Chapter 13

SEISMICALLY ISOLATED STRUCTURE DESIGN REQUIREMENTS

13.1 GENERAL

13.1.1 Scope.

Every seismically isolated structure and every portion thereof shall be designed and constructed in accordance with the requirements of these *Provisions* as modified by this chapter.

13.1.2 Definitions.

Component: See Sec. 1.1.4.

Dead load: See Sec. 4.1.3.

Design displacement: The design earthquake lateral displacement, excluding additional displacement due to actual and accidental torsion, required for design of the isolation system.

Displacement restraint system: A collection of structural elements that limits lateral displacement of seismically isolated structures due to maximum considered earthquake ground shaking.

Effective damping: The value of equivalent viscous damping consistent with the energy dissipated during cyclic response of the isolation system.

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

Isolation interface: The boundary between the upper portion of the structure, which is isolated, and the lower portion of the structure, which is assumed to move rigidly with the ground.

Isolation system: The collection of structural elements that includes all individual isolator units, all structural elements that transfer force between elements of the isolation system, and all connections to other structural elements. The isolation system also includes the wind-restraint system, energy-dissipation devices, and/or the displacement restraint system where such systems or devices are used to satisfy the design requirements of Chapter 13.

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

Live load: See Sec. 4.1.3.

Maximum considered earthquake ground motion: See Sec. 3.1.3.

Maximum displacement: The maximum considered earthquake lateral displacement, excluding additional displacement due to actual and accidental torsion.

Occupancy importance factor: See Sec. 1.1.4.

Registered design professional: See Sec. 2.1.3.

Seismic-force-resisting system: See Sec. 1.1.4.

Seismic Use Group: See Sec. 1.1.4.

Story: See Sec. 4.1.3.

Structure: See Sec. 1.1.4.

Total design displacement: The design earthquake lateral displacement, including additional displacement due to actual and accidental torsion, required for design of the isolation system or an element thereof.

Total maximum displacement: The maximum considered earthquake lateral displacement, including additional displacement due to actual and accidental torsion, required for verification of the stability of the isolation system or elements thereof, design of structure separations, and vertical load testing of isolator unit prototypes.

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

13.1.3 Notation

B_D Numerical coefficient as set forth in Table 13.3-1 for effective damping equal to β_D.

B_M Numerical coefficient as set forth in Table 13.3-1 for effective damping equal β_M

b The shortest plan dimension of the structure measured perpendicular to d.

C_d See Sec. 4.1.4.

D See Sec. 4.1.4.

D_D Design displacement at the center of rigidity of the isolation system in the direction under consideration as prescribed by Eq. 13.3-1.

D'_D Design displacement at the center of rigidity of the isolation system in the direction under consideration applicable to dynamic procedures, as prescribed by Eq. 13.4-1.

D_M Maximum displacement at the center of rigidity of the isolation system in the direction under consideration, as prescribed by Eq. 13.3-3.

D'_M Maximum displacement at the center of rigidity of the isolation system in the direction under consideration applicable to dynamic procedures, as prescribed by Eq. 13.4-2.

D_{TD} Total design displacement of an element of the isolation system including both translational displacement at the center of rigidity and the component of torsional displacement in the direction under consideration as prescribed by Eq. 13.3-5.

D_{TM} Total maximum displacement of an element of the isolation system including both translational displacement at the center of rigidity and the component of torsional displacement in the direction under consideration as prescribed by Eq. 13.3-6.

d The longest plan dimension of the structure.

E See Sec. 4.1.4.

E_{loop} Energy dissipated in an isolator unit or damping device during a full cycle of reversible load over a test displacement range from Δ^+ to Δ^- as measured by the area enclosed by the loop of the force-deflection curve.

e The 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 percent the maximum building dimension perpendicular to the direction of the force under consideration.

F^+ Positive force in an isolator unit during a single cycle of prototype testing at a displacement amplitude of Δ^+.

F^- Maximum negative force in an isolator unit during a single cycle of prototype testing a displacement amplitude of Δ^-.

g Acceleration due to gravity.

h_i See Sec. .5.1.3

h_{sx} See Sec. 4.1.4.

h_x See Sec. 5.1.3.

Level i See Sec. 4.1.4.

K_{Dmax} Maximum effective stiffness of the isolation system at the design displacement in the horizontal direction under consideration as prescribed by Eq. 13.6-3.

K_{Dmin} Minimum effective stiffness of the isolation system at the design displacement in the horizontal direction under consideration as prescribed by Eq. 13.6-4.

K_{Mmax} Maximum effective stiffness of the isolation system at the maximum displacement in the horizontal direction under consideration as prescribed by Eq 13.6-5.

K_{Mmin} Minimum effective stiffness of the isolation system at the maximum displacement in the horizontal direction under consideration, as prescribed by Eq. 13.6-6.

k_{eff} Effective stiffness of an isolator unit, as prescribed by Eq. 13.6-1.

L The effect of live load.

R See Sec. 4.1.4.

R_I Numerical coefficient related to the type of seismic-force-resisting system above the isolation system as defined in Sec. 13.3.3.2 for seismically isolated structures.

S_1 See Sec. 3.1.4.

S_{D1} See Sec. 3.1.4.

S_{DS} See Sec. 3.1.4.

S_{M1} See Sec. 3.1.4.

