Increased Seismic Protection for Bridges using the Triple Pendulum Bearings and the AASHTO Guide Specifications

Technical Presentation
for
North Carolina Department of Transportation
Raleigh, N. Carolina

October 28, 2009


Certificate of Training

This certifies that

Attended a two hour Seminar on
Increased Seismic Protection of Bridges using Triple Pendulum Bearings
and
AASHTO Guide Specifications for LRFD Seismic Bridge Design
Attending equals 2.0 PDHs or 2.0 Hours of Continuing Education

Earthquake Protection Systems

Roy A. Imbsen, D. Engr. PE
Bridge Seismic Specialist

October, 2009

Friction Pendulum

Seismic Isolation

Earthquake Protection Systems, Inc.
California, U.S.A.

AASHTO Adopted 2007 Guide Specifications

Proposed

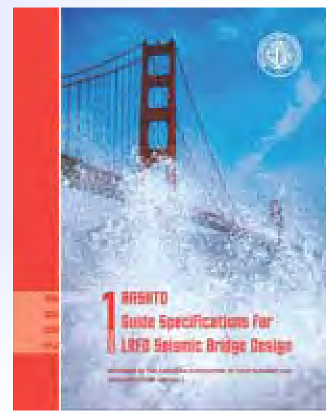
AASHTO Guide Specifications for LRFD Seismic Bridge Design

Subcommittee for Seismic Effects on Bridges
T-3

Prepared by:

Roy A. Imbsen
Imbsen Consulting

March 2007



Increased Seismic Protection using the Triple Pendulum Bearing

- *Seismic Performance of Bridge in Past Earthquakes*
- Lessons Learned in Past Earthquakes
- Seismic Isolation a Global Design Strategy in the New AASHTO Guide Specification
- Applications for Retrofit and New Construction
- Triple Pendulum Bearing Concept
- Bearing Evaluation and Prototype Testing

San Fernando Earthquake

Route 210/5 Interchange

Northridge Earthquake

Gavin Canyon Undercrossing – Collapsed Spans

Eureka Earthquake

Fields Landing Spans 1 and 2 Collapsed

Damage to the Showa-Ohashi Bridge

Niigata Earthquake (Japan), June 16, 1964
(Magnitude 7.5 on Richter Scale)

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Guatemala Earthquakes

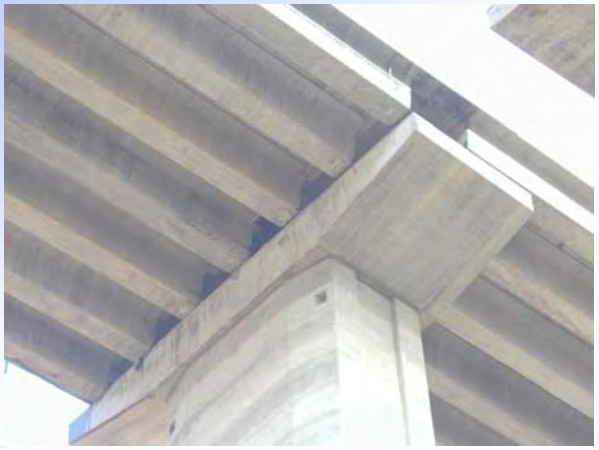
Rio Agua Caliente Bridge

Earthquake Protection Systems, Inc. 10

Bolu, Turkey Earthquake

Earthquake Protection Systems, Inc. 11

Bolu, Turkey Earthquake



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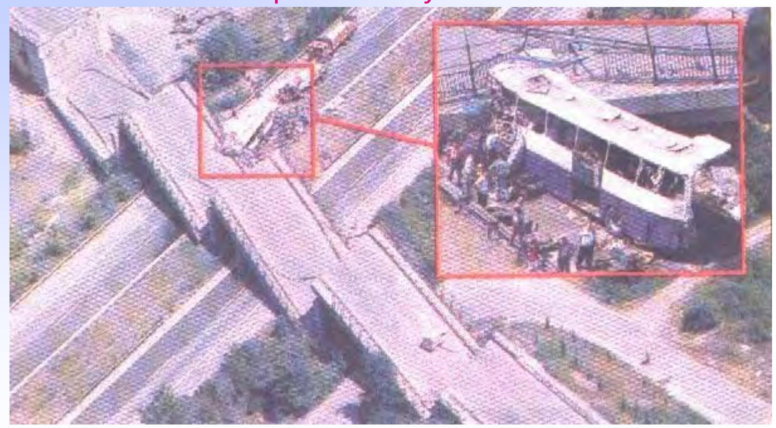
Kocaeli, Turkey Earthquake

Overpass at Arifiye Junction



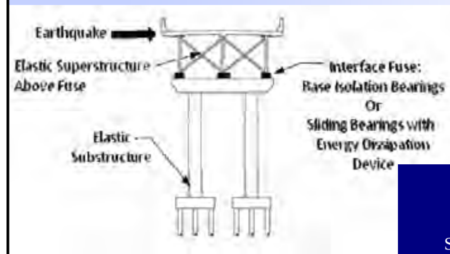
Highway Collapse, Kobe Japan 1995

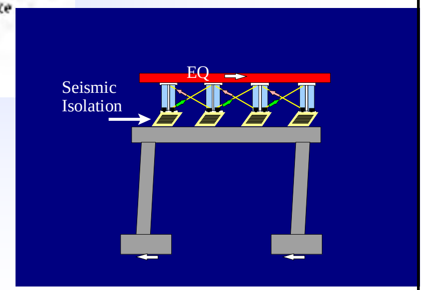
Highway Collapse, China 2008

Lessons Learned in Recent Earthquakes

- Bridge substructures are vulnerable
  - Inadequate ductility
  - Inadequate deformability
- Lack of adequate shear strength in substructure components and their connections
- Bridge superstructures have inadequate support widths to accommodate displacement demands of the substructures

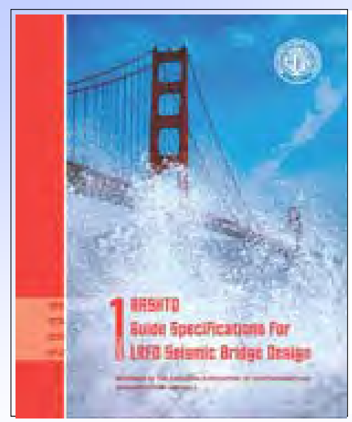
AASHTO Guide Specifications Global Design Strategy Type 3

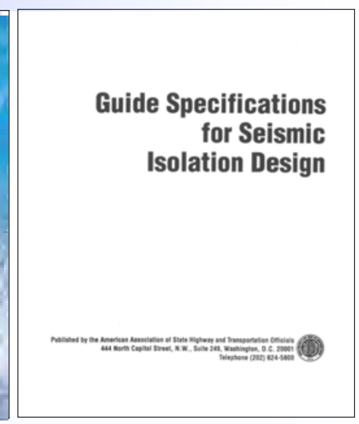




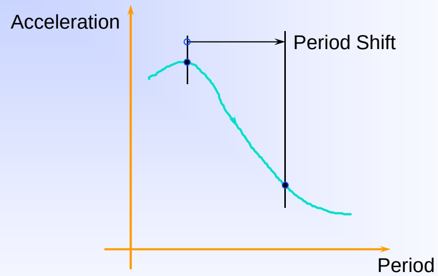
Primary Ingredients to a Successful Use of an Isolation Strategy for Bridges

- A Candidate Bridge
- Desired Seismic Performance
- Supportive Owner
- Informed Designer
- Design Specification/Guidelines
- Global Model and Analytical Support
- Product Evaluation and Testing
- Quality Control During Construction



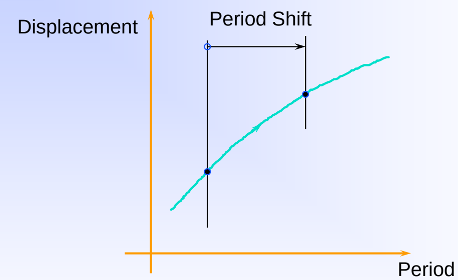


Idealized Force Response Curve



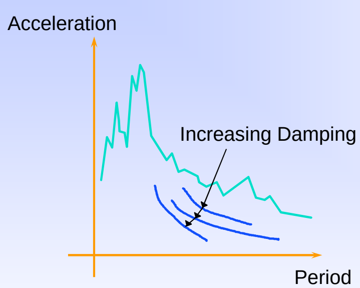
ACCELERATION RESPONSE SPECTRUM

Idealized Displacement Response Curve

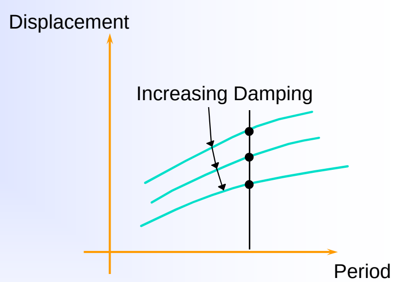


DISPLACEMENT RESPONSE SPECTRUM

Response Curves for Increasing Damping



ACCELERATION RESPONSE SPECTRUM



DISPLACEMENT RESPONSE SPECTRUM

Increased Seismic Protection using the Triple Pendulum Bearing

- Seismic Performance of Bridge in Past Earthquakes
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- Bearing Evaluation and Prototype Testing

Benicia-Martinez, CA Bridge

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Truss Span- Bearings

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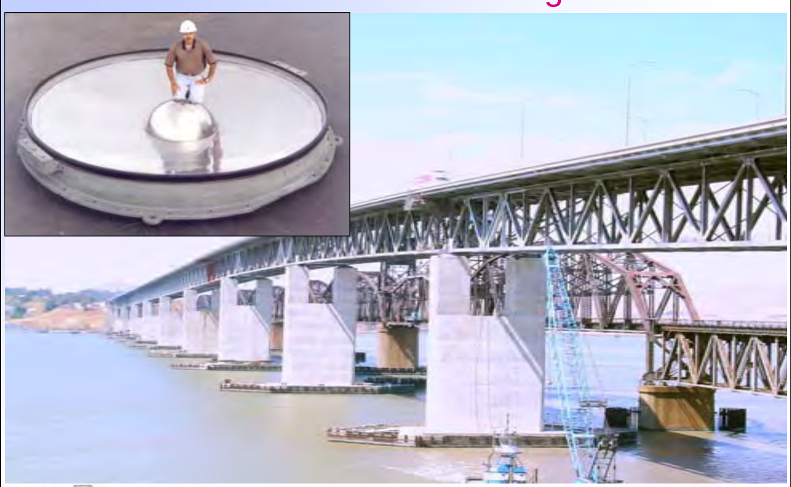
Benicia-Martinez Bridge



