

AMERICAN ASSOCIATION OF
STATE HIGHWAY AND
TRANSPORTATION OFFICIALS

AASHTO
THE VOICE OF TRANSPORTATION

GUIDE SPECIFICATIONS FOR

SEISMIC ISOLATION DESIGN

4TH EDITION



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PREFACE TO THE THIRD EDITION, 2010

This 2010 Edition of the *Guide Specifications for Seismic Isolation Design* updates the 1999 Edition by addressing major changes in the way seismic hazard is now defined in the United States, as well as changes in the state of the art of seismic isolation design for highway bridges. This Edition is based on the work of NCHRP Project 20-7, Task 262.

In summary, this revised edition reflects (a) changes in the definition of the seismic hazard as now defined in the AASHTO *LRFD Bridge Design Specifications* (hereafter referred to as the Design Specifications) and the *Guide Specifications for LRFD Seismic Bridge Design* (hereafter referred to as LRFD Seismic); (b) designer experience in the last 10 yr with the implementation of the current specifications; (c) industry trends in the design and construction of isolators; (d) the sun-setting of the AASHTO *Standard Specifications for Highway Bridges*; and (e) provisions in the Design Specifications that impact the design and testing of isolation bearings, such as in Section 14, Bearings and Expansion Joints. Major changes therefore include:

1. The seismic hazard section has been updated to be compatible with the Design Specifications and LRFD Seismic. Previous Section 3, Acceleration Coefficient, and Section 5, Site Effects and Site Coefficients, have been collapsed into a new Section 3, Seismic Hazard, to make way for a new Section 4, Design Response Spectrum, after moving seismic performance categories to Section 5. This new section presents the design spectrum in a new figure (taken from the Design Specifications and LRFD Seismic), and is used to define spectral accelerations S_{DS} and S_{D1} . There is one exception to the general rule of compatibility with the Design Specifications. Design Specifications, Article 3.10.2 requires a site-specific procedure be used if “long-duration effects are expected in the region.” This provision is not in LRFD Seismic and has not been included in these Guide Specifications (Article 3.1).
2. The requirement that the acceleration coefficient (A) for the design of isolated bridges shall not be less than 0.1 has been deleted (Article 3.1).
3. Eq. 3 for displacement, d , (now Eq. 7.1-4) has been changed to be a function of S_1 rather than peak ground acceleration (A) since maps of S_1 are now available. At the same time, the site coefficient in the expression for d was updated from S_i to F_v , and the dual units expression was replaced with one that is independent of the unit of measurement.
4. The previous Table 7.1-1 for the Damping Coefficient, B (now labeled B_L), has been replaced by an expression directly relating B_L to the viscous damping ratio ξ . The values for B_L given by this expression are almost identical to those in Table 7.1-1 over the full range of ξ . The advantage of the expression, however, is that it avoids linear interpolation to find B_L for values of ξ that are not listed in the Table.
5. Eqs. 20 and 21 for the shear strain in a bonded layer of elastomer due to a compressive load have been replaced by a single equation (Eq. 14.2.1-1) that is applicable over the full range of shape factors. This equation is consistent with the recently revised provisions in the Design Specifications for steel-reinforced elastomeric bearings (Design Specifications, Article 14.7.5). Likewise, the expression for shear strain due to rotation in Eq. 24 (now Eq. 14.2.4-1) has been updated to be consistent with the Design Specifications provisions.
6. The non-seismic requirements for elastomeric bearings (i.e., service limit states) in Design Specifications, Section 14 have recently been updated and the corresponding provisions in these Guide Specifications (Article 14.3) now reference the Design Specifications.
7. Some testing requirements for isolation hardware have been deleted or relaxed if they were judged to be redundant, no longer necessary based on experience with current isolator manufacturers, or unrealistically burdensome and no longer serving a useful purpose.
8. Additional commentary is given to clarify such terms as *design displacement*, which is used for calculating the effective stiffness of an isolator, and *total design displacement* (TDD), which is used for design and specifying the testing requirements for an isolator.
9. Editorial updates/corrections have been made to ensure compatibility with the style and format of the Design Specifications as far as possible. All references to the Standard Specifications have been replaced by corresponding references to the Design Specifications and, where appropriate, to LRFD Seismic.
10. The uniform load method of analysis (Article 7.1) has been renamed the simplified method to better reflect the nature of the method and avoid confusion with the uniform load method given in the Design Specifications and LRFD Seismic.
11. Portions of Article C7 have been determined to be more appropriate to Article 8.1.2 and have been moved accordingly. Portions of Article C7.1 contain mandatory language and have been moved to Article 7.1 in this edition of the Guide Specifications.

PREFACE TO THE FOURTH EDITION, 2014

This Fourth Edition (2014) of the *Guide Specifications for Seismic Isolation Design* updates the Third Edition (2010) principally by the addition of a set of design examples in Appendix B.

Today, about 200 bridges have been designed and constructed in the U.S. using the AASHTO *Guide Specifications for Seismic Isolation Design* but this figure is a fraction of the potential number of applications and falls far short of the number of isolated bridges in other countries.

One of the major barriers to implementation is that isolation is a significant departure from conventional seismic design and one that is not routinely taught in university degree courses. Furthermore, very few text books on this topic have been published and those that are available focus on applications to buildings rather than bridges. The absence of formal instruction and lack of reference material mean that many designers are not familiar with the approach and uncomfortable using the technique, despite the potential for significant benefits.

In an effort to correct this situation, fourteen design examples were developed to illustrate the design process and the design of related isolation hardware in accordance with the Guide Specifications. This work was funded under NCHRP 20-7, Task 262.

These design examples are included in Appendix B and illustrate the application of seismic isolation to a range of bridges for varying seismic hazard, site classification, isolator type, and bridge type. In general, each example illustrates the suitability of the bridge for isolation (or otherwise), and presents calculations for preliminary design using the Simplified Method of analysis, preliminary and final isolator design, and detailed analysis using the Multimode Spectral Analysis procedure. However, design of the superstructure, substructure (piers), and foundations is not covered.

In addition to the inclusion of a new Appendix B, a number of editorial corrections have been made to the Guide Specifications, to improve readability and correct typographical errors.

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GUIDE SPECIFICATIONS FOR SEISMIC ISOLATION DESIGN

FOURTH EDITION, 2014

1—APPLICABILITY

This document presents Guide Specifications for the seismic isolation design of highway bridges and is supplemental to the *AASHTO LRFD Bridge Design Specifications* (the Design Specifications) and the *AASHTO Guide Specifications for LRFD Seismic Bridge Design* (LRFD Seismic). Fundamental requirements for seismic isolation design are provided.

Information provided herein for bearings used in implementing seismic isolation design are supplemental to Design Specifications, Section 14. These provisions are necessary to provide a rational design procedure for isolation systems incorporating the displacements resulting from seismic response. If a conflict arises between the provisions of these Guide Specifications and those in the Design Specifications or LRFD Seismic, or both, the provisions contained herein govern.

These Guide Specifications are intended for isolation systems that are essentially rigid in the vertical direction and therefore isolate in the horizontal plane only. In addition, these Guide Specifications are intended for isolation systems that do not have active or semi-active components.

C1

These guidelines incorporate the generic requirements for seismic isolation design.

Isolating structures from the damaging effects of earthquakes is not a new idea. The first patents for base isolation schemes were obtained nearly 130 yr ago but, until the past three decades, few structures were built using these ideas (Buckle and Mayes, 1990). Early concerns were focused on the displacements at the isolation interface. These have been largely overcome with the successful development of mechanical energy dissipators. When used in combination with a flexible device such as an elastomeric bearing, an energy dissipator can control the response of an isolated structure by limiting both the displacements and the forces. Interest in seismic isolation as an effective means of protecting bridges from earthquakes has therefore been revived in recent years. To date there are several hundred bridges in New Zealand, Japan, Italy, and the United States using seismic isolation principles and technology for their seismic design (Buckle et al., 2006b).

Seismically isolated structures have performed as expected in recent earthquakes and records from these structures show good correlation between the analytical prediction and the recorded performance.

The basic intent of seismic isolation is to increase the fundamental period of vibration such that the structure is subjected to lower earthquake forces. However, the reduction in force is accompanied by an increase in displacement demand that must be accommodated within the flexible mount.

The three basic elements in seismic isolation systems that have been used to date are:

- A vertical-load carrying device that provides lateral flexibility so that the period of vibration of the total system is lengthened sufficiently to reduce the force response;
- A damper or energy dissipator so that the relative deflections across the flexible mounting can be limited to a practical design level; and
- A means of providing rigidity under low (service) load levels, such as wind and braking forces.

Flexibility—Elastomeric and sliding bearings are two ways of introducing flexibility into a structure. The typical force response with increasing period (flexibility) is shown schematically in the typical acceleration response curve in Figure C1-1. Reductions in base shear occur as the period of vibration of the structure is lengthened. The extent to which these forces are reduced primarily depends on the nature of the earthquake ground motion and the period of the fixed-base structure.

However, as noted above, the additional flexibility needed to lengthen the period of the structure will increase the relative displacements across the flexible bearing. Figure C1-2 shows a typical displacement response curve from which displacements are seen to increase with increasing period (flexibility).

