20.33 SEISMIC DESIGN OF BRIDGES WITH ISOLATION BEARINGS

20.33.1 GENERAL

This BDM provides guidelines and procedures for designing Ordinary and Recovery bridges using isolation bearings (isolators). Isolation bearings physically decouple or isolate the responses between a superstructure and its substructure in the horizontal plane during an earthquake event, leading to a substantial reduction in the horizontal forces generated by an earthquake. This memo addresses bridges that utilize isolation bearings at their superstructure-to-substructure connections. It does not cover bridge designs that utilize a combination of isolation bearings at some bents and conventional substructure-to-superstructure connections at other bents.

Isolation bearings are acceptable Earthquake Resisting Elements (EREs) with seismic energy dissipation characteristics comparable to plastic hinges in columns (see Figure 20.33.1-1) or deformable soil behind abutment backwalls. However, isolation bearings are considered nonstandard bridge elements and require a project-specific design criteria (PSDC). The PSDC should adopt, supersede, or amend the requirements stated in the latest edition of the following documents: (1) this BDM 20.33, (2) *Caltrans Seismic Design Criteria*, and *AASHTO Guide Specifications for Seismic Isolation Design* (GSSID) (AASHTO, 2014).

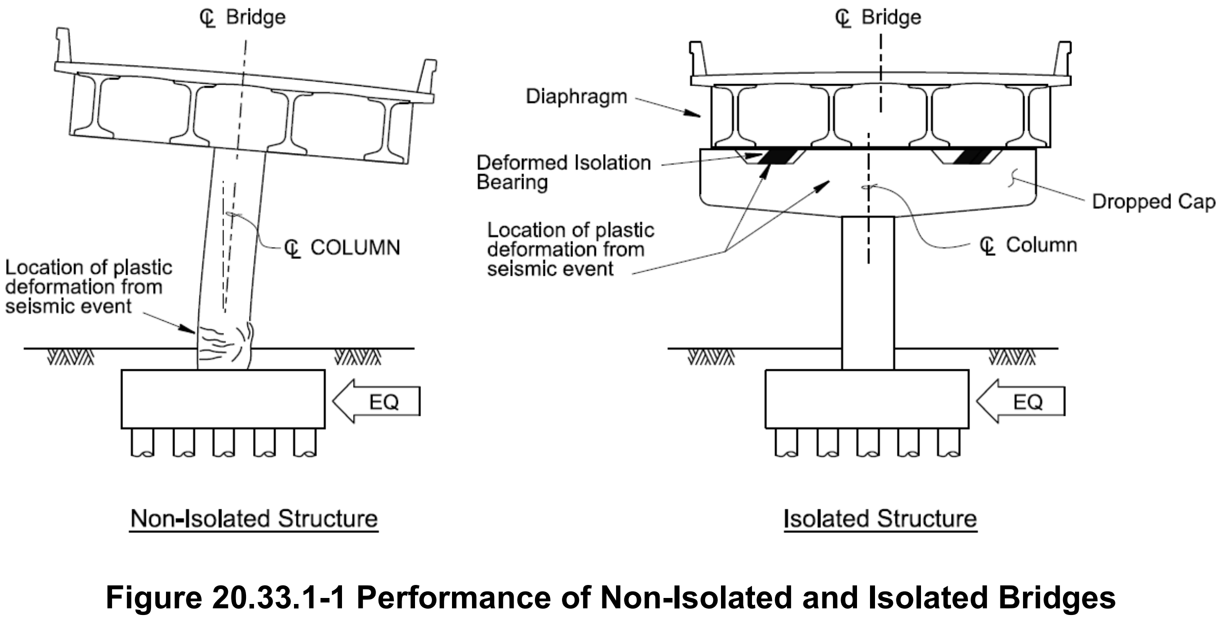


Figure 20.33.1-1 Performance of Non-Isolated and Isolated Bridges

20.33.2 DEFINITIONS

Isolator—An alternative term for isolation bearing

Isolation bearing displacement —The relative displacement between the top and bottom of an isolation bearing

Effective Period—The controlling period of a structure with a combined horizontal stiffness from isolators and substructure in the horizontal plane

20.33.3 NOTATIONS

BIRIS = Bridge Inspection Records Information System

BR = Vehicular braking force

CE = Vehicular centrifugal force

D_T = Seismic displacement demand for the isolator (in.)

D_y = Idealized yield displacement (in.)

EDC = Energy dissipation per cycle (kip-in.)