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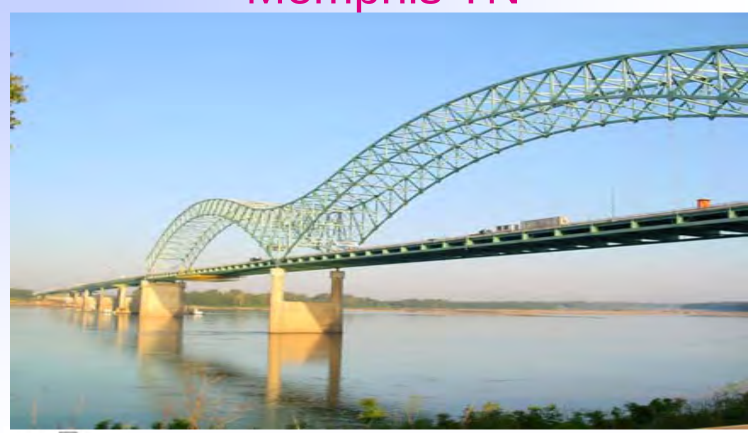
I-40 Mississippi River Bridge, Memphis TN



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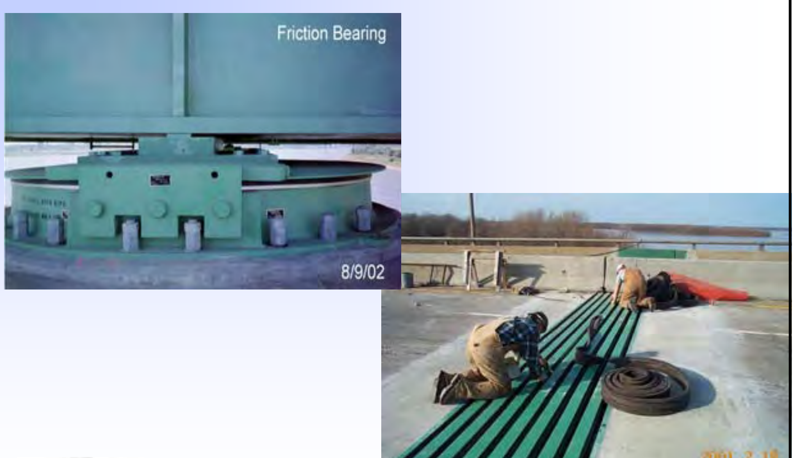
Steel Tied Arch

I-40 Modular Joint Installation (70° L&T)



Viaduct 1, Bolu, Turkey, Trans-European Motorway


P26R EDU Block;Beam A4

Antioch Bridge, CA

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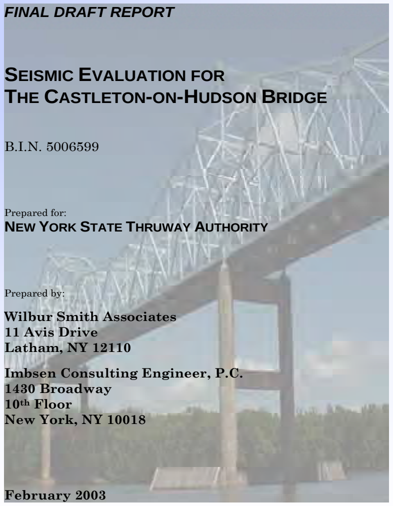
Dumbarton Bridge, CA

Earthquake Protection Systems, Inc. 38

George Washington Bridge, Seattle, WA

Earthquake Protection Systems, Inc. 39



FINAL DRAFT REPORT

SEISMIC EVALUATION FOR
THE CASTLETON-ON-HUDSON BRIDGE

B.I.N. 5006599

Prepared for:
NEW YORK STATE THRUWAY AUTHORITY

Prepared by:

Wilbur Smith Associates
11 Avis Drive
Latham, NY 12110

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1430 Broadway
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New York, NY 10018

February 2003

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Kodiak-Near Island Bridge, Kodiak, AK

Kodiak-Near Island Bridge Bearing Installation

Viaduct La Estampilla, Colombia

Viaduct La Estampilla, Colombia

Viaduct El Helicoidal, Colombia

American River Bridge, Folsom, CA

11th Avenue Viaduct over Amtrak

New York City Department of Transportation
Division of Roadway Bridges

March 2002

Black Sea Bridge, Turkey

Black Sea Bridge Bearing Location

I-90 Interchange King County, WA

I-90 Interchange Bearing Location

Mississippi River Crossing, Ontario, Canada

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Mississippi River Crossing Bearing Location

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West Span, San Francisco Bay Bridge

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West Span Bay Bridge Bearing Location

Earthquake Protection Systems, Inc. 56

West Span Bay Bridge Bearing Location

JFK AirTrain Light Rail Structure

The World's Most Important Seismically Isolated Structures

use

Friction Pendulum Bearings

by

Earthquake Protection Systems

San Francisco Airport International Terminal

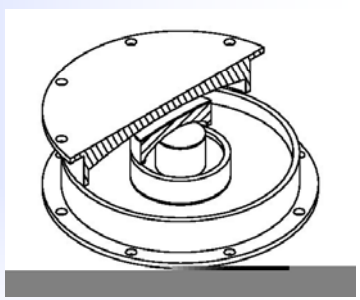
World's Second Largest Isolated Building

Ataturk Airport International Terminal İstanbul, Turkey

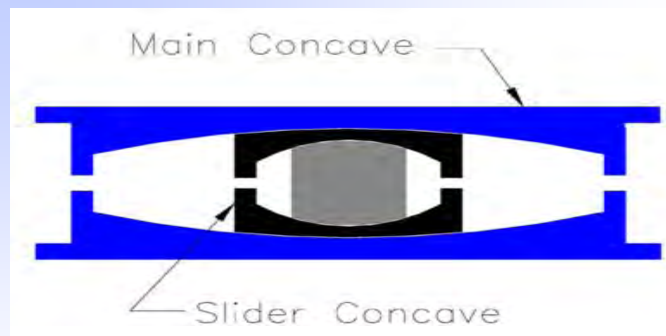
World's Largest Isolated Building

SAKHALIN II PLATFORM

Triple Pendulum Bearing



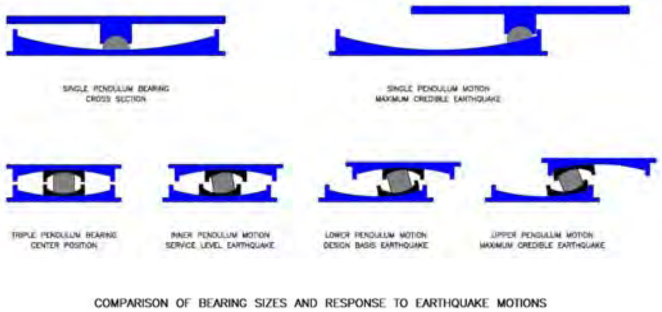
Triple Pendulum Bearing



Section of Triple Pendulum Bearing

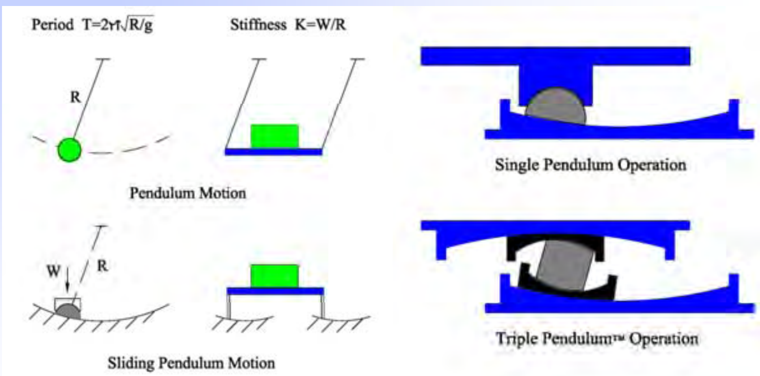
how_bearing_works_291007 (1).mpg

Triple Pendulum Bearing



How Does It Work?

Friction Pendulum Concept



Application Specific Design, Manufacture, Testing and Supply of Bearings

by

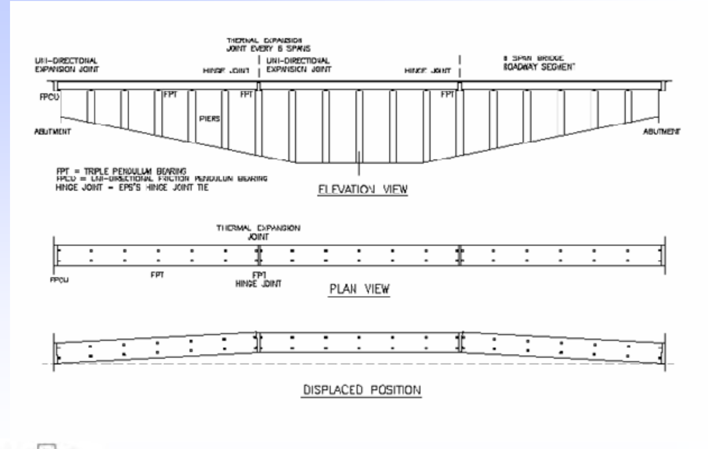
Earthquake Protection Systems, Inc.

California, U.S.A.

Friction Pendulum Roadway Movement Control

- Provides a structural displacement pattern such that there is full serviceability of all the bridge elements and joints following a severe earthquake.
- Provisions for temperature (and other service loads) movements that are completely uncoupled from seismic movements
- Operational with full serviceability after a sever earthquake

Friction Pendulum Roadway Movement Control



Friction Pendulum Roadway Movement Control

Full roadway function is maintained after a severe seismic event. Piers, railway structure, and expansion joints are all protected from damage.