T_D Effective period, in seconds, of the seismically isolated structure at the design displacement in the direction under consideration as prescribed by Eq. 13.3-2.

T_M Effective period, in seconds, of the seismically isolated structure at the maximum displacement in the direction under consideration as prescribed by Eq. 13.3-4.

V_b The total lateral seismic design force on elements of the isolation system or elements below the isolation system as prescribed by Eq. 13.3-7.

V_s The total lateral design force on elements above the isolation system as prescribed by Eq. 13.3-8.

W See Sec. 1.1.5. For calculation of the period of seismically isolated structures, the seismic weight above the isolation system.

w_i See Sec. 4.1.4.

w_x See Sec. 1.1.5.

Level x See Sec. 1.1.5.

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.

β_D Effective damping of the isolation system at the design displacement as prescribed by Eq. 13.6-7.

β_M Effective damping of the isolation system at the maximum displacement as prescribed by Eq. 13.6-8.

β_{eff} Effective damping of the isolation system as prescribed by Eq. 13.6-2.

Δ The maximum considered earthquake lateral displacement of the structure above the isolation system.

Δ^+ Maximum positive displacement of an isolator unit during each cycle of prototype testing.

Δ^- Maximum negative displacement of an isolator unit during each cycle of prototype testing.

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

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

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

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

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

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

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

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

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

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

13.2 GENERAL DESIGN REQUIREMENTS

13.2.1 Occupancy importance factor. The Occupancy Importance Factor shall be taken as 1.0 for a seismically isolated structure, regardless of the Seismic Use Group assigned in accordance with Sec. 1.2.

13.2.2 Configuration. The determination of structural configuration in accordance with Sec. 4.3.2 shall be based on the structural configuration above the isolation system.

13.2.3 Ground motion

13.2.3.1 Design spectra. Properly substantiated site-specific spectra shall be used for the design of all seismically isolated structures located on a Class F site or located at a site with S_1 greater than 0.6.

Where site-specific spectra are used, the design spectrum for the design earthquake shall be developed in accordance with Sec. 3.4. Where site-specific spectra are not used, the design spectrum for the design earthquake shall be developed in accordance with Sec. 3.3. The design spectrum for the maximum considered earthquake shall be taken as not less than 1.5 times the design spectrum for the design earthquake.

13.2.3.2 Time histories. Where response history procedures are used, ground motions shall consist of pairs of appropriate horizontal ground motion acceleration components that shall be selected and scaled from individual recorded events. Appropriate ground motions shall be selected from events having magnitudes, fault distance, and source mechanisms that are consistent with those that control the maximum considered earthquake. Where the required number of recorded ground motion pairs are not available, appropriate simulated ground motion pairs shall be used to make up the total number required. For each pair of horizontal ground motion components, an SRSS spectrum shall be constructed by taking the square root of the sum of the squares of the five-percent-damped response spectra for the scaled components (where an identical scale factor is applied to both components of a pair). Each pair of motions shall be scaled such that for each period between $0.5T_D$ and $1.25T_M$ (where T_D and T_M are defined in Sec. 13.3.2) the average of the SRSS spectra from all horizontal component pairs does not fall below 1.3 times the corresponding ordinate of the design response spectrum, determined in accordance with Sec. 13.2.3.1, by more than 10 percent.

13.2.4 Procedure selection. All seismically isolated structures shall be designed using the procedure in Sec. 13.3 or one of the procedures in Sec. 13.4, as permitted in this section.

13.2.4.1 Equivalent lateral force procedure. The equivalent lateral force procedure of Sec. 13.3 is permitted to be used for design of a seismically isolated structure provided that:

1. The structure is located at a site with S_1 less than or equal to 0.6 ;
2. The structure is located on a Class A, B, C, or D site;
3. The structure above the isolation interface is not more than four stories or 65 ft (20 m) in height;
4. The effective period of the isolated structure, T_M, is less than or equal to 3.0 sec.
5. The effective period of the isolated structure, T_D, is greater than three times the elastic, fixed-base period of the structure above the isolation system as determined in Sec. 5.2.2.1;
6. The structure above the isolation system is of regular configuration; and
7. The isolation system meets all of the following criteria:
   a. The effective stiffness of the isolation system at the design displacement is greater than one third of the effective stiffness at 20 percent of the design displacement,
   b. The isolation system is capable of producing a restoring force as specified in Sec. 13.2.5.4,
   c. The isolation system does not limit maximum considered earthquake displacement to less than the total maximum displacement.

13.2.4.2 Dynamic procedures. The dynamic procedures of Sec. 13.4 are permitted to be used for design of seismically isolated structures as indicated in this section.

13.2.4.2.1 Response spectrum procedure. The response spectrum procedure is permitted to be used for design of a seismically isolated structure provided that:

1. The structure is located on a Class A, B, C, or D site, and
2. The isolation system meets the criteria of Item 7 of Sec. 13.2.4.1.

13.2.4.2.2 Response history procedure. The response history procedure is permitted to be used for design of any seismically isolated structure.

13.2.4.3 Variations in material properties. The analysis of seismically isolated buildings, including the substructure, isolators and superstructure, shall consider variations in seismic isolator material properties over the projected life of the building including changes due to aging, contamination, environmental exposure, loading rate, scragging, and temperature.

