A Synergy for Increased Seismic Protection of Bridges

Western Bridge Engineers' Seminar

September 21-23, 2009

by

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and

Anoop Mokha, Ph.D., S.E.

Earthquake Protection Systems, Inc.

AASHTO Adopted 2007 Guide Specifications

Proposed

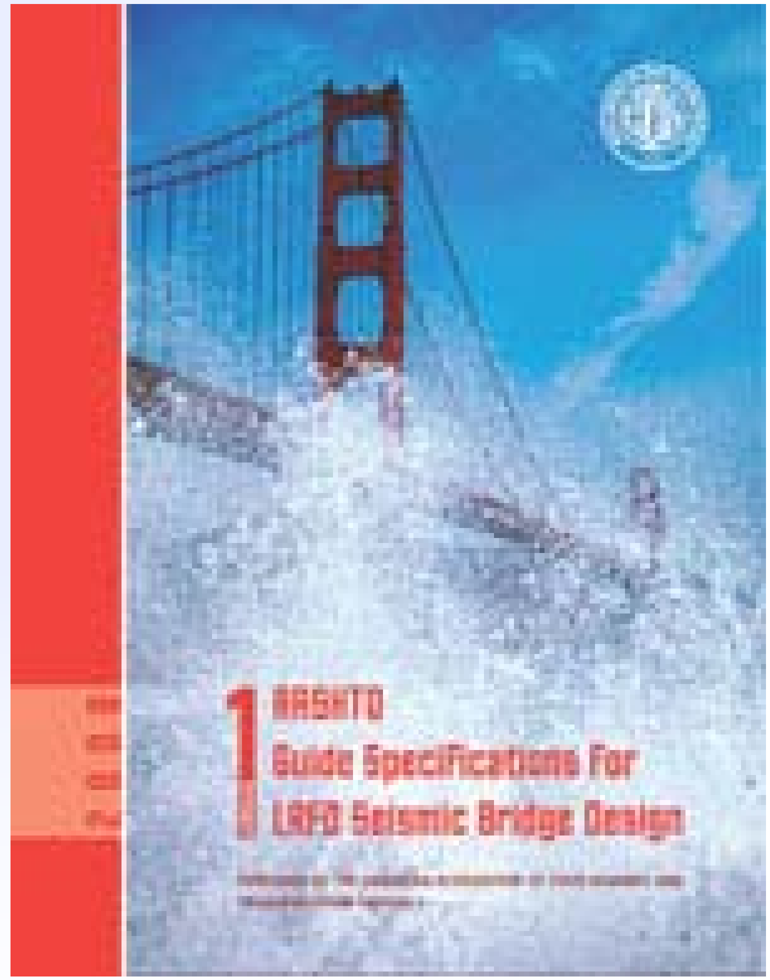
AASHTO Guide Specifications for LRFD Seismic Bridge Design

Subcommittee for Seismic Effects on Bridges
T-3

Prepared by:

Roy A. Imbsen
Imbsen Consulting

March 2007



Technical Review Team

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- Lee Marsh, BERGER/ABAM Engineers (Team Leader, 2008)
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- Stephanie Brandenberger, MT DOT
- Daniel Tobias, IL DOT
- Derrell Manceaux, FHWA
- Tony Allen, WSDOT
- Don Anderson, CH2M Hill

LRFD Guide Specifications Table of Contents

Highlights of the Guide Specifications

- Performance Based Design Criteria
- AASHTO/USGS Acceleration Maps for 1000 Year Hazard
- Maps Define the Design Spectral Shape (PGA, 0.2 sec. and 1.0 sec.)
- NEHRP Soil Site Factors
- Four Seismic Design Categories (SDC) Calibrated for the Hazard and Performance
- Flow Charts to Provide Guidance in the Application of the Guide Specifications
- Choice of Three Global Seismic Design Strategies

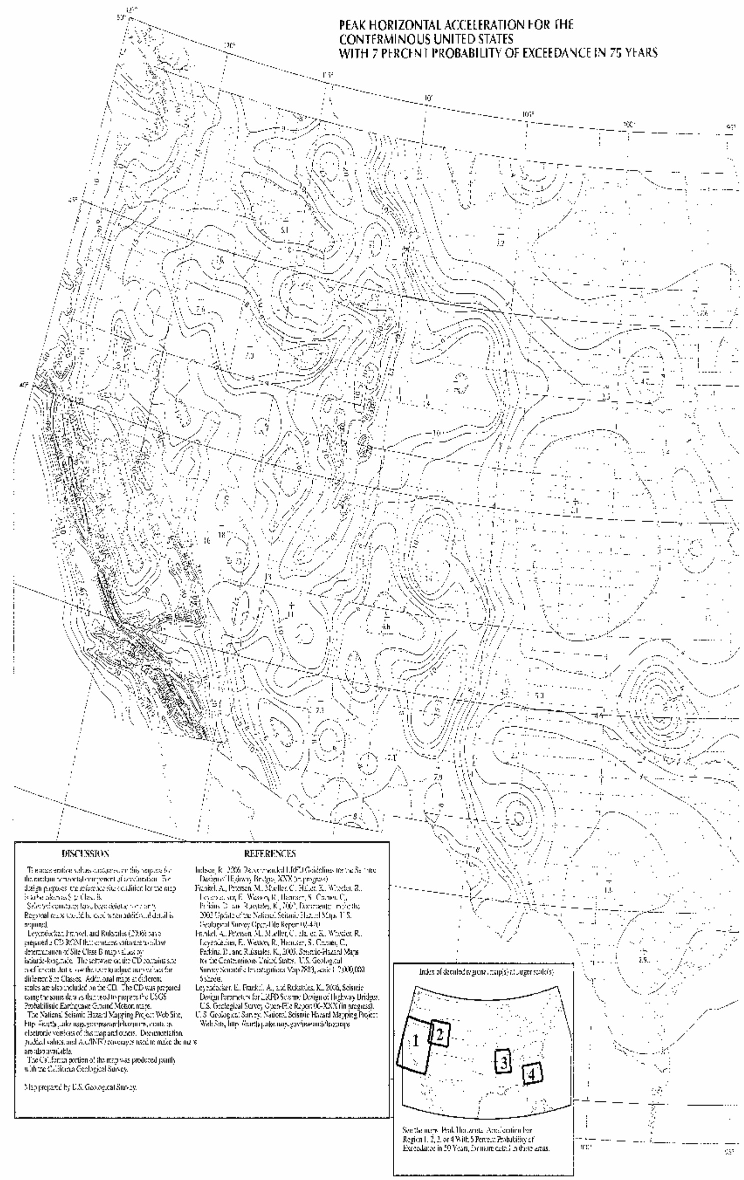
Highlights of the Guide Specifications
Continued

- Defined Earthquake Resisting Systems (ERS) and Elements (ERE)
- Recommendations on Structural and Foundation Modeling
- New Procedures for Determining Displacement Capacity to Replace the “R” Factor
- Component Capacity Protection
- Improved Procedures for Foundation Design and Liquefaction Determination
- Unanimous Support and Endorsement of the AASHTO T-3 Committee

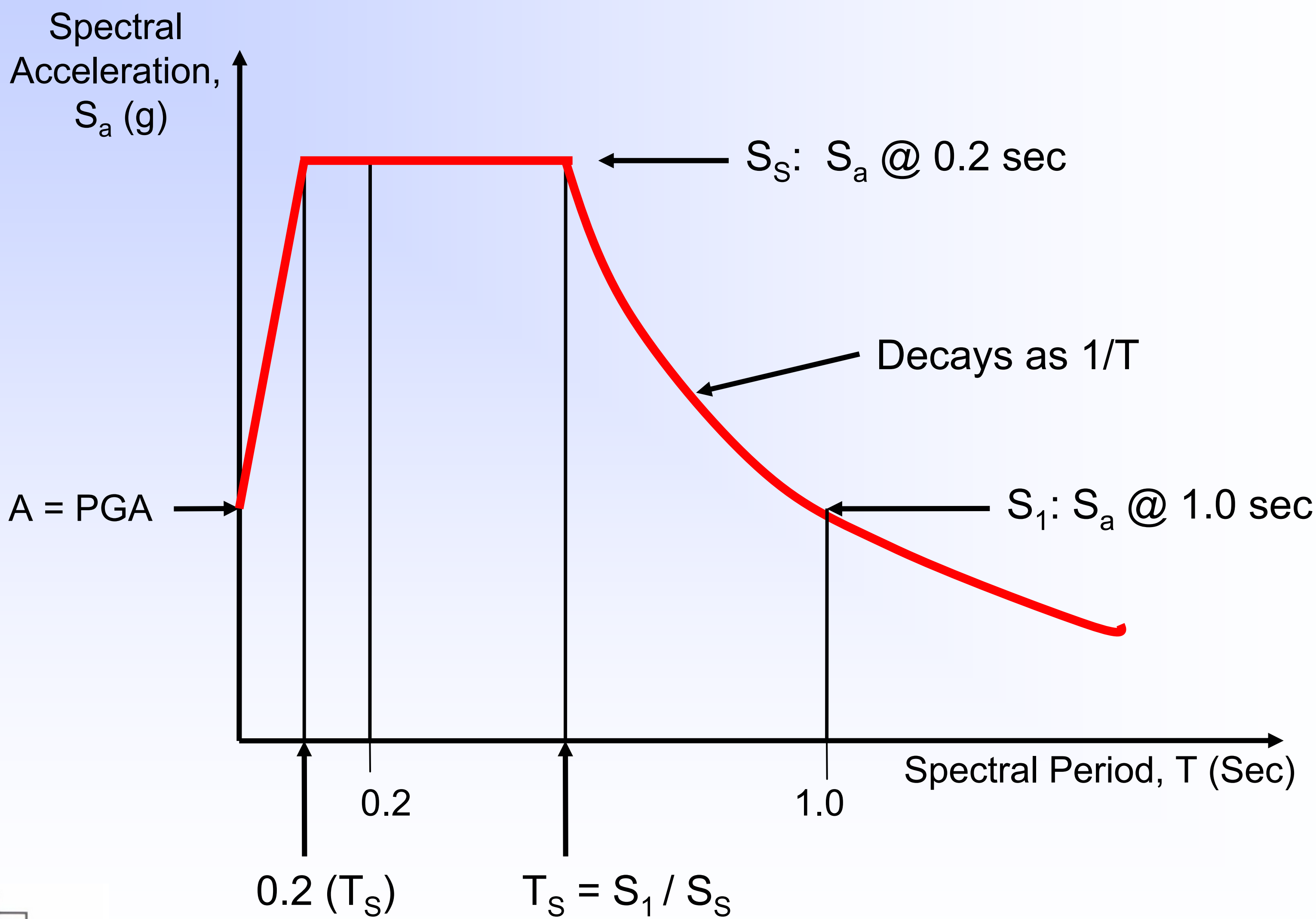
AASHTO/ USGS Maps

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**



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 $\leq$ 0.10 $S_s \leq 0.25$	$PGA = 0.20$ $S_s = 0.50$	$PGA = 0.30$ $S_s = 0.75$	$PGA = 0.40$ $S_s = 1.00$	$PGA \geq 0.50$ $S_s \geq 1.25$
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).