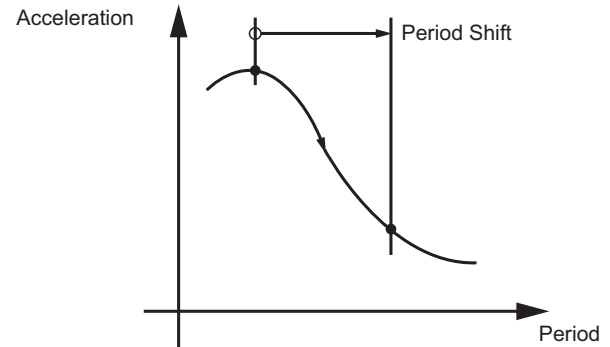


Figure C1-1—Typical Acceleration Response Curve

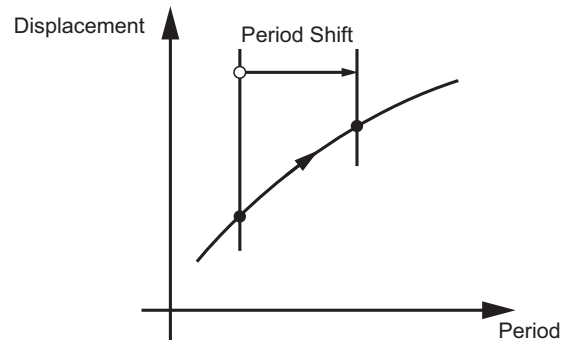
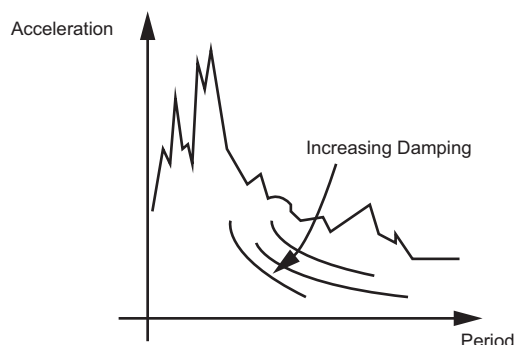
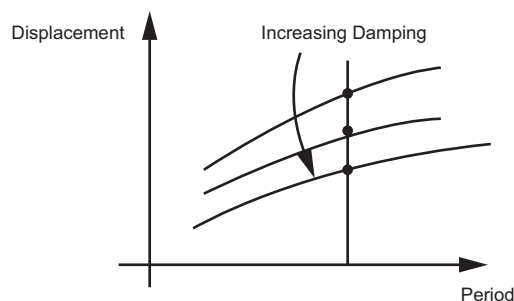


Figure C1-2—Typical Displacement Response Curve

Energy Dissipation—Relative displacements can be controlled if additional damping is introduced into the structure at the isolation level. This is shown schematically in Figure C1-3. Two effective means of providing damping are hysteretic energy dissipation and viscous energy dissipation. The term *viscous* refers to energy dissipation that is dependent on the magnitude of the velocity. The term *hysteretic* refers to the offset between the loading and unloading curves under cyclic loading. Figure C1-4 shows an idealized force-displacement hysteresis loop where the enclosed area is a measure of the energy dissipated during one cycle (*EDC*) of motion.



A—Acceleration Response Spectrum

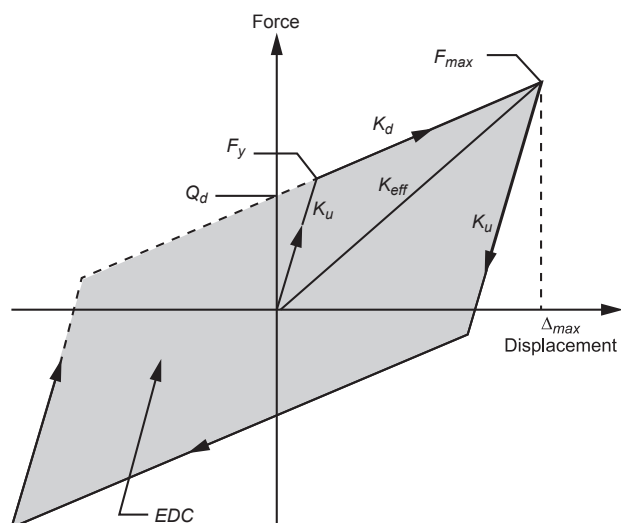


B—Displacement Response Spectrum

Figure C1-3—Response Curves for Increasing Damping

Rigidity under Low Lateral Loads—While lateral flexibility is very desirable for high seismic loads, it is clearly undesirable to have a bridge that will vibrate perceptibly under frequently occurring loads, such as wind or braking. External energy dissipators and modified elastomers may be used to provide rigidity at these service loads by virtue of their high initial elastic stiffness. As an alternative, friction in sliding isolation bearings may be used to provide the required rigidity.

Example—The principles for seismic isolation are illustrated in Figure C1-5. The dashed line is the design response spectrum as specified in the Design Specifications and LRFD Seismic for a bridge in Seismic Zone 4 and Site Class C. The solid line represents the composite response spectrum for an isolated bridge. The period shift provided by the flexibility of the isolation system reduces the spectral acceleration from A_1 to A_2 . The increased damping provided by the isolation system further reduces the spectral acceleration from A_2 to A_3 . Note that spectral accelerations A_1 and A_3 are used to determine forces for the design of conventional and isolated bridges, respectively.



- Q_d = Characteristic strength
- F_y = Yield force
- F_{max} = Maximum force
- K_d = Post-elastic stiffness
- K_u = Elastic (unloading) stiffness
- K_{eff} = Effective stiffness
- Δ_{max} = Maxim bearing displacement
- EDC = Energy dissipated per cycle = Area of hysteresis loop (shaded)

Figure C1-4—Characteristics of Bilinear Isolation Bearings

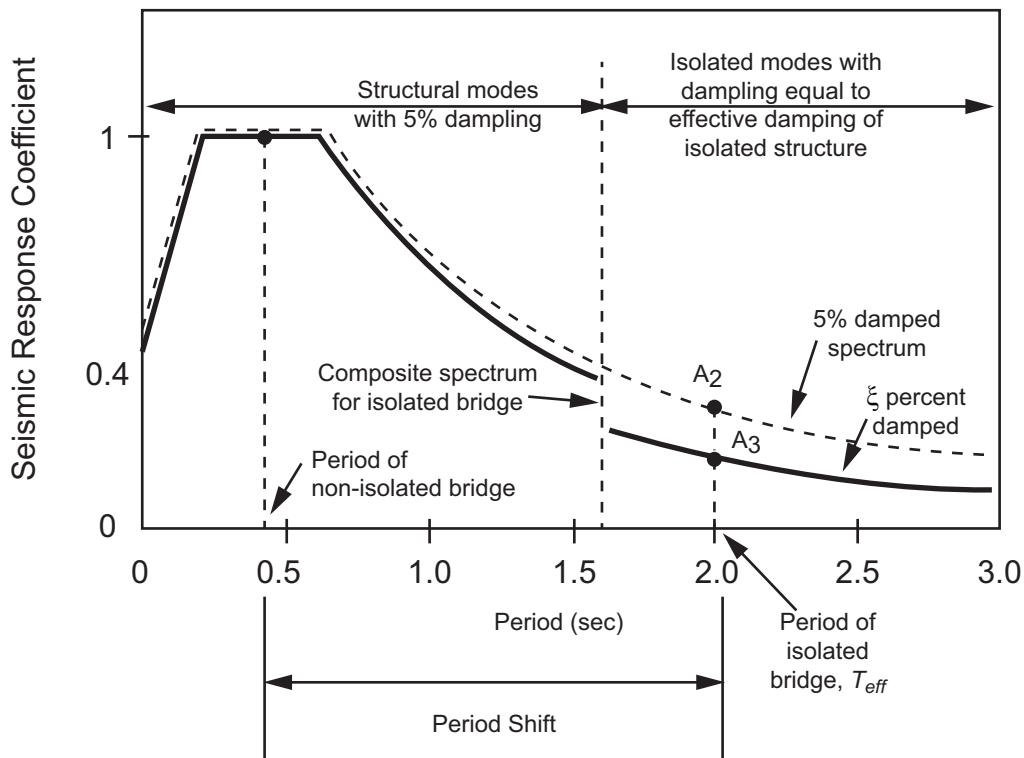


Figure C1-5—Example Design Response Spectrum for Isolated Bridge

2—DEFINITIONS AND NOTATION

2.1—Definitions

The definitions in the Design Specifications, LRFD Seismic, and those given below apply to this document.

Design Displacement—at an isolator is the maximum lateral displacement across an isolator in the longitudinal direction for longitudinal earthquake loading, and in the transverse direction for transverse earthquake loading. It does not include the displacement of the substructure supporting the isolator. This displacement is primarily used to calculate the effective stiffness of each isolator for use in equivalent elastic methods of analysis in either the longitudinal or transverse directions.

Effective Damping—is the value of equivalent viscous damping corresponding to the energy dissipated during cyclic response at the maximum displacement of the center of rigidity of the isolated structure.

Effective Stiffness—is the value of the lateral force at the instant of maximum lateral displacement in the isolation system, or an element thereof, divided by the maximum lateral displacement.

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. The isolation system does not include the substructure and deck.

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 (TDD)—is the governing resultant displacement at an isolator unit obtained from the results of two Load Cases as specified in Design Specifications, Article 3.10.8 (and LRFD Seismic Article 4.4). The resultant isolator displacements for each Load Case are calculated from the specified combinations of the maximum longitudinal and transverse displacements from two analyses, one in the longitudinal direction and the other in the transverse. These displacements include components due to the bidirectional translation of the superstructure and the torsional rotation of the superstructure about the center of rigidity. The TDD is then the largest of the resultant displacements from the two load cases. See Figure 2.1-1.