ERE = Earthquake resisting element

FPSB = Friction Pendulum Sliding Bearing

$F_{1.25DT}$ = Lateral force transmitted through each bearing when it displaces $1.25D_T$ (kip)

F_{DT} = Lateral force transmitted through each bearing when it displaces D_T (kip)

$F_{non\text{-}seis}$ = Non-seismic Lateral Force (kip)

GSSID = AASHTO Guide Specifications for Seismic Isolation Design

K_d = Restoring stiffness of the isolator unit. It is the second slope of the bilinear hysteresis curve (kip/in.)

K_{eff} = Effective stiffness of the isolator unit (kip/in.)

LRB = Lead-core Rubber Bearing

OT_{comp} = Maximum overturning compressive vertical load due to seismic (kip)

OT_{tens} = Maximum overturning tensile vertical load due to seismic (kip)

Q = Characteristic strength of the isolator unit. It is the ordinate of the hysteresis curve at zero bearing displacement (kip)

S_a = Spectral acceleration coefficient at the period of the structure

SERS = Secondary Earthquake Resisting System

T_{eff} = Effective period of the isolated structure (second)

V_U =The lateral force that can cause plastic hinging in the bent substructure (kip)

V_{Ui} =Contribution to V_U from each bearing (kip)

WA =Water load and stream pressure

WL =Wind on live load

WS =Wind load on structure

ξ = Equivalent viscous damping ratio for the isolation system (%)

20.33.4 TYPES OF ISOLATION BEARINGS

Two types of isolation bearings are currently prequalified by Caltrans: Lead-core Rubber Bearing (LRB) and Friction Pendulum Sliding Bearing (FPSB). Examples of these two types of bearings are shown in Figure 20.33.4-1.

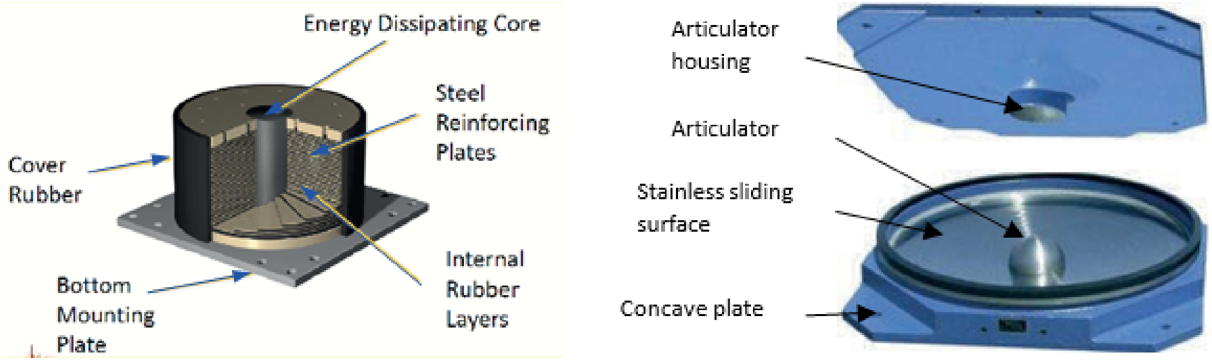
In general, the differences between these two types of bearings are as follows:

- FPSBs utilize the friction between the slider and the sliding surface to dissipate energy, while LRBs utilize the yielding of the lead core to dissipate energy. Therefore, the vertical load on FPSBs has a significant influence on the amount of energy dissipated. In contrast, the vertical load on LRBs has little effect on the amount of energy dissipated by the bearing.

- LRBs' lateral displacement capacity under the combined effect of axial and shear forces exerting on the bearing depends on the capacity of the elastomer and steel reinforcing plates. Therefore, they are usually taller and have larger base dimensions than FPSBs with the same lateral displacement capacity.

- FPSBs have more metallic components exposed to the environment, requiring more corrosion protection than LRBs.

- The elastomer in LRBs can become stiff in low ambient temperature zones. Consequently, the LRBs may generate larger than expected shear forces that are transmitted to adjacent structure members during seismic events.



(a) Lead-core Rubber Bearing (courtesy of DIS)

(b) Friction Pendulum Sliding Bearing (courtesy of EPS)

DIS = Dynamic Isolation Systems, Inc.
EPS = Earthquake Protection Systems

Figure 20.33.4-1 Caltrans Prequalified Isolation Bearings

20.33.4.1 Advantages of Isolation Bearings

Seismic isolation provides the following benefits:

- The bridge remains in full or partial service after a design-level or lower level earthquake event.
- The structural components of the bridge, such as columns and girders, suffer no damage during design-level seismic events; however, the expansion joints for ordinary bridges, shear keys (if any), and abutment back walls may be damaged. This type of damage is considered sacrificial and acceptable. They can be repaired within a short time frame at a relatively low cost compared to repairing columns that have formed plastic hinges.
- Typically, the required lateral strength of bridges designed with isolators is lower than those for non-isolated bridges. Consequently, the substructure and foundation sizes are usually smaller than those of non-isolated bridges.

