Section 15
SEISMIC ISOLATION

15.1 SCOPE

Criteria provided herein for bearings used in implementing seismic isolation design are supplemental to Section 14 of the AASHTO *LRFD Bridge Design Specifications*. These provisions are necessary to provide a rational design procedure for isolation systems incorporating the displacements resulting from the seismic response. If a conflict arises between the provisions of the LRFD Sections 14 and this section, the provisions contained herein govern. The seismic isolation provisions in this Guide Specification maintain their Section 15 nomenclature because this is a new section that will be added to the existing LRFD provisions. Sections 1 through 8 of this Guide Specification will be inserted in existing sections of the LRFD provisions.

These specifications are intended for systems that isolate in the horizontal plane only – that is, the system is assumed to be essentially rigid in the vertical direction. In addition, the criteria are currently intended for passive isolation systems only.

15.2 DEFINITIONS

- DESIGN DISPLACEMENT is the lateral seismic displacement at the center of rigidity, required for design of the isolation system.

- EFFECTIVE DAMPING is the value of equivalent viscous damping corresponding to the energy dissipated during cyclic response at the design displacement of the isolated structure.

- EFFECTIVE STIFFNESS is the value of the maximum lateral force at instance of maximum lateral displacement in the isolation system, or an element thereof, divided by the maximum lateral displacement.

- ELASTIC RESTRAINT SYSTEM is the collection of structural elements that provide restraint of the seismically isolated structure for nonseismic lateral loads. The elastic restraint system may be either an integral part of the isolation system or may be a separate device.

- ISOLATION SYSTEM is the collection of all the elements that provide vertical stiffness, lateral flexibility, and damping to the system at the isolation interface. It includes the isolator units and the elastic restraint system, if one is used.

- ISOLATOR UNIT is a horizontally flexible and vertically stiff bearing of the isolation system, which permits large lateral deformation under seismic load. The isolator unit may or may not provide energy dissipation.

- OFFSET DISPLACEMENT is the lateral displacement of an isolator unit resulting from creep, shrinkage, and 50 percent of the thermal displacement.

- TOTAL DESIGN DISPLACEMENT is the maximum lateral seismic displacement of an isolator unit resulting from the analysis and required for design of the isolation system, including both translational displacement at the center of rigidity, Δ_i, and the component of torsional displacement in the direction under consideration.

15.3 NOTATION

A_b = Bonded area of elastomer.

A_r = Overlap area between the top-bonded and bottom-bonded elastomer areas of displaced bearing (figure C15.3-1).

B = Numerical coefficient related to the effective damping of the isolation system as set forth in Table 15.4.1-1.

B_d = Bonded plan dimension or bonded diameter in loaded direction of rectangular bearing or diameter of circular bearing (FigureC15.3-1).

C_d = Elastic seismic demand response coefficient.

DL = Dead load.

E = Young's modulus of elastomer.

EDC = Energy dissipated per cycle (area of hysteresis loop).

V = Statically equivalent seismic force.

V_A = Design force for connections for bridges in Seismic Design and Analysis Procedure (SDAP A).

F_i = Force in the isolator unit at displacement Δi.

F_n = Maximum negative force in an isolator unit during a single cycle of prototype testing.

$F_{n, max}$ = Maximum negative force in an isolator unit for all cycles of prototype testing at a common displacement amplitude.

$F_{n, min}$ = Minimum negative force in an isolator unit for all cycles of prototype testing at a common displacement amplitude.

F_p = Maximum positive force in an isolator unit during a single cycle of prototype testing.

$F_{p, max}$ = Maximum positive force in an isolator unit for all cycles of prototype testing at a common displacement amplitude.

$F_{p, min}$ = Minimum positive force in an isolator unit for all cycles of prototype testing at a common displacement amplitude.

F_v = Site soil coefficient given in Article 3.4.2.

G = Shear modulus of elastomer.

g = Acceleration due to gravity.

$\bar{k}$ = Elastomer material constant.

k_{iso} = Effective stiffness of an isolator unit determined by prototype testing.

k_{max} = Maximum effective stiffness of the isolator unit at the design displacement in the horizontal direction under consideration.

k_{min} = Minimum effective stiffness of the isolator unit at the design displacement in the horizontal direction under consideration.

k_{sub} = Stiffness of the substructure protected by the isolation unit(s)

K = Bulk modulus of the elastomer (Article 15.11).

K_d = The second slope stiffness of the bilinear hysteresis curve.

K_{eff} = The sum of the effective linear stiffnesses of all bearings and substructures supporting the superstructure segment as calculated at displacement Δi for the bearings and displacement Δsub for the substructure.

LL = Live load.

LLs = Seismic live load.

OT = Additional vertical load on bearing resulting from overturning moment effect of horizontal loads.

P = Maximum vertical load resulting from the combination of dead load plus live load (including seismic live load, if applicable), plus overturning moment effect of horizontal loads.

Q_d = Characteristic strength of the isolator unit. It is the ordinate of the hysteresis loop at zero bearing displacement. Refer to Figure C15.1-4.

S_1 = The one-second period spectral acceleration given in Article 3.10.2.1.

S = Shape factor (Article 15.11).

S_A = Spectral acceleration.

S_D = Spectral displacement.

T_{eff} = Period of seismically isolated structure, in seconds, in the direction under consideration.

T_r = Total elastomer thickness.

t_i = Thickness of elastomer layer number i, which is equivalent to the term hri in Article 14.7.5.1.

W = The total vertical load for design of the isolation system (DL + LLs).

= Total deck displacement relative to ground ($_i$ + $_{sub}$).