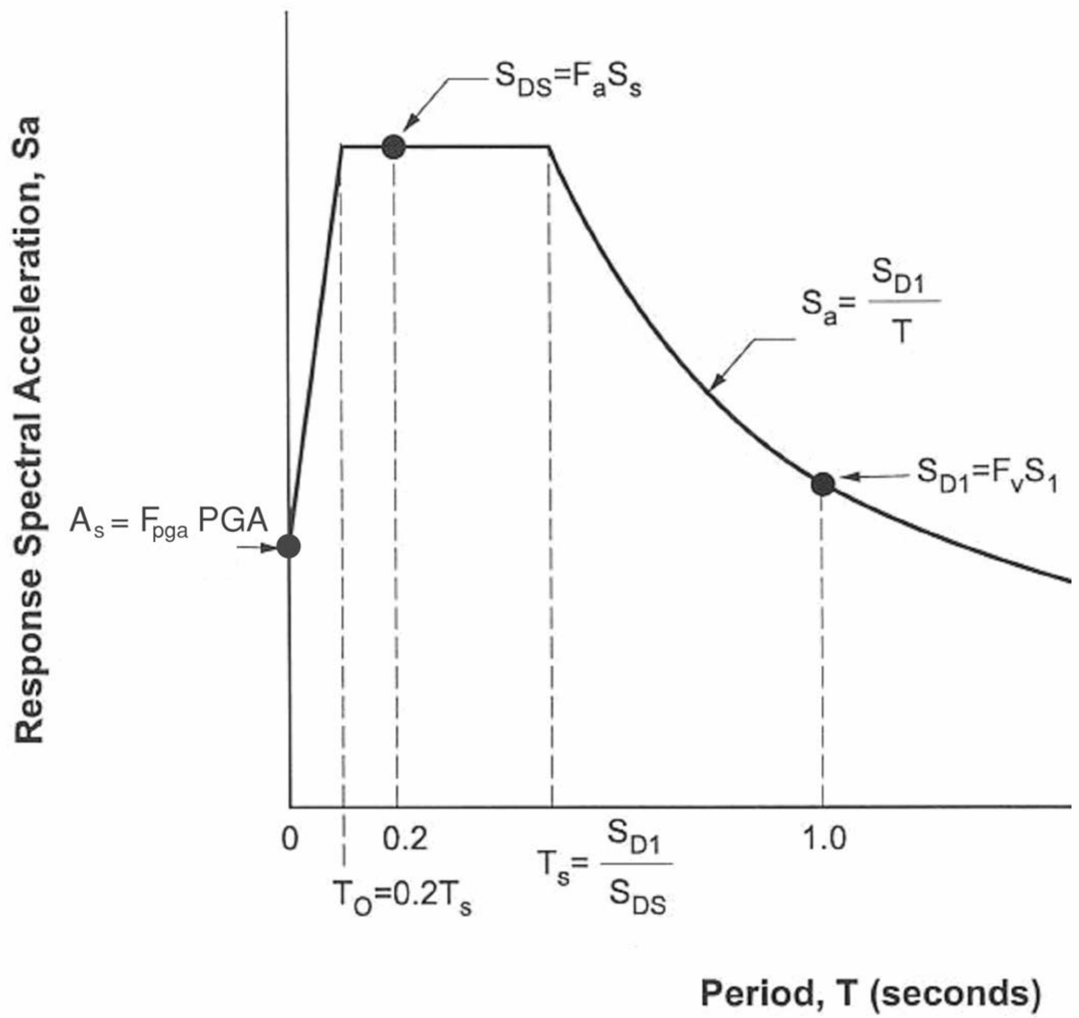
Design Spectra - General Procedure (3.4.1)