13.2.5 Isolation system

13.2.5.1 Environmental conditions. In addition to satisfying the requirements related to vertical and lateral loads 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.

13.2.5.2 Wind forces. Isolated structures shall resist design wind loads at all levels above the isolation interface. 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.

13.2.5.3 Fire resistance. The fire resistance rating for the isolation system shall be consistent with the requirements of columns, walls, or other such elements in the same area of the structure.

13.2.5.4 Lateral-restoring force. The isolation system shall be configured to produce a restoring force such that the lateral force at the total design displacement is at least $0.025W$ greater than the lateral force at 50 percent of the total design displacement.

13.2.5.5 Displacement restraint. The isolation system is permitted to be configured to include a displacement restraint that limits lateral displacement due to the maximum considered earthquake to less than S_{M1}/S_{D1} times the total design displacement if the seismically isolated structure is designed in accordance with the following criteria where more stringent than the other requirements of Sec. 13.2:

1. Maximum considered earthquake response is calculated in accordance with Sec. 13.4 including explicit consideration of the nonlinear characteristics of both the isolation system and the structure above the isolation system;
2. The ultimate capacities of the isolation system and structural elements below the isolation system shall exceed the strength and displacement demands due to the maximum considered earthquake;
3. The structure above the isolation system is adequate for the stability and ductility demands due to the maximum considered earthquake; 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.

13.2.5.6 Vertical-load stability. Each element of the isolation system shall be designed to be stable under the maximum vertical load ($1.2D + 1.0L + E$) and the minimum vertical load ($0.8D - E$) when subjected to a horizontal displacement equal to the total maximum displacement. The dead load, D, and the live load, L, are defined in Sec. 13.1.2. The effect of seismic load, E, shall be determined in accordance with Sec. 4.2.2.1 except that S_{MS} shall be used in place of S_{DS} and the vertical loads that result from application of horizontal seismic forces, Q_E, shall be based on peak response due to the maximum considered earthquake.

13.2.5.7 Overturning. The factor of safety against global structural overturning at the isolation interface shall not be 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 maximum considered earthquake and the vertical restoring force shall be based on W, the seismic weight above the isolation interface, as defined in Sec. 5.2.1.

Local uplift of individual elements is permitted if the resulting deflections do not cause overstress or instability of the isolator units or other elements of the structure.

13.2.5.8 Inspection and replacement

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

1. A registered design professional shall complete a final series of inspections or observations of structure separation areas and components that cross the isolation interface prior to the issuance of the certificate of occupancy for the seismically isolated structure. Such inspections and observations shall confirm that the conditions allow free and unhindered displacement of the structure to maximum design levels and that all components that cross the isolation interface as installed are able to accommodate the stipulated displacements.
2. The registered design professional responsible for the design of the isolation system shall establish a periodic monitoring, inspection, and maintenance program for such system.
3. Remodeling, repair, or retrofitting at the isolation interface, including that of components that cross the isolation interface, shall be performed under the direction of a registered design professional.

13.2.5.9 Quality control. As part of the quality assurance plan developed in accordance with Sec. 2.2.1, the registered design professional responsible for the structural design shall establish a quality control testing program for isolator units.

13.2.6 Structural system

13.2.6.1 Horizontal distribution of force. A horizontal diaphragm or other structural elements shall provide continuity above the isolation interface and shall have adequate strength and ductility to transmit forces (due to nonuniform ground motion) from one part of the structure to another.

13.2.6.2 Building separations. Minimum separations between the isolated structure and surrounding retaining walls or other fixed obstructions shall not be less than the total maximum displacement.

13.2.6.3 Nonbuilding structures. Nonbuilding structures shall be designed and constructed in accordance with the requirements of Chapter 14 using design displacements and forces calculated in accordance with this chapter.

13.2.7 Elements of structures and nonstructural components. Parts or portions of an isolated structure, permanent nonstructural components and the attachments to them, and the attachments for permanent equipment supported by a structure shall be designed to resist seismic forces and displacements as prescribed in this section and shall satisfy the applicable requirements of Chapter 6.

13.2.7.1 Components below the isolation interface. Elements of seismically isolated structures and nonstructural components, or portions thereof, that are below the isolation interface shall be designed for the forces and displacements indicated in Chapter 4 or Chapter 6, as appropriate.

13.2.7.2 Components crossing the isolation interface. Elements of seismically isolated structures and nonstructural components, or portions thereof, that cross the isolation interface shall be designed to withstand the total maximum displacement.

13.2.7.3 Components at or above the isolation interface. Elements of seismically isolated structures and nonstructural components, or portions thereof, that are at or above the isolation interface shall be designed to resist a total lateral force consistent with the maximum dynamic response of the element or component under consideration.

> **Exception:** Elements of seismically isolated structures and nonstructural components or portions thereof are permitted to be designed for the forces and displacements indicated in Chapter 4 or Chapter 6, as appropriate.

13.3 EQUIVALENT LATERAL FORCE PROCEDURE

Where the equivalent lateral force procedure is used to design seismically isolated structures, the requirements of this section shall apply.

13.3.1 Deformational characteristics of the isolation system. Minimum lateral earthquake design displacement and forces on seismically isolated structures shall be based on the deformational characteristics of the isolation system. The deformational characteristics of the isolation system shall explicitly include the effects of the wind-restraint system if such a system is used to meet the design requirements of these *Provisions*. The deformational characteristics of the isolation system shall be based on properly substantiated tests performed in accordance with Sec. 13.6.