An R factor of one is used in the design. Dynamic analyses and seismic designs become an order of magnitude more accurate and reliable.

There are no relative transverse seismic movements between railway sections. Costly multi-directional expansion joints are not required at any expansion joints.

Total construction costs are reduced as compared to conventional seismic designs.

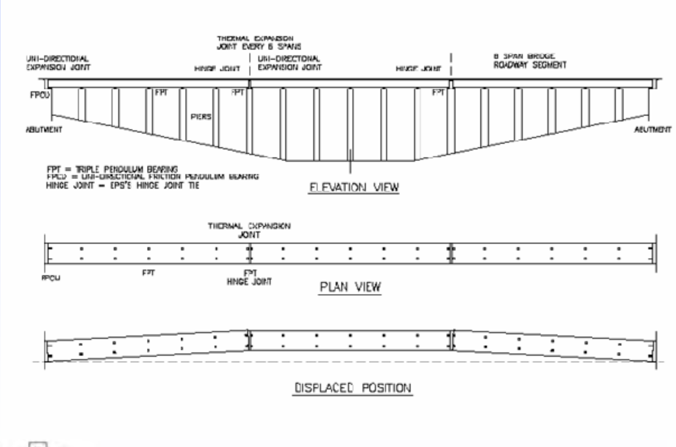
Friction Pendulum Roadway Movement Control

Triple Pendulum Bearings are located at the tops of all piers. They reduce the seismic forces transmitted to the piers. They allow thermal expansion movements. They allow live load rotations of the roadway. Construction costs of the piers and foundations are significantly reduced.

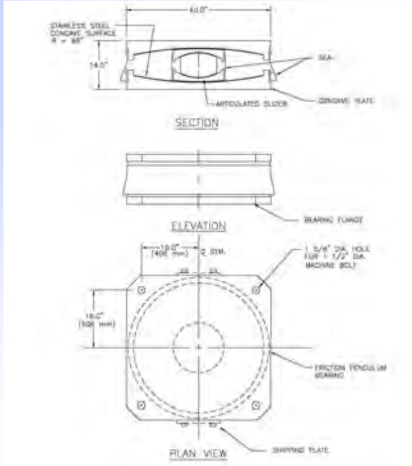
Cylindrical Friction Pendulum Bearings are located at the abutments. They permit longitudinal pendulum motions of the entire roadway. They permit full roadway structure articulation about two horizontal and one vertical axis to accommodate live load and seismic movements.

Slotted Hinge Joints tie the roadway structure sections together, acting as one continuous structure for seismic movements. Beams can not fall off of their supports.

Friction Pendulum Roadway Movement Control



Triple Pendulum Bearing (Pier Bearing)



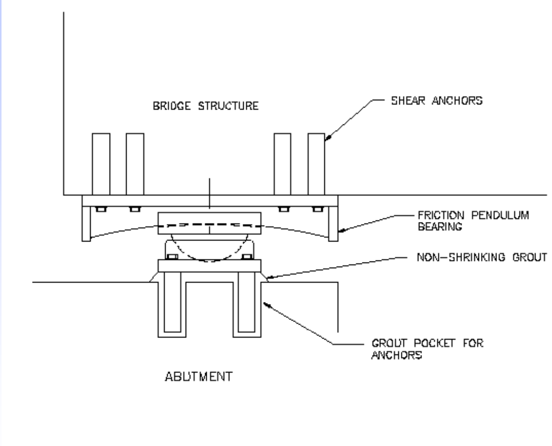
Abutment Guided Cylindrical Bearing

Guided cylindrical Friction Pendulum Bearing allows longitudinal seismic displacements to have pendulum motions.

Transverse displacements are locked. Transverse roadway shears are transferred directly to the abutments. Expansion joints are protected from transverse displacement movements.

Ordinary unidirectional expansion joints are used, with sufficient displacement capacity for seismic and thermal movements.

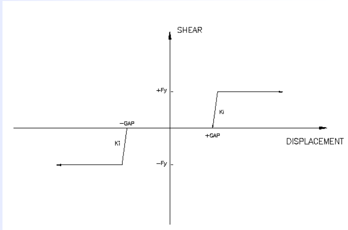
Abutment Guided Cylindrical Bearing



Friction Pendulum Roadway Movement Control

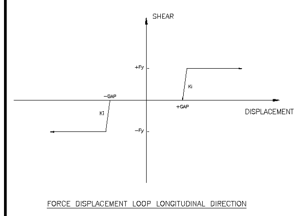
Slotted hinge joint:

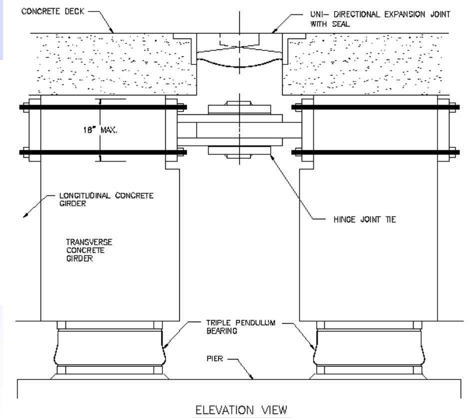
- Connects roadway structures sections together to move as one interconnected structure for seismic movements.
- Acts like a longitudinal gap element, to permit longitudinal thermal expansion
- Locks up to protect the expansion joint from longitudinal seismic displacements.
- Yields in compression or tension to protect the connections to the roadway structure from excessive seismic forces.



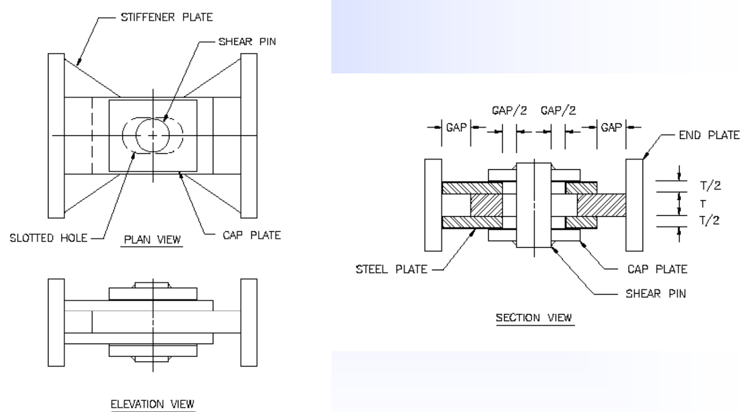
Lateral Force Vs. Displacement Response of Slotted Hinge Joint

Friction Pendulum Roadway Movement Control





Friction Pendulum Roadway Movement Control



Friction Pendulum Roadway Movement Control Advantages

Avoids Seismic Damage after the Most Severe Seismic Events. Structures Remain Fully Elastic.

Maintains Operational and Function to Allow Emergency Response and Post-Earthquake Reconstruction.

Seismic Analysis and Design Become much more, Simple, Reliable and Accurate.

Construction Costs are Reduced

Friction Pendulum Roadway Movement Control Applicability

Displacement Control Seismic Design Method

1. Railways
2. Bridges
3. Elevated Highways

22 Years of Comprehensive University Laboratory Seismic Testing and Performance Evaluations of EPS Friction Pendulum Bearings

University of California Berkeley, Earthquake Engineering Research Center

State University Of New York, National Center for Earthquake Engineering Research

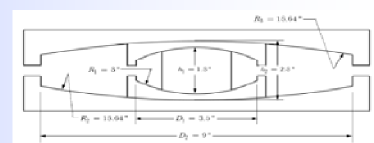
University of California San Diego, CALTRANS Seismic Response Modification Devise Testing Facility

Earthquake Engineering Research Center, University of California at Berkeley, California

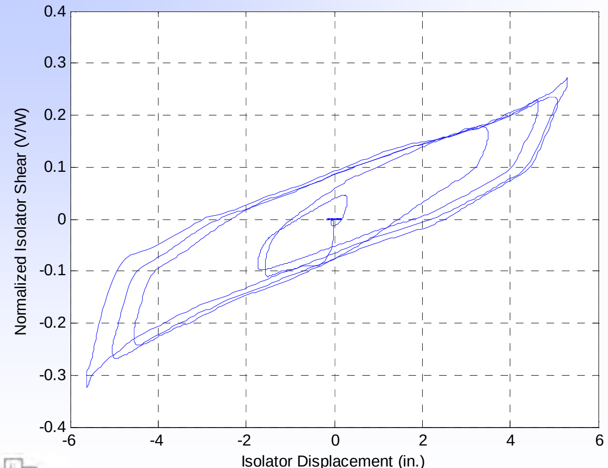
- Bi-directional testing for Bridge Structures
- Torsional Response
- Full Scale One Story Masonry Structure Shake Table Tests
- Experimental & Analytical Prediction of Response with FP Bearings
- Studies on Temperature and simulated Aging
- Compression-Shear Testing
- One & Two Story Building Structures

Experimental Specimen (Berkeley)

Reduced-Scale Triple Pendulum Bearing



Isolation System Hysteresis

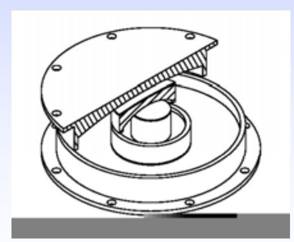


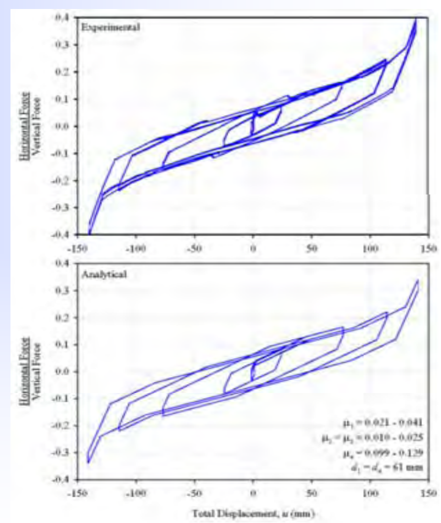
Isolation System Hysteresis

National Center for Earthquake Engineering Research, State University of New York at Buffalo, New York

