

20-22 SEISMIC DESIGN OF ORDINARY BRIDGES WITH ISOLATION BEARINGS

Introduction

Policies, guidelines and procedures for designing seismically isolated Ordinary Bridges using isolation bearings are documented in this memorandum. Seismically isolated bridges are essentially rigid in the vertical direction and fully isolated in the horizontal plane. A bridge that utilizes both isolation bearings and conventional monolithic connections between its superstructure and substructure at different bents or abutments is not considered a seismically isolated bridge; therefore, it is not addressed in this memo.

Seismic isolation systems have gained worldwide acceptance as a viable and efficient earthquake resisting system for bridges. Isolation bearings are acceptable Earthquake Resisting Elements (EREs) with seismic energy dissipation characteristics comparable to plastic hinges in columns (see Figure 20-22.1) or deformable soil in abutment embankments.

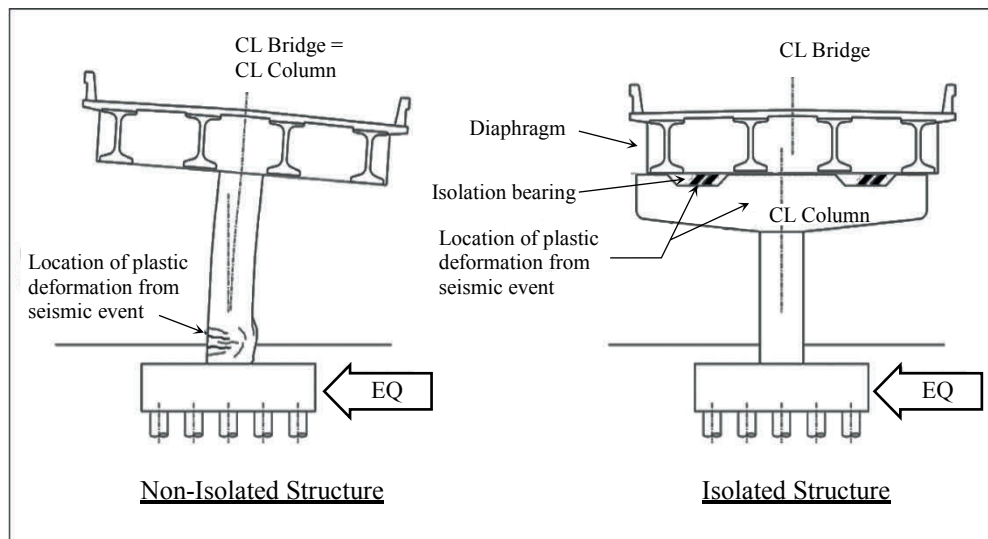


Figure 20-22.1 Performance of Non-Isolated and Isolated Bridges

Types of Isolation Bearings

Two types of isolation bearings are currently pre-qualified by Caltrans: Lead-core Rubber Bearing (LRB) and Friction Pendulum Sliding Bearing (FPSB) with single or double sliding surfaces. Examples of these two types of bearings are shown in Figure 20-22.2, under the courtesy of Dynamic Isolation Systems, Inc. (DIS) and Earthquake Protection Systems (EPS) respectively.

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 yielding of the lead core to dissipate energy. Therefore, the amount of 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 depends on the capacity of the elastomer and steel shims under the combined effect of axial and shear forces exerting on the bearing. 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 LRB's may generate larger than expected shear forces that are transmitted to adjacent structure members during seismic events.

It is recommended that the design accommodate both types of bearings as viable alternatives for the bridge unless there are factors as stated above causing a certain type of bearing to be unsuitable.

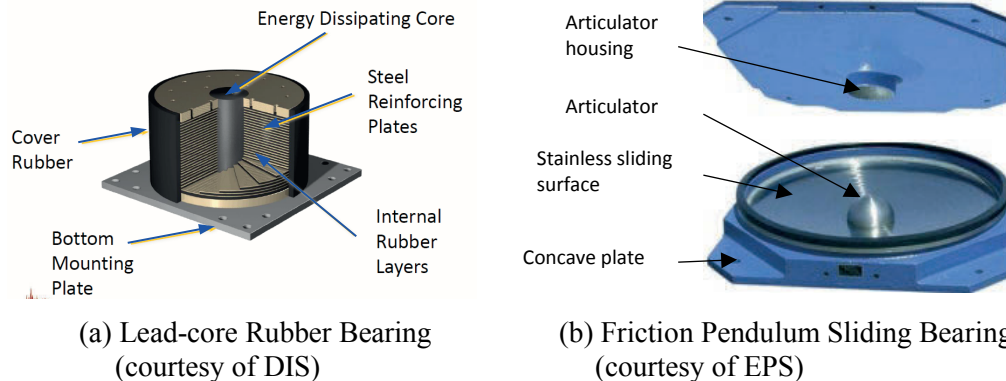


Figure 20-22.2 Lead-core Rubber Bearing and Friction Pendulum Sliding Bearing

Advantages of Isolation Bearings

Seismic isolation provides the following benefits at a minimal additional construction cost:

- The bridge remains in full or partial service after earthquakes that are within the design seismic hazard level.
- The structural components of the bridge such as columns and girders suffer no damage within the design seismic hazard level; however, the expansion joints, 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 relatively low cost compared to repairing columns that have formed plastic hinging.