13.3.2 Minimum lateral displacements

13.3.2.1 Design displacement. The isolation system shall be designed and constructed to withstand minimum lateral earthquake displacements that act in the direction of each of the main horizontal axes of the structure and such displacements shall be calculated in accordance with Eq. 13.3-1 as follows:

$$D_D = \left(\frac{g}{4\pi^2}\right)\frac{S_{D1}T_D}{B_D} \qquad (13.3\text{-}1)$$

where:

g = acceleration due to gravity.

S_{D1} = design five-percent-damped spectral acceleration parameter at one second period as determined in Chapter 3.

T_D = effective period of seismically isolated structure at the design displacement in the direction under consideration, as prescribed by Eq. 13.3-2.

B_D = numerical coefficient related to the effective damping of the isolation system at the design displacement, β_D, as set forth in Table 13.3-1.

Table 13.3-1 Damping Coefficient, B_D or B_M

Effective Damping, β_D or β_M (Percentage of Critical)[a,b]	**B_D or B_M Factor**
≤ 2	0.8
5	1.0
10	1.2
20	1.5
30	1.7
40	1.9
≥ 50	2.0

[a] The damping coefficient shall be based on the effective damping of the isolation system determined in accordance with the requirements of Sec. 13.6.4.2.
[b] The damping coefficient shall be based on linear interpolation for effective damping values other than those given.

13.3.2.2 Effective period at design displacement. The effective period of the isolated structure, T_D, shall be determined using Eq. 13.3-2 as follows:

$$T_D = 2\pi\sqrt{\frac{W}{k_{Dmin}g}} \tag{13.3-2}$$

where:

W = seismic weight above the isolation interface as defined in Sec. 5.2.1.

k_{Dmin} = minimum effective stiffness of the isolation system at the design displacement in the horizontal direction under consideration as prescribed by Eq. 13.6-4.

g = acceleration due to gravity.

13.3.2.3 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. 13.3-3 as follows:

$$D_M = \left(\frac{g}{4\pi^2}\right)\frac{S_{M1}T_M}{B_M} \tag{13.3-3}$$

where:

g = acceleration due to gravity.

S_{M1} = maximum considered five-percent-damped spectral acceleration parameter at 1 sec period as determined in Chapter 3.

T_M = effective period of seismic-isolated structure at the maximum displacement in the direction under consideration as prescribed by Eq. 13.3-4.

B_M = numerical coefficient related to the effective damping of the isolation system at the maximum displacement, β_M, as set forth in Table 13.3-1.

13.3.2.4 Effective period at maximum displacement. The effective period of the isolated structure at maximum displacement, T_M, shall be determined using Eq. 13.3-4 as follows:

$$T_M = 2\pi\sqrt{\frac{W}{k_{Mmin}g}} \tag{13.3-4}$$

where:

W = seismic weight above the isolation interface as defined in Sec. 5.2.1.

k_{Mmin} = minimum effective stiffness of the isolation system at the maximum displacement in the horizontal direction under consideration as prescribed by Eq. 13.6-6.

g = acceleration due to gravity.

13.3.2.5 Total displacements. The total design displacement, D_{TD}, and the total maximum displacement, D_{TM}, of elements of the isolation system shall include additional displacement due to inherent and accidental torsion calculated considering the spatial distribution of the lateral stiffness of the isolation system and the most disadvantageous location of eccentric mass.

The total design displacement, D_{TD}, and the total maximum displacement, D_{TM}, of elements of an isolation system with uniform spatial distribution of lateral stiffness shall not be taken less than that prescribed by Eq. 13.3-5 and Eq. 13.3-6, respectively, as follows:

$$D_{TD} = D_D\left[1 + y\left(\frac{12e}{b^2 + d^2}\right)\right] \tag{13.3-5}$$

$$D_{TM} = D_M \left[1 + y\left(\frac{12e}{b^2 + d^2} \right) \right] \tag{13.3-6}$$

where:

D_D = design displacement at the center of rigidity of the isolation system in the direction under consideration as prescribed by Eq. 13.3-1.

D_M = maximum displacement at the center of rigidity of the isolation system in the direction under consideration as prescribed in Eq. 13.3-3.

y = the distance between the center of rigidity of the isolation system and the element of interest measured perpendicular to the direction of seismic loading under consideration.

e = the actual horizontal eccentricity between the center of mass of the structure above the isolation interface and the center of rigidity of the isolation system, plus the accidental eccentricity, taken as 5 percent of the longest plan dimension of the structure perpendicular to the direction of force under consideration.

b = the shortest plan dimension of the structure measured perpendicular to d.

d = the longest plan dimension of the structure.

Exception: The total design displacement, D_{TD}, and the total maximum displacement, D_{TM}, are permitted to be taken less than the values prescribed by Eq. 13.3-5 and Eq. 13.3-6, respectively, but not less than 1.1 times D_D and D_M, respectively, if the isolation system is shown by calculation to be configured to resist torsion accordingly.