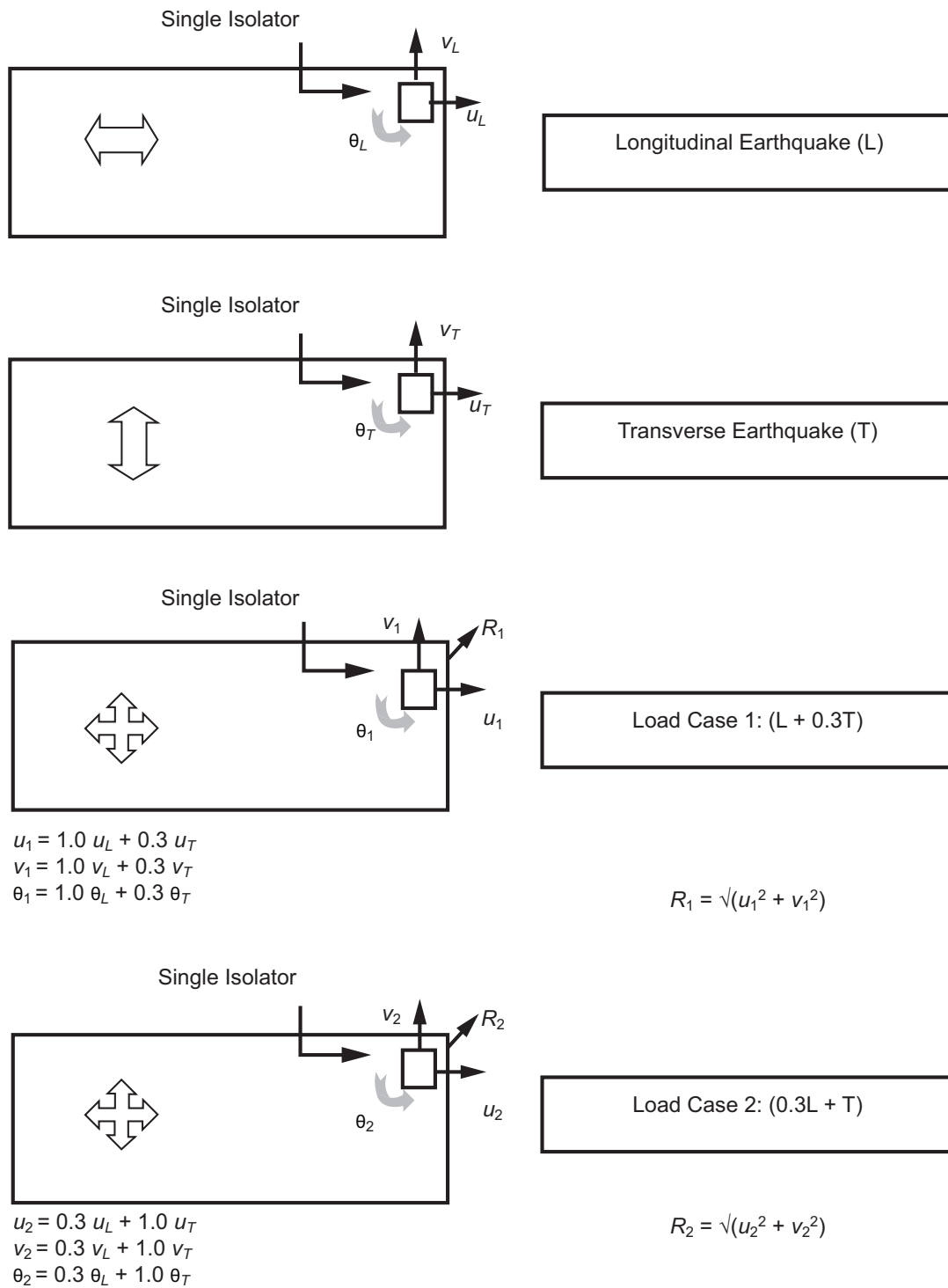


Figure 2.1-1—Plan View of Bridge Showing Displacements of Single Isolator and Derivation of Total Design Displacement (TDD)

2.2—Notation

The notation in the Design Specifications, LRFD Seismic, and that given below apply to this document.

A_b = bonded area of elastomer

A_r = overlap area between the top-bonded and bottom-bonded elastomer areas of displaced bearing (Figure 2.2-1).

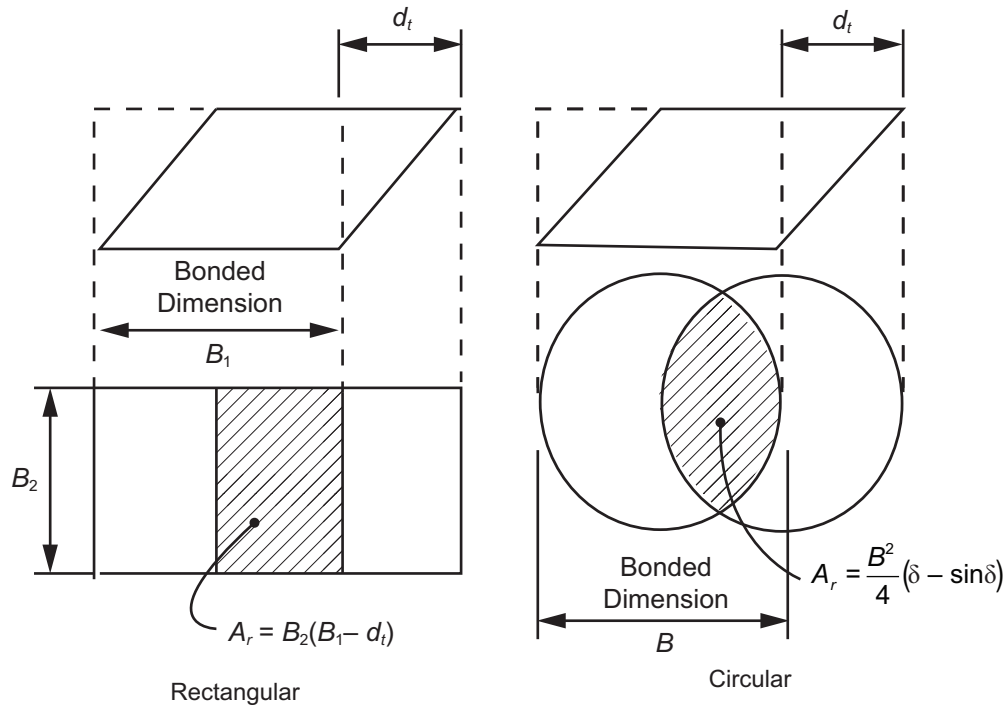


Figure 2.2-1—Overlap Areas for Elastomeric Bearings

B_L = numerical coefficient related to the effective damping of the isolation system in long-period range of the design response spectrum as defined by Eq. 7.1-3

B = bonded plan dimension or bonded diameter in loaded direction of rectangular bearing or diameter of circular bearing (Section 14) (Figure 2.1-1)

C_{sm} = elastic seismic response coefficient at five percent damping

C_{smd} = elastic seismic response coefficient at ξ percent damping

D_c = shape coefficient for shear strains due to compression (14.2.1)

D_r = shape coefficient for shear strains due to rotation (14.2.4)

DL = dead load

d = total deck displacement relative to ground ($d_i + d_{sub}$)

d_a = displacement based on a minimum spectral acceleration coefficient, S_{D1} as defined in Eq. 10-1

d_d = maximum viscous damper displacement

d_i = design displacement across isolator unit in direction of earthquake loading

d_s = offset displacement of the isolator unit, including creep, shrinkage, and 50 percent of the thermal displacement

d_{sub} = substructure displacement

d_t = total design displacement (TDD)

d_y = isolator yield displacement

E = Young's modulus of elastomer

E_c	=	compression modulus of elastomeric layer
EDC	=	energy dissipated per cycle (area of hysteresis loop)
F_a	=	site factor for short-period range of the design response spectrum
F	=	statically equivalent seismic force
F_A	=	design force for connections for bridges in Seismic Zone 1
F_i	=	force in the isolator unit at displacement d_i
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_{pga}	=	site factor at zero-period of design response spectrum
$F_{p, max}$	=	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 factor for long-period range of the design response spectrum
f_1, f_2	=	factors used to calculate maximum force in a viscous damper
G	=	shear modulus of elastomer
lg	=	acceleration due to gravity
K_d	=	second slope stiffness of the bilinear hysteresis curve
K_{eff}	=	sum of the effective linear stiffnesses of all bearings and substructures supporting the superstructure segment as calculated at displacement d_i for the bearings and displacement d_{sub} for the substructure
k_{eff}	=	effective stiffness of an isolator unit determined by prototype testing
$k_{eff, di}$	=	effective stiffness of the isolator unit calculated at displacement d_i
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 factor depicted in Figure 7.1-1 for substructure unit (7.1)
LL	=	live load
LL_s	=	seismic live load; shall be determined by the Engineer as a percentage of the total live load considered applicable for the design. Typically live load is not considered in Extreme Event I of the Design Specifications and LRFD Seismic. However, since isolated structures are generally more flexible than non-isolated bridges, the additional mass from the live load may need to be considered when calculating the period of the isolated bridge and the displacements in the isolators
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) using a γ factor of one
PGA	=	peak ground acceleration coefficient on rock (Site Class B)
Q_d	=	characteristic strength of the isolator unit. It is the ordinate of the hysteresis loop at zero bearing displacement. Refer to Figure C1-4
S	=	shape factor of elastomeric layer
S_1	=	horizontal response spectral acceleration coefficient at 1.0-s period on rock (Site Class B)

S_A	=	spectral acceleration
S_D	=	spectral displacement
S_{D1}	=	horizontal response spectral acceleration coefficient at 1.0-s period modified by long-period site factor
S_{DS}	=	horizontal response spectral acceleration coefficient at 0.2-s period modified by short-period site factor
S_S	=	horizontal response spectral acceleration coefficient at 0.2-s period on rock (Site Class B)
T_0	=	reference period used to define spectral shape (s)
T_{eff}	=	period of seismically isolated structure in the direction under consideration
T_m	=	period of vibration of m th mode (s)
T_r	=	total elastomer thickness
T_S	=	corner period at which spectrum changes from being independent of period to being inversely proportional to period (s)
t_i	=	thickness of elastomer layer number i , which is equivalent to the first definition of the term h_{ri} in Design Specifications Article 14.3
W	=	total vertical load for design of the isolation system ($DL + LL_s$)
Δ	=	shear deformation in isolator
Δ_n	=	maximum negative displacement of an isolator unit during each cycle of prototype testing
Δ_p	=	maximum positive displacement of an isolator unit during each cycle of prototype testing
Δ_s	=	shear deformation of isolator from non-seismic displacement of the superstructure (including temperature, shrinkage, and creep)
ξ	=	equivalent viscous damping ratio for the isolation system
ξ_d	=	portion of equivalent viscous damping ratio contributed by viscous dampers
ξ_i	=	equivalent viscous damping ratio for isolator
γ_c	=	shear strain due to vertical loads
$\gamma_{s,eq}$	=	shear strain due to the total design displacement (TDD), d_t
$\gamma_{s,s}$	=	shear strain due to maximum horizontal displacement resulting from creep, post-tensioning, shrinkage, and thermal effect computed between the installation temperature and the least favorable extreme temperature
γ_r	=	shear strain due to imposed rotation
ϵ_c	=	compression strain in bearing due to vertical loads
ϵ_u	=	minimum elongation-at-break of elastomer
σ_s	=	average compressive stress in elastomeric bearing
θ	=	rotation imposed on bearing
λ_a	=	aging effects factor (including corrosion) (8.2.1)
λ_c	=	contamination effects factor (in sliding systems) (8.2.1)
$\lambda_{max}, \lambda_{min}$	=	system property modification factors to account for effects of temperature, aging, scragging, velocity, and variability of materials (Article 8.2)
λ_{scrag}	=	scragging of bearing effects factor (elastomeric systems) (8.2.1)
λ_t	=	temperature effects factor (8.2.1)
λ_{tr}	=	travel effects factor (wear) (8.2.1)
λ_v	=	velocity effects factor (including frequency for elastomeric systems); the ratio of the property value at the design velocity, frequency to the corresponding value at velocity, or frequency of testing (8.2.1)

3—SEISMIC HAZARD

3.1—Acceleration Coefficient

The seismic hazard at the site of an isolated bridge shall be characterized in the same way as for the site of a conventional bridge. Either an acceleration response spectrum or a set of time histories of ground acceleration shall be used for this purpose.

The acceleration spectrum shall be determined using either the general procedure specified in Design Specifications Article 3.10.2.1 or the site-specific procedure specified in Design Specifications, Article 3.10.2. In both procedures, the effect of site class shall be considered.