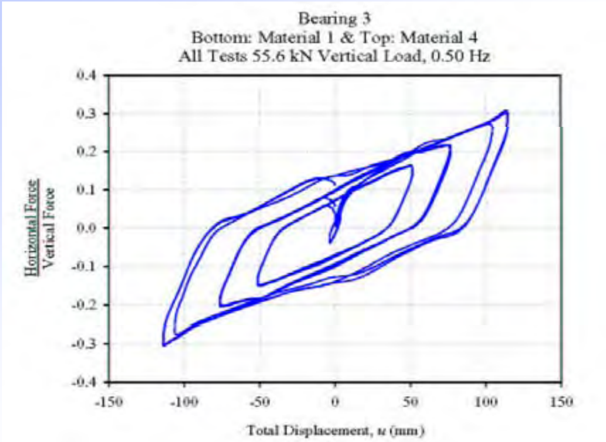
- Multistory Building & Bridge Structures
- Experimental & Analytical Prediction of Response with FP Bearings
- Friction Modeling, Temperature, Wear and Aging Studies
- Compression-Shear Testing of Model FP Bearings
- Shake Table Testing of 1/4th Scale Building Frame Model on FP Bearings
- Shake Table Testing & Analytical Prediction with Tension FP & Double Concave FP Bearings
- Response of Secondary Systems in Structures Isolated with FP Bearings

Component Testing Of Triple Pendulum Bearing At MCEER, Suny Buffalo

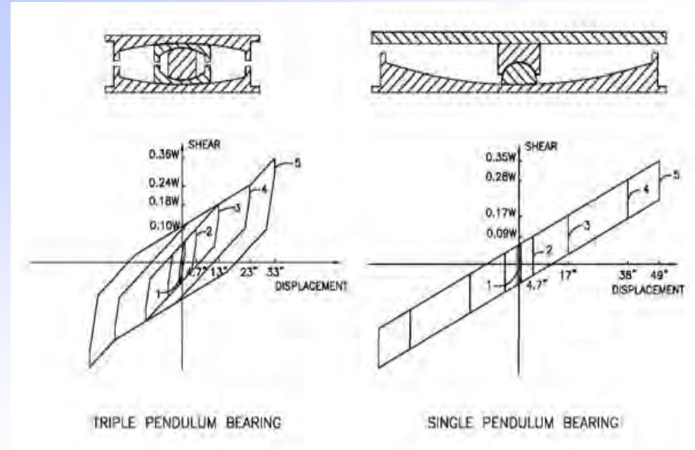




Triple Pendulum Hysteresis



Advantages Of Triple Pendulum Bearing



Advantages Of Triple Pendulum Bearing

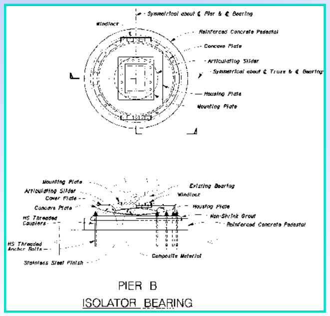
- Multi-Stage Adaptive Seismic Isolation Bearing.
- Improved Structural Performance at Lower Bearing Cost
- Three Seismic isolators Incorporated in a single Triple Pendulum Bearing
- Lowers in-Structural Accelerations and Shears and reduces Bearing Displacement.
- Single Triple Pendulum Bearing accommodates optimal Structural Performance at Service, Design, and Maximum Credible Earthquakes.

University of California at San Diego, San Diego, California

High-Speed Testing of Full-Scale FPB's for:

- Benicia-Martinez Bridge Retrofit Project
- I-40 Bridge Over Mississippi River Project
- West-Span Bay Bridge Retrofit Project
- Trans-European Motorway Bridge Retrofit Project

Friction Pendulum Bearing

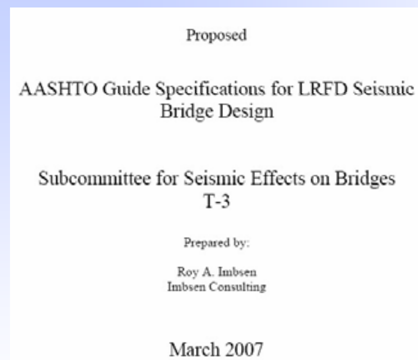


Friction Pendulum Bearing

EPS Friction Pendulum Bearing **Testing**

- Performance
- Quality assurance
- Tension capacity
- Compression strength
- Torsion properties
- Compression stiffness
- Unscragged and scragged properties w/ lateral loads
- Temperature effects (rated at -320ºF to +400ºF)
- Material longevity & aging
- Fire resistance (rating to 600º F)

AASHTO Adopted 2007 Guide Specifications


Proposed

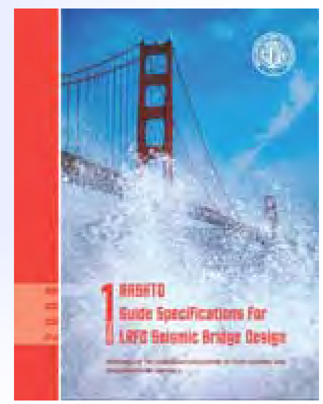
AASHTO Guide Specifications for LRFD Seismic Bridge Design

Subcommittee for Seismic Effects on Bridges
T-3

Prepared by:

Roy A. Imbsen
Imbsen Consulting

March 2007



Technical Review Team

- Mark Mahan, CA DOT (Team Leader, 2007)
- Lee Marsh, BERGER/ABAM Engineers (Team Leader, 2008)
- Roy A. Imbsen, Imbsen Consulting
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- Jay Quiogue, CA DOT
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- Fadel Alameddine, CA DOT
- Chyuan-Shen Lee, WSDOT
- Stephanie Brandenberger, MT DOT
- Daniel Tobias, IL DOT
- Derrell Manceaux, FHWA
- Tony Allen, WSDOT
- Don Anderson, CH2M Hill

Current Seismic Design Provisions for Bridges

- AASHTO Standard Specifications, Division 1-A. American Association of State Highway and Transportation Officials (AASHTO). *Standard Specifications for Highway Bridges, Division 1-A*, 17th Edition, 2002, with Interim Revisions through 2008.
- AASHTO LRFD Design Specifications. American Association of State Highway and Transportation Officials (AASHTO). *LRFD Bridge Design Specifications*, Fourth Edition, 2007, with Interim Revisions through 2008.
- AASHTO LRFD Guide Specifications for Seismic Bridge Design, Adopted 2007.

LRFD Guide Specifications Table of Contents

Highlights Seismic Guide Specification

- Performance Based Design Criteria - No Collapse
- New Hazard - 1000 Year Return Period
- Calibration of Hazard and Performance
- Four Seismic Design Categories (SDC) A to D
- Application – Design Procedure Flow Charts
- Strategy and Selection of “Key” Component
- Displacement Demand and Capacity Analysis
- Design/Capacity Protection

Highlights Seismic Guide Specification

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- ♦ New Hazard - 1000 Year Return Period
- ♦ Calibration of Hazard and Performance
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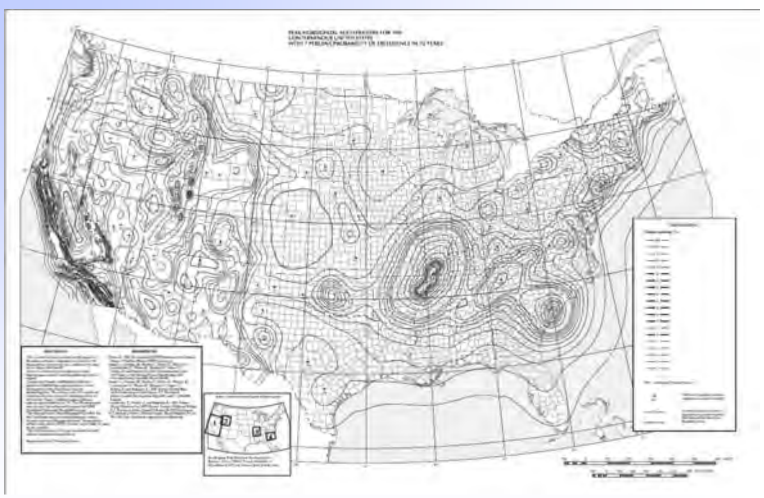
- ♦ Displacement Demand and Capacity Analysis
- ♦ Design/Capacity Protection

Earthquake Protection Systems, Inc. 101

New Hazard

- ♦ AASHTO /USGS Uniform Hazard Acceleration for 1000 year Return Period (7% P of E in 75 Years)
- ♦ Contour Maps for: PGA, 0.2 sec. and 1.0 sec. Define the Design Spectral Shape
- ♦ NEHRP Soil Factors
- ♦ New Procedures for Determining Liquefaction Potential

Earthquake Protection Systems, Inc. 102



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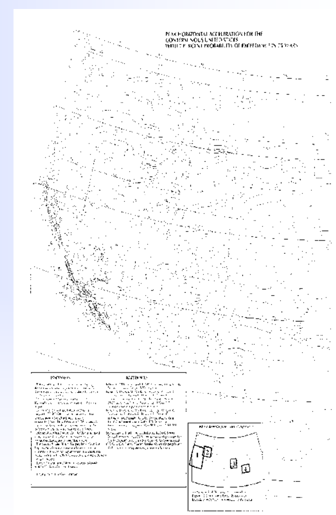
AASHTO/ USGS Maps

Figure 3.4.1-2 thru 3.4.1-22 Peak Horizontal Ground Acceleration for the Conterminous United States (Western) With 7 Percent Probability of Exceedance in 75 Years (Approx. 1000 Year Return Period) for:

- **PGA**
- **0.2 SEC.**
- **1.0 SEC**



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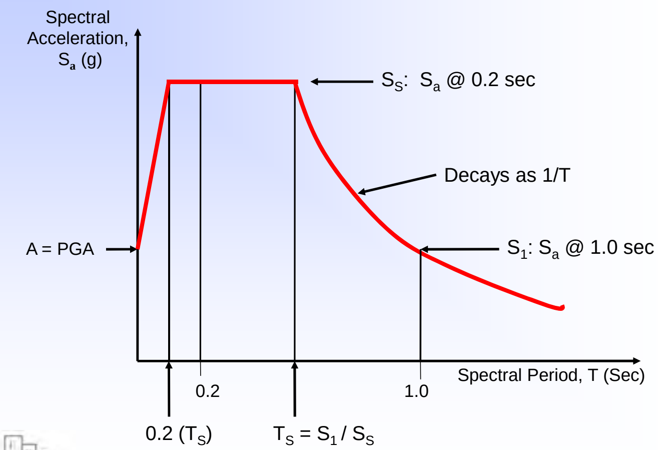
Design Spectrum using a 3 Point Method



Site Coefficients for F_{pga} and F_a

Table 3.4.2.3-1 Values of F_{pga} and F_a as a Function of Site Class and Mapped Peak Ground Acceleration or Short-Period Spectral Acceleration Coefficient.