13.3.3 Minimum lateral forces

13.3.3.1 Isolation system and structural elements below the isolation system. The isolation system, the foundation, and all structural elements below the isolation system shall be designed and constructed to withstand a minimum lateral force, V_b, using all of the appropriate provisions for a nonisolated structure. V_b shall be determined in accordance with Eq. 13.3-7 as follows:

$$V_b = k_{Dmax} D_D \tag{13.3-7}$$

where:

k_{Dmax} = maximum effective stiffness of the isolation system at the design displacement in the horizontal direction under consideration as prescribed by Eq. 13.6-3.

D_D = design displacement at the center of rigidity of the isolation system in the direction under consideration as prescribed by Eq. 13.3-1.

In all cases, V_b shall not be taken less than the maximum force in the isolation system at any displacement up to and including the design displacement.

13.3.3.2 Structural elements above the isolation system. The structure above the isolation system shall be designed and constructed to withstand a minimum lateral force, V_s, using all of the appropriate provisions for a nonisolated structure. V_s shall be determined in accordance with Eq. 13.3-8 as follows:

$$V_s = \frac{k_{Dmax} D_D}{R_I} \tag{13.3-8}$$

where:

k_{Dmax} = maximum effective stiffness of the isolation system at the design displacement in the horizontal direction under consideration as prescribed by Eq. 13.6-3.

D_D = design displacement at the center of rigidity of the isolation system in the direction under consideration as prescribed by Eq. 13.3-1.

R_I = numerical coefficient related to the type of seismic-force-resisting system above the isolation system.

R_I shall be based on the type of seismic-force-resisting system used for the structure above the isolation system and shall be taken as the lesser of 2.0 or 3/8 of the *R* value given in Table 4.3-1, but need not be taken less than 1.0.

In no case shall V_s be taken less than the following:

1. The lateral force required by Sec. 5.2 for a fixed-base structure of the same weight, *W*, and a period equal to the isolated period, T_D;
2. The base shear corresponding to the factored design wind load; and
3. The lateral force required to fully activate the isolation system (e.g., the yield level of a softening system, the ultimate capacity of a sacrificial wind-restraint system, or the break-away friction level of a sliding system) multiplied by 1.5.

13.3.4 Vertical distribution of forces. The total force shall be distributed over the height of the structure above the isolation interface in accordance with Eq. 13.3-9 as follows:

$$F_x = V_s \frac{w_x h_x}{\sum_{i=1}^{n} w_i h_i} \tag{13.3-9}$$

where:

V_s = total lateral design force on elements above the isolation system.

W_x = portion of *W* that is located at or assigned to Level *x*.

h_x = height above the base Level *x*.

w_i, w_x = portion of *W* that is located at or assigned to Level *i* or Level *x*, respectively.

h_i = height, above the base, to Level *i*.

At each Level *x* the force, F_x, shall be applied over the area of the structure in accordance with the distribution of mass at the level. Stresses in each structural element shall be determined by applying to an analytical model the lateral forces, F_x, at all levels above the base.

13.3.5 Drift limits. The drift limits specified in this section shall supercede those found in Sec. 4.5.1. The maximum story drift of the structure above the isolation system shall not exceed $0.015h_{sx}$. The drift shall be calculated using Eq. 5.2-15 except that C_d for the isolated structure shall be taken equal to R_I as defined in Sec. 13.3.3.2.

13.4 DYNAMIC PROCEDURES

Where dynamic analysis is used to design seismically isolated structures, the requirements of this section shall apply.

13.4.1 Modeling. The mathematical models of the isolated structure including the isolation system, the seismic-force-resisting system, and other structural elements shall be developed in accordance with Sec. 5.3.1 and this section.

13.4.1.1 Isolation system. The isolation system shall be modeled using deformational characteristics developed and verified by testing in accordance with the requirements of Sec. 13.3.1. 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 eccentric mass;
3. Assess overturning/uplift forces on individual isolator units; and
4. Account for the effects of vertical load, bilateral load, and the rate of loading if the force-deflection properties of the isolation system are dependent on such attributes.

The total design displacement and total maximum displacement across the isolation system shall be calculated using a model of the isolated structure that incorporates the force-deflection characteristics of nonlinear elements of the isolation system and the seismic-force-resisting system.

13.4.1.2 Isolated structure

The maximum displacement of each floor and design forces and displacements in elements of the seismic-force-resisting system are permitted to be calculated using a linear elastic model of the isolated structure provided that:

1. Stiffness properties assumed for the nonlinear components of the isolation system are based on the maximum effective stiffness of the isolation system, and
2. No elements of the seismic-force-resisting system of the structure above the isolation system are nonlinear.

Seismic-force-resisting systems with nonlinear elements include, but are not limited to, irregular structural systems designed for a lateral force less than 100 percent of V_s and regular structural systems designed for a lateral force less than 80 percent of V_s, where V_s is determined in accordance with Sec. 13.3.3.2.

13.4.2 Description of procedures. The response spectrum procedure, linear response history procedure, and nonlinear response history procedure shall be performed in accordance with Sec. 5.3, 5.4, and 5.5, respectively, and the requirements of this section.

13.4.2.1 Input earthquake. The design earthquake shall be used to calculate the total design displacement of the isolation system and the lateral forces and displacements of the isolated structure. The maximum considered earthquake shall be used to calculate the total maximum displacement of the isolation system.