A site-specific procedure shall be used if any one of the following conditions exist:

- The site is located within 6 mi of an active fault, The site is being classified as Site Class F (Design Specifications, Article 3.10.3.1), or
- The importance of the bridge is such that a lower probability of exceedance (and therefore a longer return period) should be considered.

If time histories of ground acceleration are used to characterize the seismic hazard for the site, they shall be determined in accordance with Design Specifications, Article 4.7.4.3.4a. The effect of site class shall be explicitly included in this determination.

3.2—Site Effects and Site Factors

Site effects shall be determined according to the site class and corresponding site factors. Site Classes A–F are defined in Design Specifications, Table 3.10.3.1-1 and corresponding Site Factors for zero-period (F_{pga}), short-period (F_a), and long-period (F_v) portions of the acceleration spectrum are given in Tables 3.10.3.2-1, 3.10.3.2-2, and 3.10.3.2-3, respectively.

4—DESIGN RESPONSE SPECTRUM

The five percent damped design response spectrum shall be taken as specified in Figure 4-1. This spectrum is calculated using the mapped peak ground acceleration coefficients and the spectral acceleration coefficients

C3.1

The seismic input requirements for the design of both isolated and non-isolated bridges typically involve three components: 1) a set of spectral accelerations to represent the design ground motion, 2) a site factor to account for local soil amplification or attenuation effects at the site, and 3) an elastic response spectrum to obtain the maximum forces (and displacements) that must be used in design according to the period of the bridge.

Values for the spectral accelerations have been mapped for the United States by the U.S. Geological Survey (USGS) and these maps are presented in both the Design Specifications and LRFD Seismic. Mapped values include peak ground acceleration (PGA) and spectral accelerations at modal periods of 0.2 s (S_s) and 1.0 s (S_1). These values have a seven percent probability of being that exceedance in the life of a bridge, which is taken to be 75 yr. Ground motion with this probability of exceedance has a return period of approximately 1,000 yr.

The occurrence of larger ground motions than those with a return period of 1,000 yr should be considered in design, particularly if severe damage is unacceptable in rare events. In the Central and Eastern United States 2,500-yr ground motions could be 1.5–2.5 times higher than those with a return period of 1,000 yr.

This issue is important for seismic isolation design. First, it is important that the isolators are capable of resisting the 2,500-yr design displacements. Article 12.3 attempts to meet this requirement by requiring larger test displacements for lower seismic zones. The second key aspect of the design process is that the R -factor used for design should limit the damage sustained to acceptable levels. If an R -factor of 1.5 is used, as prescribed in Section 6 for 1,000-yr ground motions, the structure may be damaged in extreme cases (e.g., 2,500-yr motions) but it should not collapse.

C3.2

The behavior of a bridge during an earthquake is strongly related to the soil conditions at the site. Soils can amplify ground motions in the underlying rock, sometimes by factors of two or more. The extent of this amplification is dependent on the profile of soil types at the site and the intensity of shaking in the rock below. Sites are classified by type and profile for the purpose of defining the overall seismic hazard, which is quantified as the product of the soil amplification and the intensity of shaking in the underlying rock.

C4

The long-period portion of the response spectrum in Figure 4-1 is inversely proportional to the period, T .

For periods exceeding 3–6 s, it has been observed that the spectral displacements tend to a constant value.



from Design Specifications, Figures 3.10.2.1-1 to 3.10.2.1-21, scaled by the zero-, short-, and long-period site factors, F_{pga} , F_a , and F_v , respectively.

which implies that the acceleration spectrum becomes inversely proportional to T^2 at these periods. As a consequence, the spectrum in Figure 4-1 (and Eq. 4-5) may give conservative results for long-period isolated bridges.

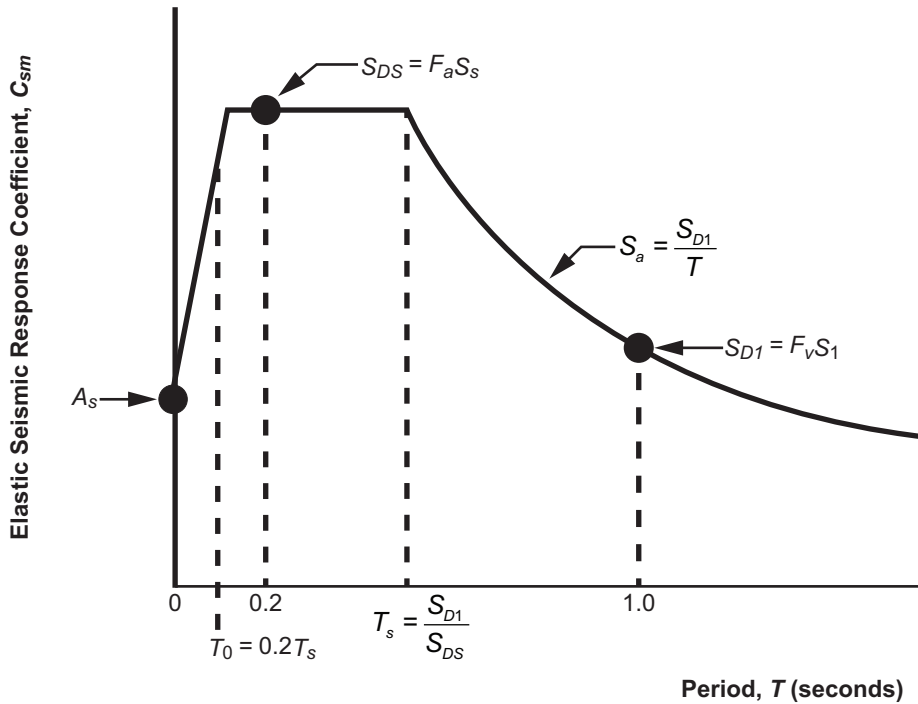


Figure 4-1—Design Response Spectrum

For periods less than or equal to T_0 , the elastic seismic coefficient, C_{sm} , shall be taken as:

$$C_{sm} = A_s + (S_{DS} - A_s) (T_m / T_0) \quad (4-1)$$

in which:

$$A_s = F_{pga} PGA \quad (4-2)$$

$$S_{DS} = F_a S_s \quad (4-3)$$

$$T_0 = 0.2 T_s \quad (4-4)$$

$$T_s = S_{D1} / S_{DS} \quad (4-5)$$

where:

PGA = peak ground acceleration coefficient on rock (Site Class B)

S_s = horizontal response spectral acceleration coefficient at 0.2 s period on rock (Site Class B)

T_m = period of vibration of m th mode (s)

T_0 = reference period used to define spectral shape (s)

T_S = corner period at which spectrum changes from being independent of period to being inversely proportional to period (s)

For periods greater than or equal to T_0 and less than or equal to T_S , the elastic seismic response coefficient shall be taken as:

$$C_{sm} = S_{DS} \quad (4-6)$$

For periods greater than T_S , the elastic seismic response coefficient shall be taken as:

$$C_{sm} = \frac{S_{D1}}{T_m} \quad (4-7)$$

$$S_{D1} = F_v S_1 \quad (4-8)$$

where:

S_1 = horizontal response spectral acceleration coefficient at 1.0 s period on rock (Site Class B)

F_v = site factor for long-period range of the design response spectrum

5—SEISMIC ZONES

Each bridge shall be assigned to one of four seismic zones in accordance with Table 5-1 using the value of S_{D1} given by Eq. 4-8.

Table 5-1—Seismic Zones

Acceleration Coefficient, S_{D1}	Seismic Zone
$S_{D1} \leq 0.15$	1
$0.15 < S_{D1} \leq 0.30$	2
$0.30 < S_{D1} \leq 0.50$	3
$0.50 < S_{D1}$	4

6—RESPONSE MODIFICATION FACTOR (R)

The response modification factor (R) for all substructures shall not be greater than one-half of those given in Design Specifications, Table 3.10.7.1-1 but need not be less than 1.5.

The importance categories used in Design Specifications, Table 3.10.7.1-1 shall be as defined in Design Specifications, Article 3.10.

R -factors shall not be used for the substructures if the provisions of LRFD Seismic are being followed for the design of the bridge.

C5

These seismic zones reflect the variation in seismic hazard across the United States and are used to permit different requirements for methods of analysis, minimum support lengths, column design details, and foundation and abutment design procedures in the Design Specifications.

C6

Although it is preferable to keep the columns of an isolated bridge fully elastic, it may not be economical to do so. In this case, response modification factors may be used to further reduce the design forces for the columns below that are achieved through isolation. However, restrictions are placed on the value of the factors that may be used to ensure the proper performance of the isolation system.

To demonstrate the concept, consider the case of an isolated bridge without redundancies (e.g., all piers and all isolator units have identical deformational characteristics). Moreover, consider isolator units with $Q_d = 0.06W$ and $F_{max} = 0.2W$ (based on the description provided in Figure C1-4), where W is the gravity load

on the isolator units. F_{max} represents the statically equivalent seismic force on the substructure which was calculated on the assumption of elastic substructure behavior. Consider now that the substructure is designed for an R -factor of 5, that is, the substructure is designed to have a strength of $0.04W$. Actual strength, when accounting for material overstrength, is about $0.06W$. Accordingly, inelastic action in the substructure will commence nearly instantaneously with inelastic deformation in the isolator units. Since typically the substructure has lower (essentially elastoplastic) post-yielding stiffness than the isolator units above, deformation will occur in the substructure with the isolator units rendered ineffective. The result will be excessive ductility demand in the substructure.

The specified R -factors are in the range of 1.5 to 2.5, of which the ductility based portion is near unity and the remainder accounts for material overstrength and structural redundancy inherent in most structures. That is, the lower R -factors ensure, on the average, essentially elastic substructure behavior in the design-basis earthquake. It should be noted that the calculated response by the procedures described in this document represents an average value which may be exceeded given the inherent variability in the characteristics of the design-basis earthquake. A detailed study on R -factors for seismically isolated bridges, which justifies the use of lower values, has been presented by Constantinou and Quarshie (1998).

LRFD Seismic does not use R -factors to calculate design forces in bridge substructures. Instead, a pushover technique is used to establish the capacity of the columns and foundations that have been designed to satisfy the strength limit states. Ductile detailing is then provided to satisfy the imposed displacement demands due to the seismic loads and protect the foundations against damage. LRFD Seismic is therefore said to be “displacement-based.” R -factors can only be used if the bridge is designed in accordance with the Design Specifications, which are a set of “force-based” specifications.