Site Class	Mapped Peak Ground Acceleration or Spectral Response Acceleration Coefficient at Short Periods				
	PGA ≤ 0.10 $S_s \le 0.25$	PGA = 0.20 S_s = 0.50	PGA = 0.30 S_s = 0.75	PGA = 0.40 S_s = 1.00	PGA ≥ 0.50 $S_s \ge 1.25$
A	0.8	0.8	0.8	0.8	0.8
B	1.0	1.0	1.0	1.0	1.0
C	1.2	1.2	1.1	1.0	1.0
D	1.6	1.4	1.2	1.1	1.0
E	2.5	1.7	1.2	0.9	0.9
F	*a*	*a*	*a*	*a*	*a*

Table notes: Use straight line interpolation for intermediate values of *PGA* and S_s, where *PGA* is the peak ground acceleration and S_s is the spectral acceleration coefficient at 0.2 sec. obtained from the ground motion maps.
a: Site-specific geotechnical investigation and dynamic site response analyses shall be performed (Article 3.4.3).

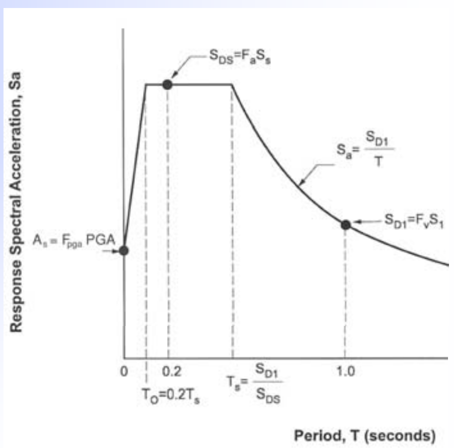
Design Spectra - General Procedure (3.4.1)

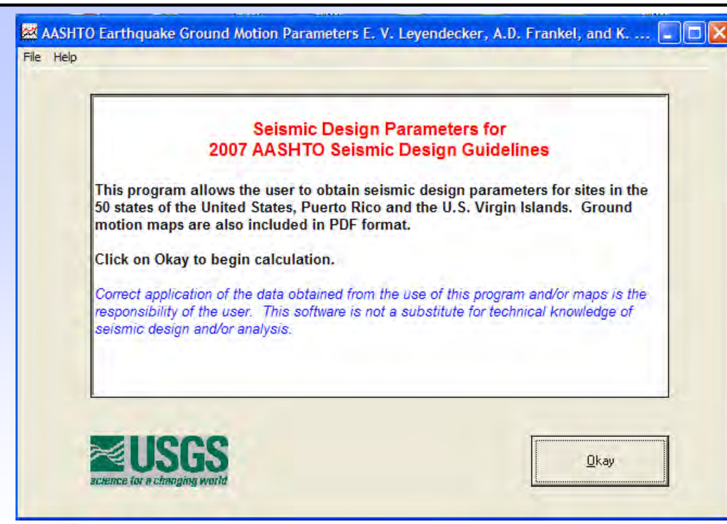
- Response spectrum accelerations
- Site factors

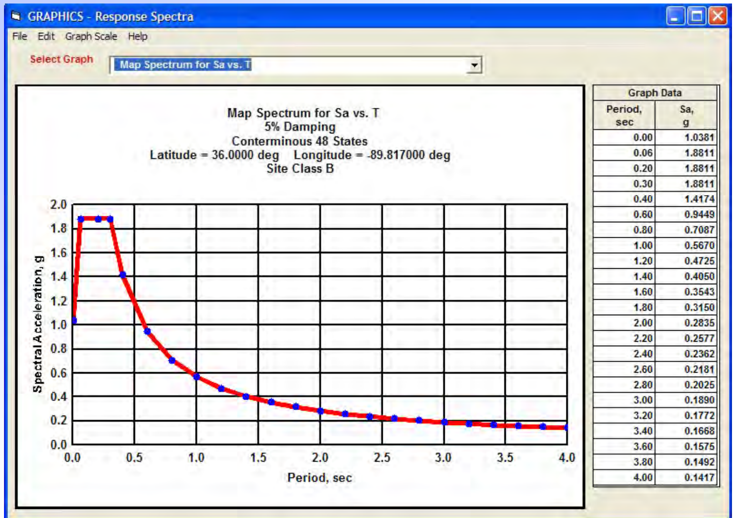
$$A_s = F_{pga} PGA$$

$$S_{DS} = F_a S_s$$

$$S_{D1} = F_v S_1$$







Graph Data

Period, sec	Sa, g
0.00	1.0381
0.06	1.8811
0.20	1.8811
0.30	1.8811
0.40	1.4174
0.60	0.9449
0.80	0.7087
1.00	0.5670
1.20	0.4725
1.40	0.4050
1.60	0.3543
1.80	0.3150
2.00	0.2835
2.20	0.2577
2.40	0.2362
2.60	0.2181
2.80	0.2025
3.00	0.1890
3.20	0.1772
3.40	0.1668
3.60	0.1575
3.80	0.1492
4.00	0.1417

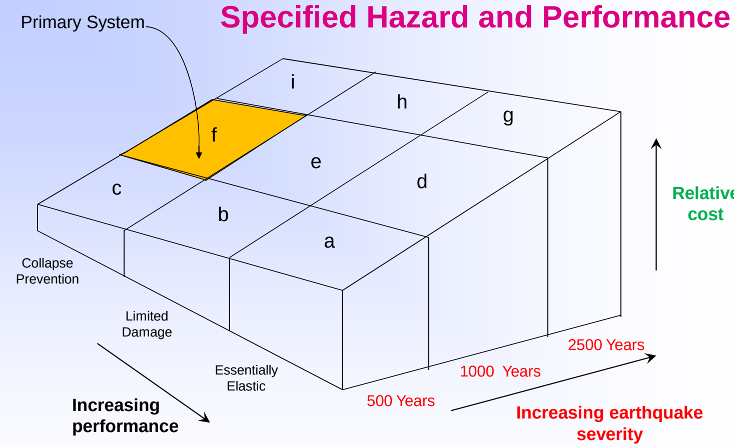
Adoption of the New Hazard

- 2007 - MCEER/FHWA Seismic Retrofitting Manual for Highway Structures
- 2007 - AASHTO Guide Specifications for LRFD Seismic Bridge Design Completed
- 2007 – AASHTO LRFD Bridge Design Specifications Modified to Include 2007; 1,000 Year Seismic Hazard
- 2008 – NCHRP Seismic Analysis and Design of retaining Walls, Buried Structures Slopes and Embankments; NCHRP Report 20-7

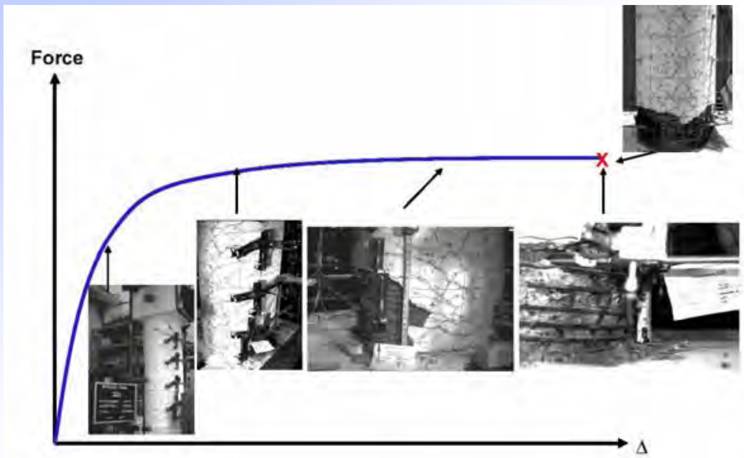
Highlights Seismic Guide Specification

- Performance Based Design Criteria - No Collapse
- New Hazard - 1000 Year Return Period
- Calibration of Hazard and Performance
- Four Seismic Design Categories (SDC) A to D
- Application – Design Procedure Flow Charts
- Strategy and Selection of "Key" Component
- Displacement Demand and Capacity Analysis
- Design/Capacity Protection

Specified Hazard and Performance



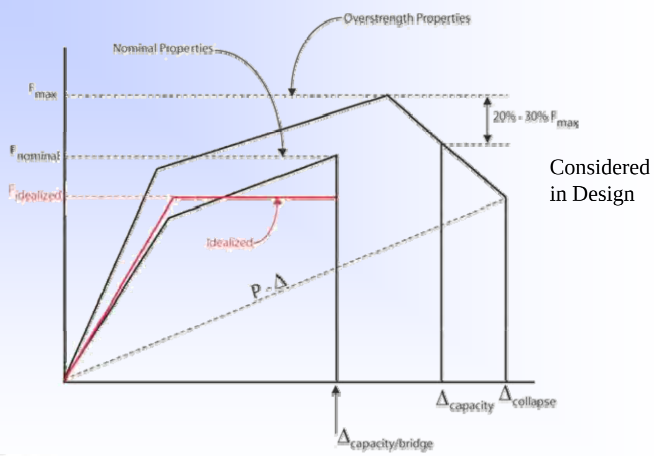
Calibration Objectives



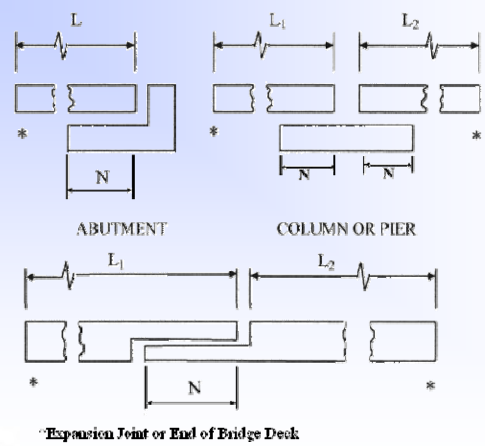
LRFD Guidelines-Background Task 2-Sources of Conservatism