13.4.2.2 Response spectrum procedure. Response spectrum analysis shall be performed using a modal damping value for the fundamental mode in the direction of interest not greater than the effective damping of the isolation system or 30 percent of critical, whichever is less. Modal damping values for higher modes shall be selected consistent with those that would be appropriate for response spectrum analysis of the structure above the isolation system assuming a fixed base.

Response spectrum analysis used to determine the total design displacement and the total maximum displacement shall include simultaneous excitation of the model by 100 percent of the ground motion in the critical direction and 30 percent of the ground motion in the perpendicular, horizontal direction. The maximum displacement of the isolation system shall be calculated as the vectorial sum of the two orthogonal displacements.

The design shear at any story shall not be less than the story shear resulting from application of the story forces calculated using Eq. 13.3-9 and a value of V_s equal to the base shear obtained from the response-spectrum analysis in the direction of interest.

13.4.2.3 Response history procedure. Where a response history procedure is performed, a suite of not fewer than three appropriate ground motions shall be used in the analysis and the ground motions shall be selected and scaled in accordance with Sec. 13.2.3.2. Each pair of ground motion components shall be applied to the model considering the most disadvantageous location of eccentric mass. The maximum displacement of the isolation system shall be calculated from the vectorial sum of the two orthogonal displacement components at each time step.

For each ground motion analyzed, the parameters of interest shall be calculated. If at least seven ground motions are analyzed, the average value of the response parameter of interest shall be permitted to be used for design. If fewer than seven ground motions are analyzed, the maximum value of the response parameter of interest shall be used for design.

13.4.3 Minimum lateral displacements and forces

13.4.3.1 Isolation system and structural elements below the isolation system. The isolation system, the foundation, and all structural elements below the isolation system shall be designed and constructed using all of the appropriate requirements for a nonisolated structure and the forces obtained from the dynamic analysis without reduction, but the design lateral force shall not be taken less than 90 percent of V_b determined in accordance with Sec. 13.3.3.1.

The total design displacement of the isolation system shall be taken as not less than 90 percent of D_{TD}. The total maximum displacement of the isolation system shall be taken as not less than 80 percent of D_{TM}. These limits shall be evaluated using values of D_{TD} and D_{TM} determined in accordance with Sec. 13.3.2.5 except that D'_D and D'_M, as calculated using Eq. 13.4-1 and 13.4-2, shall be permitted to be used in lieu of D_D and D_M, respectively.

$$D'_D = \frac{D_D}{\sqrt{1+\left(\frac{T}{T_D}\right)^2}} \tag{13.4-1}$$

$$D'_M = \frac{D_M}{\sqrt{1+\left(\frac{T}{T_M}\right)^2}} \tag{13.4-2}$$

where:

D_D = design displacement at the center of rigidity of the isolation system in the direction under consideration, determined in accordance with Sec. 13.3.2.1.

D_M = maximum displacement at the center of rigidity of the isolation system in the direction under consideration, determined in accordance with Sec. 13.3.2.3.

T = elastic, fixed-base period of the structure above the isolation system, determined in accordance with Sec. 5.2.2.

T_D = effective period of the seismically isolated structure at the design displacement in the direction under consideration, determined in accordance with Sec. 13.3.2.2.

T_M = effective period of the seismically isolated structure at the maximum displacement in the direction under consideration, determined in accordance with Sec. 13.3.2.4.

13.4.3.2 Structural elements above the isolation system. Subject to the procedure-specific limits of this section, structural elements above the isolation system shall be designed using the appropriate provisions for a nonisolated structure and the forces obtained from the dynamic analysis divided by R_I, where R_I is determined in accordance with Sec. 13.3.3.2.

Where the response spectrum procedure is used and the structure is regular in configuration, the design lateral force on the structure above the isolation system shall be taken as not less than 80 percent of V_s as determined in accordance with Sec. 13.3.3.2. Where the response spectrum procedure is used and the structure is irregular in configuration, the design lateral force on the structure above the isolation system shall be taken as not less than 100 percent of V_s as determined in accordance with Sec. 13.3.3.2.

Where the response history procedure is used and the structure is regular in configuration, the design lateral force on the structure above the isolation system shall be taken as not less than 60 percent of V_s as determined in accordance with Sec. 13.3.3.2. Where the response history procedure is used and the structure is irregular in configuration, the design lateral force on the structure above the isolation system shall be taken as not less than 80 percent of V_s as determined in accordance with Sec. 13.3.3.2.

13.4.3.3 Scaling of results. Where the design lateral force on structural elements, determined using either the response spectrum or response history procedure, is less than the minimum level required by Sec. 13.4.3.1 and 13.4.3.2, all response parameters, including member forces and moments, shall be adjusted proportionally upward.

13.4.4 Drift limits. The drift limits specified in this section shall supercede those found in Sec. 4.5.1. The maximum story drift of the structure above the isolation system corresponding to the design lateral force, including displacement due to vertical deformation of the isolation system, shall not exceed $0.015h_{sx}$ where the response spectrum procedure is used, or $0.020h_{sx}$ where the response history procedure is used.

Drift shall be calculated using Eq. 5.3-8 with C_d for the isolated structure taken equal to R_I as defined in Sec. 13.3.3.2.

The secondary effects of the maximum considered earthquake lateral displacement, Δ, of the structure above the isolation system combined with gravity forces shall be investigated if the story drift ratio exceeds $0.010/R_I$.

