of the upper- and lower-bound results, or the upper- and lower-bound results may be treated separately, in which case two vertical load stability tests shall be required.

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

Local uplift of individual components and elements shall be permitted, provided that the resulting deflections do not cause overstress or instability of the isolator units or other building components and elements. A tie-down system to limit local uplift of individual components and elements shall be permitted, provided that the seismically isolated building is designed in accordance with the following criteria where they are more stringent than the requirements of Section 14.2.3:

1. BSE-2X response is calculated in accordance with the dynamic analysis requirements of Section 14.2.5, 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 exceeds the force and displacement demands of the BSE-2X; and
3. The isolation system is designed and shown by test to be stable per Section 14.2.8.2.4 for BSE-2X loads that include additional vertical load because of the tie-down system.

C14.2.7.2.7 Overturning As noted in Section 14.2.4.3, whenever a Limited Performance Objective is selected, the displacement design requirements for the devices are 200% of the BSE-1X values.

For example, if the selected performance objective is Immediate Occupancy in the BSE-1X earthquake, then the isolation system must accommodate 200% of the BSE-1X displacement demands ($2D_{TD}$). Similar requirements have not been defined for isolator axial load and uplift displacement demands because a simple scalar could not be readily established.

If the registered design professional believes that axial loads and/or uplift displacements may be significantly higher at the BSE-2X than those observed at the BSE-1X, then it is recommended that the BSE-2X system performance be investigated to characterize and design for these demands.

14.2.7.2.8 Inspection and Replacement Access for inspection and replacement of all components and elements of the isolation system shall be provided.

14.2.7.2.9 Manufacturing Quality Control A manufacturing quality control testing program for isolator units shall be established by the registered design professional. At a minimum, this testing program shall confirm the adequacy of isolator component material properties and evaluate the acceptability of results from a specified sample of tested isolator units. The test results shall be verified to fall within the acceptable range described in the project specifications. These limits shall be the same as the specification tolerances on nominal design properties established in Section 14.2.2.1.2.

C14.2.7.2.9 Manufacturing Quality Control The registered design professional must define in the project specifications the scope of the manufacturing quality control test program, as well as allowable variations in the measured properties of the production isolation units. Typically, 100% of the isolators of a given size are tested in combined compression and shear, and the allowable variation of the mean test result shall be within the specified tolerance of Section 14.2.2.1.2 (typically ±10% or ±15% from the nominal design properties). Individual isolators may be permitted a wider variation (±15% or ±20%) when all isolators of a given size are tested. If less than 100% of the isolators of a given size are tested, then each isolator shall meet the specified tolerance of Section 14.2.2.1.2.

For example, the mean of the effective stiffness for all tested isolators might be permitted to vary no more than ±10% from the specified value, but the effective stiffness for any individual isolator may be permitted to vary no more than ±15% from the specified value. The registered design professional must decide on the acceptable range of variation of isolator properties on a project-by-project basis.

Another aspect of the quality control test program that must be established by the registered design professional is the number of production isolation units that must be tested. This number can range from a small sample (recommended to be at least 20%) of the total number of isolation units produced to 100% of the isolator produced. Typical practice has been to perform quality control testing on all isolators, but there is no codified requirement to do so. Factors that may figure into a decision on the proportion of production isolators to test include the complexity of the isolator or test, expected variations in material properties, and the experience of the manufacturer in producing the specified type and size of isolator.

The most important class of testing to be performed in a quality control program is combined compression and shear testing. This test reveals the most relevant characteristics of the completed isolator and permits the designer to verify that the production isolators provide load-deflection behavior that is consistent with the structural design assumptions. Although vertical load-deflection tests have historically been specified in quality control testing programs, these test data are typically of limited value. Consideration should be given to the overall cost and schedule effects of performing multiple types of quality control tests, and only those tests that are directly relevant to verifying the design properties of the isolators should be specified.