Source of Conservatism	Safety Factor
Computational vs. Experimental Displacement Capacity of Components	1.3
Effective Damping	1.2 to 1.5
Dynamic Effect (i.e., strain rate effect)	1.2
Pushover Techniques Governed by First Plastic Hinge to Reach Ultimate Capacity	1.2 to 1.5
Out of Phase Displacement at Hinge Seat	Addressed in Task 3

Idealized Load – Deflection Curve



Minimum Support Length Requirements SDC A, B, C & D



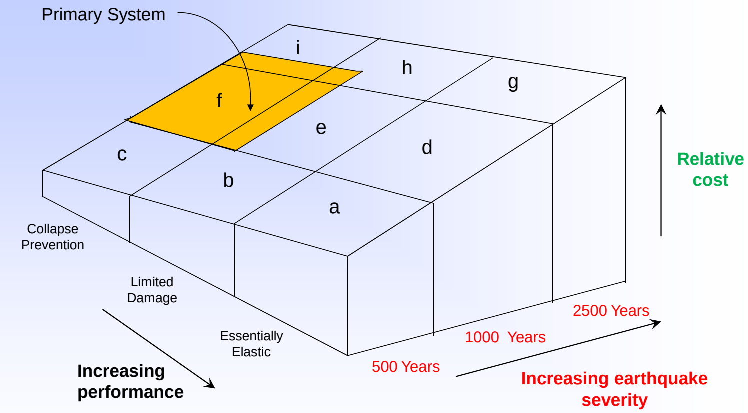
Minimum Support Length Requirements SDC A, B, C & D

$$N = (8 + 0.02L + 0.08H)(1 + 0.000125S^2) \qquad (4.12.2\text{-}1)$$

Table 4.12.2-1 Percentage N by SDC and effective peak ground acceleration, A_s

SDC	Effective peak ground acceleration, A_s	Percent N
A	< 0.05	≥ 75
A	≥ 0.05	100
B	All applicable	150
C	All applicable	150

Estimated Hazard and Performance



Calibration Objectives

Highlights Seismic Guide Specification

- Performance Based Design Criteria - No Collapse
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Seismic Design Category (SDC)

Table 3.5-1 Partitions for Seismic Design Categories A, B, C and D.

Value of $S_{D1} = F_v S_1$	SDC
$S_{D1} < 0.15$	A
$0.15 \leq S_{D1} < 0.30$	B
$0.30 \leq S_{D1} < 0.50$	C
$0.50 \leq S_{D1}$	D

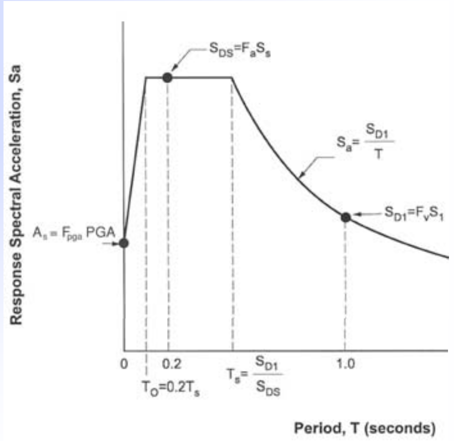
Design Spectra - General Procedure (3.4.1)

- Response spectrum accelerations
- Site factors

$$A_s = F_{pga} PGA$$

$$S_{DS} = F_a S_s$$

$$S_{D1} = F_v S_1$$



Seismic Design Categories (SDC)

Requirements	A	B	C	D
Global Strategy	-------	Recommended	Required	Required
Identification ERS	-------	Recommended	Required	Required
Support Connections	Required	Required	Required	Required
Support Length	Required	Required	Required	Required
Demand Analysis	-------	Required	Required	Required
Implicit Capacity	-------	Required	Required	-------
Push Over Capacity	-------	-------	-------	Required
Detailing - Ductility	-------	SDC B	SDC C	SDC D
Capacity Protection	-------	Recommended	Required	Required
P-Δ Effect	-------	-------	Required	Required
Minimum Lateral Strength	-------	Required	Required	Required
Liquefaction	-------	Recommended	Required	Required

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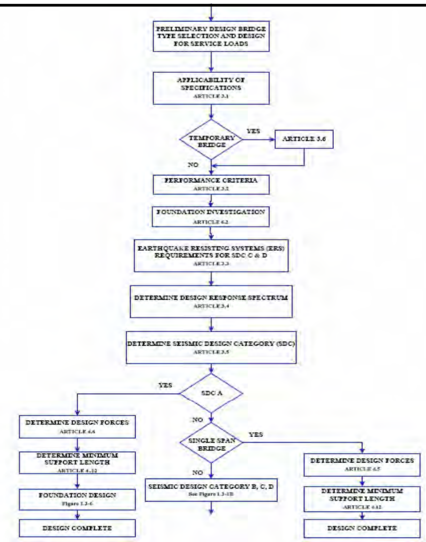
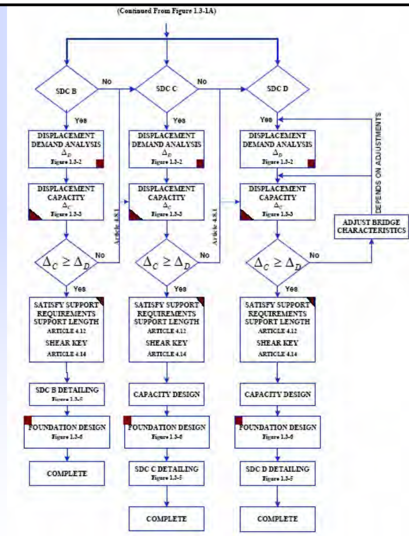
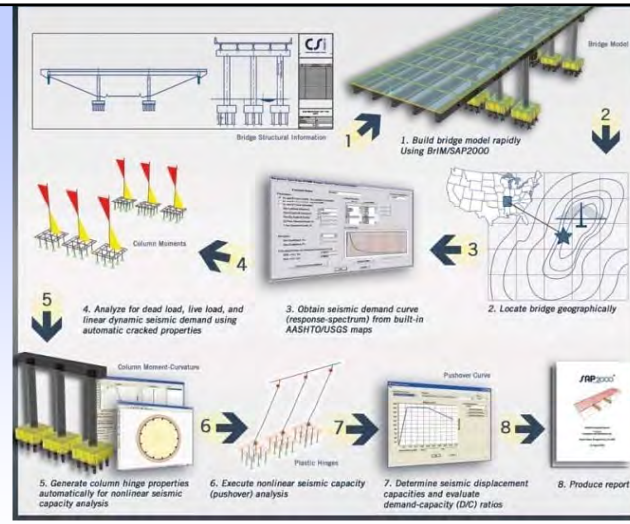
LRFD Flow Chart Fig 1.3-1A



LRFD Flow Chart Fig 1.3-1B





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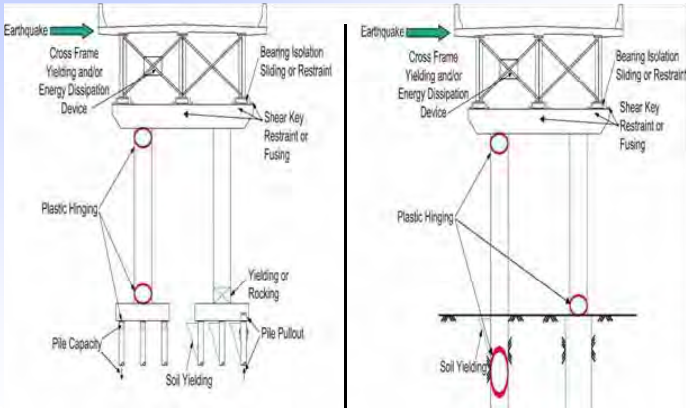
Strategy and Selection of "Key" Components

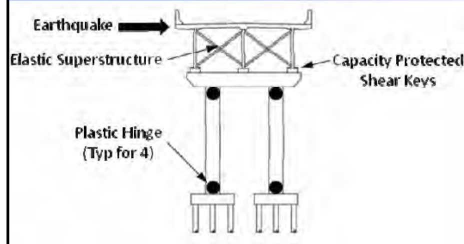
- Global Design Strategies
- Earthquake Resisting Systems (ERS)
- Earth quake Resisting Elements (ERE)

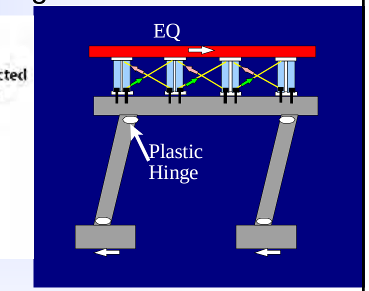
Guidelines-General Seismic Load Path and Affected Components



Global Design Strategies

Type 1 Design



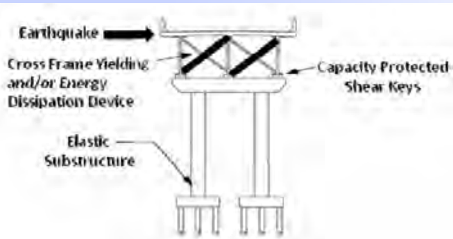


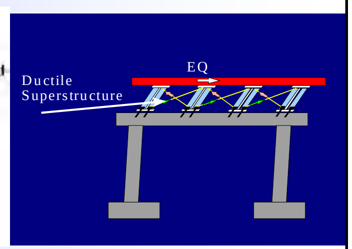
Type 1 - Design a ductile substructure with an essentially elastic superstructure (i.e., yielding columns)

- 1 concrete substructure
- 1* steel substructure
- 1** concrete filled steel pipe substructure

Global Design Strategies

Type 2 Design

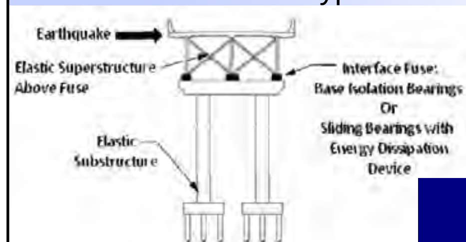




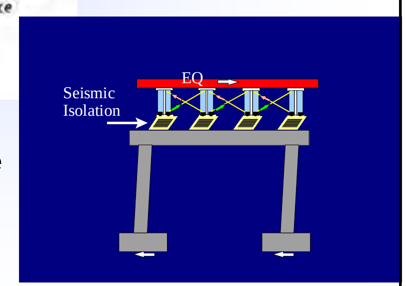
Type 2 - Design an essentially elastic substructure with a ductile superstructure (i.e., steel girder bridge with buckling diagonal members in the end diaphragms.