7—ANALYSIS PROCEDURES

One or more of the following procedures shall be used in the analysis of a seismically isolated bridge:

Procedure 1: simplified method

Procedure 2: single mode spectral method

Procedure 3: multi-modal spectral method

Procedure 4: time-history method

Selection of an appropriate procedure shall be in accordance with either Design Specifications, Article 4.7.4.3.1 or LRFD Seismic Article 4.2 where the applicability provisions for the uniform load method shall be used for the simplified method.

The analysis of an isolated bridge shall be performed using the design properties of the isolation system. To

C7

The basic premise for Procedures 1, 2, and 3 in these seismic isolation design provisions (consistent with those for buildings) is twofold. First, the energy dissipation of the isolation system can be expressed in terms of equivalent viscous damping; and second, the stiffness of the isolation system can be expressed as an effective linear stiffness. These two basic assumptions permit both the single mode and multi-modal methods of analysis to be used for seismic isolation design.

The force deflection characteristics of a bilinear isolation system (Figure C1-4) have two important variables, some of which are influenced by environmental and temperature effects. The key variables are K_d , the stiffness of the second branch of the

represent the nonlinear behavior of the isolator unit, a bilinear simplification may be used. The analysis shall be repeated using upper-bound properties ($Q_{d,max}$, $K_{d,max}$) in one analysis and lower-bound properties ($Q_{d,min}$, $K_{d,min}$) in another, where the maximum and minimum values are defined in Article 8.1.2.

An upper- and lower-bound analysis shall not be required if the displacements, using Eq. 7.1-3, and the statically equivalent seismic forces, using Eqs. 7.1-1 and 7.1-2, 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_L values corresponding to more than 30 percent damping may be used to establish the ± 15 percent limits.

A nonlinear time-history analysis shall be required for structures with effective periods greater than 3 s.

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.

bilinear curve, and Q_d , the characteristic strength. The area of the hysteresis loop, EDC , and hence the damping coefficient, B , are affected primarily by Q_d . The effective stiffness K_{eff} is influenced by Q_d and K_d .

The two important design variables of an isolation system are K_{eff} and B , since they affect the period (Eq. 7.1-4), the displacement (Eq. 7.1-3), and the base shear forces (Eq. 7.1-2). Since K_{eff} and B are affected differently by K_d and Q_d , the impact of variations in K_d and Q_d on the key design variables need to be assessed (Figure C7-1). Section 8 provides a method to determine λ_{min} and λ_{max} values for both K_d and Q_d .

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.

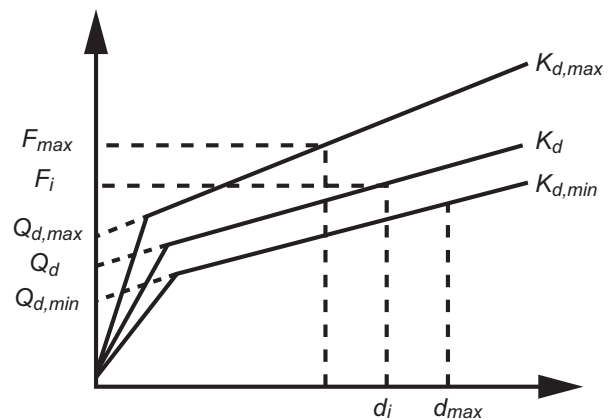


Figure C7-1—Impact of Variations in K_d and Q_d on F_{max} and d_{max}

The design forces on the columns and abutments generally will be at their maximum value when both K_d and Q_d are at their maximum values. Therefore, an analysis is required using $Q_{d,max}$ and $K_{d,max}$ to determine the maximum forces that will occur on the substructures. The design displacements will be at their maximum value when both Q_d and K_d are at their minimum values. Therefore, an analysis is required using $Q_{d,min}$ and $K_{d,min}$ to determine the maximum displacements that will occur across the isolator units.

Using the design properties of the isolator units, Q_d and K_d (Figures C1-4 and C7-1), the design forces F_i and displacements d_i are first calculated with Eqs. 7.1-1, 7.1-2, and 7.1-3. The design properties K_d and Q_d are then multiplied by $\lambda_{max,Kd}$, $\lambda_{max,Qd}$, $\lambda_{min,Kd}$, and $\lambda_{min,Qd}$, as prescribed in Article 8.1.2 to obtain upper- and lower-bound values of K_d and Q_d . The analyses are then repeated using the upper-bound values, $K_{d,max}$ and $Q_{d,max}$, to determine F_{max} and the lower-bound values, $K_{d,min}$ and $Q_{d,min}$, to determine d_{max} . These upper- and lower-bound values account for all anticipated variations in the design properties of the isolation system resulting from temperature, aging, scragging, velocity, wear or travel, and contamination. The exception is that only one analysis is required using the design properties provided that the

7.1—Simplified Method

The simplified method of analysis may be used for isolated bridges which respond predominantly as a single degree of freedom system with no coupling of displacement between any two or three coordinate directions.

This analysis shall be performed independently along two perpendicular axes and combined as specified in Design Specifications, Article 3.10.

This method shall not be used if Site Class 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 (Eq. 7.1-1).

For the purpose of this method, the statically equivalent seismic force shall be determined as:

$$F = C_{smd} W \quad (7.1-1)$$

where:

$$\begin{aligned} C_{smd} &= \frac{C_{sm}}{B_L} \\ &= \frac{S_{D1}}{T_{eff} B_L} \\ &< \frac{S_{DS}}{B_L} \end{aligned} \quad (7.1-2)$$

$$B_L = \left(\frac{\xi}{0.05} \right)^{0.3} \quad (7.1-3)$$

where:

- B_L = damping coefficient for the long-period range of the design response spectrum
- ξ = equivalent viscous damping ratio
- W = the total vertical load for design of the isolation system ($DL + LL_s$)

maximum and minimum values of the forces and displacements are within ± 15 percent of the design values.

The λ_{max} and λ_{min} factors for each of the six variables are to be determined by the system characterization tests prescribed in Article 13.1 or by the default values given in Appendix A.

The prototype tests of Article 13.2 are required to validate the design properties of the isolation system. These tests do not account for property modification factors except for those associated with scragging and velocity.

Acceptable system property variations (K_{eff} , EDC) in the prototype tests are ± 10 percent of the design properties.

C7.1

The simplified method is analogous to the uniform load method in the Design Specifications and LRFD Seismic. It has been adapted for application to isolated bridges.

For seismic isolation design, the elastic seismic coefficient, C_{smd} , is directly related to the elastic ground-response spectra. For five percent damping, this coefficient is given by Design Specifications, Eq. 3.10.4.2-5 or LRFD Seismic Eq. 3.4.1-7.

Isolated bridges usually have a damping ratio in excess of five percent, and to account for this higher level of damping, a damping coefficient, B_L , is included in the equation for C_{sm} in these Guide Specifications (Eq. 7.1-2).

The quantity C_{smd} is a dimensionless design coefficient, which when multiplied by the acceleration due to gravity (g) produces the spectral acceleration (S_A). This spectral acceleration is related to the spectral displacement (S_D) by the relationship:

$$S_A = \omega^2 S_D \quad (C7.1-1)$$

where ω is the natural angular frequency (rads/s) and is given by $2\pi/T_{eff}$. Therefore, since:

$$\begin{aligned} S_A &= C_{smd} g \\ &= \frac{S_{D1} g}{T_{eff} B_L} \end{aligned} \quad (C7.1-2)$$

it follows that:

$$\begin{aligned} S_D &= \frac{S_{D1} g}{\omega^2 T_{eff} B_L} \\ &= \frac{T_{eff}^2 S_{D1} g}{4\pi^2 T_{eff} B_L} \\ &= \frac{g S_{D1} T_{eff}}{4\pi^2 B_L} \end{aligned} \quad (C7.1-3)$$

The equivalent viscous damping ratio, ξ , for hysteretically damped systems depends on the energy dissipated and stored by the isolation system, which shall be verified by test of the isolation system's characteristics. It shall be calculated in accordance with Eq. 13.3-2. For isolation systems where the equivalent viscous damping ratio, ξ , exceeds 30 percent, either a nonlinear time-history analysis shall be performed utilizing the hysteresis curves of the system or the damping coefficient, B_L , shall be taken as 1.7.

If the damping is truly linear viscous, then the damping coefficient given by Eq. 7.1-3 may be extended to 50 percent ($B_L = 2.0$).

The displacement, d , shall be determined as:

$$d = \left(\frac{g}{4\pi^2} \right) \left(\frac{S_{D1} T_{eff}}{B_L} \right) \quad (7.1-4)$$

The effective period, T_{eff} (s), is given by:

$$T_{eff} = 2\pi \sqrt{\frac{W}{K_{eff} g}} \quad (7.1-5)$$

When calculating the effective stiffness (K_{eff}), the configuration and individual stiffnesses of the isolator units and substructures shall be determined as:

$$K_{eff} = \sum_j K_{effj} \quad (7.1-6)$$

in which:

$$K_{effj} = \frac{k_{sub} k_{eff}}{k_{sub} + k_{eff}} \quad (7.1-7)$$

where:

k_{eff} = stiffness factor depicted in Figure 7.1-1 for substructure unit

k_{sub} = stiffness factor depicted in Figure 7.1-1 for substructure unit

g = acceleration due to gravity

The above summation shall extend over all substructures.

In customary U.S. Units, $g = 384.6 \text{ in./s}^2$ and substitution gives:

$$S_D = \frac{9.79 S_{D1} T_{eff}}{B_L} \text{ (in.)} \quad (C7.1-4)$$

Denoting S_D as d , the deck displacement relative to the ground, the above expression leads to the following approximate result:

$$d \approx \frac{10 S_{D1} T_{eff}}{B_L} \text{ (in.)} \quad (C7.1-5)$$

An alternate form for C_{sm} is possible. Since the coefficient C_{sm} is defined by the relationship:

$$F = C_{smd} W \quad (C7.1-6)$$

where F is the earthquake design force and W is the weight of the structure, it follows that:

$$C_{smd} = \frac{F}{W} = \frac{K_{eff} d}{W} \quad (C7.1-7)$$

where K_{eff} is the sum of the effective stiffnesses of all the isolators supporting the superstructure segment.