The quality control program should also include testing of isolator component materials in a similar fashion to other construction materials for the project. The objective of this material testing is to ensure consistency throughout the entire run of production isolators for the project with a previously tested prototype isolator. The registered design professional should coordinate with the isolator manufacturer to establish the details of the material testing program.

14.2.7.3 Structural System

14.2.7.3.1 Horizontal Distribution of Force A horizontal diaphragm or other structural components and elements shall provide continuity above the isolation interface. The diaphragm or other structural components and elements shall have adequate strength and ductility to transmit forces (because of nonuniform ground motion) calculated in accordance with this section from one part of the building to another and shall have sufficient stiffness to effect rigid diaphragm response above the isolation interface.

14.2.7.3.2 Building Separations Separations between the isolated building and surrounding retaining walls or other fixed obstructions shall be not less than the total maximum displacement or 200% of the total design displacement if a Limited Performance Objective has been selected.

14.2.8 Isolation System Testing and Design Properties

14.2.8.1 General The deformation characteristics and damping values of the isolation system used in the design and analysis of seismically isolated structures shall be based on the following tests of prototype samples of the isolator devices before construction.

The isolation system components to be tested shall include isolators, 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 nominal design properties of the isolation system and shall not be considered as satisfying the manufacturing quality control testing requirements of Section 14.2.7.2.9.

14.2.8.2 Prototype Tests

14.2.8.2.1 General Prototype tests shall be performed separately on two full-sized specimens of each type and size of isolator of the isolation system. The test specimens shall include components of the wind-restraint system, as well as individual isolators, if such components are used in the design. Supplemental energy dissipation devices shall be tested in accordance with Section 14.3.8. Specimens tested shall not be used for construction unless approved by the registered design professional responsible for the structural design.

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

14.2.8.2.3 Sequence and Cycles The following sequence of tests shall 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: $0.25D_D$, $0.50D_D$, $1.0D_D$, from the BSE-1X level and $1.0D_M$; from the BSE-2X level;
3. Three fully reversed cycles at the total maximum displacement, $1.0D_{TM}$; from the BSE-2X level; and
4. $30S_{X1} / (S_{XS}B_{D1})$, but not less than 10, fully reversed cycles of loading at the design displacement, $1.0D_D$. S_{X1} and S_{XS} shall be evaluated for the BSE-1X level.

14.2.8.2.4 Vertical Load-Carrying Isolators If an isolator is also a vertical-load-carrying component, then Item 2 of the sequence of cyclic tests specified in Section 14.2.8.2.3 shall be performed for two additional vertical load cases:

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

where D, L, and E refer to dead, live, and earthquake loads, respectively. Q_D and Q_L are as defined in Section 7.2.2. The vertical test load on an individual isolator unit shall include the load increment Q_E caused by earthquake overturning and shall 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 shall be taken as the typical or average downward force on all isolators of a common type and size.

The maximum vertical loads and maximum displacements shall be the envelope of those determined from separate analyses using upper- and lower-bound isolator properties. Alternatively, it is acceptable to perform multiple tests for the combinations of vertical load and horizontal displacement obtained from the upper- and lower-bound isolator property analyses.

14.2.8.2.5 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 Sections 14.2.8.2.3 and 14.2.8.2.4 shall be performed dynamically at a frequency equal to the inverse of the effective period, T_D, of the isolated structure. Alternatively, lambda (λ) factors for velocity effects may be established using data from testing of similar isolators in accordance with Section 14.2.2.1.3.

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

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

14.2.8.2.6 Isolators Dependent on Bilateral Load If the force-deflection properties of the isolators are dependent on bilateral load, then the tests specified in Sections 14.2.8.2.3 and 14.2.8.2.4 shall 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. Alternatively, lambda (λ) factors for bilateral effects may be established using data from testing of similar isolators in accordance with Section 14.2.2.1.3.

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

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

14.2.8.2.7 Maximum and Minimum Vertical Load Isolators that carry vertical load shall be statically tested for the maximum and minimum vertical load at the total maximum displacement. In these tests, the combined vertical loads of $1.2Q_D + 1.0Q_L + |Q_E|$ shall be taken as the maximum vertical force, and the combined vertical load of $0.8Q_D - |Q_E|$ shall 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, shall be based on peak building response caused by the BSE-2X.