$_i$ = Design displacement at the center of rigidity of the isolation system in the direction under consideration.

$_{os}$ = Offset displacement of the isolator unit, including creep, shrinkage, and 50 percent of the thermal displacement.

$_{sub}$ = Substructure displacement.

$_t$ = Total design displacement.

$_n$ = Maximum negative displacement of an isolator unit during each cycle of prototype testing.

$_p$ = Maximum positive displacement of an isolator unit during each cycle of prototype testing.

$_s$ = Shear deformation of bearing from non-seismic displacement of the superstructure (including temperature, shrinkage, and creep).

ß = Equivalent viscous damping ratio for the isolation system.

$ß_i$ = Equivalent viscous damping ratio for isolator.

γ_c = Shear strain due to vertical loads.

$\gamma_{s,eq}$ = Shear strain due to $_t$, the total seismic design displacement.

$\gamma_{s,s}$ = Shear strain due to maximum horizontal displacement resulting from creep, post-tensioning, shrinkage, and thermal effects computed between the installation temperature and the least favorable extreme temperature.

γ_r = Shear strain due to imposed rotation.

θ = Rotation imposed on bearing.

$\lambda_{max}, \lambda_{min}$ = System property modification factors to account for effects of temperature, aging, scragging, velocity, and variability of materials (Article 15.5.2).

15.4 ANALYSIS PROCEDURES

Articles 3.7 and 5.1 shall be used to define the analysis procedures.

The analysis of the bridge shall be performed using the design properties of the isolation system. To simplify the nonlinear behavior of the isolator unit, a bilinear simplification may be used. The analysis shall be repeated using upper-bound properties (Qd,max, Kd,max) in one analysis and lower-bound properties (Qd,min, Kd,min) in another, where the maximum and minimum values are defined in Article 15.5.1.2. The purpose of this upper- and lower-bound analysis is to determine the maximum forces on the substructure elements and the maximum displacements of the isolation system.

An upper- and lower-bound analysis is not required if the displacements, using Equation 15.4.1-3, and the statically equivalent seismic force, using Equation 15.4.1-2a, do not vary from the design values by more than ±15 percent when the maximum and minimum values of the isolator units properties are used. For these simplified calculations, B values corresponding to more than 30-percent damping can be used to establish the ±15-percent limits.

A nonlinear time-history analysis is required for structures with effective periods greater than 3 seconds.

For isolation systems where the effective damping expressed as a percentage of critical damping exceeds 30 percent of critical, a three-dimensional nonlinear time-history analysis shall be performed utilizing the hysteresis curves of the isolation system.

15.4.1 Capacity Spectrum Method

This method of analysis can be used when the regularity requirements of Table 5.4.2.1-1 are met.

The statically equivalent seismic force is given by

$$V = C_d W \qquad (15.4.1\text{-}1)$$

The elastic seismic response demand coefficient, C_d, used to determine the equivalent force, is given by the dimensionless relationship

$$C_d = \frac{K_{eff} \times \Delta}{W} = \frac{F_v S_1}{T_{eff} B} \qquad (15.4.1\text{-}2)$$

The displacement is given by

$$\Delta = \frac{0.25 F_v S_1 T_{eff}}{B} \text{ (m)} \qquad (15.4.1\text{-}3a)$$

$$\Delta = \frac{10 F_v S_1 T_{eff}}{B} \text{ (inches)} \qquad (15.4.1\text{-}3b)$$

$$T_{eff} = 2\pi \sqrt{\frac{W}{K_{eff}\, g}} \qquad (15.4.1\text{-}4)$$

Note: This method of analysis shall not be used if Type E and F soils are present. For systems that include a viscous damper, the maximum force in the system may not correspond to the point of maximum displacement (Equation 15.4.1-1). The procedure described in the commentary shall be used.

Table 15.4.1-1 Damping Coefficient *B*

	Damping (Percentage of Critical)*						
	≤2	5	10	20	30	40	50
B	0.8	1.0	1.2	1.5	1.7	1.9	2.0

*The percentage of critical damping depends on the energy dissipated and stored by the isolation system, which shall be determined by test of the isolation system's characteristics, and by the substructure. The damping coefficient shall be based on linear interpolation for damping levels other than those given. Note that for isolation systems where the effective damping exceeds 30 percent, a nonlinear time-history analysis shall be performed utilizing the hysteresis curves of the system.

15.4.2 Uniform Load Method

The statically equivalent force determined according to Article 15.4.1, which is associated with the displacement across the isolation bearings, shall be applied using the uniform load method of analysis described in Article 5.4.2.2 independently along two perpendicular axes and combined as specified in Article 3.6. The effective stiffness of the isolators used in the analysis shall be calculated at the design displacement.

15.4.3 Multimode Spectral Method

An equivalent linear response spectrum shall be performed using the requirements of Article 5.4.2.3 when required by the regularity limitations of Article 5.4.2.1. The 5% damped spectra may be scaled by the damping coefficient (B), as defined in Article 15.4.1, to represent the actual seismic hazard and the effective damping of the isolation system for the isolated modes. Scaling by the damping coefficient B shall apply only for periods greater than 0.8 Teff. The 5-percent ground-motion response spectra shall be used for all other modes. The effective linear stiffness of the isolators shall correspond to the design displacement.

The combination of orthogonal seismic forces shall be as specified in Article 3.6.

15.4.4 Time-History Method

For isolation systems requiring a time-history analysis, the following requirements and Article 5.4.4 shall apply:

(a) The isolation system shall be modeled using the nonlinear deformational characteristics of the isolators determined and verified by test in accordance with the requirements of Article 15.10.