13.5 DESIGN REVIEW

A design review of the isolation system and related test programs shall be performed by an independent team of registered design professionals in the appropriate disciplines and others experienced in seismic analysis methods and the theory and application of seismic isolation. Isolation system design review shall include, but need not be limited to, the following:

1. Review of site-specific seismic criteria including the development of site-specific spectra and ground motion time histories and all other design criteria developed specifically for the project;
2. Review of the preliminary design including the determination of the total design displacement of the isolation system and the lateral force design level;
3. Overview and observation of prototype testing, performed in accordance with Sec. 13.6;
4. Review of the final design of the entire structural system and all supporting analyses; and
5. Review of the isolation system quality control testing program developed in accordance with Sec. 13.2.5.9.

13.6 TESTING

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

The isolation system components to be tested shall include the wind-restraint system if such a system is used in the design.

The tests specified in this section are for establishing and validating the design properties of the isolation system and shall not be considered as satisfying the manufacturing quality control tests of Sec. 13.2.5.9.

13.6.1 Prototype tests. Prototype tests shall be performed separately on two full-size specimens (or sets of specimens, as appropriate) for each predominant type and size of isolator unit of the isolation system. The test specimens shall include the wind restraint system as well as individual isolator units if such system is used in the design. Specimens tested shall not be used for construction unless accepted by the registered design professional.

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

13.6.1.2 Sequence and cycles. For all isolator units of a common type and size, the following sequence of tests shall be performed for the prescribed number of cycles while the test specimen is subjected to a vertical load equal to the average dead load plus one-half the average live load:

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 increments of displacement: $0.25D_D$, $0.5D_D$, $1.0D_D$, and $1.0D_M$;
3. Three fully reversed cycles of loading at the total maximum displacement, D_{TM}; and
4. $30S_{D1}/B_DS_{DS}$ but not less than ten, fully reversed cycles of loading at the total design displacement, D_{TD}.

If an isolator unit is also a vertical-load-carrying element, then Item 2 of the sequence of cyclic tests specified above shall be performed for two additional vertical load cases: 1) $1.2D + 0.5L + |E|$ and 2) $0.8D - |E|$, where each vertical load case is based on the average downward force on all isolator units of a common type and size. The dead load, D, and the live load, L, are defined in Sec. 13.1.2. The effect of seismic load, E, shall be determined in accordance with Sec. 4.2.2.1 and the vertical loads that result from application of horizontal seismic forces, Q_E, shall be based on peak response corresponding to the test displacement being evaluated.

13.6.1.3 Units dependent on loading rates. If the force-deflection properties of the isolator units are dependent on the rate of loading, then each set of tests specified in Sec. 13.6.1.2 shall be performed dynamically at a frequency equal to the inverse of the effective period of the isolated structure, T_D. The force-deflection properties of an isolator unit shall be considered to be dependent on the rate of loading if the measured property (effective stiffness or effective damping) at the design displacement where tested at any frequency in the range of 0.1 to 2.0 times the inverse of T_D is different from the property where tested at a frequency equal to the inverse of T_D by more than 15 percent.

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 be manufactured with the same processes and quality as full-scale prototypes and shall be tested at a frequency that represents full-scale prototype loading rates.

13.6.1.4 Units dependent on bilateral load. If the force-deflection properties of the isolator units are dependent on bilateral load, the tests specified in Sec. 13.6.1.2 and 13.6.1.3 shall be augmented to include bilateral load at the following increments of the total design displacement, D_{TD}: 0.25 and 1.0, 0.50 and 1.0, 0.75 and 1.0, and 1.0 and 1.0. The force-deflection properties of an isolator unit shall be considered to be dependent on bilateral load if the effective stiffness where subjected to bilateral loading is different from the effective stiffness where subjected to unilateral loading by more than 15 percent.

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

13.6.1.5 Maximum and minimum vertical load. In addition to the cyclic testing requirements of Sec. 13.6.1.2, isolator units that are vertical-load-carrying elements shall be statically tested by subjecting them to the total maximum displacement while under the maximum and minimum vertical load. In these tests, the maximum vertical load shall be taken as the maximum effect of $1.2D + 1.0L + |E|$ and the minimum vertical load shall be taken as the minimum effect of $0.8D - |E|$ for any one isolator of a common type and size. The dead load, D, and the live load, L, are defined in Sec. 13.1.2. The effect of seismic load, E, shall be determined in accordance with Sec. 4.2.2.1 except that S_{MS} shall be used in place of S_{DS} and the vertical loads that result from application of horizontal seismic forces, Q_E, shall be based on peak response due to the maximum considered earthquake.

13.6.1.6 Sacrificial wind-restraint systems. If a sacrificial wind-restraint system is to be utilized, the ultimate capacity shall be established by test.

13.6.1.7 Testing similar units. The prototype tests are not required if an isolator unit is of similar dimensional characteristics and of the same type and material as a prototype isolator unit that has been previously tested using the specified sequence of tests.

13.6.2 Determination of force-deflection characteristics. The force-deflection characteristics of the isolation system shall be based on the cyclic load tests of isolator prototypes specified in Sec. 13.6.1.