The maximum vertical loads and maximum displacements shall be the envelope of those determined from separate analyses using upper- and lower-bound isolator properties. Alternatively, it is acceptable to perform multiple tests for the combinations of vertical load and horizontal displacement obtained from the upper- and lower-bound isolator property analyses.

14.2.8.2.8 Sacrificial Wind-Restraint Systems If a sacrificial wind-restraint system is part of the isolation system, then the ultimate capacity shall be established by testing in accordance with this section.

14.2.8.2.9 Testing Similar Units Prototype tests need not be performed if an isolator unit, where compared with another tested unit, complies with the following criteria:

1. It is of similar dimensional characteristics;
2. It is of the same type and materials; and
3. It is fabricated using identical manufacturing and quality control procedures.

The testing exemption shall be approved by the independent design reviewer specified in Section 14.2.7.1.

C14.2.8.2.9 Testing Similar Units Suggested limits for dimensional similarity are ±20% for overall dimensions and key characteristic dimensions. The previously tested unit should have been subjected to test forces and displacements that result in at least the same or more severe demand than anticipated for the project prototype isolators.

14.2.8.3 Determination of Force-Deflection Characteristics The force-deflection characteristics of the isolation system shall be based on the cyclic load testing of isolator prototypes specified in Section 14.2.8.2.3.

As required, the effective stiffness of an isolator unit, k_{eff}, shall be calculated for each cycle of deformation by Eq. (14-17):

$$k_{\text{eff}} = \frac{|F^+| + |F^-|}{|\Delta^+| + |\Delta^-|} \tag{14-17}$$

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}, shall be calculated for each cycle of deformation by Eq. (14-18):

$$\beta_{\text{eff}} = \frac{2}{\pi}\left(\frac{E_{\text{Loop}}}{k_{\text{eff}}\left(|\Delta^+| + |\Delta^-|\right)^2}\right) \tag{14-18}$$

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

14.2.8.4 System Adequacy The performance of the test specimens shall be assessed as adequate if the following conditions are satisfied:

1. The force-deflection plots of all tests specified in Section 14.2.8.2 have a nonnegative incremental force-carrying capacity.
2. For each increment of test displacement specified in Section 14.2.8.2.3, Item 2, and for each vertical load case specified in Section 14.2.8.2.4, the following criteria are met:
    - 2.1. There is no greater than a ±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; and
    - 2.2. 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 ±20% change in the initial effective stiffness of each test specimen over the $30S_{X1} / S_{XS}B_{D1}$, but not less than 10, cycles of the test specified in Section 14.2.8.2.3, Item 3. S_{X1} and S_{XS} shall be evaluated for the BSE-1X event.
4. For each specimen, there is no greater than a 20% decrease in the initial effective damping over the $30S_{X1}/S_{XS}B_{D1}$, but not less than 10, cycles of the test specified in Section 14.2.8.2.3, Item 4. S_{X1} and S_{XS} shall be evaluated for the BSE-1X event.
5. All specimens of vertical-load-carrying components of the isolation system remain stable at the total maximum displacement for static load as prescribed in Section 14.2.8.2.4.
6. The effective stiffness and effective damping of test specimens fall within the limits specified by the registered design professional as described by the lambda factors (λ) in Section 14.2.2.1.2.

14.2.8.5 Nominal Properties of the Isolation System

14.2.8.5.1 Isolator Effective Stiffness The nominal effective stiffness of the isolation system shall be based on the average properties from the three-cycle tests of Section 14.2.8.2 at each displacement level. If isolator properties are dependent on axial load, they may be averaged across the three test axial loads. Lambda factors shall be established, as appropriate, to account for variations from the nominal average properties for use in Section 14.2.2.1.3.

The forces corresponding to these effective stiffnesses shall be used to establish a nominal backbone curve for each isolator type for use in the NSP.