- Response spectrum accelerations
- Site factors

$$A_s = F_{pga} PGA$$

$$S_{DS} = F_a S_s$$

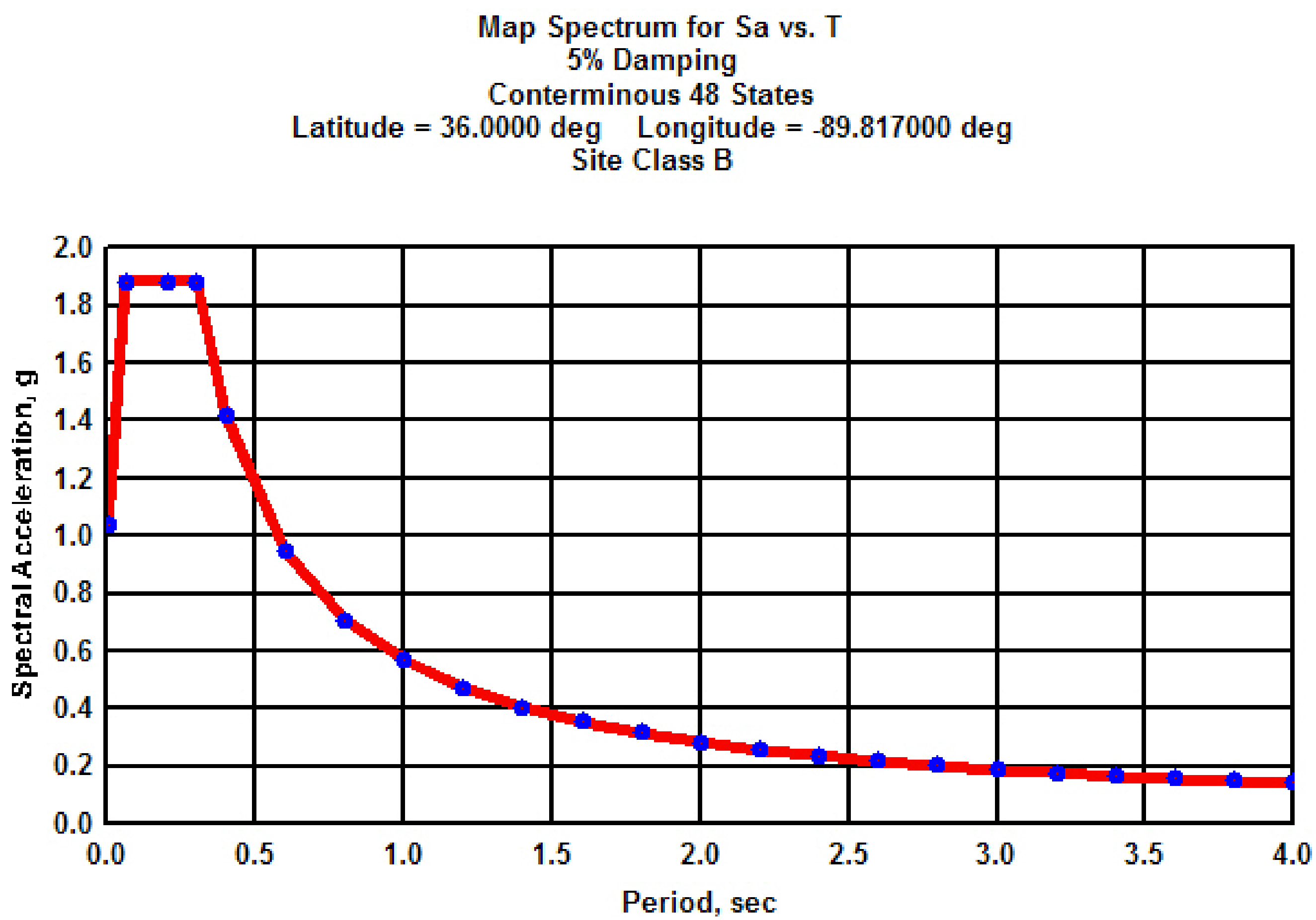
$$S_{D1} = F_v S_1$$



GRAPHICS - Response Spectra

File Edit Graph Scale Help

Select Graph: Map Spectrum for Sa vs. T



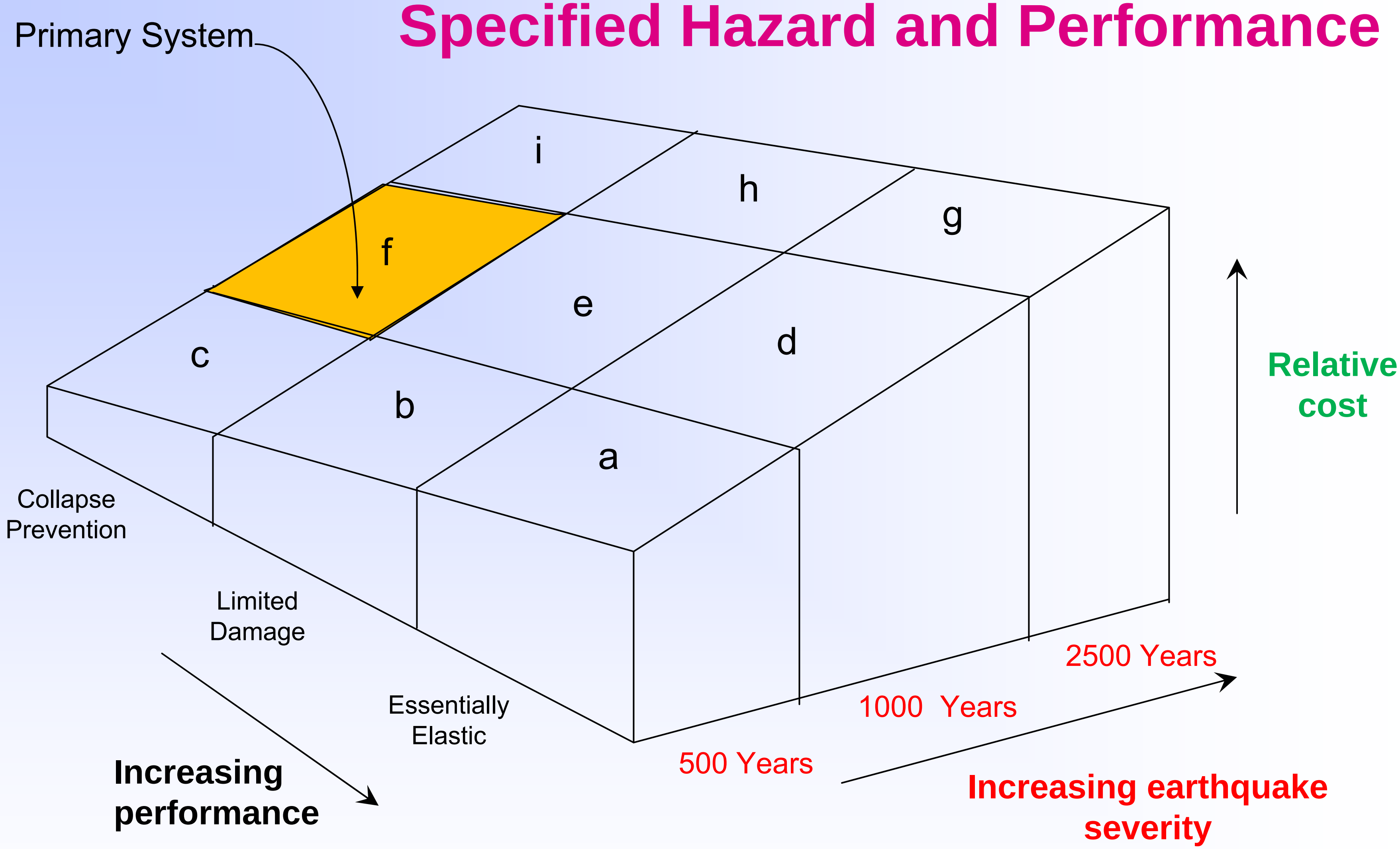
Graph Data

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

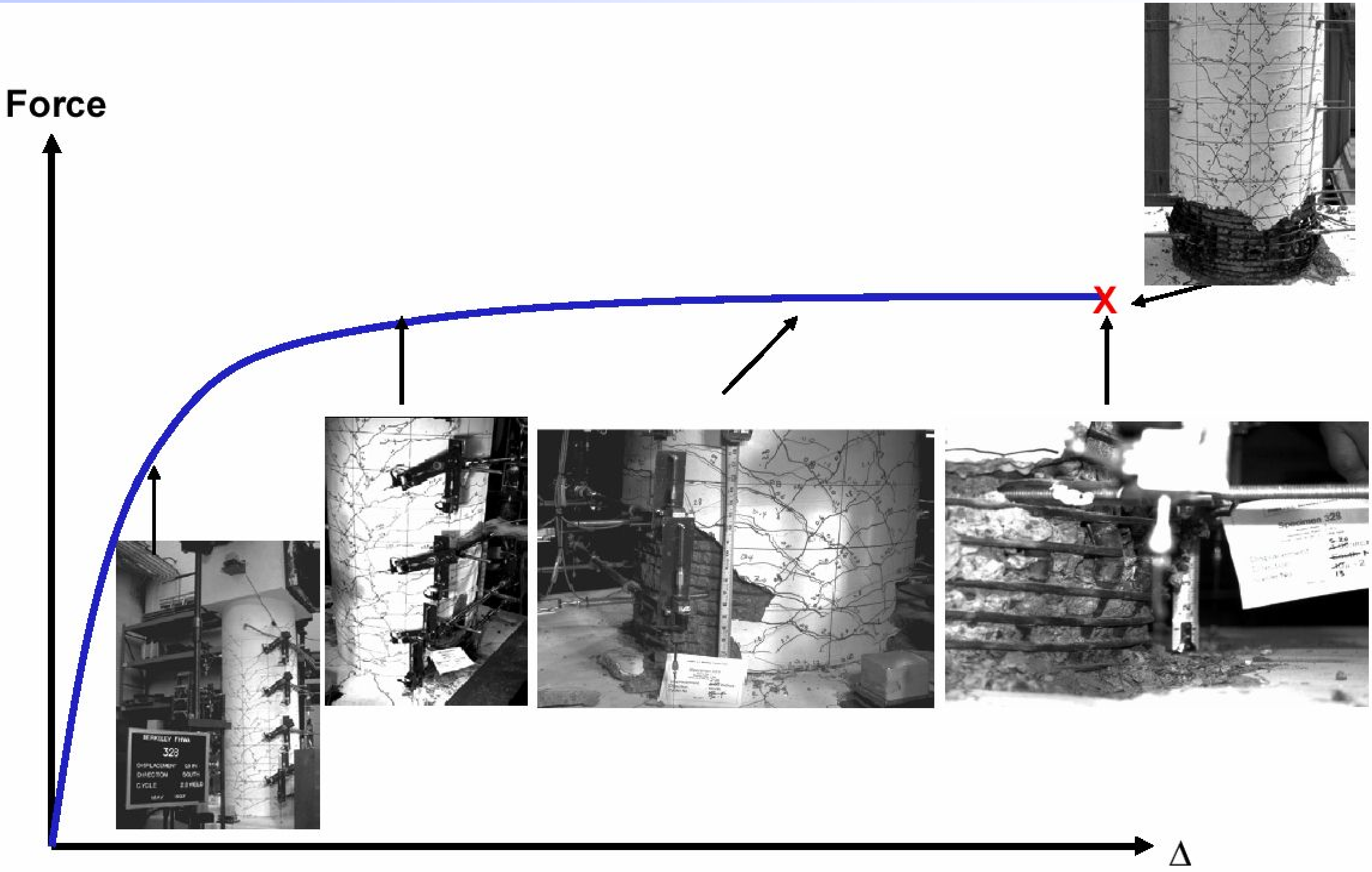
Adoption of the New Hazard

- 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

Specified Hazard and Performance



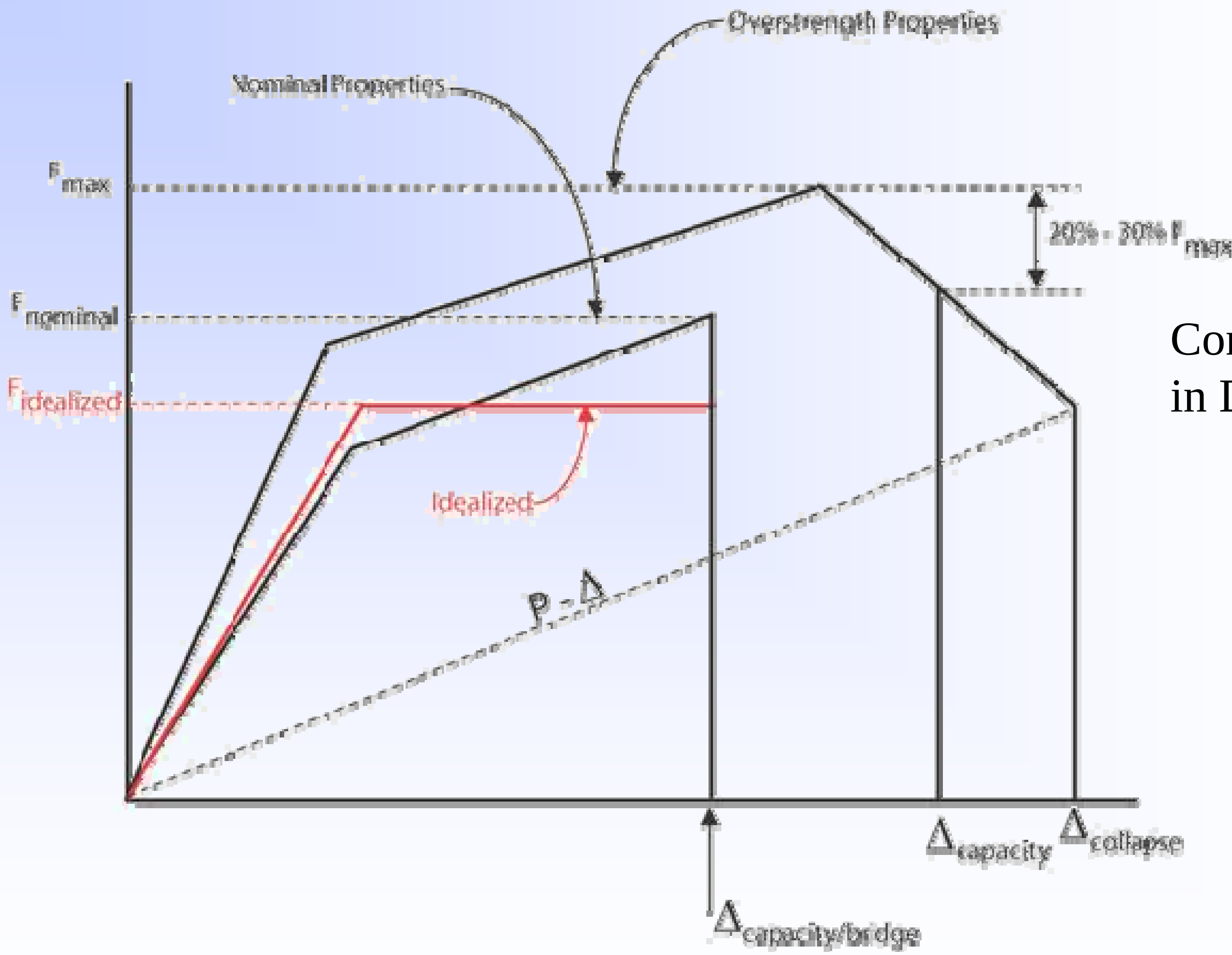
Calibration Objectives


Force
Δ

LRFD Guidelines-Background Task 2-Sources of Conservatism

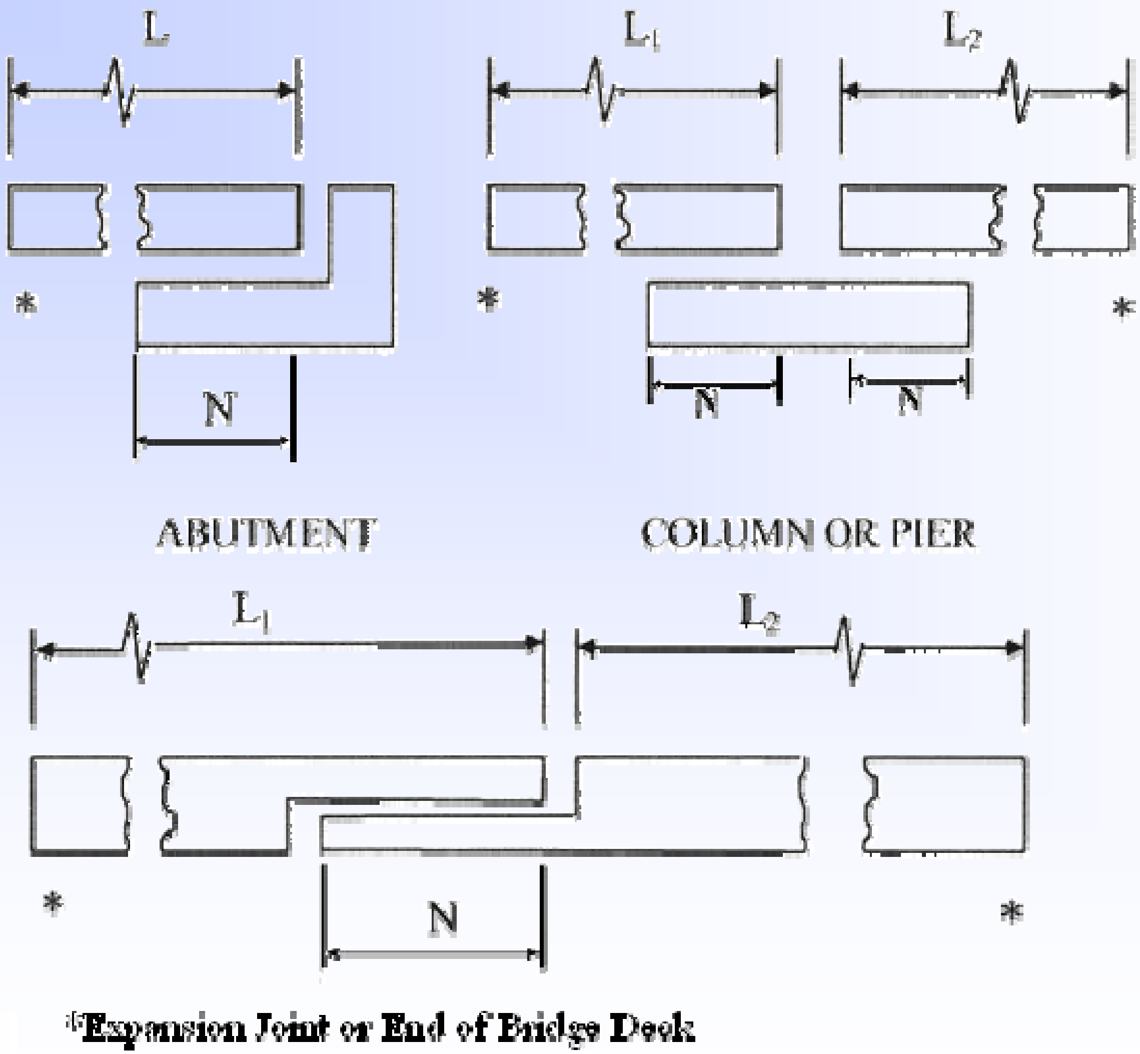
Source of Conservatism	Safety Factor