Global Design Strategies

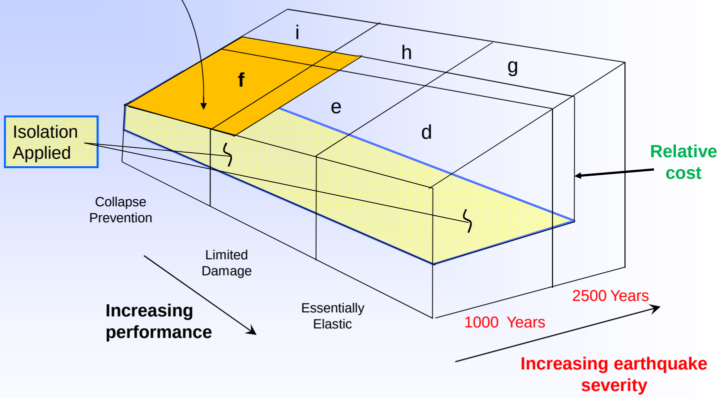
Type 3 Design



Type 3 - Design an elastic superstructure and substructure with a fusing (e.g., isolation) mechanism at the interface.



Seismic Isolation



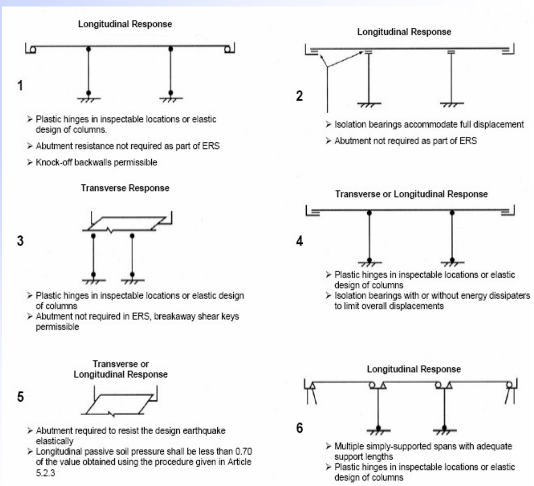
Calibration Objectives

Guidelines Performance Criteria

- Type 1 – Design a ductile substructure with an essentially elastic superstructure (i.e., yielding columns)
  - 1 concrete substructure
  - 1* steel substructure
  - 1** concrete filled steel pipe substructure
- Type 2 – Design an essentially elastic substructure with a ductile superstructure (i.e., steel girder bridge with buckling diagonal members in the end diaphragms.
- Type 3 – Design an elastic superstructure and substructure with a fusing (e.g., isolation) mechanism at the interface.

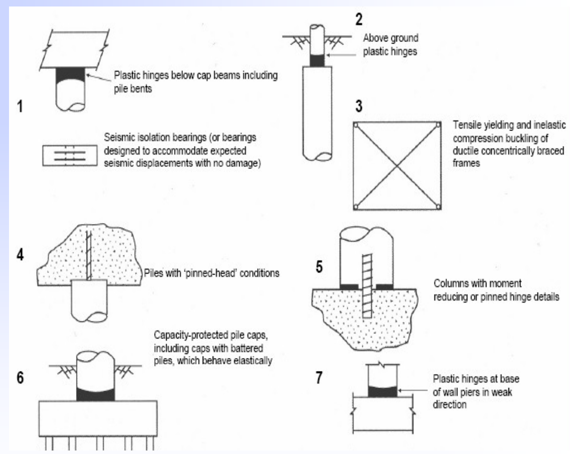
ERS

Permissible Earthquake Resisting Systems (ERS)



ERS

Permissible Earthquake Resisting Elements



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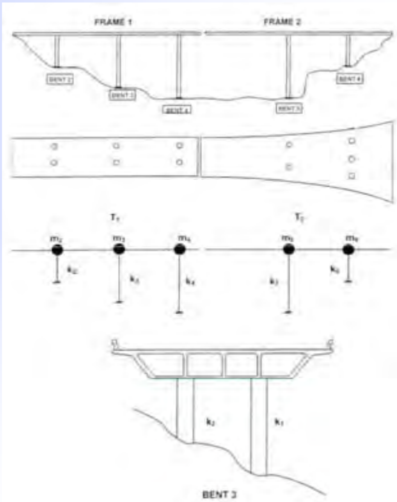
Displacement Demand

- Modeling Recommendations
  - Structure
  - Foundation
- Analysis Procedures
  - 1. Equivalent Static Analysis
  - 2. Elastic Dynamic Analysis
  - 3.Nonlinear Time History Analysis

Balanced Stiffness Recommendation



Foundation Modeling Method I and II

Foundation Type	Modeling Method I	Modeling Method II
Spread Footing	Rigid	Rigid for Site Classes A and B. For other soil types, foundation springs required if footing flexibility contributes more than 20% to pier displacement.
Pile Footing with Pile Cap	Rigid	Foundation springs required if footing flexibility contributes more than 20% to pier displacement.
Pile Bent/Drilled Shaft	Estimated depth to fixity	Estimated depth to fixity or soil-springs based on P-y curves.

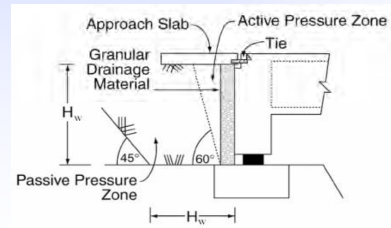
- Foundation Modeling Method I is required as a minimum for SDC B & C provided foundation is located in Site Class A, B, C, or D. Otherwise, Foundation Modeling Method II is required.
- Foundation Modeling Method II is required for SDC D.

Abutment Longitudinal Response for SDC D

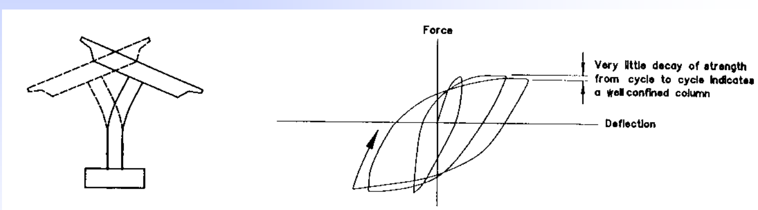
- For SDC D, passive pressure resistance in soils behind integral abutment walls and back walls for seat abutments will usually be mobilized due to the large longitudinal superstructure displacements associated with the inertial loads.
- *Case 1:* **Earthquake Resisting System (ERS) without Abutment Contribution**
  - Abutments may contribute to limiting the displacement and providing additional capacity and better performance that are not directly accounted for in the analytical model
  - A check of the abutment displacement demand and overturning potential should be made.

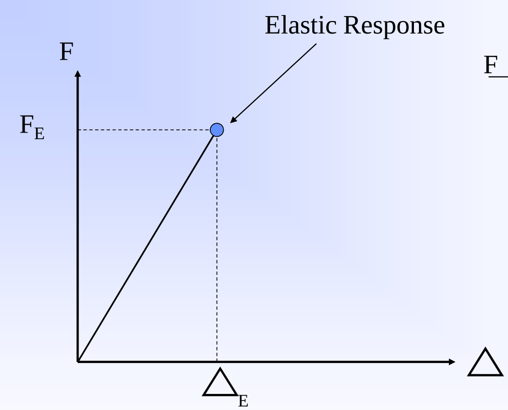
Abutment Longitudinal Response for SDC D

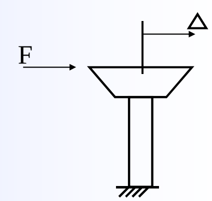
- *Case 2:* **Earthquake Resisting System (ERS) with Abutment Contribution.**
  - Whether presumptive or computed passive pressures are used for design as stated in Article 5.2.3.3, backfill in this zone should be controlled by specifications, unless the passive pressure considered is less than 70% of presumptive passive pressures