20.33.4.2 Disadvantages of Isolation Bearings

Seismic isolation has the following disadvantages:

- Isolation bearings may appear out of plumb during service due to thermal displacement, creep, and shrinkage of the superstructure. However, the serviceability may not be affected.
- The bridge may have residual displacement after a seismic event if re-centering does not occur, in addition to being subject to larger displacement demands and corresponding concerns associated with P-delta effects.
- Isolation bearings require periodic inspection and may need replacement during the design life of the bridge. Design engineers should incorporate design details that consider future isolation bearing replacement.
- The installation and maintenance of isolation bearings can be complex and may require specialized knowledge and testing protocols.

20.33.5 DESIGN CONSIDERATIONS

20.33.5.1 Objectives

- The isolated structure should perform at the same or greater level as a conventional non-isolated structure in all service and strength limit states.
- The fundamental period of the structure should be increased to reduce inertia force. Isolation devices dissipate earthquake energy to keep the structural members essentially elastic during the design seismic hazards. Isolation bearings should not be used if the spectral acceleration increases as the period of the structure increases.
- The isolated structure should remain functional without any plastic damage during the design seismic hazards.
- The isolated structure should include a Secondary Earthquake Resisting (SER), such as plastic hinging in columns, should an event larger than the design seismic hazard occur during the life span of the structure.

20.33.5.2 Design Effectiveness

Seismic isolation is most effective for bridges where an increase in the effective period can achieve a significant reduction in the spectrum acceleration.

The goal of seismic isolation design is to optimize the structure displacement and seismic forces in the structural members by shifting the fundamental period and increasing damping through the isolation devices. Figure 20.33.5.2-1 shows the general shapes of acceleration response spectrum curves for typical stiff and soft soil sites. It is evident that increasing the period of structures at soft soil sites does not decrease spectral acceleration as effectively as at stiff soil sites.

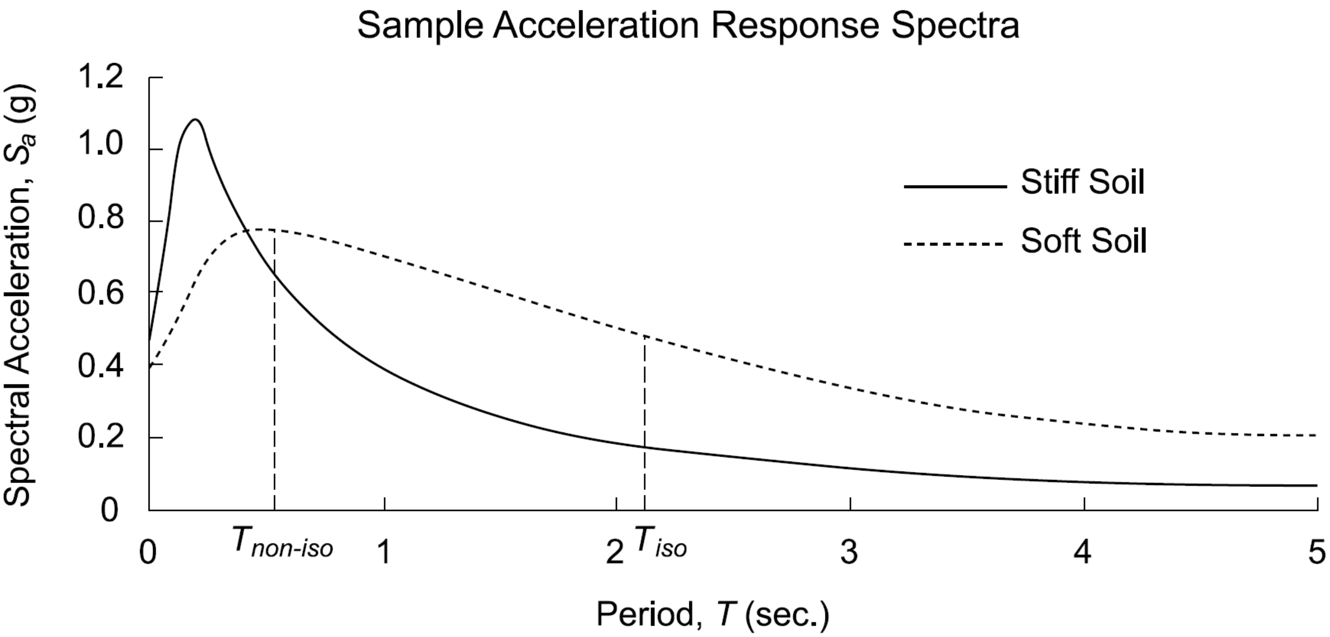


Figure 20.33.5.2-1 Acceleration Response Spectra Curves for Different Soils

20.33.5.3 Target Design Parameters

The target values listed in Table 20.33.5.3-1 should be considered when optimizing the design of isolated structures. Using values outside of those recommended in Table 20.33.5.3-1 may lead to a less economical design in the form of a design requiring larger support lengths, larger superstructure joints, larger substructure members, and/or larger foundation elements.