- The seismic forces in the structure are smaller because isolation devices dissipate most of the seismic energy. Consequently, the substructure and foundation size are usually smaller than those of non-isolated bridges.

Disadvantages of Isolation Bearings

Seismic isolation has the following disadvantages:

- The isolation bearings may appear out of plumb during service due to thermal displacement, creep, and shrinkage of the superstructure. However, the serviceability will not be affected.
- The bridge may have residual displacement after a strong seismic event if complete re-centering does not occur.
- The isolation bearings require periodic inspection and may need replacement during the design life of the bridge.

Isolation Design Objectives

- The structure performs at the same level as conventional non-isolated structure in all service and strength limit states.
- The fundamental period of the structure is increased to reduce inertia force. Isolation devices dissipate earthquake energy to keep the structure members essentially elastic within the design seismic hazard level.
- The structure remains functional without any plastic damage within the design seismic hazard level.
- The structure includes a Secondary Earthquake Resisting System (SERS) such as plastic hinging in columns should an event larger than design seismic hazard level occur during the life span of the structure.

Isolation Design Effectiveness

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

The goal of seismic isolation design is to optimize the structure displacement and seismic forces in the structure members to a manageable level by shifting the fundamental period and increasing damping through the isolation devices. Figure 20-22.3 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 spectra acceleration as effectively as at stiff soil sites.

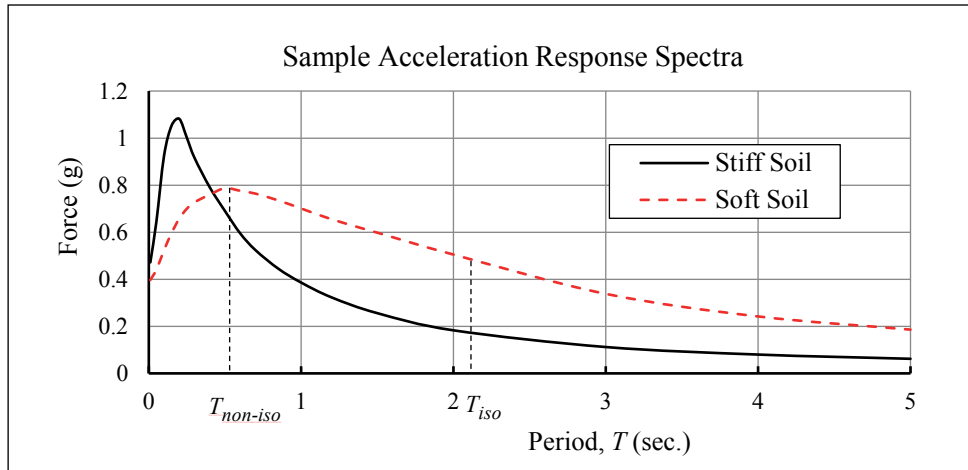


Figure 20-22.3 Acceleration Response Spectra Curves for Different Soil Site Conditions

Isolation Design Parameter Targets

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

The designer should consider the target values listed in Table 20-22.1 when optimizing the design of isolated structures. The designs using isolators can still be feasible outside of these target values. However, the structure may require features including larger support widths and larger superstructure joints if displacements are excessive, or larger substructure and foundations to resist higher isolator forces. These features may lead to a less economical design.

Table 20-22.1 Target Parameter Values for Effective Use of Isolation Bearings

Parameter	Transverse	Longitudinal
Seismic Displacement Demand for Isolator (D_I)	6 to 24 inches	6 to 24 inches
Isolated Structure Effective Period (T_{eff})	1.5 to 4 seconds	1.5 to 4 seconds
Non-seismic Displacement for Isolators (Wind, Braking, etc. but exclude thermal)	Less than 1 inch	N/A



Policy

Seismic isolation design of Ordinary Bridges is considered Nonstandard and must establish a Project Specific Seismic Design Criteria (PSDC). The procedure for establishing PSDC can be found in Caltrans *Bridge Memo to Designers* (MTD) 20-11.