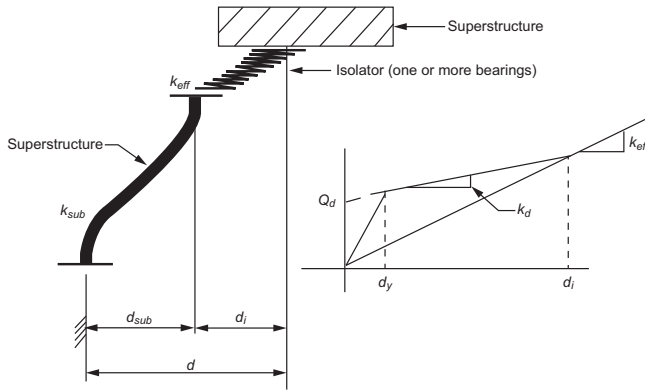


Figure 7.1-1—Isolator and Substructure Deformations Due to Lateral Load

The corresponding equivalent damping ratio, ξ , shall be determined as follows:

- For a single isolator and substructure j (Figure 7.1-1):

$$\xi = \frac{\text{Energy Dissipated}}{2\pi K_{eff\ j} d^2} \quad (7.1-8)$$

in which energy dissipated in a single isolator = $4Q_d(d_i - d_y)$.

Substitution gives:

$$\xi = \frac{2Q_d(d_i - d_y)}{\pi(d_i + d_{sub})^2 K_{eff\ j}} \quad (7.1-9)$$

- For multiple isolators and substructures supporting a continuous segment of the superstructure:

$$\xi = \frac{\text{Total Dissipated Energy}}{2\pi \sum_j (K_{eff\ j} d^2)} \quad (7.1-10)$$

$$= \frac{2\sum_j [Q_d(d_i - d_y)]}{\pi \sum_j [K_{eff\ j} (d_i + d_{sub})^2]} \quad (7.1-11)$$

where:

Q_d = characteristic strength of the isolator unit. It is the ordinate of the hysteresis loop at zero bearing displacement. Refer to Figures C1-4 and 7.1-1

d = total deck displacement relative to ground ($d_i + d_{sub}$), as depicted in Figure 7.1-1

d_i = design displacement across isolator unit in direction of earthquake loading, as depicted in Figure 7.1-1

d_{sub} = substructure displacement, as depicted in Figure 7.1-1

d_y = isolator yield displacement, as depicted in Figure 7.1-1

The above summations shall extend over all substructures including the abutments.

Substructure damping may be added to the value given for ξ by Eqs. 7.1-9 and 7.1-11 with the approval of the Engineer.

Eq. 7.1-1 shall only be used for systems that do not have added damping of a truly viscous nature such as viscous dampers.

For systems with added viscous damping, as in the case of elastomeric or sliding systems with viscous dampers, Eq. 7.1-4 may be taken as valid, in which case the damping coefficient B_L shall be based on the energy dissipated by all elements of the isolation system, including the viscous dampers. Equivalent damping shall be determined by Eq. 13.3-2. The seismic force shall be determined in three distinct situations as follows:

- *At maximum bearing displacement*—Determined by Eq. 7.1-1. Note that at this stage, the viscous damping forces are zero.
- *At maximum velocity and zero bearing displacement*—Determined as the combination of the characteristic strength of the isolation bearings and the peak viscous damper force. The latter shall be determined at a velocity equal to $2\pi d_d / T_{eff}$, where d_d is the peak damper displacement. (Note that displacement d_d is related to the isolator displacement d_i).
- *At maximum superstructure acceleration* (i.e., total inertia force)—Determined as:

$$F = (f_1 + 2 \xi_d f_2) C_{smd} W \quad (7.1-12)$$

in which:

$$f_1 = \cos [\tan^{-1} (2\xi_d)] \quad (7.1-13)$$

and:

$$f_2 = \sin [\tan^{-1} (2\xi_d)] \quad (7.1-14)$$

where:

C_{smd} = given by Eq. 7.1-2

K_{eff} = the contribution of all elements of the isolation system other than viscous dampers

ξ_d = a portion of the effective damping ratio of the isolated bridge contributed by the viscous dampers

The distribution of this force to elements of the substructure shall be based on bearing displacements equal to $f_1 d_i$, substructure displacements equal to $f_1 d_{sub}$, and damper velocities equal to $f_2 (2\pi d_d / T_{eff})$ where d_d is the peak damper displacement.

Eq. 7.1-12 provides an estimate of the maximum total inertia force on the bridge superstructure.

7.2—Single Mode Spectral Method

The single mode spectral method of analysis specified in Design Specifications, Article 4.7.4.3.2b may be used for isolated bridges which respond predominantly as a single degree of freedom system with no coupling of displacement between any two or three coordinate directions in the predominant mode of vibration.

This analysis shall be performed independently along two perpendicular axes and combined as specified in Design Specifications, Article 3.10.

The effective stiffness of the isolators used in the analysis shall be calculated at the design displacement.

7.3—Multimode Spectral Method

The multimode spectral method of analysis specified in Design Specifications, Article 4.7.4.3.3 and LRFD Seismic Article 5.4.3 shall be used for isolated bridges in which coupling occurs between displacements in more than one of the three coordinate directions within any of the predominant modes of vibration.

For this method, the five percent damped ground-motion response spectrum shall be taken as defined in Figure 4-1. This spectrum may be scaled by the damping coefficient (B_L), as defined in Article 7.1, to include the effective damping of the isolation system for the isolated modes. Scaling by the damping coefficient B_L shall apply only for periods greater than $0.8 T_{eff}$. The five percent damped response spectrum shall be used for all other modes. The effective linear stiffness of the isolators shall correspond to the design displacement. Structure system damping shall include all structural elements and be obtained by a rational method.

The combination of orthogonal seismic forces shall be as specified in Design Specifications, Article 3.10.8.

7.4—Time-History Method

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

- A linear or nonlinear time-history method of analysis shall satisfy the requirements of either Design Specifications Article 4.7.4.3.4 or LRFD Seismic Article 5.4.4.
- The isolation system shall be modeled using the nonlinear deformational characteristics of the

C7.2

The single mode method of analysis given in Design Specifications, Article 4.7.4.3.2b is appropriate for seismic isolation design. In this method, equivalent elastic properties are used to represent the stiffness of the nonlinear isolators and are required to be calculated at the design displacement. Since this displacement is generally not known at the beginning of an analysis, iteration may be necessary to obtain a solution.

Typically, the perpendicular axes are the longitudinal and transverse axes of the bridge but the choice is open to the designer. The longitudinal axis of a curved bridge may be taken as the chord connecting the two abutments.

C7.3

The guidelines given in either Design Specifications, Article 4.7.4.3.3 or LRFD Seismic Article 5.4.3 are appropriate for the multi-modal response spectrum analysis of an isolated structure with the following modifications:

- The isolation bearings are modeled by use of their effective stiffness properties determined at the design displacement d_i (Figure C1-4). Since this displacement is generally not known at the beginning of an analysis, iteration may be necessary to obtain a solution.
- The ground response spectrum is modified to incorporate the effective damping of the isolated structure (Figure C1-5).

The response spectrum required for the analysis needs to be modified to incorporate the higher damping value of the isolation system. The modified portion of the response spectrum should only be used for the isolated modes of the bridge and will then have the form shown in Figure C1-5.

A rational method is described in Article C7.1.

Care should be taken with the combination of modal maxima. If the complete quadratic combination (CQC) method is being used for this purpose, allowance should be made for the high damping in modes that deform the isolators compared to the relatively low damping in modes that do not. If it is not possible to specify different damping ratios in different modes in the software being used for the CQC method, the square root of the sum of the squares (SRSS) method should be used instead.

isolators that are verified by test in accordance with the requirements of Section 13.

- Time-history analysis shall be performed with at least three appropriate sets of time histories of ground motion. Each set shall comprise three orthogonal components selected in accordance with Design Specifications, Article 4.7.4.3.4b or LRFD Seismic Article 3.4.4.

Each set 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.

8—DESIGN PROPERTIES OF ISOLATION SYSTEM

8.1—Nominal Design Properties

8.1.1—Minimum and Maximum Effective Stiffness

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 .

8.1.2—Minimum and Maximum K_d and Q_d

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

$$K_{d,max} = K_d \lambda_{max,Kd} \quad (8.1.2-1)$$

$$K_{d,min} = K_d \lambda_{min,Kd} \quad (8.1.2-2)$$

$$Q_{d,max} = Q_d \lambda_{max,Qd} \quad (8.1.2-3)$$

$$Q_{d,min} = Q_d \lambda_{min,Qd} \quad (8.1.2-4)$$

System property modification factors, λ (defined in Article 8.2), 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 A may be used.

C8.1.2

Constantinou et al. (1999, 2007) and Warn and Whittaker (2006) provide guidance and data that may be used to select property modification factors for typical systems such as those described by Buckle et al. (2006a, 2006b). Potential variations in the key parameters for these systems are as follows:

Lead-Rubber Isolator Unit—The value of Q_d is determined primarily by the lead core. However, in cold temperatures, the contribution of the natural rubber to Q_d may increase significantly. Other factors influencing Q_d include velocity and history of inelastic action. The value of K_d depends on the properties of the rubber. Rubber properties are affected by aging, frequency of testing, strain, and temperature.

High-Damping Rubber Isolator Unit—Values for Q_d and K_d are functions of the additives in the rubber. High-damping rubber properties are affected by aging, frequency of testing, strain, temperature, and scragging.

Friction Pendulum System[®]—The value of Q_d is a function primarily of the dynamic coefficient of friction. The value of K_d is a function of the curvature of the sliding surface. The dynamic coefficient of friction is affected by aging, temperature, velocity, contamination, and length of travel or wear.

EradiQuake[®]—The value of Q_d is a function of the dynamic coefficient of the disc bearing and the preload friction force, when it is used. The value of K_d is a function of whatever springs are incorporated in the device. The dynamic coefficient of friction is affected by aging, temperature, velocity, contamination, and length of travel or wear. The variations in spring properties depend on the materials used.

Viscous Damping Devices—These can be used in conjunction with either elastomeric bearings or sliders. The value of Q_d is a function of both the viscous damper and the bearing element. The value of K_d is primarily a function of the bearing element.

8.2—System Property Modification Factors (λ)

Determination of the mechanical properties of the isolator units shall include consideration of the effects of temperature, aging, scragging, velocity, travel, and contamination.