Computational vs. Experimental Displacement Capacity of Components	1.3
Effective Damping	1.2 to 1.5
Dynamic Effect (i.e., strain rate effect)	1.2
Pushover Techniques Governed by First Plastic Hinge to Reach Ultimate Capacity	1.2 to 1.5
Out of Phase Displacement at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

Idealized Load – Deflection Curve



Considered
in Design

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



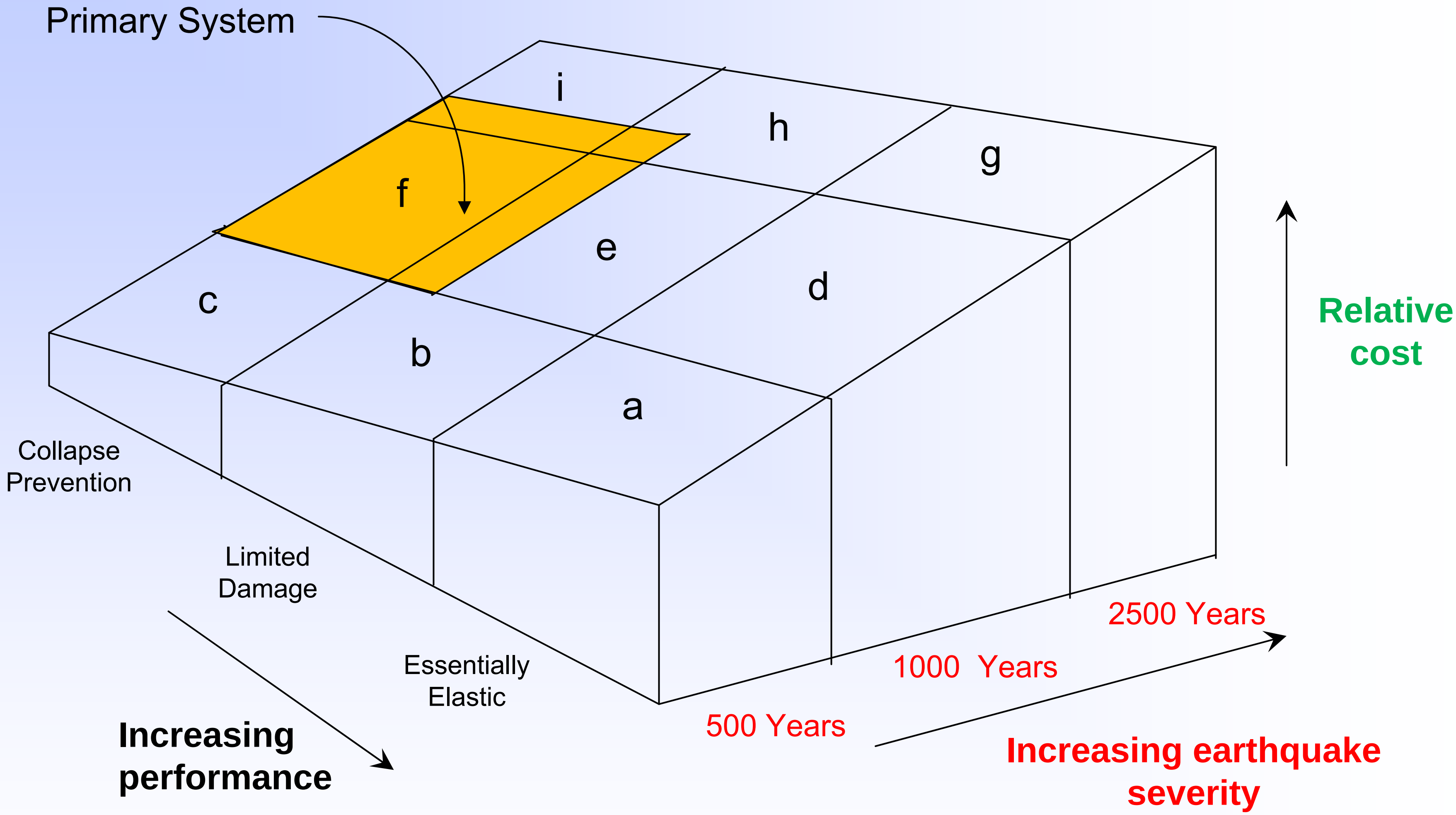
Minimum Support Length Requirements SDC A, B, C & D

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

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

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
$0.15 \le S_{D1} < 0.30$	B
$0.30 \le S_{D1} < 0.50$	C
$0.50 \le S_{D1}$	D