Seismic isolation design must in accordance with *AASHTO Guide Specifications for Seismic Isolation Design* (GSSID) (AASHTO, 2014) and current Caltrans *Seismic Design Criteria* (SDC) except as noted otherwise in this document. The PSDC may add or supersede requirements stated herein. The type of isolation system and its applicability to a given type of bridge is subject to the approval of the Office of Earthquake Engineering Analysis and Research. Any exceptions to the requirements stated herein must be explicitly addressed in the PSDC.

Seismic Design Requirements for Isolated Bridges

Vertical Acceleration

Isolated bridges must be analyzed and designed for vertical acceleration per Caltrans SDC requirements or geotechnical requirements of the PSDC. In addition, a separate vertical response spectrum analysis of the isolated structure or a nonlinear time history analysis with vertical component of ground motions included may be required. The design criteria for vertical acceleration must be addressed in the PSDC.

Mass/Stiffness Ratio Balance

Bents and columns excluding isolation bearings' contribution (i.e. isolation bearings are modeled as pinned connections) must meet the following balance criteria using stiffness-to-mass ratio as defined in the SDC except the following:

- The smallest ratio must be no less than 25% of that of the largest among the columns in the same bent.
- The smallest ratio must be no less than 25% of that of the largest among the bents in the same frame.

There is a risk of the isolators exhausting their ultimate displacement capacity and locking up if an earthquake is larger than the design hazard. The unbalance among columns or bents could cause stiffer bents to suffer more damage while flexible bents may not fully participate in the SERS.

Secondary Earthquake Resisting Elements

The structure must include a SERS such as column plastic hinging should a larger than design seismic hazard event occurs. Isolation bearings are considered the primary Earthquake Resisting Elements (EREs) to absorb and dissipate most, if not all, of the



seismic energy. Ductile columns and piles/shafts are considered as secondary EREs. In some unique situations where forming plastic hinges in substructure members is not feasible because substructure members are shear critical (per MTD 20-18), the fuse elements may be used as secondary EREs. This must be explicitly addressed in the PSDC.

Capacity Protected Members

Bent cap beams and foundation elements such as footings and piles, or Type II shafts, must be designed as capacity-protected members. Columns in isolated bridges must meet the isolation design requirements in this memorandum.

Isolation Bearings

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

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

The Safety Evaluation Earthquake (SEE) hazard level for isolated bridges must be the same as that for non-isolated bridges at the same project site. However, the design response spectra may be modified to account for the increased damping of the isolated bridge according to GSSID (see Figure 20-22.4). When this method is used, the reduction factor for the spectral acceleration (S_a) must be no greater than 1.7, i.e. $(\xi/5)^{0.3} \leq 1.7$.