The ratio of the maximum and minimum isolator effective stiffness over each cycle to the average over three cycles shall be used to establish λ_{cyclic} factors as required in Section 14.2.2.1.3.

$$K_D = \frac{\sum|F_D^+| + \sum|F_D^-|}{2D_D} \tag{14-19}$$

$$K_M = \frac{\sum|F_M^+| + \sum|F_M^-|}{2D_M} \tag{14-20}$$

C14.2.8.5.1 Isolator Effective Stiffness These testing provisions imply that lambda factors for cyclic variation can be established using the results of the three cycle tests specified in Section 14.2.8.2.3. As an alternative to the use of lambda factors, cyclic variation of isolator properties may be captured directly in the analysis.

If the registered design professional believes that the isolation system may be subjected to a long duration of shaking, it may be appropriate to consider property variation over a larger number of cycles.

14.2.8.5.2 Effective Damping At both the BSE-1X and BSE-2X displacements, the nominal effective damping of the isolation system, β, shall be based on the cyclic tests of Section 14.2.8.2 and shall be calculated by Eqs. (14-21) and (14-22):

$$\beta_D = \frac{1}{2\pi}\left(\frac{\sum E_D}{K_D D_D^2}\right) \tag{14-21}$$

$$\beta_M = \frac{1}{2\pi}\left(\frac{\sum E_M}{K_M D_M^2}\right) \tag{14-22}$$

In Eqs. (14-21) and (14-22), the total energy dissipated in the isolation system per displacement cycle, ΣE, shall be taken as the sum of the average energy dissipated per cycle in all isolators measured at test displacements, Δ^+ and Δ^-, that are three cycle tests equal in magnitude to the design displacement under consideration for the BSE-1X and BSE-2X event. Lambda factors shall be developed to account for variations from the nominal average properties.

14.2.8.5.3 Isolator Nominal Design Properties for Analysis When nonlinear analysis is used, similar methods to those described above shall be used to compute the relevant modeling parameters for each isolator type, such as isolator initial and postyield stiffness and isolator strength. The selected modeling parameters shall result in reasonable agreement between the shape of the nominal and test hysteresis loop for each isolator type. The selected modeling parameters shall be applicable over the expected range of displacements, or separate properties shall be developed in accordance with Sections 14.2.2.1.3 and 14.2.2.1.4. The isolation system effective stiffness and damping shall be developed separately corresponding to upper- and lower-bound isolator modeling parameters.

14.3 PASSIVE ENERGY DISSIPATION SYSTEMS

14.3.1 General Requirements Passive energy dissipation systems classified as displacement dependent, velocity dependent, or other, as defined in Section 14.3.3, shall comply with the requirements of Section 14.3. Linear and nonlinear analyses shall be performed, as required, in accordance with Section 14.3.4 and 14.3.5, respectively. Additional requirements for passive energy dissipation systems, as defined in Section 14.3.6, shall be met. Passive energy dissipation systems shall be reviewed and tested in accordance with Sections 14.3.7 and 14.3.8, respectively.

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

For voluntary seismic upgrades, a Limited Performance Objective (LPO) of Life Safety at BSE-1X is permitted. However, the damping devices shall have reserve capacity beyond the BSE-1X demands. If an LPO is adopted, each story shall have at least four energy dissipation devices in each principal direction of the building, with at least two devices located on each side of the center of stiffness of the story in the direction under consideration.

The mathematical model of the building shall include the plan and vertical distribution of the energy dissipation devices. Analyses shall 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 shall be conducted to bound the effects of the varying mechanical characteristics of the devices.

Energy dissipation devices shall be capable of sustaining larger displacements and forces for displacement-dependent devices and larger displacements, velocities, and forces for velocity-dependent devices than the maximum calculated for the BSE-2X or BSE-1X for an LPO in accordance with the following criteria:

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-2X or 200% of the maximum calculated displacement in the device at BSE-1X for an LPO. A velocity-dependent device, as described in Section 14.3.3, shall be capable of sustaining the force and displacement associated with a