(b) Pairs of horizontal ground-motion time-history components shall be selected from no fewer than three earthquakes as required by Article 3.4.4.

(c) Time-history analysis shall be performed with at least three appropriate pairs of horizontal time-history components.

Each pair of time histories shall be applied simultaneously to the model. The maximum displacement of the isolation system shall be calculated from the vectorial sum of the orthogonal displacements at each time step.

The parameter of interest shall be calculated for each time-history analysis. If three time-history analyses are performed, then the maximum response of the parameter of interest shall be used for design. If seven or more time-history analyses are performed, then the average value of the response parameter of interest may be used for design.

15.5. DESIGN PROPERTIES OF THE ISOLATION SYSTEM

15.5.1 Nominal Design Properties

The minimum and maximum effective stiffness of the isolation system (K_{min} and K_{max}) shall be determined from the minimum and maximum values of K_d and Q_d.

The minimum and maximum values of K_d and Q_d shall be determined as follows:

$$K_{d,max} = K_d \times \lambda_{max,K_d} \quad (15.5.1\text{-}1)$$

$$K_{d,min} = K_d \times \lambda_{min,K_d} \quad (15.5.1\text{-}2)$$

$$Q_{d,max} = Q_d \times \lambda_{max,Q_d} \quad (15.5.1\text{-}3)$$

$$Q_{d,min} = Q_d \times \lambda_{min,Q_d} \quad (15.5.1\text{-}4)$$

System property modification factors (λ) (defined in Article 15.5.2) used for design shall be established by system characterization tests and approved by the engineer. In lieu of the test values, the λ values given in Appendix 15A may be used

15.5.2 System Property Modification Factors (λ)

The mechanical properties of the isolator units are affected by temperature, aging, scragging, velocity, travel, and contamination.

15.5.2.1 Minimum and Maximum System Property Modification Factors

$$\lambda_{min,K_d} = \lambda_{min,t,K_d} \times \lambda_{min,a,K_d} \times \lambda_{min,v,K_d} \times \lambda_{min,tr,K_d} \times \lambda_{min,c,K_d} \times \lambda_{min,scrag,K_d} \quad (15.5.2\text{-}1)$$

$$\lambda_{max,K_d} = \lambda_{max,t,K_d} \times \lambda_{max,a,K_d} \times \lambda_{max,v,K_d} \times \lambda_{max,tr,K_d} \times \lambda_{max,c,K_d} \times \lambda_{max,scrag,K_d} \quad (15.5.2\text{-}2)$$

$$\lambda_{min,Qd} = \lambda_{min,t,Qd} \times \lambda_{min,a,Qd} \times \lambda_{min,v,Qd} \times \lambda_{min,tr,Qd} \times \lambda_{min,c,Qd} \times \lambda_{min,scrag,Qd} \quad (15.5.2\text{-}3)$$

$$\lambda_{max,Qd} = \lambda_{max,t,Qd} \times \lambda_{max,a,Qd} \times \lambda_{max,v,Qd} \times \lambda_{max,tr,Qd} \times \lambda_{max,c,Qd} \times \lambda_{max,scrag,Qd} \quad (15.5.2\text{-}4)$$

where:

λ_t = Factors to account for effects of temperature

λ_a = Factors to account for effects of aging (including corrosion)

λ_v = Factors to account for effects of velocity (including frequency for elastomeric systems)

$$\lambda_v = \frac{\text{Property value at relevant velocity}}{\text{Property value at velocity of testing}}$$

λ_{tr} = Factors to account for effects of travel (wear)

λ_c = Factors to account for effects of contamination (in sliding systems)

λ_{scrag}= Factors to account for effects of scragging a bearing (in elastomeric systems)

15.5.2.2 System Property Adjustment Factors

Adjustment factors are applied to individual λ factors to account for the probability of occurrence. The following adjustment factors shall apply to all λ factors except λ_v:

1.0 for operational bridges

0.67 for all other bridges

The adjustment factors shall apply to the portion of a λ that deviates from unity.

15.6 CLEARANCES

The clearances in the two orthogonal directions shall be the maximum displacement determined in each direction from the analysis. The clearance shall not be less than

$$\frac{0.20 F_v S_1 T_{eff}}{B} \text{(m)} \quad (15.6\text{-}1a)$$

$$\frac{8F_vS_1T_{eff}}{B}\text{(inches)} \qquad (15.6\text{-}1b)$$

or 1 inch (25 mm), whichever is greater.

Displacements in the isolators resulting from load combinations involving BR, WS, WL, CE, and T shall be calculated and adequate clearance provided.

The minimum design forces shall be consistent with the clearances calculated with Equation 15.6-1.

15.7 DESIGN FORCES FOR SDAP A1 AND A2

The seismic design force for the connection between superstructure and substructure at each bearing is given by

$$V_A = k_{eff}\Delta_t \qquad (15.7\text{-}1)$$

where Δ_t shall be based on a minimum value of F_vS_1, not less than 0.25.

15.8 DESIGN FORCES FOR SDAP C, D, AND E

The seismic design force for columns and piers shall not be less than the forces resulting from the yield level of a softening system, the friction level of a sliding system, or the ultimate capacity of a sacrificial service restraint system. In all cases the larger of static or dynamic conditions shall apply.

If the elastic foundation forces are less than the forces resulting from column hinging, they may be used for the foundation design. The foundation shall be designed using an R value equal to 1.0.

The seismic design force for the connection between the superstructure and substructure at each bearing is given by

$$V_a = k_{eff}\,\Delta_t \qquad (15.8\text{-}1)$$

Where Δ_t is the total design displacement and includes Δ_i the center of mass displacement from seismic forces plus any displacement resulting from torsional effects.