Table 20.33.5.3-1 Target Parameter Values for Effective Use of Isolation Bearings

Parameter	Transverse	Longitudinal
Seismic Displacement Demand for Isolator (D_T)	6 to 24 inches	6 to 24 inches
Isolated Structure Effective Period (T_{eff})	1.5 to 4 seconds	1.5 to 4 seconds
Additional service limit state displacement combination for isolators ($1.0CE+1.0BR+1.0WA+1.0WS+1.0WL$)	Less than 1 inch	Less than 1 inch

20.33.6 DESIGN REQUIREMENTS

20.33.6.1 Vertical Acceleration

Isolated bridges should be analyzed and designed for vertical acceleration per Caltrans SDC Section 7.2.2 or PSDC requirements. In addition, a separate vertical response spectrum analysis of the isolated structure or a nonlinear time history analysis with a vertical component of ground motions included may be required. Consideration should be given to incorporating performance-based design in the analysis of vertical acceleration by evaluating the bridge's response to a range of potential seismic events. This allows a more comprehensive understanding of its behavior under varying seismic hazard conditions. The PSDC should address the design criteria for vertical acceleration.

20.33.6.2 Mass/Stiffness Ratio Balance

Bents and columns, excluding isolation bearings’ contribution, should satisfy the following effective stiffness-to-mass ratios:

- The smallest ratio should be no less than 25% of that of the largest among the columns in the same bent

- The smallest ratio should be no less than 25% of that of the largest among the bents in the same frame

The above two bullets may be expressed mathematically as:

$$0.25 \le \left(\frac{k_i^e}{m_i}\right) / \left(\frac{k_j^e}{m_j}\right) \le 4 \qquad (20.33.6.2\text{-}1)$$

where:

$\left(k_i^e / m_i\right)$ = effective stiffness-to-mass ratio of column i (in the case of the first bullet) or effective stiffness-to-mass ratio of bent i (in the case of the second bullet)

$\left(k_j^e / m_j\right)$ = effective stiffness-to-mass ratio of column j (in the case of the first bullet) or effective stiffness-to-mass ratio of bent j (in the case of the second bullet)

In a non-isolated bridge with an unbalanced bent or frame, the stiffer supports will generally attract earthquake forces. This effect is mitigated in an isolated bridge because the bearings are the primary EREs. Therefore, the limits on the mass-to-stiffness ratio are relaxed relative to the requirements of the SDC. Design limits of Equation 20.33.6.2-1 are intended to improve the performance of the SERS, should it become engaged.

20.33.6.3 Secondary Earthquake Resisting System

The structure should include an SER, such as column plastic hinging, to prevent collapse when a larger-than-design seismic hazard event occurs. Isolation bearings are considered the primary EREs to absorb and dissipate most, if not all of the seismic energy. Plastic hinges in ductile columns and piles/shafts are considered secondary EREs. In situations where forming plastic hinges in substructure members is not feasible because substructure members are shear critical, fuse elements may be used as secondary EREs. This should be explicitly addressed in the PSDC.

20.33.6.4 Capacity Protected Members

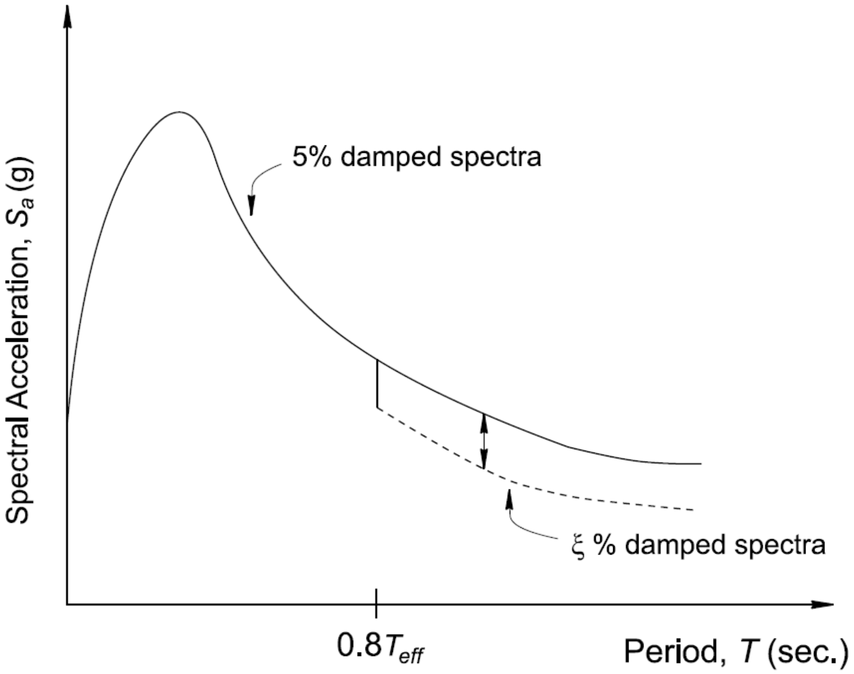
Bridge members designated as capacity protected members should be designed in accordance with Caltrans SDC (Caltrans, 2024). This requirement does not apply to the superstructure of seismically isolated bridges because the isolator decouples it from the substructure.