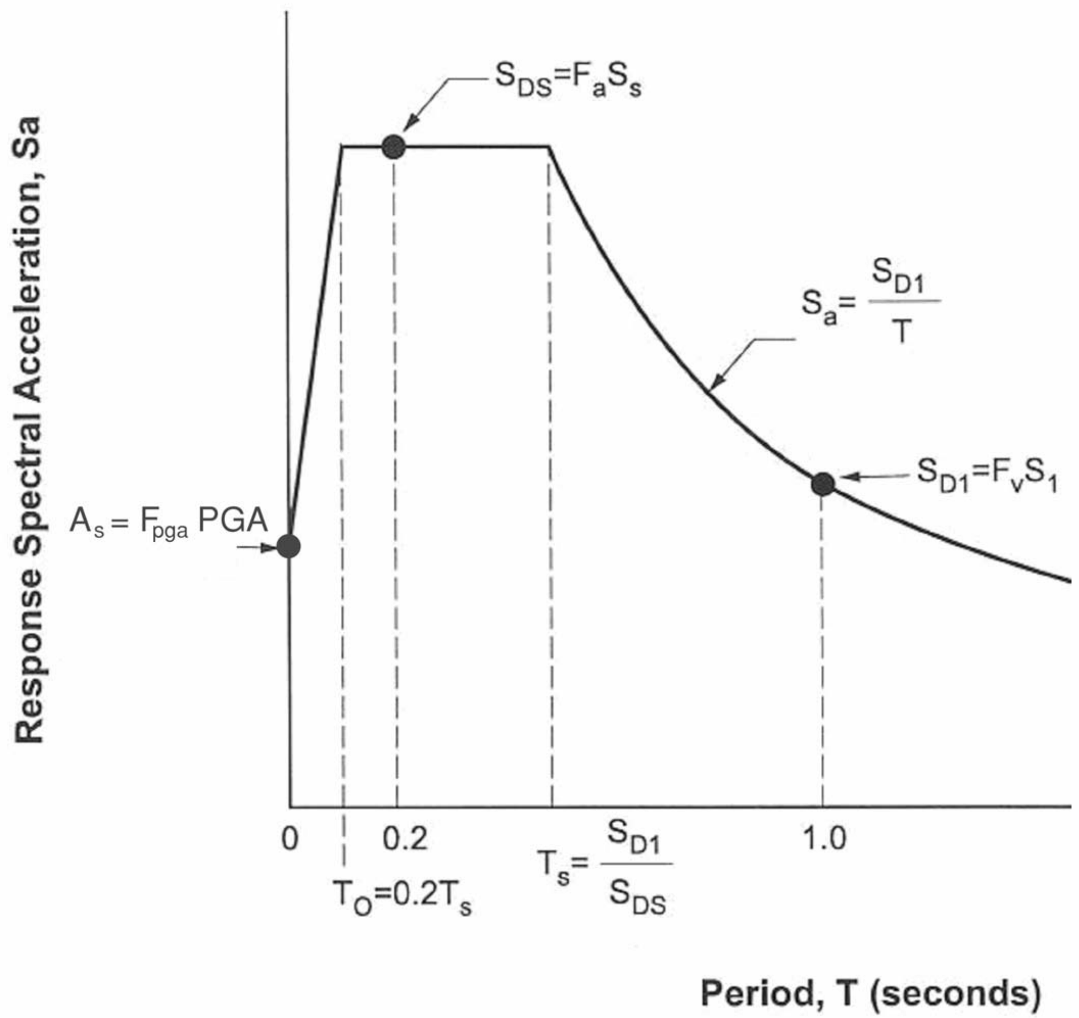
Design Spectra - General Procedure (3.4.1)

- Response spectrum accelerations
- Site factors

$$A_s = F_{pga} PGA$$

$$S_{DS} = F_a S_s$$

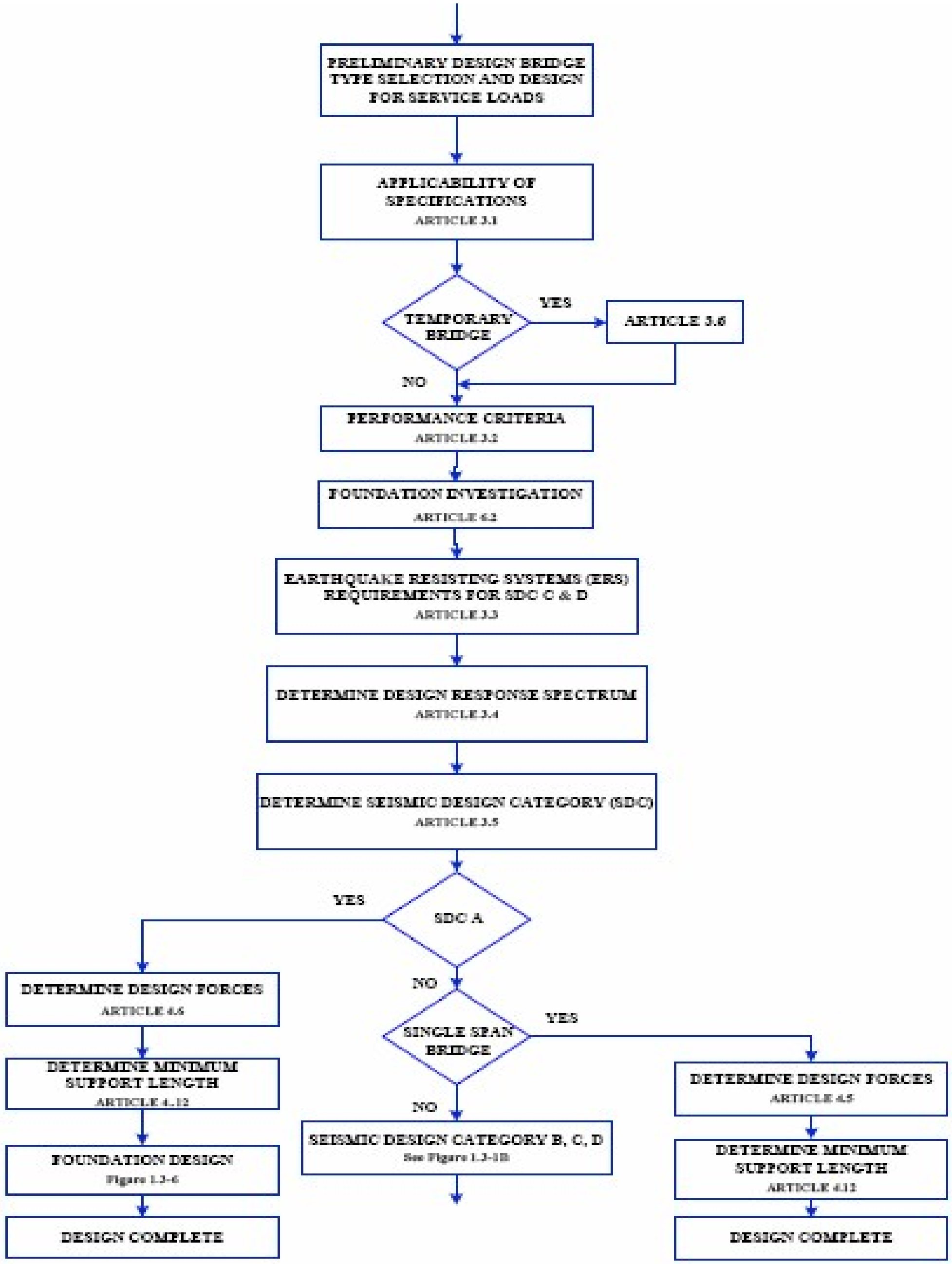
$$S_{D1} = F_v S_1$$



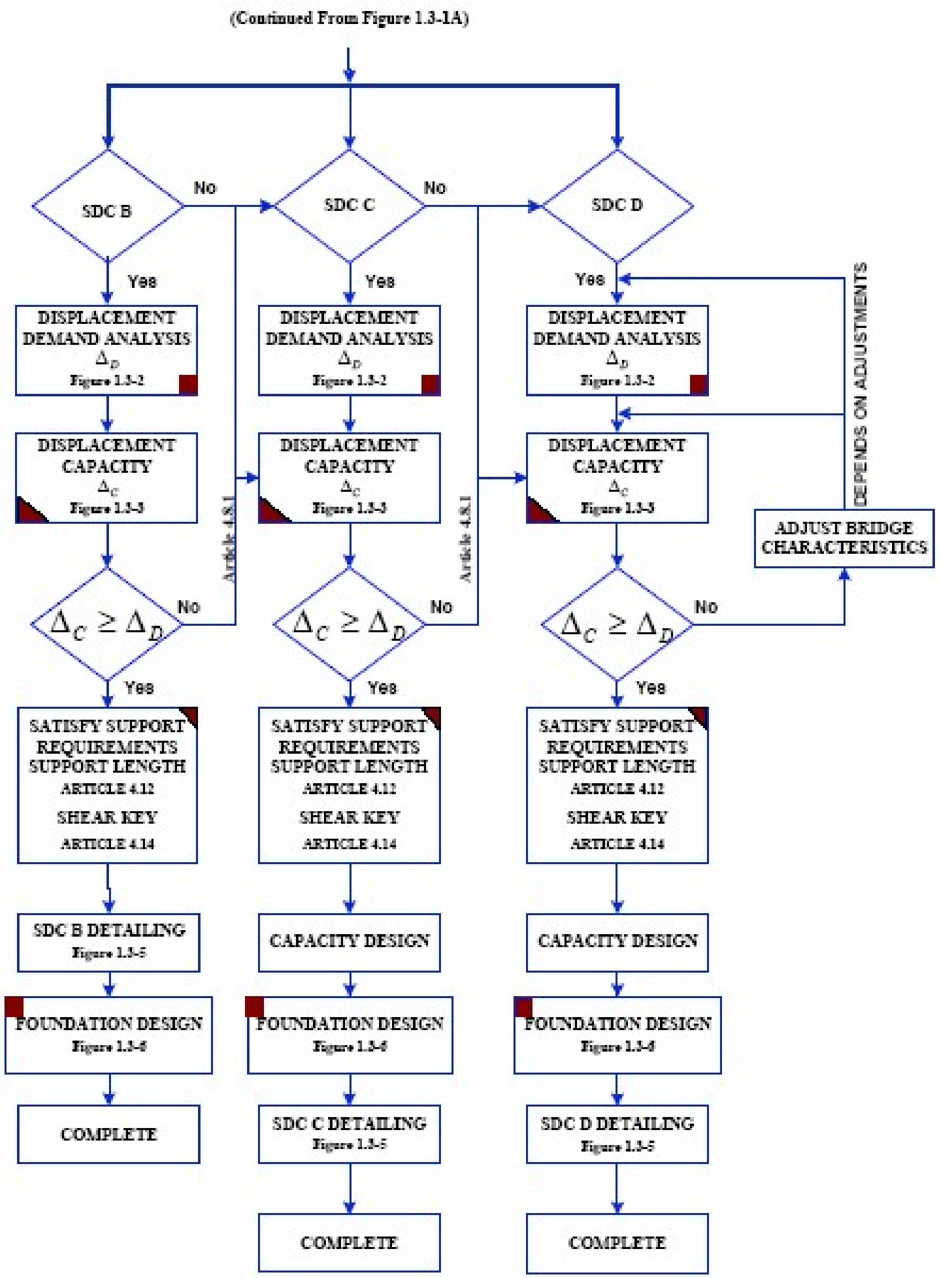
Seismic Design Categories (SDC)