15.9 OTHER REQUIREMENTS

15.9.1 Non-Seismic Lateral Forces

The isolation system must resist all non-seismic lateral load combinations applied above the isolation interface. Such load combinations are those involving WS, WL, BR, CE, and T.

15.9.1.1 Service Force Resistance

Resistance to forces such as wind, centrifugal, and braking, and forces induced by restraint of thermal displacements, shall be established by testing in accordance with Article 15.10.2.

15.9.1.2 Cold Weather Requirements

Cold weather performance shall be considered in the design of all types of isolation systems. Low-temperature zones shall conform with Figure 14.7.5.2-1 in the absence of more site-specific data.

15.9.2 Lateral Restoring Force

The isolation system shall be configured to produce a lateral restoring force such that the period corresponding to its tangent stiffness based on the restoring force alone at any displacement, , up to its design displacement shall be less than 6 seconds (Figure C15.9.2-1). Also the restoring force at Δ_i shall be greater than the restoring force at 0.5 Δ_i by not less than W/80. Isolation systems with constant restoring force need not satisfy the requirements above. In these cases, the combined constant restoring force of the isolation system shall be at least equal to 1.05 times the characteristic strength of the isolation system under service conditions.

Forces that are not dependent on displacements, such as viscous forces, may not be used to meet the minimum restoring force or tangent stiffness requirements.

15.9.3 Vertical Load Stability

The isolation system shall provide a factor of safety of at least three (3) for vertical loads (dead load plus live load) in its laterally undeformed state. It shall also be designed to be stable under 1.2 times the dead load plus any vertical load resulting from seismic live load, plus overturning at a horizontal displacement equal to the offset displacement plus 1.1 times the total design displacement, plus 0.5 times the design rotation.

15.9.4 Rotational Capacity

The design rotation capacity of the isolation unit shall include the effects of dead load, live load, and construction misalignments. In no case shall the design rotation for the construction misalignment be less than 0.005 radians.

15.10 REQUIRED TESTS OF ISOLATION SYSTEMS

All isolation systems shall have their seismic performance verified by testing. In general, there are three types of tests to be performed on isolation systems: (1) system characterization tests, described in Article 15.10.1; (2) prototype tests, described in Article 15.10.2; and (3) quality control tests, described in Articles 15.12, 15.14 and 15.15.

15.10.1 System Characterization Tests

The fundamental properties of the isolation system shall be evaluated by testing prior to its use. The purpose of system characterization tests is to substantiate the properties of individual isolator units as well as the behavior of an isolation system. Therefore, these tests include both component tests of individual isolator units and shake table tests of complete isolation systems.

At a minimum, these tests shall consist of

- Tests of individual isolator units in accordance with the National Institute of Standards and Technology (NIST) guidelines or the Highway Innovative Technology Evaluation Center (HITEC) guidelines.

- Shaking table tests at a scale no less than 1/4 full scale. Scale factors must be well-established and approved by the engineer.

15.10.1.1 Low-Temperature Test

If the isolators are for low-temperature areas, then Test 6 specified in section 15.10.2 shall be performed at temperatures of 20, 5, –5, or –15 degrees F (–7, –15, –21, or –26 degrees C) for temperature zones A, B, C, and D, respectively.

The specimen shall be cooled for a duration not less than the maximum number of consecutive days below freezing specified in Table 14.7.5.2-2.

15.10.1.2 Wear and Fatigue Tests

Wear or travel and fatigue tests are required to account for movements resulting both from imposed thermal displacements and live load rotations. Thermal displacements and live load rotations shall correspond to at least 30 years of expected movement. Tests shall be performed at the design contact pressure at 68 degrees F ± 15 degrees (20 degrees C ±8 degrees). The rate of application shall not be less than 2.5 inches/minute (63.5 mm/minute). As a minimum, the following displacements shall be used for the test:

- Bearings: 1 mile (1.6 km)

- Dampers (attached to the web at the neutral axis): 1 mile (1.6 km)

- Dampers (attached to the girder bottom): 2 miles (3.2 km)

Additional wear or travel and fatigue will occur in long structures with greater thermal movements, high traffic counts, and lively spans.

If the isolator units are for low-temperature areas, then 10 percent of the test shall be performed at temperatures of 20, 5, –5, or –15 degrees F (–7, –15, –21, –26 degrees C) for temperature zones A, B, C, and D, respectively.

In lieu of the low-temperature test criteria, the components may be tested for a cumulative travel of twice the calculated service displacements or twice the values above when approved by the engineer.

15.10.2 Prototype Tests

The deformation characteristics and damping values of the isolation system used in the design and analysis shall be verified by prototype tests. Tests on similarly sized isolator units may be used to satisfy the requirements of this section. Such tests must validate design properties that can be extrapolated to the actual sizes used in the design.

Prototype tests shall be performed on a minimum of two full-size specimens of each type and size similar to that used in the design. The test specimens shall include the elastic restraint system if such a system is used in the design. Prototype test specimens may be used in construction, if they have the specified stiffness and damping properties and they satisfy the project quality control tests after having successfully completed all prototype tests. All sacrificial elements shall be replaced prior to use.

Reduced-scale prototype specimens will only be allowed when full-scale specimens exceed the capacity of existing testing facilities and approval is granted by the engineer of record.

If reduced-scale prototype specimens are used to quantify properties of isolator units, specimens shall be geometrically similar and of the same type and material. The specimens shall also be manufactured with the same processes and quality as full-scale prototypes, and shall be tested at a frequency that represents full-scale prototypes.