20.33.6.5 Isolation Bearings

Bearings should not be subjected to uplift under seismic loading conditions. Special mechanisms should be provided to prevent the bearing from experiencing tension. These mechanisms should not interfere with the free lateral movement of the isolation bearings.

The design displacement demand of the isolation bearing (D_T) should be determined according to the methods provided in the GSSID. The seismic hazard should be determined according to Caltrans SDC or through a site-specific analysis by the geotechnical engineer.

The Safety Evaluation Earthquake (SEE) hazard for isolated bridges should be the same as for non-isolated bridges. However, the design response spectrum may be modified to account for the increased damping of the isolated bridge according to GSSID (see Figure 20.33.6.5-1). When this method is used, the reduction factor for the spectral acceleration coefficient (S_a) should not be greater than 1.7, i.e. $(\xi/5)^{0.3} \leq 1.7$.



T_{eff} = Fundamental period of isolated bridge

ξ is obtained from AASHTO GSSID

Reduced $S_a = S_a / (\xi/5)^{0.3} \geq S_a/1.7$

Figure 20.33.6.5-1 **Reduction of ARS Curve to Account for Increased Damping**

The ultimate displacement capacity of the isolation bearing, which is defined as the displacement that the bearing can achieve without shear failure, should be determined from the manufacturer's recommendation but should not be less than $1.5D_T$. The 1.5 factor is to account for the uncertainty in the design seismic hazards. While the 975-year event is adopted as the SEE, 2475-year earthquake events are still possible, with a potential variation of two standard deviations in both the 975-year and 2475-year events. The 1.5 factor and the use of SERS contribute to addressing this uncertainty.

When LRBs are used, it is expected that both the isolation bearing and the seismic critical member (SCM) will jointly contribute to energy dissipation after a bearing displacement of $1.25D_T$ until either the bearings fail/lock up or a plastic hinge occurs in the SCM. No strain hardening is allowed in an LRB before a displacement of $1.25D_T$.

As shown in Figure 20.33.6.6-1, FPSB stiffens as the slider reaches the edge of the sliding surface, which either has a steeper slope or a stepped-up shear ring around the perimeter, while LRB hardens gradually before the rubber layers and steel shims delaminate. The idealized yield displacement of a LRB is denoted as D_y.

The total ultimate lateral strength of the isolation bearings at each bent should be larger than the lateral force that can cause plastic hinging in the substructure, V_U. See Figure 20.33.6.6-1 for the contribution from each bearing to lateral force (V_{Ui}). In special cases, auxiliary external restraints such as shear blocks or restrainers can be used if the isolation bearings cannot provide sufficient lateral strength for plastic hinging to occur in the columns when the isolators fail. This ensures that secondary EREs will be activated when the isolation bearings fail as a result of the seismic event exceeding the design seismic hazard level. A fusing element should be provided if the substructure is a shear critical element where forming plastic hinges is not feasible. For example, the isolation bearing anchor bolts can be designed to fuse such that they break when the bearing displaces more than $1.25D_T$ but less than the ultimate displacement capacity of the bearing. In this situation, a catcher platform should also be provided to prevent the superstructure from an excessive vertical drop should the fuse elements become damaged.

Superstructure supports at bents and abutments should be designed to accommodate a displacement of at least $1.5D_T$.

Examples of isolator performance curves and Parameter Tables for Design plan sheets are included in the Appendices.

Design examples for isolation bearings can be found in the GSSID Appendix. Additionally, the plan sheets for bridges with isolation bearings, such as those below, can be found in the Caltrans BIRIS system.

1. Sacramento River Bridge (08-0095 R/L) - Strengthening, Seismic, and Scour retrofit (used LRB).
2. Smith River Bridge (01-0041) - Replacement (used FPSB).