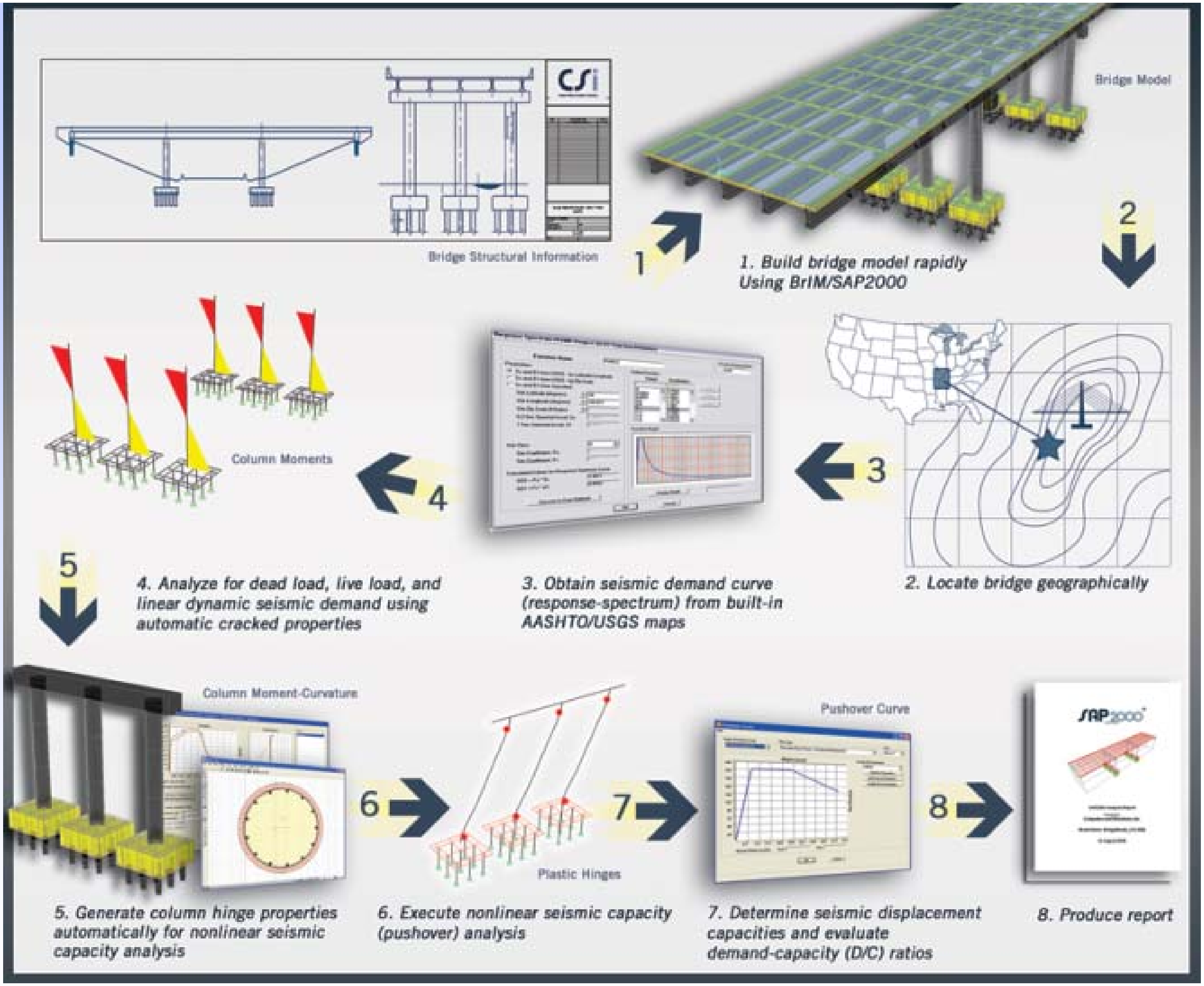
Requirements	*A*	*B*	*C*	*D*
Global Strategy	-------	Recommended	Required	Required
Identification ERS	-------	Recommended	Required	Required
Support Connections	Required	Required	Required	Required
Support Length	Required	Required	Required	Required
Demand Analysis	-------	Required	Required	Required
Implicit 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

LRFD Flow Chart Fig 1.3-1A



LRFD Flow Chart Fig 1.3-1B





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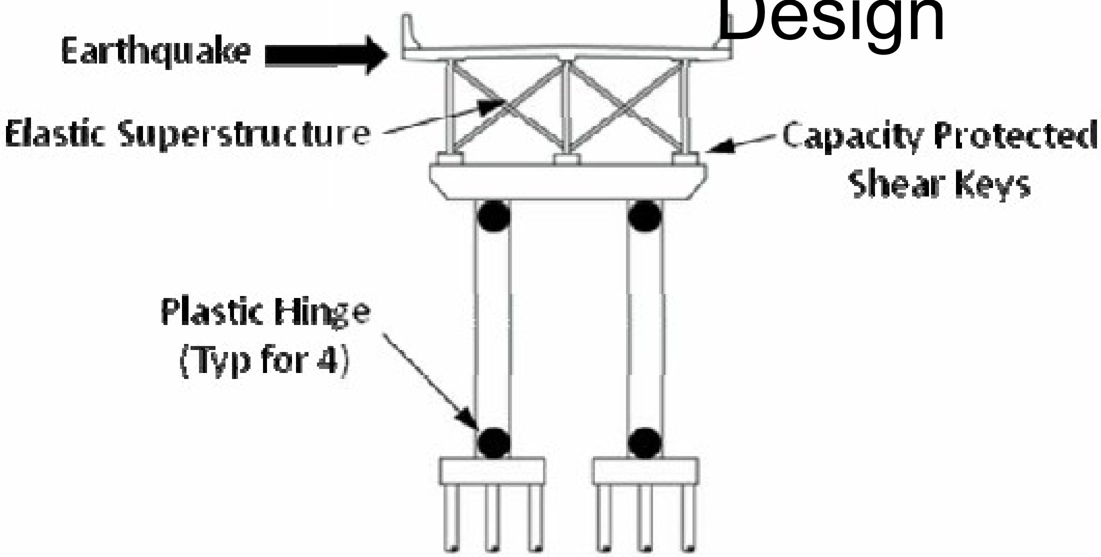
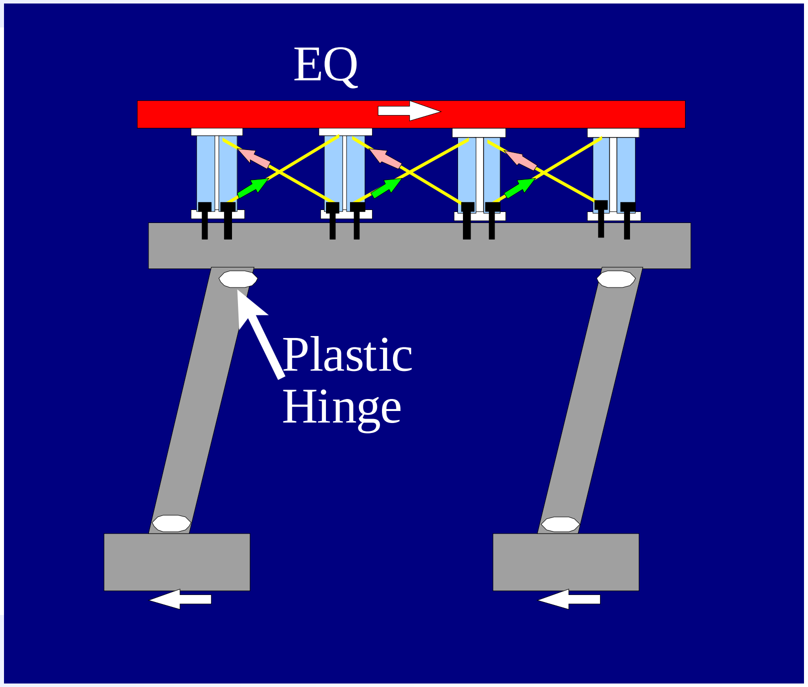
Strategy and Selection of "Key" Components