The following sequence of tests shall be performed for the prescribed number of cycles at a vertical load similar to the typical or average dead load on the isolator units of a common type and size. The design displacement for these tests is defined in Article 15.4.

Test 1, Thermal – Three fully reversed cycles of loads at a lateral displacement corresponding to the maximum thermal displacement. The test velocity shall not be less than 0.003 inches per minute.

Test 2, Wind and Braking – Twenty fully reversed cycles between limits of plus and minus the maximum load for a total duration not less than 40 seconds. After the cyclic testing, the maximum load shall be held for 1 minute.

Test 3, Seismic – Three fully reversed cycles of loading at each of the following multiples of the total design displacement: 1.0, 0.25, 0.50, 0.75, 1.0, and 1.25, in the sequence shown.

Test 4, Seismic – 20 cycles of loading at 1.0 times the design displacement. The test shall be started from a displacement equal to the offset displacement.

Test 5, Wind and Braking – Three fully reversed cycles between limits of plus and minus the maximum load for a total duration not less than 40 seconds. After the cyclic testing, the maximum load shall be held for 1 minute.

Test 6, Seismic Performance Verification – Three fully reversed cycles of loading at the total design displacement.

Test 7, Stability Verification – The vertical load-carrying elements of the isolation system shall be demonstrated to be stable under one fully reversed cycle at the displacements given in Article 15.4. In these tests, the combined vertical load of

$$1.2\,D + LL_S + OT \qquad (15.10.2\text{-}1)$$

shall be taken as the maximum downward force, and the combined vertical load of

$$0.8\,D - OT \qquad (15.10.2\text{-}2)$$

shall be taken as the minimum downward force.

- If a sacrificial elastic restraint system is utilized, then its ultimate capacity shall be established by test.
- The prototype and quality control tests shall include all components that comprise the isolation system.
- For systems that are not restrained to perform unidirectionally, Test 6 shall be performed in the direction of loading orthogonal to the original direction of loading. For systems that include unidirectional devices, or those that are sensitive to orthogonal effects, Test 6 shall be repeated at 45 degrees to the primary axis of the unidirectional device.
- The force-deflection properties of an isolator unit shall be considered to be dependent on the rate of loading if there is greater than a plus or minus 15-percent difference in either K_d or Q_d for the test at

the design displacement when dynamically tested at any frequency in the range of 0.5 to 1.5 times the inverse of the effective period of the isolated structure.

If the force-deflection properties of the isolator units are dependent on the rate of loading, then each set of tests specified in Article 15.10.2 shall be performed dynamically at a frequency equal to the inverse of the effective period of the isolated structure. If the test can not be performed dynamically, then a l factor must be established that relates properties K_d or Q_d determined at the actual speed of testing with the dynamic velocities in accordance with Article 15.5.2.1.

15.10.3 Determination of System Characteristics

(a) The force-deflection characteristics of the isolation system shall be based on the cyclic load test results for each fully reversed cycle of loading.

(b) The effective stiffness of an isolator unit shall be calculated for each cycle of loading as follows:

$$k_{eff} = \frac{F_p - F_n}{\Delta_p - \Delta_n} \qquad (15.10.3\text{-}1)$$

where Δ_p and Δ_n are the maximum positive and maximum negative test displacements, respectively, and F_p and F_n are the maximum positive and maximum negative forces at instance of displacements Δ_p and Δ_n, respectively.

(c) Equivalent Damping. The equivalent viscous damping ratio (ß) of the isolation system shall be calculated as

$$\beta = \frac{1}{2\pi} \times \frac{\text{Total EDC Area}}{\sum\left(k_{eff}\Delta_i^2\right)} \qquad (15.10.3\text{-}2)$$

The total EDC area shall be taken as the sum of the areas of the hysteresis loops of all isolator units. The hysteresis loop area of each isolator unit shall be taken as the minimum area of the three hysteresis loops established by the cyclic tests in Test 3 of Article 15.10.2 at a displacement amplitude equal to the design displacement.

15.10.3.1 System Adequacy

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

- The force-deflection plots, excluding any viscous damping component, of all tests specified in Article 15.10.2 show a positive incremental force-carrying capacity consistent with the requirements of Article 15.9.2.

- For Test 1, the maximum measured force shall be less than the design value.

- For Tests 2 and 5, the maximum measured displacement shall be less than the design value.

- The average effective stiffness measured in the last three cycles to the total design displacement specified in Test 3 shall lie within 10 percent of the value used in design.

For each test displacement level specified for Test 3, the minimum effective stiffness measured during the three cycles shall not be less than 80 percent of the maximum effective stiffness.

For Test 4, the minimum effective stiffness measured during the specified number of cycles shall not be less than 80 percent of the maximum effective stiffness. At the discretion of the engineer, a larger variation may be accepted, provided that both the minimum and maximum values of effective stiffness are used in the design.

- For Test 4, the minimum EDC measured during the specified number of cycles shall not be less than 70 percent of the maximum EDC. At the discretion of the engineer, a larger variation may be accepted, provided that both the minimum and maximum values of EDC are used in the design.

All vertical load-carrying elements of the isolation system shall remain stable (positive incremental stiffness) at the displacements specified in Article 15.9.3 for static loads as prescribed for Test 7.

Test specimens shall be visually inspected for evidence of significant deterioration. If any deterioration exists, then the adequacy of the test specimen shall be determined by the engineer.

15.11 ELASTOMERIC BEARINGS

15.11.1 General

The following shall be considered supplemental to Section 14 of the LRFD provisions.

Elastomeric bearings utilized in implementing seismic isolation design shall be designed by the procedures and specifications given in the following subsections. Additional test requirements for seismic isolation bearings are given in Article 15.12. The design procedures are based on service loads excluding impact. The elastomeric bearings must be reinforced using steel reinforcement. Fabric reinforcement is not permitted.