20.33.6.6 Columns, Piles, and Shafts

Columns, piles, and shafts should remain essentially elastic when all bearings on a bent displace less than $1.25D_T$. V_U should be greater than or equal to the sum of $F_{1.25D_T}$ from all bearings on the bent. This is to account for the variability in the seismic demand. In addition, V_U should be greater than or equal to 10% of the dead load reaction on the substructure. Figure 20.33.6.6-1 shows the relationship between V_{Ui} and bearing force with respect to bearing displacements. In Figure 20.33.6.6-1, V_{Ui} denotes the contribution to V_U from each bearing, and Q denotes the characteristic strength of the bearing, which is defined as the lateral force in the bearing when its hysteresis curve (as shown in Appendices A and C) crosses zero displacement.

The potential plastic hinging elements (e.g., columns) should satisfy the local ductility requirements, shear capacity, and P-Δ moment requirements per Caltrans SDC. The P-Δ moment is computed using the relative displacement between the center of the isolator and the center of the plastic hinge near the bottom of the column when the plastic hinge forms.

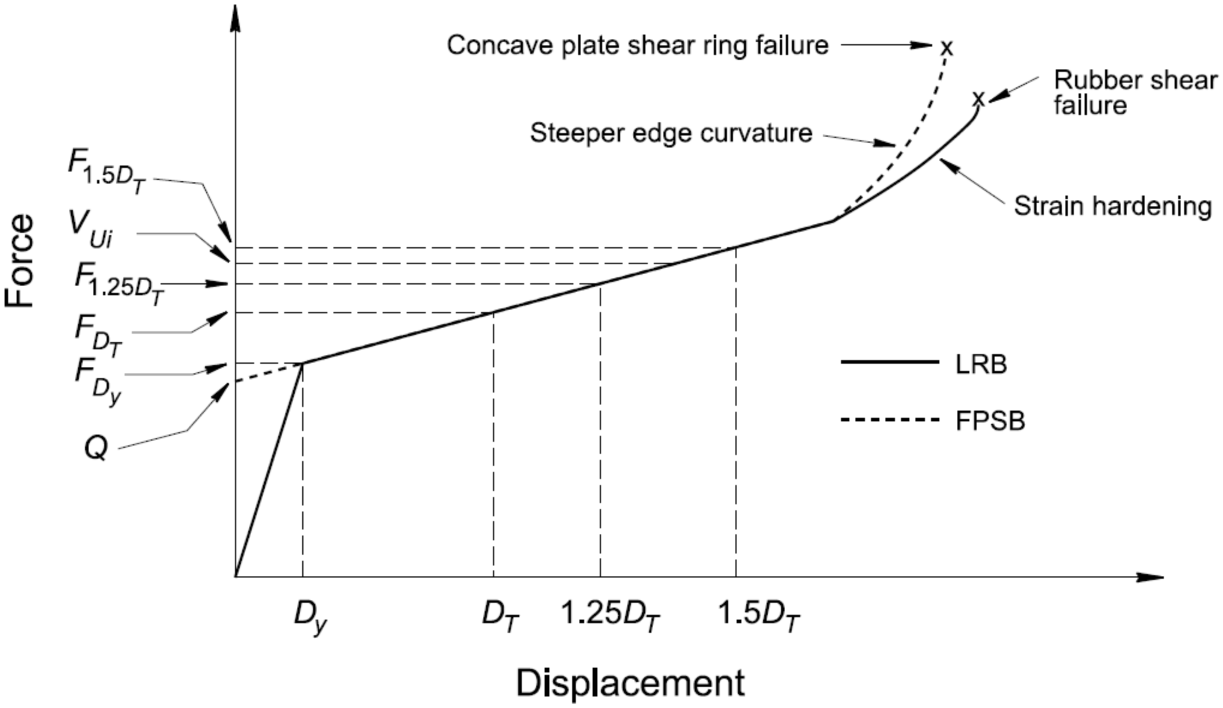


Figure 20.33.6.6-1 **Force Displacement Curve for Isolation Bearings**

20.33.6.7 Abutments and In-span Hinges

Abutment and in-span hinge support lengths should accommodate seismic displacement demands and satisfy the minimum requirements per Caltrans SDC. Expansion joints in the isolated bridge should be designed for service loads but may be damaged by earthquakes. Steel plates can be used temporarily over the damaged joints to return the bridge to service. If special seismic joints are used, they should be designed to be damage-free when the design seismic hazard occurs.

Superstructure unseating from the bearing should be prevented or mitigated in the extreme event that actual bearing displacement demands exceed the bearing displacement capacity. Prevention strategies may include using large platform seats or catcher blocks. Any drop of the superstructure onto the catcher or platform seat should be made as small as possible to prevent structural damage from impact.