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

Global Design Strategies

Type 1 Design



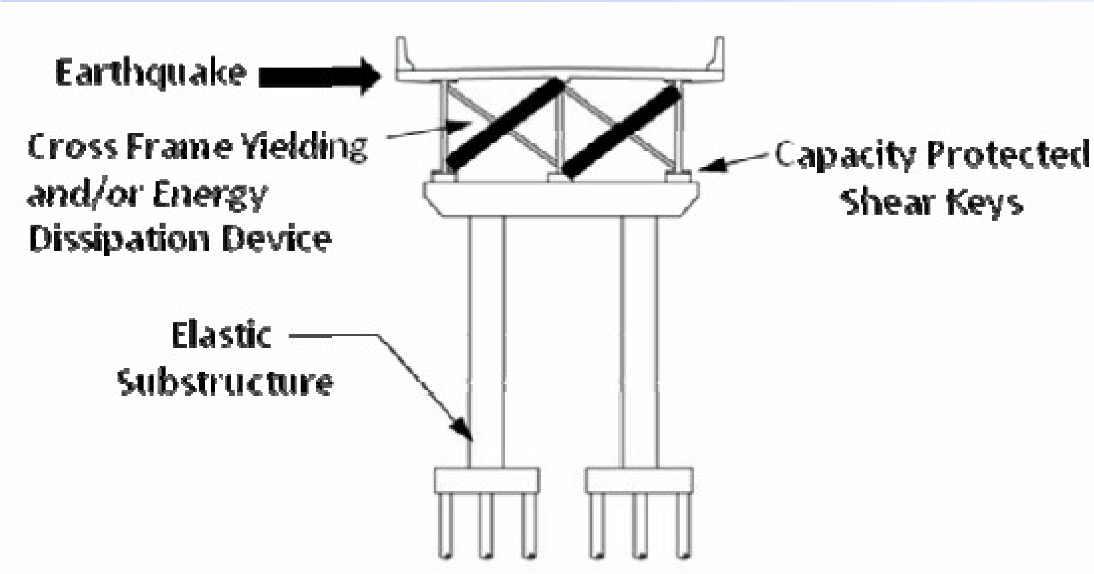


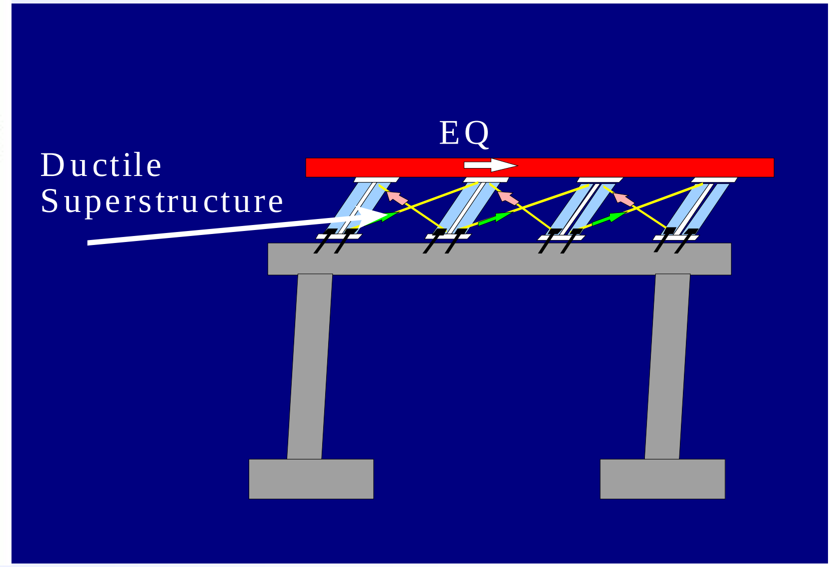
Type 1 - Design a ductile substructure with an essentially elastic superstructure (i.e., yielding columns)

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

Global Design Strategies

Type 2 Design

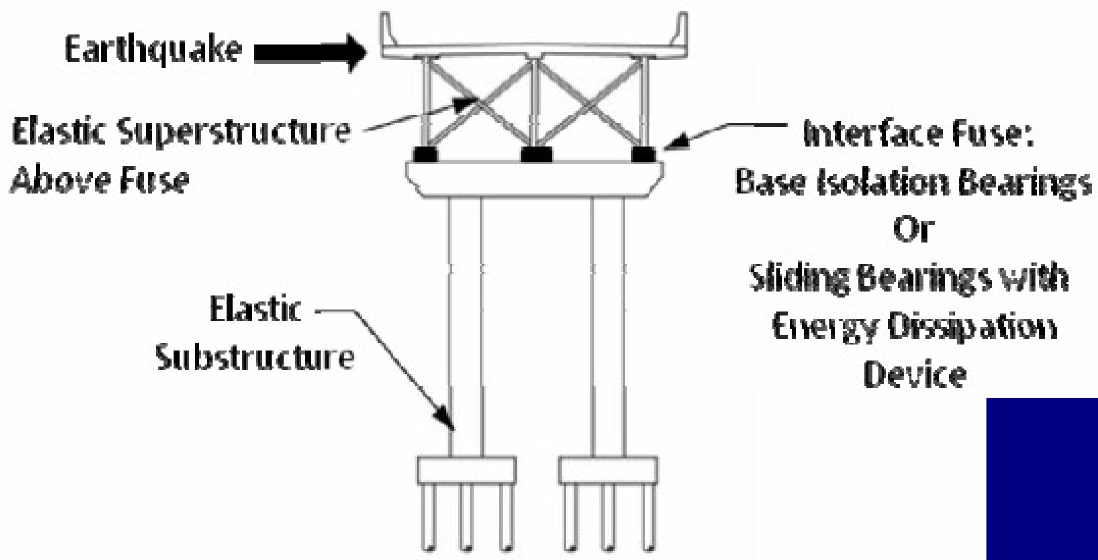




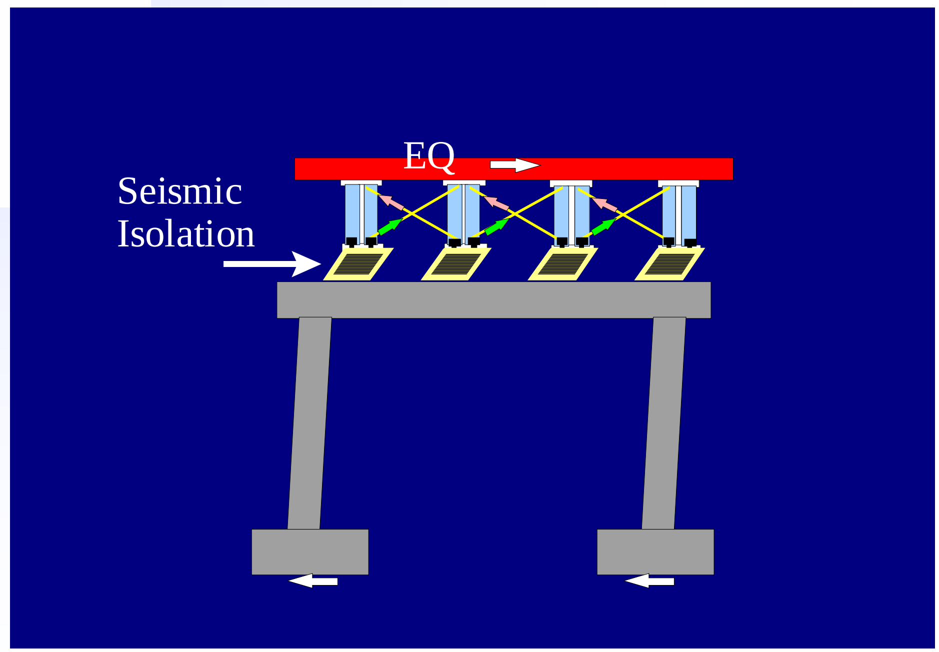
Type 2 - Design an essentially elastic substructure with a ductile superstructure (i.e., steel girder bridge with buckling diagonal members in the end diaphragms.