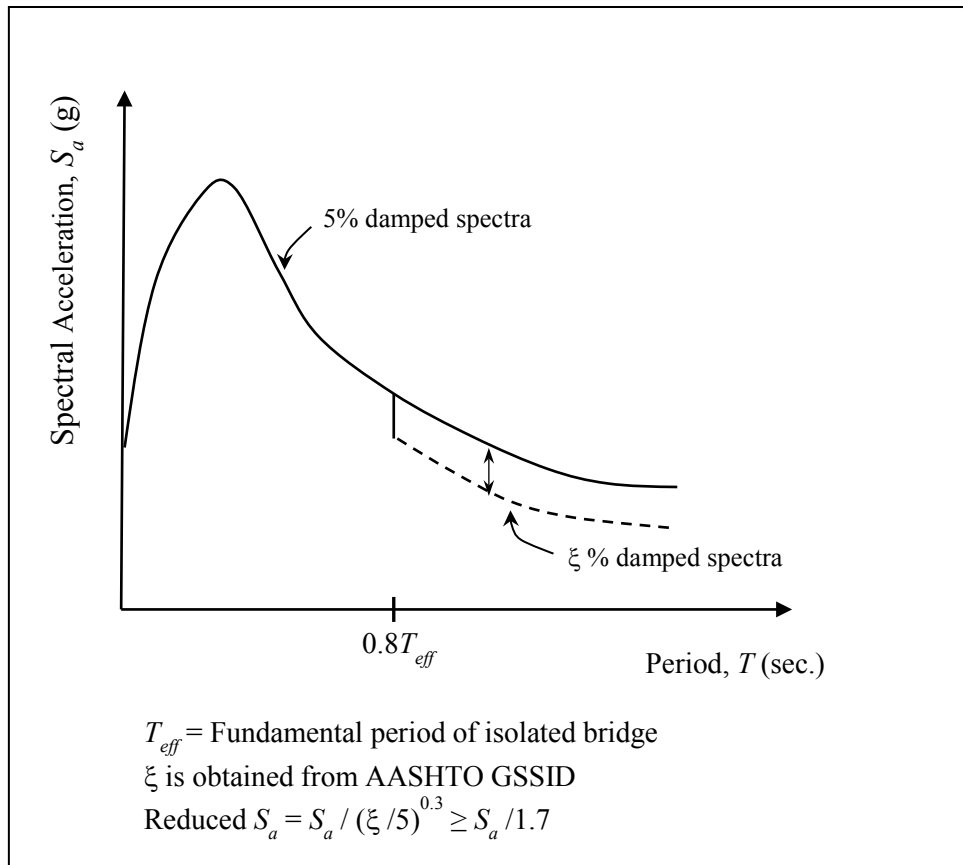


Figure 20-22.4 Reduction of ARS Curve to Account for Increased Damping

The ultimate displacement capacity of the isolation bearing, which is defined as the displacement that the bearing can achieve without shear failure, must be determined from the manufacturer's recommendation, but not less than $1.5D_T$. When LRBs are used, no strain hardening is allowed before $1.25D_T$. As shown in Figure 20-22.5, the 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 the 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 individual bent must be larger than V_U (see Figure 20-22.5), where V_U is the lateral force that can cause plastic hinging in the substructure at the same bent. In special cases, auxiliary external restraints such as shear blocks or restrainers can be used if the isolation bearings cannot provide sufficient lateral strength to force plastic hinging in the columns. This ensures that secondary EREs are activated before the isolation bearings fail when the seismic event exceeds the design seismic hazard level. If the substructure is a shear critical element (see MTD 20-18) where the forming plastic hinges is not feasible, a fusing element must be provided. 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 must also be provided to prevent the superstructure from an excessive vertical drop should the fuse elements become damaged.

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

Substructure/Column/Shaft/Piles

Columns, piles, and shafts must remain elastic when all bearings on the same bent displace less than $1.25D_T$. That is, V_U must be no less than the summation of $F_{1.25D_T}$ from all bearings on the same bent. ($F_{1.25D_T}$ denotes the lateral force transmitted through each bearing when it displaces $1.25D_T$). This is to account for the variability in the seismic demand. In addition, V_U must be no less than 10% of the dead load reaction on the substructure. Figure 20-22.5 shows the relationship between V_{U_i} and bearing force with respect to bearing displacements. V_{U_i} denotes the contribution to V_U from each bearing. Q denotes the characteristic strength of the bearing, which is defined as the lateral force in the bearing when its hysteresis curve crosses zero displacement.

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

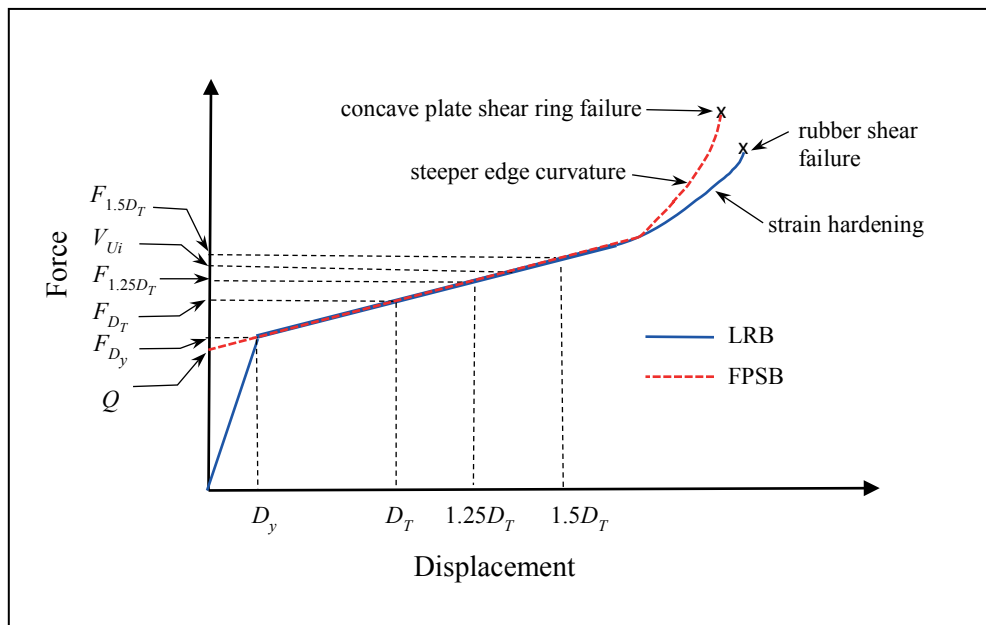


Figure 20-22.5 Force Displacement Curve for Isolation Bearings



Abutments and In-span Hinges

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

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

Service Design Requirements

Isolated bridges must meet the service and strength limit state requirements per the currently adopted *AASHTO LRFD Bridge Design Specifications* (LRFD) with current *California Amendments to AASHTO LRFD Bridge Design Specifications*.

Isolation bearings must not be subjected to tension under service and strength limit states.