8.2.1—Minimum and Maximum System Property Modification Factors

Minimum and maximum system property modification factors shall be determined as:

$$\lambda_{min,Kd} = (\lambda_{min,t,Kd}) (\lambda_{min,a,Kd}) (\lambda_{min,v,Kd}) (\lambda_{min,tr,Kd}) (\lambda_{min,c,Kd}) (\lambda_{min,scrag,Kd}) \quad (8.2.1-1)$$

$$\lambda_{max,Kd} = (\lambda_{max,t,Kd}) (\lambda_{max,a,Kd}) (\lambda_{max,v,Kd}) (\lambda_{max,tr,Kd}) (\lambda_{max,c,Kd}) (\lambda_{max,scrag,Kd}) \quad (8.2.1-2)$$

$$\lambda_{min,Qd} = (\lambda_{min,t,Qd}) (\lambda_{min,a,Qd}) (\lambda_{min,v,Qd}) (\lambda_{min,tr,Qd}) (\lambda_{min,c,Qd}) (\lambda_{min,scrag,Qd}) \quad (8.2.1-3)$$

$$\lambda_{min,Qd} = (\lambda_{min,t,Qd}) (\lambda_{min,a,Qd}) (\lambda_{min,v,Qd}) (\lambda_{min,tr,Qd}) (\lambda_{min,c,Qd}) (\lambda_{min,scrag,Qd}) \quad (8.2.1-4)$$

where:

- λ_t = temperature effects factor
- λ_a = aging effects factor (including corrosion)
- λ_v = velocity effects factor (including frequency for elastomeric systems); the ratio of the property value at the design velocity, frequency to the corresponding value at velocity, or frequency of testing
- λ_{tr} = travel effects factor (wear)
- λ_c = contamination effects factor (in sliding systems)
- λ_{scrag} = scragging of bearing effects factor (elastomeric systems)

C8.2.1

All λ_{min} values are unity at this time. Available test data for λ_{min} values produce forces and displacements that are within 15 percent of the design values. If the Engineer believes a particular system may produce displacements outside of the ± 15 percent range, then a λ_{min} analysis should be performed.

8.2.2—System Property Adjustment Factors

Adjustment factors shall be 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 :

- 1.00 for critical bridges,
- 0.75 for essential bridges, and
- 0.66 for all other bridges.

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

9—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 80 percent of the displacement given by Eq. 7.1-4, or 1 in., whichever is greater.

Displacements in the isolators resulting from load combinations involving *BR*, *WS*, *WL*, *CE*, *TU*, and *TG* as defined in the Design Specifications shall be calculated and adequate clearance provided.

10—DESIGN FORCES FOR SEISMIC ZONE 1

The seismic design force for the connection between superstructure and substructure at each bearing shall be determined as:

$$F_A = k_{eff} d_a \quad (10-1)$$

where:

d_a = displacement based on a minimum spectral acceleration coefficient, S_{D1} , as defined in Eq. 4-8. The minimum value of S_{D1} shall not be less than 0.15.

k_{eff} = effective stiffness determined from the contribution of all elements of the isolation system other than viscous dampers

C8.2.2

Only critical bridges need to be designed for the simultaneous accrual of all the maximum λ -factors. The adjustment factors for essential and other bridges are based on engineering judgment.

Example for an essential bridge

$$\lambda_{max,c} = 1.2 \text{ without adjustment factor}$$

$$\lambda_{max,c} = 1 + (1.2 - 1)0.75 = 1.15 \text{ for adjustment factor of } 0.75$$

C9

Adequate clearance shall be provided for the displacements resulting from the seismic isolation analysis of either Articles 7.1, 7.2, 7.3, or 7.4 in either of the two orthogonal directions.

In customary U.S. units, the minimum clearance specified in this Article is given by:

$$\frac{8S_{D1}T_{eff}}{B_L} \text{ (in.)}$$

The purpose of the default value for minimum clearance, regardless of the results of more rigorous methods of analysis, is to provide a minimum level of capacity to cover uncertainties in the ground motions and material properties.

As a design alternate in the longitudinal direction, a knock-off abutment detail may be provided for the seismic displacements between the abutment and deck slab. Adequate clearance for the seismic displacement must be provided between the girders and the abutment.

Displacements in the isolators resulting from longitudinal forces, wind loads, centrifugal forces, and thermal effects will be a function of the force-deflection characteristics of the isolators. Adequate clearance at all expansion joints must be provided for these movements.

C10

This Article permits utilization of the actual elastic force reduction, provided by seismic isolation, when calculating minimum connection forces for design.

The value of F_A shall not be less than that calculated at a displacement equal to the minimum clearance specified in Section 9.

11—DESIGN FORCES FOR SEISMIC ZONES 2, 3, AND 4

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 in either Design Specifications, Section 10 or LRFD Seismic, Section 6.

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 shall be determined as:

$$F_A = k_{eff} d_t \quad (11-1)$$

The value of F_A shall not be less than that calculated at a displacement equal to the minimum clearance specified in Section 9.

12—OTHER REQUIREMENTS

12.1—Non-seismic Lateral Forces

The isolation system must resist all non-seismic lateral load combinations applied above the isolation interface. Such load combinations shall be those involving BR , WS , WL , CE , TU , and TG as defined in the Design Specifications.

12.1.1—Strength Limit State Resistance

Strength resistance to forces such as wind, centrifugal, braking, and forces induced by restraint of thermal displacements shall be established by testing in accordance with Article 13.2.

12.1.2—Cold Weather Requirements

Cold weather performance shall be considered in the design of all types of isolation systems. In the absence of site-specific data, low-temperature zones shall conform to Design Specifications, Figure 14.7.5.2-1.

C11

Although vertical ground motion is not explicitly included in the design and analysis process, it may be important to approximate its effect on key structural elements. This includes the vertical stability of bearings and the additional lateral loads that may be developed in columns. Additional information on the effects of vertical shaking can be found in Warn and Whittaker (2008).

C12.1

Since an element of flexibility is an essential part of an isolation system, it is also important that the isolation system provide sufficient rigidity to resist frequently occurring wind and other service loads. The displacements resulting from non-seismic loads need to be checked.

C12.1.2

Low temperatures increase the coefficient of friction on sliding systems and the shear modulus and characteristic strength of elastomeric systems. These changes increase the effective stiffness of the isolation system. The test temperatures used to determine low-temperature performance in Article 13.1 represent 75 percent of the difference between the base temperature and the extreme temperature in Design Specifications, Table 14.7.5.2-1.

12.2—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, Δ , up to its total design displacement (TDD), d_t , shall be less than 6 s (Figure C12.2-1). Also the restoring force at d_t shall be greater than the restoring force at $0.5d_t$ 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 (Q_d) 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.

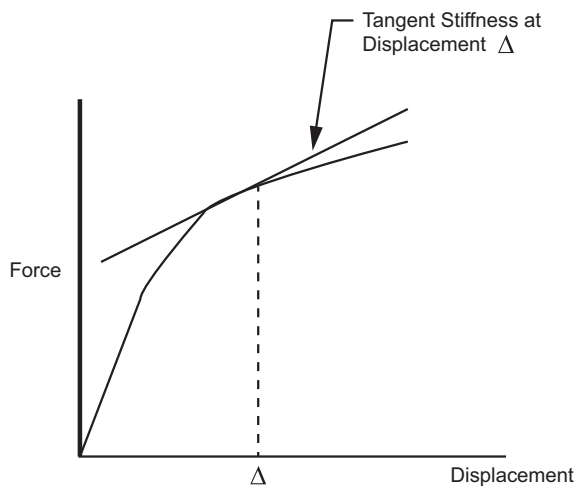


Figure 12.2-1—Tangent Stiffness of Isolation System

12.3—Vertical Load Stability

The vertical load capacity of the isolation system in its laterally undeformed state shall be at least three times the applied vertical load (unfactored dead load plus live load).

The isolation system shall also be designed to be stable under 1.2 times the sum of 1) the dead load, 2) any vertical load resulting from seismic live load, and 3) any vertical load resulting from overturning. This assessment shall be made at a displacement equal to the sum of the offset displacement and the larger of the following displacements:

- 1.1 multiplied by the TDD for the maximum considered earthquake,

C12.2

The purpose for the lateral restoring force requirement is to prevent cumulative displacements and to accommodate isolator installation imperfections, such as out of level.

The lateral restoring force requirements are applicable to systems with restoring force that is dependent on displacement, that is, spring-like restoring force. However, it is possible to provide constant restoring force that is independent of displacement. There are two known means for providing constant restoring force: a) using compressible fluid springs with preload and b) using sliding bearings with a conical surface. Figure C12.2-1 illustrates a typical force-displacement relation of these devices.

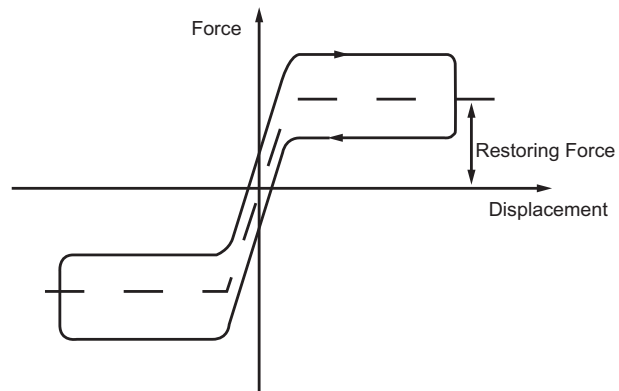


Figure C12.2-1—Force-Displacement Relation of Systems with Constant Restoring Force

In these cases, the combined constant lateral restoring force of the isolation system shall be at least equal to 1.05 times the combined characteristic strength of the isolation system under service conditions. For example, when constant restoring force devices are combined with frictional elements (e.g., sliding bearings), the restoring force must be at least equal to 1.05 times the static friction force. This requirement ensures that the restoring force is sufficiently large to overcome the characteristic strength and, thus, provide recentering capability.

C12.3

This Article provides minimum requirements for the design of the isolation system. The detailed design requirements of the system will be dependent on the type of system. In some of the low seismic risk areas (Seismic Zones 1 and 2) of the United States, a multiplier of 2.0 is appropriate since displacements during a longer return period event (2,500 yr) may be two times greater than the 1,000-yr event. The 1.2 factor accounts for vertical acceleration effects and uncertainty in the dead load.

In the absence of a site-specific hazard study, the maximum considered earthquake may be taken as one with a 2,500-yr return period. Ground motions for such return periods are available from the U.S. Geological Survey.

- In Seismic Zones 1 and 2, 2.0 multiplied by the TDD for a 1,000-yr return period earthquake, or
- In Seismic Zones 3 and 4, 1.5 multiplied by the TDD for a 1,000-yr return period earthquake.

12.4—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 rad. The design rotation capacity of the isolator shall exceed the maximum seismic rotation.

13—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 13.1;
2. Prototype Tests, described in Article 13.2; and
3. Quality Control Tests, described in Sections 15, 17, and 18.

13.1—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 nationally recognized guidelines approved by the Engineer.
- Shaking table tests at a scale no less than one-fourth full scale. Scale factors must be approved by the Engineer.