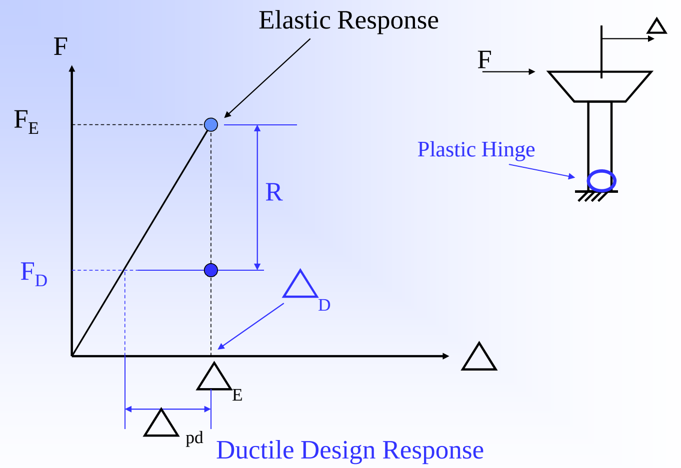
Ductile Response

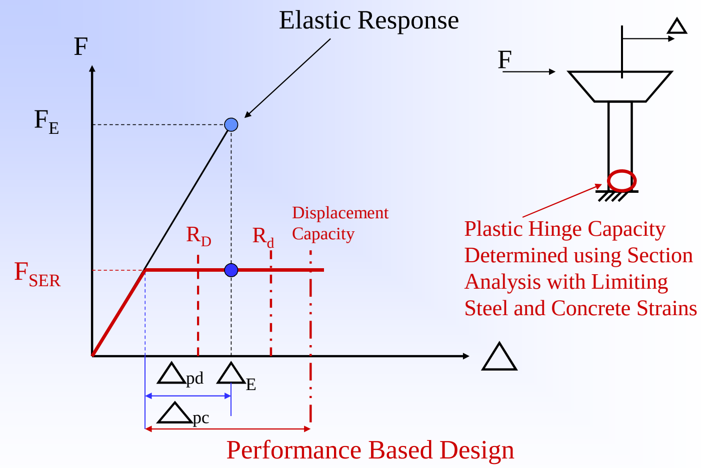






Forced Based Method





Design Approaches

-Force-

- Division 1A and Current LRFD Specification
- Complete design w/ service load requirements
- Elastic demand forces w/ applied prescribed ductility factors "R" for anticipated deformability
- Ductile response is assumed to be adequate w/o verification
- Capacity protection assumed

-Displacement-

- New 2007 Adopted Guide Specification
- Complete design w/ service load requirements
- Displacements demands w/ displacement capacity evaluation for deformability as designed for service loads
- Ductile response is assured with limitations prescribed for each SDC
- Capacity protection assured

Displacement Capacity

- Implicit Formulas for SDC B and C
- Inelastic Quasi-static Pushover Analysis SDC D

Replacement for the "*R*" Factor in the Force Based Approach

Displacement Capacity SDC B & C

For SDC B:

$$\Delta_C^L = 0.12H_o\left(-1.27\ln(x) - 0.32\right) \geq 0.12H_o \qquad (4.8.1\text{-}1)$$

For SDC C:

$$\Delta_C^L = 0.12H_o\left(-2.32\ln(x) - 1.22\right) \geq 0.12H_o \qquad (4.8.1\text{-}2)$$

in which:

$$x = \frac{\Lambda B_o}{H_o} \qquad (4.8.1\text{-}3)$$

Displacement Capacity SDC B & C

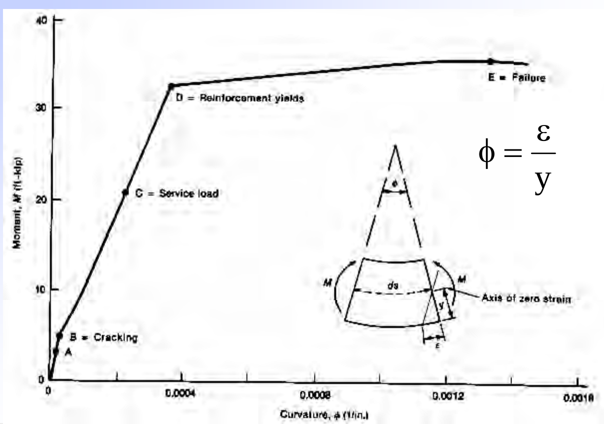
H_o = Height of column measured from top of footing to top of column (ft.)

B_o = Column diameter or width measured parallel to the direction of the displacement under consideration (ft.)

Λ = factor representing column end restraint condition
= 1.0 for fixed-free column boundary conditions
= 2.0 for fixed-fixed column boundary conditions

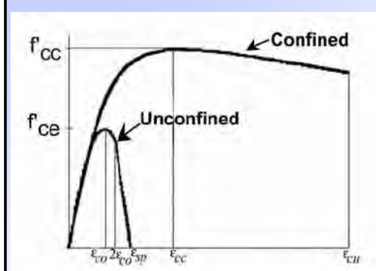
For partial restraint at the column ends, interpolation is permitted.

Moment-Curvature Diagram



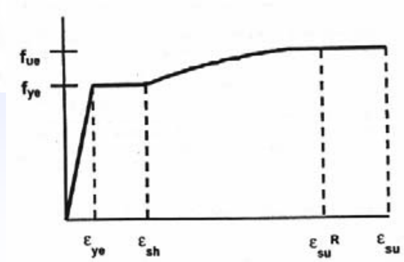
$$\phi = \frac{\varepsilon}{y}$$

Material Properties



Mander's Concrete Model

Reinforcing Steel Stress-Strain



Plastic Moment Capacity for Ductile Concrete Members for SDC B, C, and D

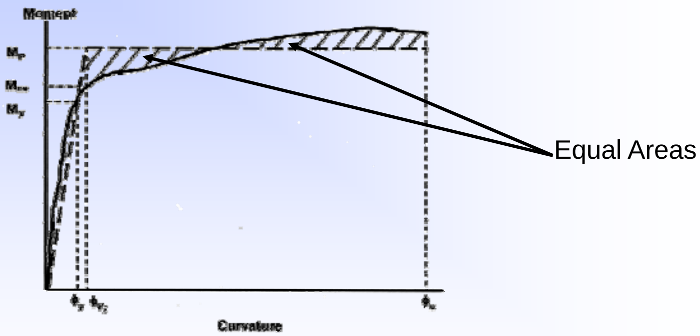
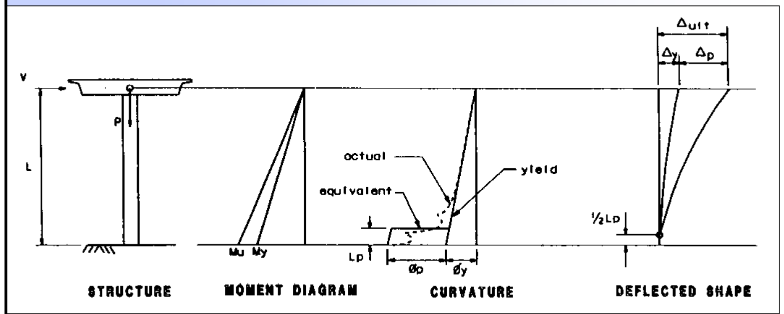


Figure 8.5-1 Moment-Curvature Model

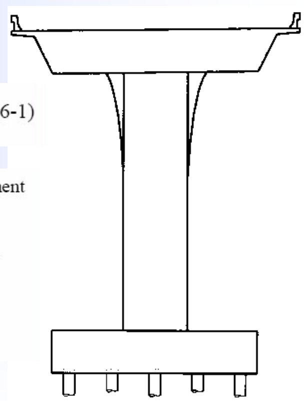
Elastic-Plastic Displacement of a Column Pushover Analysis for SDC D



Analytical Plastic Hinge Length Framing into a Footing or a Cap

$$L_p = 0.08L + 0.15 f_{ye} d_{bl} \geq 0.3 f_{ye} d_{bl} \qquad (4.11.6\text{-}1)$$

- L = length of column from point of maximum moment to the point of moment contra-flexure (in.)
- f_{ye} = expected yield strength of longitudinal column reinforcing steel bars (ksi)
- d_{bl} = nominal diameter of longitudinal column reinforcing steel bars (in.)



LRFD - Member Ductility Requirement for SDC D

$$\mu_D = 1 + \frac{\Delta_{pd}}{\Delta_{yi}} \qquad (4.9\text{-}5)$$

Where:

Δ_{pd} = plastic displacement demand (in.)

Δ_{yi} = idealized yield displacement corresponding to the idealized yield curvature, ϕ_{yi} , shown in figure 8.5-1 (in.)

Pile shafts should be treated similar to columns.

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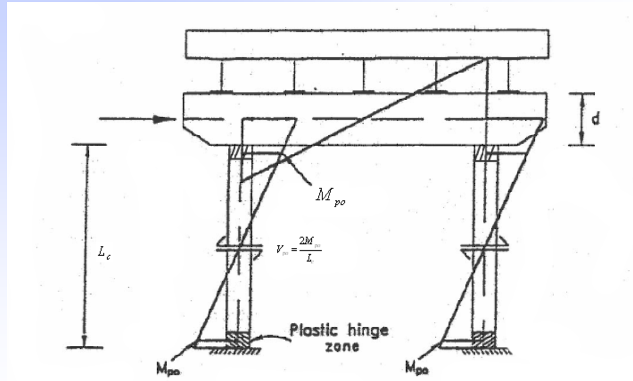
LRFD – Over-strength Capacity Design Concepts for SDC C & D Trans.



Concluding Remarks

- Single Level Hazard for 1000 year return period applicable to all regions of the US
- Single Performance Criteria for "No Collapse"
- Uniform Hazard Design Spectra using Three Point Method with the new AASHTO/USGS Maps for the PGA, 0.2 sec, and 1.0 sec
- NEHRP Site Class Spectral Acceleration Coefficient

Concluding Remarks (continued)

- Partition of Seismic Design Category (SDC) into four groups (A,B,C & D) with increasing levels of design requirements
- Identification of Global Design Strategy and an Earthquake Resistant System
- Using an Isolation Global Design Strategy a No-Collapse Performance level can be increased to Essentially Elastic Performance (i.e. no damage level) at a reduced overall construction cost

Concluding Remarks (continued)

- Displacement Based Approach with design factors calibrated to prevent collapse
- Use of closed form equations for implicit displacement capacity for SDC B and C
- Pushover Analysis for Displacement Capacity of SDC D
- New Seat width equation for SDC D Capacity
- Protection of column shear, superstructure and substructure
- Steel Superstructure Design Option based on Force Reduction Factors including the use of ductile end-diaphragms

EPS Manufacturing Facility, Vallejo, CA

Bearing Sub-Assemblies

Ready To Ship

FULL-SCALE HIGH-SPEED TEST MACHINE

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TESTING OF TRIPLE PENDULUM BEARING

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TEST MACHINE

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EPS Advantages

- Expert Seismic Engineering
- Lowest Seismic Shears
- Reliable Bearing Properties
- Real-time Tests
- Fastest Bearing Deliverables
- Lowest Construction Costs

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Thank You

Earthquake

Protection

Systems

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