Designers must account for all lateral forces generated by non-seismic loads (such as live load, wind load, braking force, etc.) such that they are transmitted to the columns and foundations of each support without yielding the isolation bearings. This is achieved by properly sizing the isolators or by providing external shear keys or restraining elements (namely, wind locks). The purpose is to prevent isolation bearings from yielding and minimize bridge movement especially in the transverse direction under service load conditions. External shear keys and restraining elements (see Appendix), if required, must allow for thermal displacements in the longitudinal direction and be designed to break at the force level no more than $0.85\sum F_{D_T}$ at the same bent (See Figure 20-22.6), where $\sum F_{D_T}$ denotes the summation of all the isolator forces at their respective design displacements, D_T . To design otherwise requires approval through the PSDC.

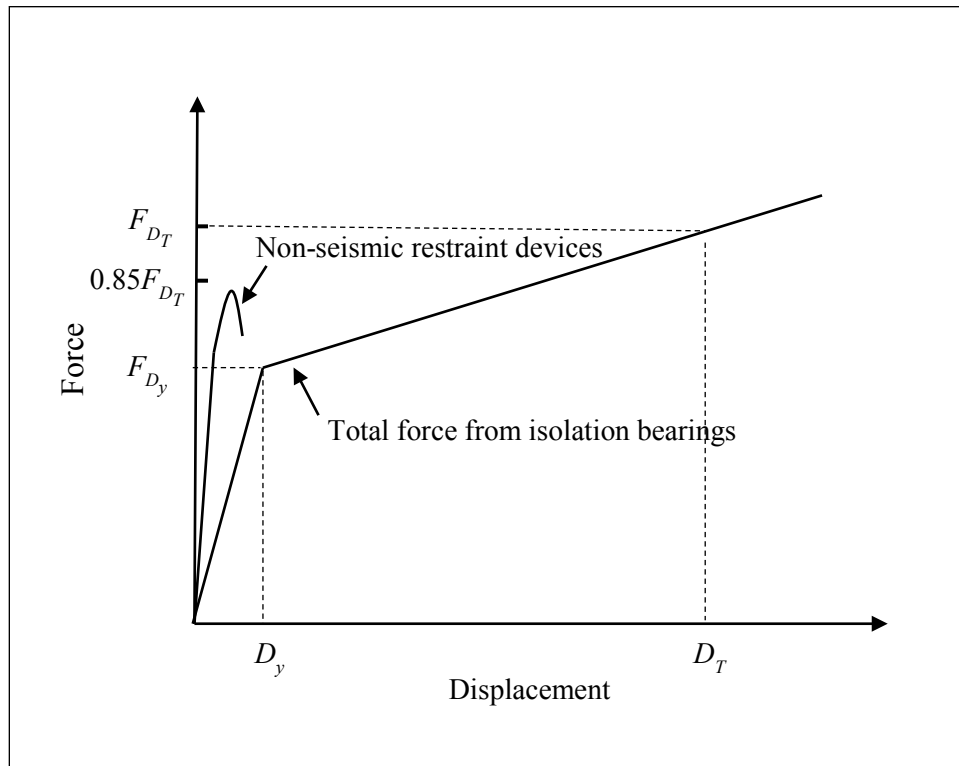


Figure 20-22.6 Performance of Shear Keys in Isolated Systems

The isolation bearing must be designed to meet the rotational demands for Strength and Service Limit States per LRFD.

The isolation bearing design must account for creep and prestress shortening to reserve sufficient displacement capacity for seismic demands. One of the methods to eliminate these displacements is to offset the isolation bearings longitudinally during bearing installation. The designer must specify the amount of offset on the plans. Offsets are expected to increase with the distance from the bearing location to the point of no movement. The amount of offset will vary with time, concrete type, geometry, and prestressing force (see Figure 20-22.7.). This requirement is pertinent when isolating post-tensioned box girder superstructures. Other alternatives to eliminate the isolation bearing offset may be allowed if the additional displacement due to creep and prestress shortening is accounted for in the design per LRFD (Section 5.14.1.4.4, “Age of girder when continuity is established”) and in the corresponding construction sequence. The designer may also make provisions such as an adjustable anchorage connection on the plans for re-adjusting bearings while in service. The designer should inform Structure Maintenance if out-of-plumb bearings are expected.