13.1.1—Low-Temperature Test

If the isolators are in low-temperature areas, the test specified in Article 13.2.2.6 shall be performed at temperatures of 20, 5, -5, or -15°F for temperature zones A, B, C, and D, respectively. Prior to testing, the core temperature of the isolator unit shall reach the specified temperature.

The specimen shall be cooled for a duration not less than the maximum number of consecutive days below freezing

C12.4

Larger construction rotations may be allowed, provided that they do not damage the isolator unit.

C13

The design requirements in these Guide Specifications are predicated on the fact that design properties are based on tested properties of isolator units. This Article provides a comprehensive set of prototype tests to confirm the adequacy of the isolator properties used in the design. Systems that have been previously tested with this specific set of tests on similar type and size of isolator units do not need to have these tests repeated. Design properties must therefore be based on manufacturers' preapproved or certified test data. Extrapolation of design properties from tests of similar type and size of isolator units is permissible.

Isolator units used for the system characterization tests (except shaking table), prototype tests, and quality control tests shall have been manufactured by the same manufacturer with the same materials.

C13.1

These tests are usually not project specific. They are conducted to establish the fundamental properties of individual isolator units as well as the behavior of an isolation system. They are normally conducted when a new isolation system or isolator unit is being developed or a substantially different version of an existing isolation system or isolator unit is being evaluated.

Several nationally recognized guidelines for these tests have been developed. Examples include the guidelines developed by HITEC for the evaluation of seismic isolation and energy dissipation devices (HITEC, 1996; 2002) and by NIST (NIST, 1996).

C13.1.1

The test temperatures represent 75 percent of the difference between the base temperature and the extreme temperature in Design Specifications, Table 14.7.5.2-1.

specified in Design Specifications, Table 14.7.5.2-1.

13.1.2—Wear and Fatigue Tests

Thermal displacements and live load rotations shall correspond to at least 30 yr of expected movement. Tests shall be performed at the design contact pressure at $68^{\circ}\text{F} \pm 15^{\circ}$. The rate of application shall not be less than 2.5 in./min. As a minimum, the following displacements shall be used for the test:

- bearings: 1 mi,
- dampers (attached to the web at the neutral axis): 1 mi, and
- dampers (attached to the girder bottom): 2 mi.

If the isolator units are for low-temperature areas, 10 percent of the test shall be performed at temperatures of 20, 5, -5 , or -15°F 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.

13.2—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.

13.2.1—Test Specimens

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. Prototype test specimens may be used in construction if they have the specified stiffness and damping properties, and if they satisfy the project quality control tests after having successfully completed all prototype tests.

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

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 corresponds to full-scale prototypes.

13.2.2—Required Tests

The following set 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

C13.1.2

Wear or travel and fatigue tests are required to account for movements resulting both from imposed thermal displacements and live load rotations.

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

The movement that is expected from live load rotations is dependent on structure type, span length and configuration, girder depth, and average daily traffic. The total movement resulting from live load rotations can be calculated as shown in Figure C13.1.2-1.

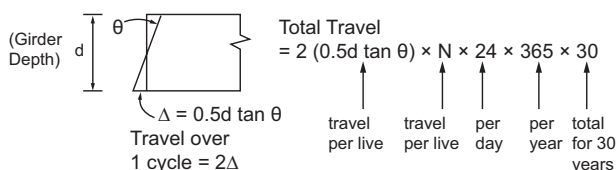


Figure C13.1.2-1—Calculation of Movement Due to Live Load Rotation

C13.2.1

Scaling isolators to give units that adequately represent the properties of full scale prototypes is a complex exercise. In general, small scale specimens do not exhibit the same characteristics as full-size specimens unless tested under conditions that simulate the correct thermodynamic effects. Examples of scaling sliding and elastomeric bearings are given by Constantinou et al. (2007) and Kalpakidis et al. (2008).

C13.2.2

The TDD for Articles 13.2.2.3 and 13.2.2.5 is defined in Section 2.

common type and size as described in Articles 13.2.2.1 through 13.2.2.6.

13.2.2.1—Thermal

Three fully reversed cycles of loads shall be performed at a lateral displacement corresponding to the maximum thermal displacement. The test velocity shall not be less than 0.003 in./min.

13.2.2.2—Wind and Braking: Preseismic Test

Twenty fully reversed cycles between limits of plus and minus the maximum load shall be performed for a total duration not less than 40 s. After the cyclic testing, the maximum load shall be held for 1 min.

13.2.2.3—Seismic

Three fully reversed cycles of loading shall be performed at each of the following multiples of the TDD: 1.0, 0.25, 0.50, 0.75, 1.0, and 1.25 in the sequence shown.

13.2.2.4—Wind and Braking: Post-Seismic Test

Three fully reversed cycles between limits of plus and minus the maximum load shall be performed for a total duration not less than 40 s. After the cyclic testing, the maximum load shall be held for 1 min.

13.2.2.5—Seismic Performance Verification

Seismic performance verification consists of three fully reversed cycles of loading at the TDD. For bidirectional isolator units that are not restrained to perform unidirectionally, this test shall be performed in the direction of loading orthogonal to the direction of loading in Article 13.2.2.3. For isolator units that include unidirectional devices, or those units that are sensitive to orthogonal effects, this test shall be performed at 45 degrees to the primary axis of the unidirectional device.

13.2.2.6—Stability

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 12.3. In these tests, the combined vertical load of:

$$1.2D + LL_s + OT \quad (13.2.2.6-1)$$

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

$$0.8D - OT \quad (13.2.2.6-2)$$

shall be taken as the minimum downward force.

C13.2.2.1

This test verifies the lateral force exerted by the isolation system at maximum thermal displacement.

C13.2.2.2

This test verifies the resistance of the isolation system under service load conditions.

C13.2.2.3

This test verifies the dynamic response of the isolation system for various displacements. The sequence of fully reversed cycles is important to developing hysteresis loops at varying displacements. By starting with a multiple of 1.0 times the TDD, the performance of the unscragged and scragged bearing may be directly compared.

C13.2.2.4

This test verifies service load performance after a seismic event.

C13.2.2.5

This test verifies the performance of the isolator after the sequence of tests has been completed, in a direction that is orthogonal to the test direction for bidirectional units, and at 45 degrees for unidirectional units.

C13.2.2.6

Stability is demonstrated if the applied lateral load at maximum displacement has a nonzero value and is in the same direction as the displacement.

13.2.3—Components to be Tested

The prototype and quality control tests shall include all components that comprise the isolation system.

13.2.4—Rate Dependency

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 ± 15 percent difference in either K_d or Q_d for the test at the TDD 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 13.2 shall be performed dynamically at a frequency equal to the inverse of the effective period of the isolated structure. If the test cannot be performed dynamically, then a λ -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 8.2.1.

13.3—Determination of System Characteristics

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

The effective stiffness of an isolator unit shall be determined for each cycle of loading as follows:

$$k_{eff} = (F_p - F_n) / (\Delta_p - \Delta_n) \quad (13.3-1)$$

where:

Δ_p = maximum positive test displacement

Δ_n = maximum negative test displacement

F_p = force corresponding to Δ_p

F_n = force corresponding to Δ_n

The equivalent viscous damping ratio (ξ) of the isolation system shall be determined as:

$$\xi = \frac{\text{total energy dissipated per cycle}}{2\pi \Sigma (k_{eff} d_i^2)} \quad (13.3-2)$$

The total energy dissipated per cycle shall be taken as the sum of the areas of the hysteresis loops of all isolator units. The hysteresis loop area of each unit shall be taken as the minimum area of the three hysteresis loops established by the cyclic tests of Article 13.2.2.3 at a displacement amplitude equal to the TDD.

C13.3

The basic premise of these seismic isolation design provisions is that the energy dissipation of the system can be expressed in terms of equivalent viscous damping, and the stiffness may be represented by an effective linear stiffness. The requirements of this Article provide the basis by which this premise is satisfied.

The parameters used to define effective stiffness in Eq. 13.3-1 are illustrated in Figure C13.3-1.

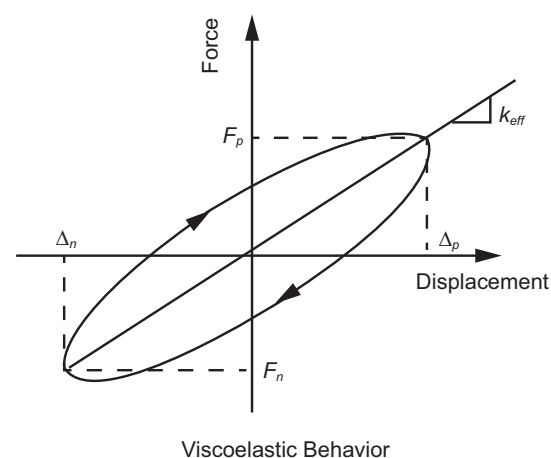
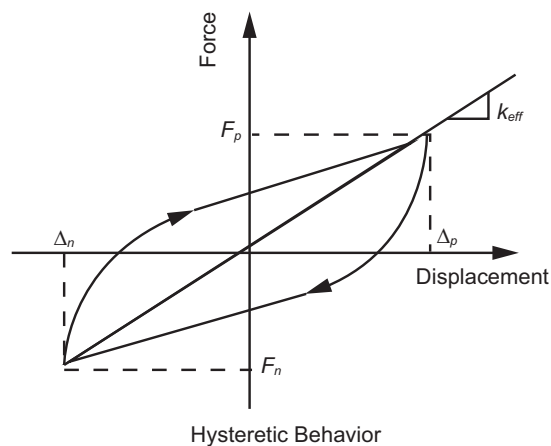


Figure C13.3-1—Definition of Effective Stiffness

13.3.1—System Adequacy

The performance of the test specimens shall be assessed as adequate if the conditions in Articles 13.3.1.1 through 13.3.1.8 are satisfied. Alternate acceptance criteria may be specified by the Engineer.

13.3.1.1—Incremental Force Capacity

The force-deflection plots, excluding any viscous damping component, of all tests specified in Article 13.2 shall show a positive incremental force-carrying capacity consistent with the requirements of Article 12.2.

13.3.1.2—Maximum Measured Force

For the test specified in Article 13.2.2.1, the maximum measured force shall be less than the specified value.

C13.3.1.1

An isolation system needs a positive incremental force-carrying capacity to satisfy the requirements of Article 12.2. The purpose of this requirement is to ensure that the hysteretic elements of the system are stable. A viscous damper will have a negative incremental force-carrying capacity toward the point of maximum displacement. Since this behavior is acceptable, it should not be included in the stability evaluation.