15.11.2 Shear Strain Components for Isolation Design

The various components of shear strain in the bearing shall be computed as follows:

- Shear strain (γ_c) due to compression by vertical loads is given by

$$\gamma_c = \frac{3SP}{2A_r G(1+2\bar{k}S^2)} \qquad (15.11.2\text{-}1)$$

if $S \leq 15$, or

$$\gamma_c = \frac{3P(1+8G\bar{k}S^2/K)}{4G\bar{k}SA_r} \qquad (15.11.2\text{-}2)$$

if $S > 15$,

where K is the bulk modulus of the elastomer. In absence of measured data, K may be taken as 300,000 psi (2,000 MPa). The shape factor S shall be taken as the plan area of the elastomer layer divided by the area of perimeter free to bulge.

- Shear strain ($\gamma_{s,s}$) due to imposed non-seismic lateral displacement is given by

$$\gamma_{s,s} = \frac{\Delta_s}{T_r} \qquad (15.11.2\text{-}3)$$

- Shear strain ($\gamma_{s,eq}$) due to earthquake-imposed lateral displacement is given by

$$\gamma_{s,eq} = \frac{\Delta_t}{T_r} \qquad (15.11.2\text{-}4)$$

- Shear strain (γ_r) due to rotation is given by

$$\gamma_r = \frac{B_d^2\theta}{2t_i T_r} \qquad (15.11.2\text{-}5)$$

The design rotation (θ) shall include the rotational effects of DL, LL, and construction.

15.11.3 Load Combinations

Elastomeric bearings shall satisfy

$$\gamma_c \leq 2.5 \qquad (15.11.3\text{-}1)$$

$$\gamma_c + \gamma_{s,s} + \gamma_r \leq 5.0 \qquad (15.11.3\text{-}2)$$

$$\gamma_c + \gamma_{s,eq} + 0.5\,\gamma_r \leq 5.5 \qquad (15.11.3\text{-}3)$$

15.12 ELASTOMERIC BEARINGS – CONSTRUCTION

15.12.1 General Requirements

The following shall be considered supplemental to article 18.2 of the AASHTO Standard Specifications (Division II). The provision of Article 15.12.2 replaces those in articles 18.2.7.6, 18.2.7.7, and 18.2.7.8 of the AASHTO Standard Specifications (Division II).

The layers of elastomeric bearings used in seismic isolation shall be integrally bonded during vulcanization. Cold bonding is not allowed.

15.12.2 Quality Control Tests

The following quality control tests shall also be performed on elastomeric bearings.

15.12.2.1 Compression Capacity

A 5-minute sustained proof load test shall be conducted on each bearing. The compressive load for the test shall be 1.5 times the maximum (dead load plus live load). If bulging suggests poor laminate bond, the bearing shall be rejected.

15.12.2.2 Combined Compression and Shear

All bearings shall be tested in combined compression and shear. The bearings may be tested in pairs. The compressive load shall be the average dead load of all bearings of that type, and the bearings shall be subjected to five fully reversed cycles of loading at the larger of the total design displacement or 50 percent of the elastomer thickness.

For each bearing, the effective stiffness and EDC shall be averaged over the five cycles of the test. For each group of similar bearings of the same type and size, the effective stiffness and EDC shall be averaged. The results shall not differ from the design values by more than the limits given in Table 15.12.2.2-1.

Table 15.12.2.2-1

	K_{eff}	EDC
Individual Bearings	±20%	–25%
Average of Group	±10%	–15%

15.12.2.3 Acceptance Criteria

After quality control testing, all bearings shall be visually inspected for defects. The following faults shall be cause for rejection:

- Lack of rubber-to-steel bond.
- Laminate placement fault.
- Surface cracks on the rubber that are wider or deeper than 2/3 of the rubber cover thickness.
- Permanent deformation.

15.13 SLIDING BEARINGS – DESIGN

15.13.1 General

Sliding bearings used in isolation systems may use flat or curved surfaces.

15.13.2 Materials

15.13.2.1 PTFE Bearing Liners

All PTFE surfaces, other than guides, shall satisfy the requirements specified herein. The PTFE bearing liner shall be made from virgin PTFE resin satisfying the requirements of ASTM D1457. It may be fabricated as unfilled sheet, filled sheet, or fabric woven from PTFE and other fibers.

Unfilled sheets shall be made from PTFE resin alone. Filled sheets shall be made from PTFE resin uniformly blended with glass fibers, carbon fibers, or other chemically inert reinforcing fibers.

Sheet PTFE may contain dimples to act as reservoirs for lubricant. Their diameter shall not exceed 0.32 inch (8 mm) at the surface of the PTFE and their depth shall be not less than 0.08 inch (2 mm) and not more than half the thickness of the PTFE. The reservoirs should cover more than 20 percent, but less than 30 percent of the contact surface. Dimples should not be placed to intersect the edge of the contact area. Lubricant shall be silicone grease, effective to –30½ F (–34º C). Silicone grease shall conform to Military specification MIL-S-8660.

15.13.2.2 Other Bearing Liner Materials

Other materials may be used for the bearing liner if test results demonstrate a stable long-term coefficient of friction, chemical stability, and wear resistance in accordance with Article 15.10.1.2, and are approved by the engineer.

15.13.2.3 Mating Surface

Mating surfaces shall be stainless steel (welded overlay, solid, or sheet metal). Stainless steel shall have a corrosion resistance and strength equal to or exceeding type 304, conforming to ASTM A167/A264. The average surface roughness shall not exceed 32 micro inches (0.8 micro meters) R_a (arithmetic average) as determined by procedures described in ANSI/ASME B46.1-1985 (ASME, 1985).