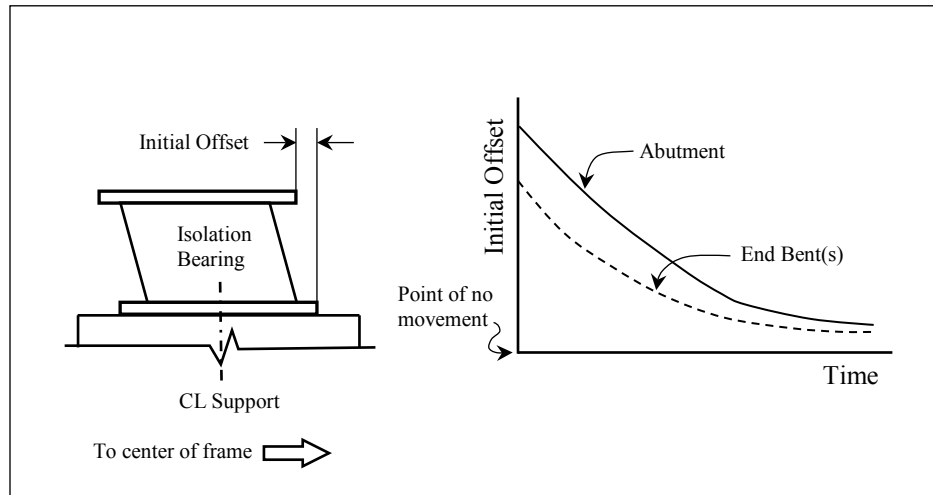


Figure 20-22.7 Offset of Isolation Bearings to counteract Creep and Prestress Shortening

Isolation Bearing Design Details, Drawings, and Special Provisions

Isolation bearings must be located between the superstructure and the substructure of bridges. This is in accordance with the Type 3 Earthquake-Resistant Systems which are composed of an elastic superstructure and substructure with a fusing mechanism between them per *AASHTO Guide Specifications for LRFD Seismic Bridge Design* (AASHTO, 2011). The isolation device would be above the abutments and bent caps for most girder and truss bridges (see Figure 20-22.1). Isolation bearings perform better when directly supporting the superstructure in a location that is free of debris and water. Isolation devices must be protected from contaminants, vandalism, and against corrosion.

Adequate access and space must be provided to allow for installation, inspection, maintenance, and replacement. Moreover, jacking locations on substructure and superstructure must be designed and shown in the design drawings for future replacement of bearings without the need for falsework.

Isolation Bearing Design Drawings

Designers must ensure design plans for the isolation bearings contain the following information:

- Maximum dimensions of the isolation bearings.
- Isolation bearing design performance curve (see Figure 20-22.A3 and Figure 20-22.A4 in Appendix). The parameters that define the performance curve are based



on the design methods per GSSID. Design examples are included in the Appendix of GSSID.

- Isolation bearing design loading (unfactored) on each bearing including Dead Load, Live Load, overturning vertical force due to earthquake, non-seismic lateral force (e.g. wind load), and displacement and allowable lateral force due to temperature effect.
- Isolation bearing design parameters including bearing design displacement with associated bearing lateral force, effective stiffness, and energy dissipation per cycle, bearing characteristic strength, yield displacement and force, post elastic stiffness, rotational capacity, and expected bearing vibration period (see Table 20-22A.1 and Table 20-22A.2 in Appendix).
- Preset displacement on the bearing for eliminating prestress shortening and creep if required.

Isolation Bearing Special Provisions

Designers must ensure the following items in the Special Provisions are addressed adequately:

- A schedule for the submittal of working drawings, testing programs, test reports, and review time for all submittals.
- A required testing protocol matrix and associated acceptance criteria. Testing protocols can be modified from AASHTO GSSID to fit the specific project needs.
- Any special requirements and procedures for bearing installation.

APPENDIX

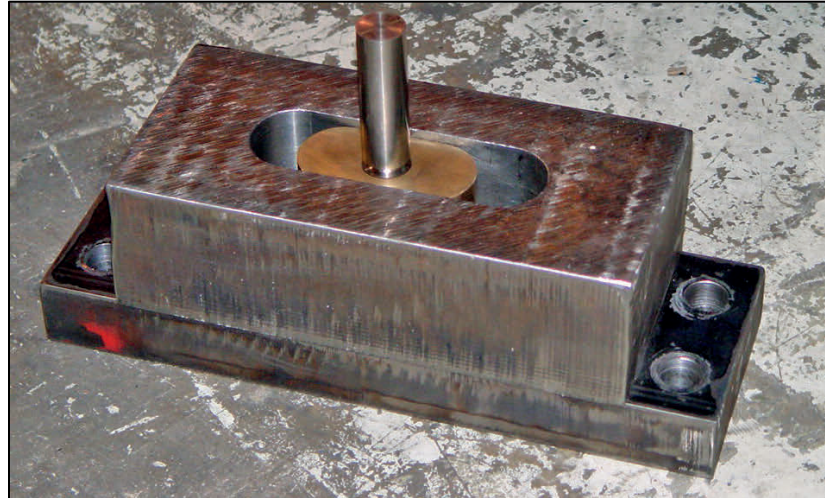


Figure 20-22.A1 External Transverse Restraining System for Service Load Conditions