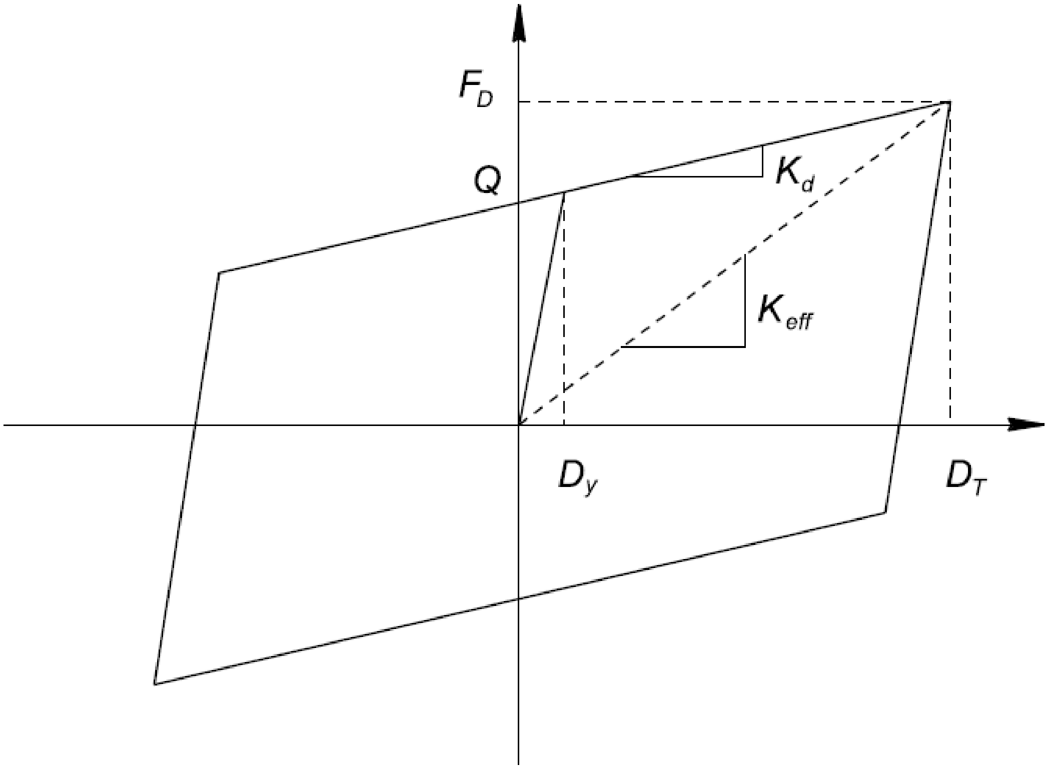
20.33.8 REFERENCES

1. AASHTO. (2017). AASHTO LRFD Bridge Design Specifications, 8th Edition, American Association of State Highway and Transportation Officials, Washington DC.
2. AASHTO, (2014). Guide Specifications for Seismic Isolation Design, American Association of State Highway and Transportation Officials, 4th Edition with 2023 Interim Revisions, Washington DC.
3. Caltrans. (2025). Caltrans Seismic Design Criteria, Version 2.1, California Department of Transportation, Sacramento, CA.
4. Caltrans. (2019). California Amendments to AASHTO LRFD Bridge Design Specifications, 8th Edition, California Department of Transportation, Sacramento, CA.