15.13.3 Geometry

15.13.3.1 Minimum Thickness

15.13.3.1.1 PTFE Bearing Liner

The minimum thickness for PTFE shall be at least 0.0625 inch (1.6 mm) after compression. Recessed sheet PTFE shall be at least 0.1875 inch (4.8 mm) thick when the maximum dimension of the PTFE is less than or equal to 24.0 inches (610 mm), and 0.25 inch (6.4 mm) when the maximum dimension of the PTFE is greater than 24.0 inches (610 mm). Woven fabric PTFE shall have, after compression, a minimum thickness of 0.0625 inch (1.6 mm) and a maximum thickness of 0.125 inch (3.2 mm).

15.13.3.1.2 Other Bearing Liner Materials

The minimum thickness for all other bearing liners shall be determined by conducting wear tests in accordance with Article 15.10.1.2.

15.13.3.2 Mating Surface

The thickness of the stainless steel mating surface sheet shall be at least 16 gauge when the maximum dimension of the surface is less than or equal to 12.0 inches (305 mm), and at least 13 gauge when the maximum dimension is larger than 12.0 inches (305 mm) and less than or equal to 36.0 inches (915 mm). When the maximum dimension is larger than 36.0 inches (915 mm), the thickness of the stainless steel mating surface shall be verified by performance of suitable system characterization tests.

The minimum thickness of stainless steel weld overlays shall be 3/32 inch (2.4 mm) thick after welding, grinding, and polishing.

15.13.3.3 Displacement Capacity

The mating surface dimensions shall be large enough to ensure that the sliding surface does not come into contact with the edge of the mating surface at the total design displacement plus the offset displacement.

15.13.4 Loads and Stresses

15.13.4.1 Contact Pressure

Contact stresses for bearing liners shall be established by testing. Test pressures shall be at least 110 percent of the value used in design and must satisfy the wear requirements in Article 15.10.1.2. As a minimum, 50 percent of the usable bearing liner thickness must remain after completion of the wear test. Allowable contact stresses for PTFE liners tabulated in Table 15.13.4.1-1 may be used without completing the wear test, provided that the stainless steel mating surface has a surface roughness less than 20 micro inches (0.5 micro meter) Ra.

Table 15.13.4.1-1
Allowable Average Contact Stress for PTFE

Material	Allowable Contact Stress					
	Service Loads				Seismic Loads	
	Average Stress		Edge Stress		Average Stress	
	ksi	MPa	ksi	MPa	ksi	MPa
Unfilled sheets (recessed)	3.5	24	5.0	34	6.0	41
Filled sheets (recessed)	3.5	24	5.0	34	6.0	41
Woven PTFE fiber over a metallic substrate	3.5	24	10.0	69	6.0	41

15.13.4.2 Coefficient of Friction

15.13.4.2.1 Service Coefficient of Friction

The service limit state coefficient of friction of the PTFE sliding surface shall be taken as specified in Table 15.13.4.2.1-1. Intermediate values may be determined by interpolation. The coefficient of friction shall be determined by using the stress level associated with the service load combination specified in Table 3.4.1-1. Different values may be used if verified by tests and adjusted by the appropriate λ values in accordance with Article 15.5.

Table 15.13.4.2.1-1 Service Coefficients of Friction

Type of Surface	Temp.		Average Bearing Stress				
			0.5	1.0	2.0	≥3.0	ksi
	°F	°C	3.5	6.9	13.8	20.7	MPa
Dimpled lubricated PTFE sheets	68	20	0.04	0.03	0.025	0.02	
	–13	–25	0.06	0.045	0.04	0.03	
	–49	–45	0.10	0.075	0.06	0.05	
Unfilled PTFE sheets	68	20	0.08	0.07	0.05	0.03	
	–13	–25	0.20	0.18	0.13	0.10	
	–49	–45	0.20	0.18	0.13	0.10	
Filled PTFE sheets	68	20	0.24	0.17	0.09	0.06	
	–13	–25	0.44	0.32	0.25	0.20	
	–49	–45	0.65	0.55	0.45	0.35	
Woven PTFE fiber	68	20	0.08	0.07	0.06	0.045	
	–13	–25	0.20	0.18	0.13	0.10	
	–49	–45	0.20	0.18	0.13	0.10	

Service coefficients of friction for other surface finishes, stresses, and bearing liners shall be established by testing. The testing procedures and results shall be subject to the approval of the engineer.

15.13.4.2.2 Seismic Coefficient of Friction

The seismic coefficient of friction may be determined from the area under the force displacement loops of three cycles divided by the total travel distance and vertical load (Q_d/vertical load).

15.13.5 Other Details

15.13.5.1 Bearing Liner Attachment

All sheet PTFE shall be recessed for one-half of its thickness and bonded into a metal backing plate.

All bearing liners shall be attached to resist a shear force of 0.15 times the applied compressive force or 2 times Q_d, whichever is greater.

15.13.5.2 Mating Surface Attachment

The mating surface for the bearing liner shall be attached to a backing plate by welding or other suitable means in such a way that it remains free of undulations and in full contact with its backing plate throughout its service life. The attachment shall include an effective moisture seal around the entire perimeter of the mating surface to prevent interface corrosion. The attachment shall be capable of resisting the maximum friction force that can be developed by the bearing under service limit state and seismic load combinations. The welds used for the attachment shall be clear of the contact and sliding area of the bearing liner.