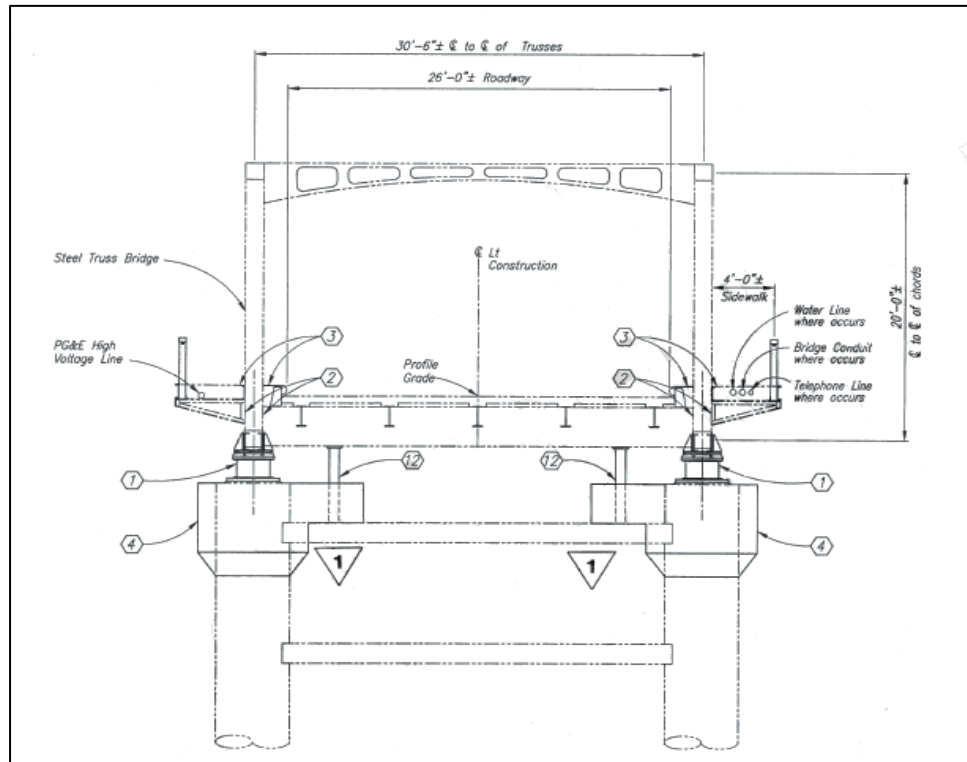


Figure 20-22.A2 Example of non-seismic lateral restrainer, (12), adjacent to isolation bearing, (1)