APPENDICES

APPENDIX A

Example of LRB Dynamic Performance Curve for Design Plan Sheets



APPENDIX B

Example of LRB Parameter Table for Design Plan Sheets

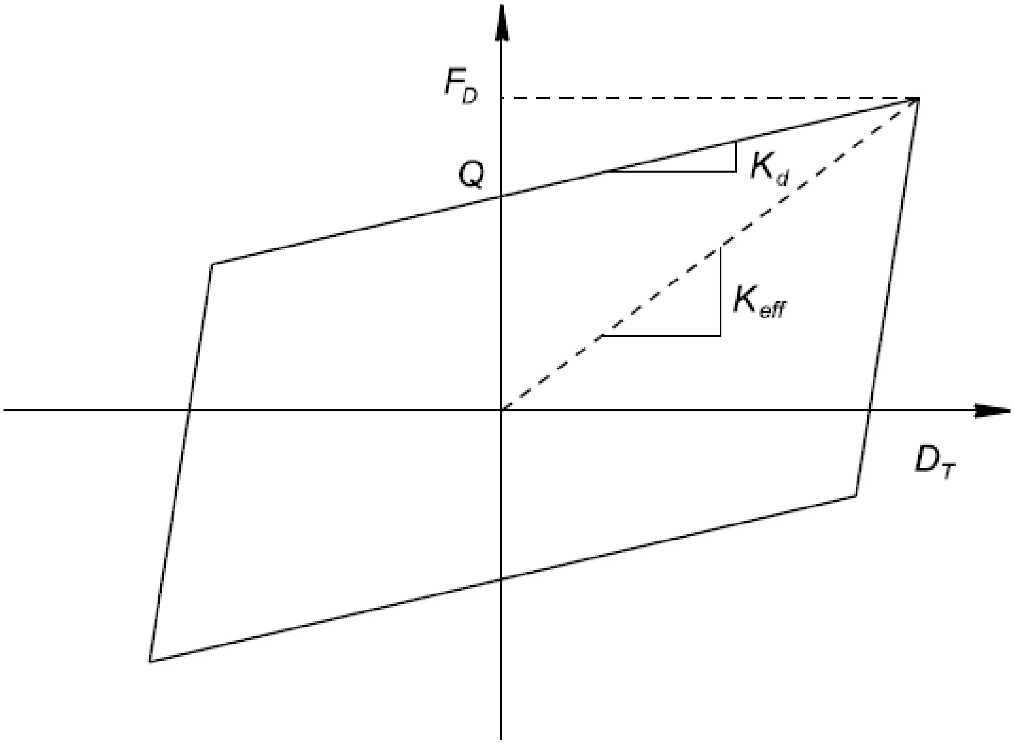
Bearing Location	N/A	Abut. 1 & 5	Bent 2	Bent 3&4
Bearing Type	N/A	--	--	--
Number of Bearings	EA	--	--	--
Characteristic Strength, Q^a	kip	--	--	--
Maximum Yield Displacement, $D_y{}^a$	in.	--	--	--
Restoring Stiffness, $K_d{}^a$	k/in.	--	--	--
Design Seismic Lateral Force, $F_D{}^a$	kip	--	--	--
Design Seismic Lateral Displacement, D_T	in.	--	--	--
Effective Stiffness, $K_{eff}{}^a$	k/in.	--	--	--
Energy Dissipation per Cycle, EDC[a,b]	k-in.	--	--	--
Rotational Capacity	radian	--	--	--
Non-seismic Lateral Force, $F_{non\text{-}seis}$	kip	--	--	--
Average Design Dead Load on Bearing, *DL*	kip	--	--	--
Average Design Live Load on Bearing, *LL*	kip	--	--	--
Maximum Overturning Compressive Vertical Load due to Seismic, OT_{comp}	kip	--	--	--
Maximum Overturning Tensile Vertical Load due to Seismic, OT_{tens}	kip	--	--	--
Maximum Thermal Displacement	in.	--	--	--
Maximum Thermal Force	kip	--	--	--
Effective Period of Bearing, T_{eff}	second	--	--	--
Offset Displacement due to Prestress Shortening, Creep, and Shrinkage	in.	--	--	--

[a] The value is based on the bearing subjected to Average Design Dead Load (*DL*)

[b] The area enclosed by the hysteresis curve shown in Appendix A

APPENDIX C

Example of FPSB Dynamic Performance Curve for Design Plan Sheets



APPENDIX D

Example of FPSB Parameter Table for Design Plan Sheets

Bearing Location	N/A	Abut. 1 & 5	Bent 2	Bent 3&4
Bearing Type	N/A	--	--	--
Number of Bearings	EA	--	--	--
Characteristic Strength, Q^a	kip	--	--	--
Restoring Stiffness, $K_d{}^a$	k/in.	--	--	--
Design Seismic Lateral Force, $F_D{}^a$	kip	--	--	--
Design Seismic Lateral Displacement, D_T	in.	--	--	--
Effective Stiffness, $K_{eff}{}^a$	k/in.	--	--	--
Energy Dissipation per Cycle, EDC^{a,b}	k-in.	--	--	--
Rotational Capacity	radian	--	--	--
Non-seismic Lateral Force, $F_{non\text{-}seis}$	kip	--	--	--
Average Design Dead Load on Bearing, *DL*	kip	--	--	--
Average Design Live Load on Bearing, *LL*	kip	--	--	--
Maximum Overturning Compressive Vertical Load due to Seismic, OT_{comp}	kip	--	--	--
Maximum Overturning Tensile Vertical Load due to Seismic, OT_{tens}	kip	--	--	--
Maximum Thermal Displacement	in.	--	--	--
Maximum Thermal Force	kip	--	--	--
Effective Period of Bearing, T_{eff}	second	--	--	--
Offset Displacement due to Prestress Shortening, Creep, and Shrinkage	in.	--	--	--

[a] The value is based on the bearing subjected to Average Design Dead Load (*DL*)

[b] The area enclosed by the hysteresis curve shown in Appendix C