As required, the effective stiffness of an isolator unit, k_{eff}, shall be calculated for each cycle of loading by Eq. 13.6-1 as follows:

$$k_{eff} = \frac{|F^+| + |F^-|}{|\Delta^+| + |\Delta^-|} \tag{13.6-1}$$

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

As required, the effective damping, β_{eff}, of an isolator unit shall be calculated for each cycle of loading by Eq. 13.6-2 as follows:

$$\beta_{eff} = \frac{2}{\pi}\left[\frac{E_{loop}}{k_{eff}\left(|\Delta^+| + |\Delta^-|\right)^2}\right] \tag{13.6-2}$$

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

13.6.3 Test specimen adequacy. The performance of the test specimens shall be deemed adequate if the following conditions are satisfied:

1. The force-deflection plots for all tests specified in Sec. 13.6.1 have a positive incremental force carrying capacity. For each increment of test displacement specified in Item 2 of Sec. 13.6.1.2 and for each vertical load case specified in Sec. 13.6.1.2,
   a. For each test specimen, the difference between the effective stiffness at each of the three cycles of test and the average value of effective stiffness is no greater than 15 percent; and
   b. For each cycle of test, the difference between effective stiffness of the two test specimens of a common type and size of the isolator unit and the average effective stiffness is no greater than 15 percent.
2. For each specimen there is no greater than a 20 percent change in the initial effective stiffness over the cycles of test specified in Item 4 of Sec. 13.6.1.2;
3. For each specimen there is no greater than a 20 percent decrease in the initial effective damping over the cycles of test specified in Item 4 of Sec. 13.6.1.2; and
4. All specimens of vertical-load-carrying elements of the isolation system remain stable when tested in accordance with Sec. 13.6.1.5.

13.6.4 Design properties of the isolation system

13.6.4.1 Maximum and minimum effective stiffness. At the design displacement, the maximum and minimum effective stiffness of the entire isolated system, k_{Dmax} and k_{Dmin}, shall be based on the cyclic tests of individual isolator units in accordance with Item 2 of Sec. 13.6.1.2 and calculated using Eq. 13.6-3 and 13.6-4 as follows:

$$k_{Dmax} = \frac{\sum\left|F_D^+\right|_{max} + \sum\left|F_D^-\right|_{max}}{2D_D} \quad (13.6\text{-}3)$$

$$k_{Dmin} = \frac{\sum\left|F_D^+\right|_{min} + \sum\left|F_D^-\right|_{min}}{2D_D} \quad (13.6\text{-}4)$$

At the maximum displacement, the maximum and minimum effective stiffness of the entire isolation system, k_{Mmax} and k_{Mmin}, shall be based on the cyclic tests of individual isolator units in accordance with Item 2 of Sec. 13.6.1.2 and calculated using Eq. 13.6-5 and 13.6-6 as follows:

$$k_{Mmax} = \frac{\sum\left|F_M^+\right|_{max} + \sum\left|F_M^-\right|_{max}}{2D_M} \quad (13.6\text{-}5)$$

$$k_{Mmin} = \frac{\sum\left|F_M^+\right|_{min} + \sum\left|F_M^-\right|_{min}}{2D_M} \quad (13.6\text{-}6)$$

The maximum effective stiffness of the isolation system, k_{Dmax} (or k_{Mmax}), shall be based on forces from the cycle of prototype testing at a test displacement equal to D_D (or D_M) that produces the largest value of effective stiffness. Minimum effective stiffness of the isolation system, k_{Dmin} (or k_{Mmin}), shall be based on forces from the cycle of prototype testing at a test displacement equal to D_D (or D_M) that produces the smallest value of effective stiffness.

For isolator units that are found by the tests of Sec. 13.6.1.2, 13.6.1.3 and 13.6.1.4 to have force-deflection characteristics that vary with vertical load, rate of loading, or bilateral load, respectively, the values of k_{Dmax} and k_{Mmax} shall be increased and the values of k_{Dmin} and k_{Mmin} shall be decreased to bound the effects of measured variation in effective stiffness.

13.6.4.2 Effective damping. At the design displacement, the effective damping of the entire isolation system, β_D, shall be based on the cyclic tests of individual isolator units in accordance with Item 2 of Sec. 13.6.1.2 and calculated using Eq. 13.6-7 as follows:

$$\beta_D = \frac{1}{2\pi}\left(\frac{\sum E_D}{k_{Dmax} D_D^2}\right) \quad (13.6\text{-}7)$$

In Eq. 13.6-7, the total energy dissipated per cycle of design displacement response, ΣE_D, shall be taken as the sum of the energy dissipated per cycle in all isolator units measured at a test displacement equal to D_D, and shall be based on forces and deflections from the cycle of prototype testing that produces the smallest value of effective damping.

At the maximum displacement, the effective damping of the entire isolation system, β_M, shall be based on the cyclic tests of individual isolator units in accordance with Item 2 of Sec. 13.6.1.2 and calculated using Eq. 13.6-8 as follows:

$$\beta_M = \frac{1}{2\pi}\left(\frac{\sum E_M}{k_{Mmax} D_M^2}\right) \quad (13.6\text{-}8)$$

In Eq. 13.6-8, the total energy dissipated per cycle of maximum displacement response, ΣE_M, shall be taken as the sum of the energy dissipated per cycle in all isolator units measured at a test displacement equal to D_M, and shall be based on forces and deflections from the cycle of prototype testing that produces the smallest value of effective damping.