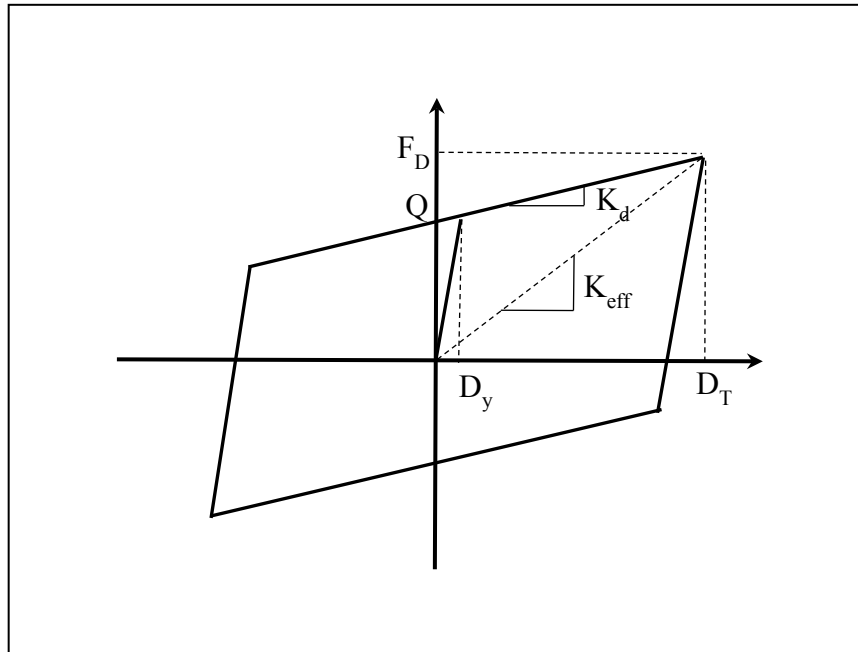


Figure 20-22.A3 Example of LRB Dynamic Performance Curve for Design Plan Sheets

Table 20-22.A1 Example of LRB Parameter Table for Design Plan Sheets

Bearing Location		Abut. 1 & 5	Bent 2	Bent 3&4
Bearing Type		A	B	C
Number of Bearings	EA			
Quaracheristic Strength, Q_d^*	kips			
Maximum Yield Displacement, D_y	in			
Restoring Stiffness, K_d^*	k/in			
Design Seismic Lateral Force, F_D^*	kips			
Design Seismic Lateral Displacement, D_T	in			
Effective Stiffness, K_{eff}^*	k/in			
Energy Dissipation per Cycle, EDC*	k-inch			
Rotational Capacity	radian			
Non-seismic Lateral Force, $F_{non-seis}$	kips			
Average Design Dead Load on Bearing, DL	kips			
Average Design Live Load on Bearing, LL	kips			
Maximum Overturning Compressive Vertical Load due to Seismic, OT_{comp}	kips			
Maximum Overturning Tensile Vertical Load due to Seismic, OT_{tens}	kips			
Maximum Thermal Displacement	in			
Maximum Thermal Force	kips			
Effective Period of Bearing, T	seconds			
Offset Displacement due to Prestress Shortening, Creep, and Shrinkage	in			
Note: * - The value is based on the bearing subjected to Average Design Dead Load (DL)				

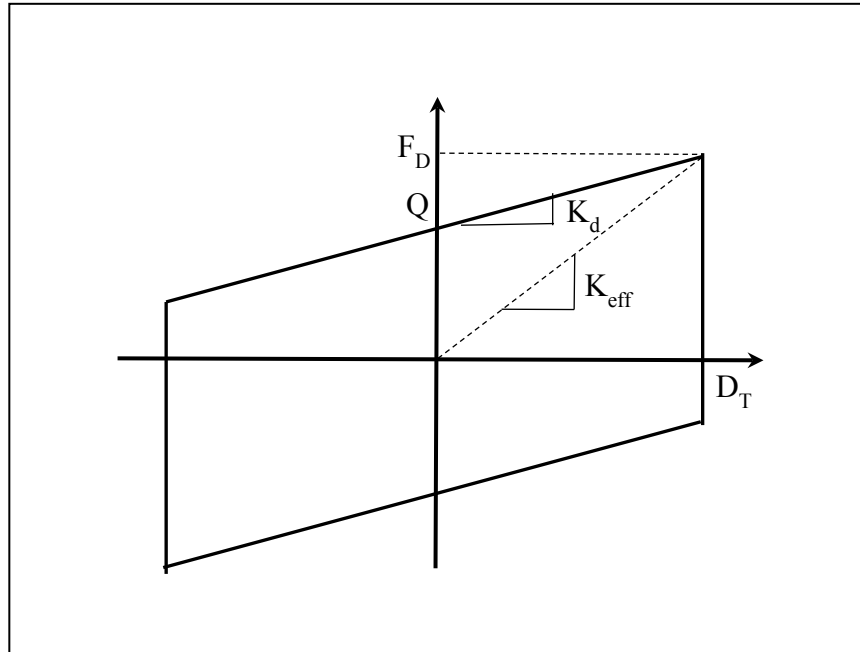


Figure 20-22.A4 Example of FPSB Dynamic Performance Curve for Design Plan Sheets

Table 20-22.A2 Example of FPSB Parameter Table for Design Plan Sheets

Bearing Location		Abut. 1 & 5	Bent 2	Bent 3&4
Bearing Type		A	B	C
Number of Bearings	EA			
Characteristic Strength, Q^*	kips			
Restoring Stiffness, K_d^*	k/in			
Design Seismic Lateral Force, F_D^*	kips			
Design Seismic Lateral Displacement, D_T	in			
Effective Stiffness, K_{eff}^*	k/in			
Energy Dissipation per Cycle, EDC*	k-inch			
Rotational Capacity	degree			
Non-seismic Lateral Force, $F_{non-seis}$	kips			
Average Design Dead Load on Bearing, DL	kips			
Average Design Live Load on Bearing, LL	kips			
Maximum Overturning Compressive Vertical Load due to Seismic, OT_{comp}	kips			
Maximum Overturning Tensile Vertical Load due to Seismic, OT_{tens}	kips			
Maximum Thermal Displacement	in			
Maximum Thermal Force	kips			
Effective Period of Bearing, T	seconds			
Offset Displacement due to Prestress Shortening, Creep, and Shrinkage	in			
Note: * - The value is based on the bearing subjected to Average Design Dead Load (DL)				



References

AASHTO, (2011). *Guide Specifications for LRFD Seismic Bridge Design*, American Association of State Highway and Transportation Officials, 2nd Edition, Washington DC.

AASHTO, (2014). *Guide Specifications for Seismic Isolation Design*, American Association of State Highway and Transportation Officials, 4th Edition, Washington DC.

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