15.13.6 Materials for Guides

Bearing guides may be made from materials not described in Article 15.13.2. The materials used shall have sufficient strength, stiffness, and resistance to creep and decay to ensure the proper functioning of the guide throughout its design life.

15.14 SLIDING BEARINGS – CONSTRUCTION

15.14.1 General Requirements

Isolator units that use sliding bearings shall be constructed in accordance with the applicable provisions of articles 18.4 and 18.8.2 of the AASHTO Standard Specifications (Division II).

15.14.2 Quality Control Tests

The following quality control tests shall also be performed on sliding isolation bearings.

15.14.2.1 Compression Capacity

A 5-minute sustained proof load test shall be conducted on each bearing. The compressive load for the test shall be 1.5 times the maximum (dead load plus live load). If flow of the bearing liner suggests inadequate bonding, or it leaves a permanent deformation in the mating surface, the bearing shall be rejected.

15.14.2.2 Combined Compression and Shear

All bearings shall be tested in combined compression and shear. The bearings may be tested in pairs. The compressive load shall be the average dead load of all bearings of that type, and the bearings shall be subjected to five fully reversed cycles of loading at the total design displacement.

For each bearing, the effective stiffness and EDC shall be averaged over the five cycles of the test. For each group of similar bearings of the same type and size, the effective stiffness and EDC shall be averaged. The results shall not differ from the design values by more than the limits given in table 15.12.2.2-1.

15.14.2.3 Acceptance Criteria

After quality control testing, all bearings shall be visually inspected and, if applicable, disassembled and inspected for defects. The following faults shall be cause for rejection:

(1) Lack of bearing-liner-to-metal bond.

(2) Scoring of stainless steel plate.

(3) Permanent deformation.

(4) Leakage.

15.15 OTHER ISOLATION SYSTEMS

15.15.1 Scope

All isolation units or systems that contain a flexible element, restoring force capacity, and energy dissipation capacity, and that are not covered in Articles 15.11 to 15.14 of this specification, shall be subject to the requirements of this section and approved by the engineer.

Isolation bearings that depend on a metal roller element for lateral displacement shall satisfy the requirements of Article 14.7.

Acceptance of the system shall be based on satisfying the requirements of Articles 15.15.2 through 15.15.6.

Materials used for contact surfaces, such as sliding or rolling elements, shall be selected so as to provide the least possible change in those properties over time.

15.15.2 System Characterization Tests

The characteristics of the isolation system that are used in design shall be verified by tests and approved by the engineer. At a minimum, the following tests shall be conducted:

- Lateral load tests to determine properties and capacities in accordance with tests prescribed in the NIST report (National Institute of Standards and Technology 1996; ASCE Standards Committee on Testing of Base Isolation Systems 1996) or HITEC report (Highway Innovation Technology Center 1996).

- Shaking table tests at a scale no less than 1/4 full scale. Scale factors must be well-established and approved by the engineer.

- Tests to investigate the variations in system properties and their effects on response. At a minimum, the effects on temperature, rate-dependency, prior loading (including wear), and environmental effects shall be investigated. Values for λ_{min} and λ_{max}, similar to those defined in Article 15.5, shall be developed from these tests.

In addition to the foregoing test data, information from previous field experience in other applications may be used to demonstrate the system characteristics.

For all tests, no adjustments to the system may be made except those that are explicitly included in the maintenance plan, which must be given to the engineer prior to the start of prototype testing.

15.15.3 Design Procedure

A complete, rational design procedure for the isolation system shall be provided to the engineer prior to the start of the prototype testing defined in section 18.5. This procedure shall include

- the basis for the selection of the limiting material stresses, deformations, or other critical response quantities;
- the method for predicting the cyclic load deformation relationship of the system; and
- the method for predicting the stability limit of the system.

At least one design example shall be submitted with the design procedure, including the calculations for obtaining the maximum force response and maximum displacement response.

15.15.4 Fabrication, Installation, Inspection, and Maintenance Requirements

All special requirements for fabrication, installation, inspection, and maintenance shall be submitted, in writing, to the engineer prior to the start of prototype testing. At a minimum, these shall include

- materials to be used and the specifications they must satisfy,
- any special material testing requirements,
- fabrication sequence and procedures,
- fabrication tolerances and surface finish requirements,
- any special handling requirements,
- installation procedures and tolerances, and
- maintenance requirements, including a schedule for replacement of any components, for the lifetime of the system.

15.15.5 Prototype Tests

Prototype testing shall be conducted for each job in order to demonstrate that the design achieves the performance requirements set out in the job specifications. Insofar as possible, the tests shall conform to those defined in Article 15.10.2. The engineer may, at his or her discretion, require additional tests to verify particular characteristics of the system.

Prior to the start of testing, design values for critical response quantities shall be submitted to the engineer, and the engineer shall establish criteria for accepting the system on the basis of the prototype tests. At a minimum, those criteria shall include permissible variations from the design values of the resistance and energy dissipation at critical displacements, velocities, or accelerations.

15.15.6 Quality Control Tests

Quality control testing shall be conducted on every bearing. Test requirements and acceptance requirements shall be established by the engineer.

15.15.6.1 Compression Capacity

A 5-minute sustained proof load test shall be conducted on each bearing. The compressive load for the test shall be 1.5 times the maximum (dead load plus live load).

15.15.6.2 Combined Compression and Shear

All bearings shall be tested in combined compression and shear. The bearings may be tested in pairs. The compressive load shall be the average dead load of all bearings of that type, and the bearings shall be subjected to five fully reversed cycles of loading at the total design displacement.

15.15.6.3 Acceptance Criteria

Acceptance criteria for requirements specified in this section shall be determined by the engineer.

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