Global Design Strategies

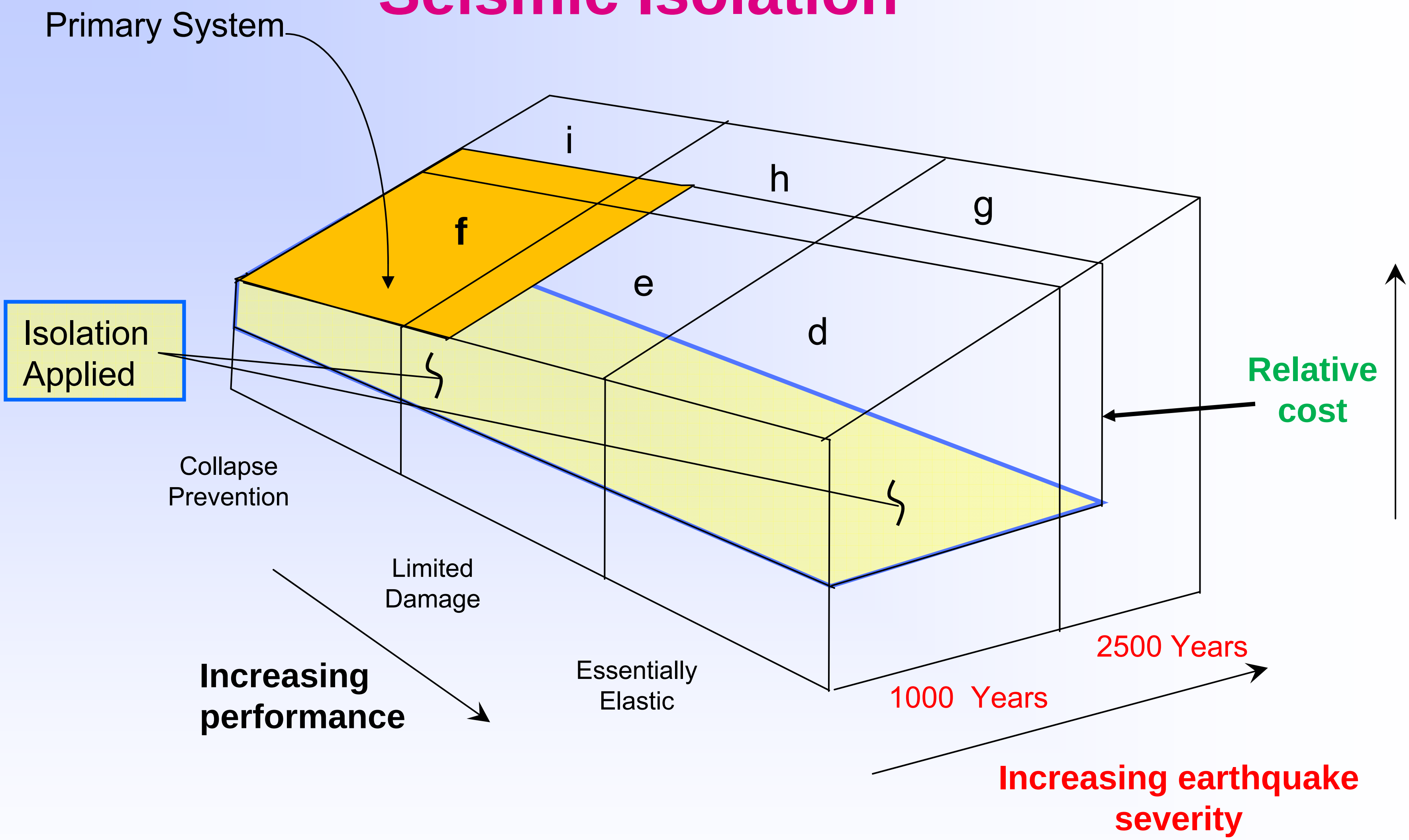
Type 3 Design



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



Seismic Isolation



Calibration Objectives with Isolation

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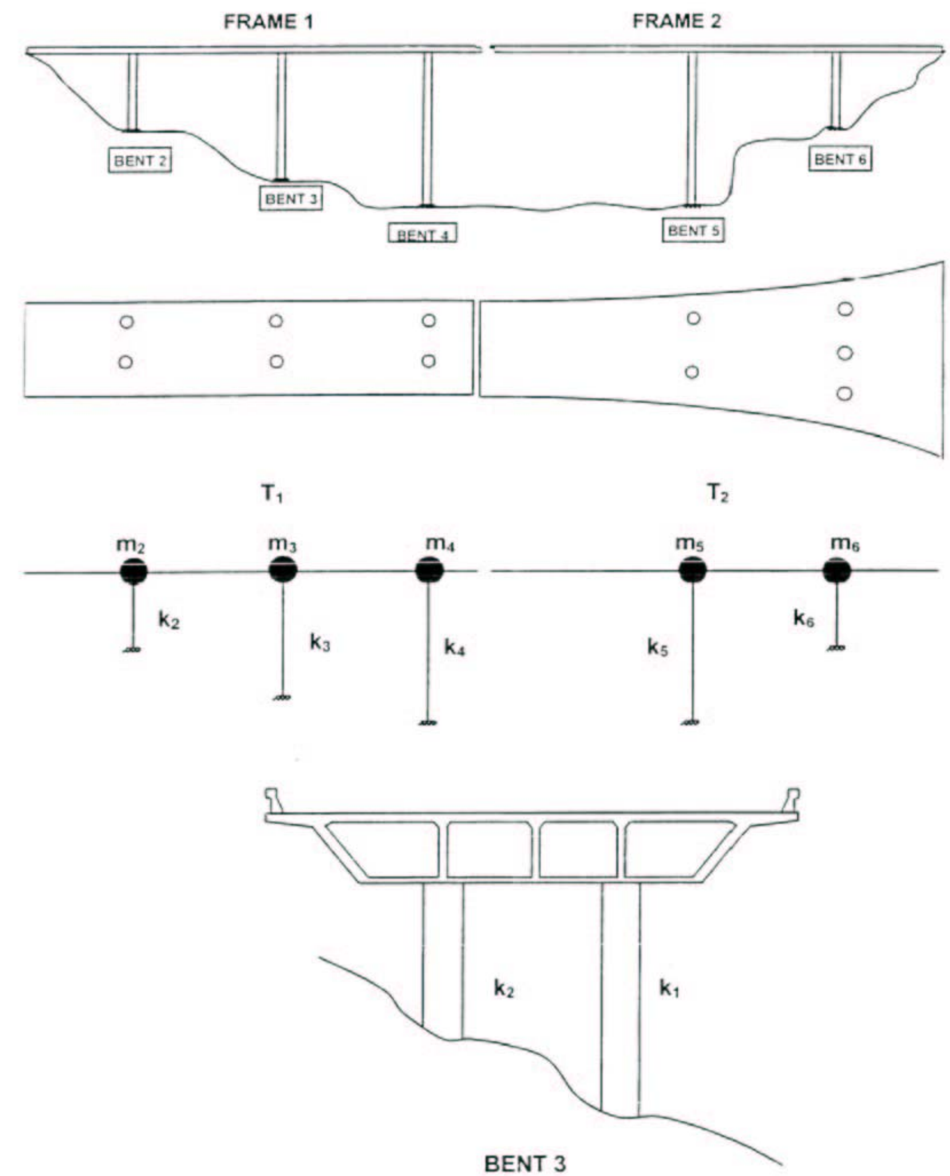
Balanced Stiffness Recommendation



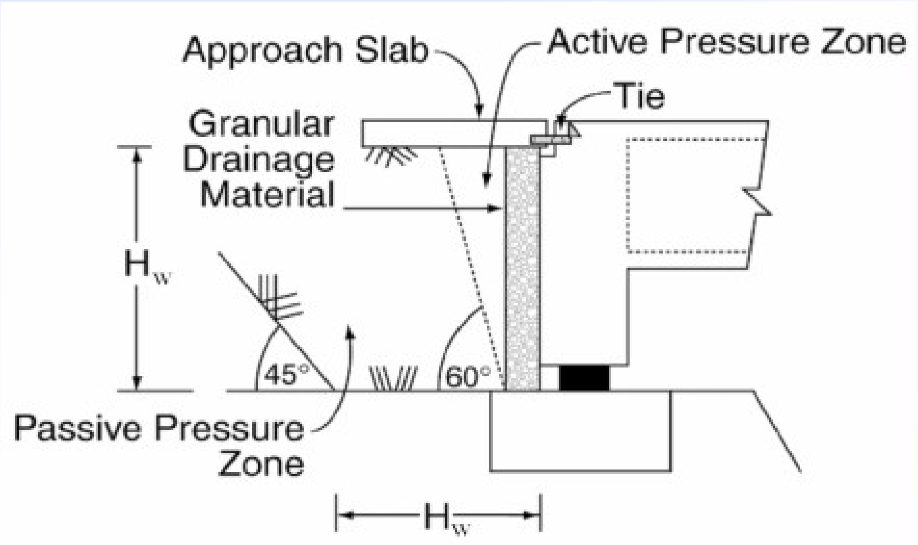
Foundation Modeling Method I and II

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

- *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



Displacement Capacity

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

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

Displacement Capacity SDC B & C

For SDC B:

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

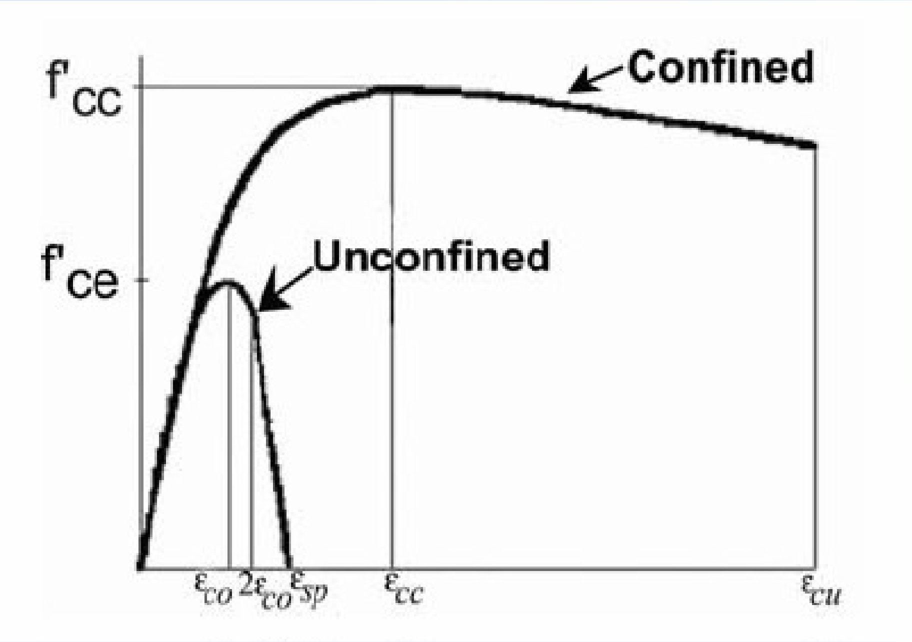
For SDC C:

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

in which:

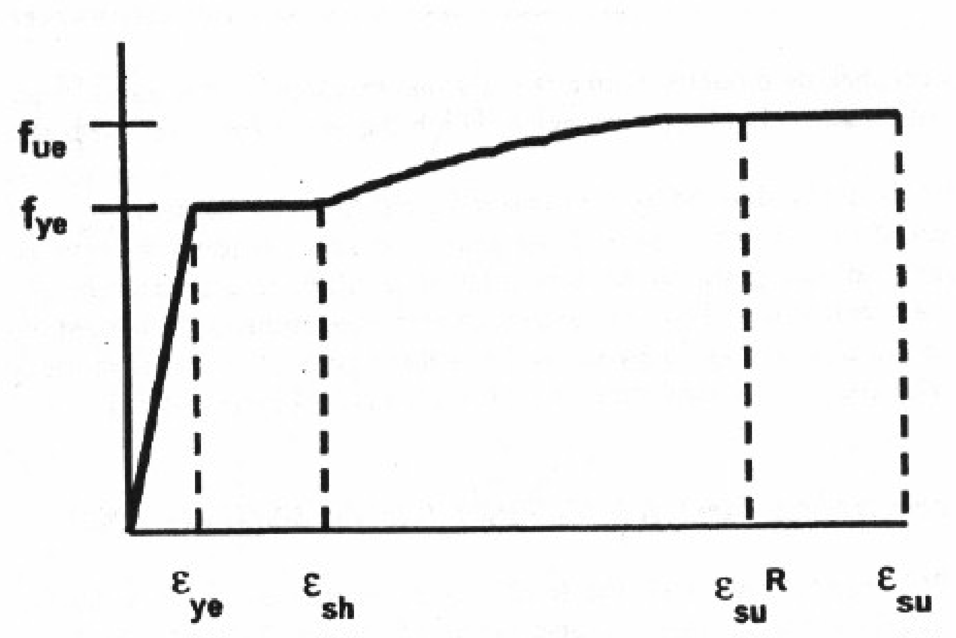
$$x = \frac{\Lambda B_o}{H_o} \qquad (4.8.1\text{-}3)$$

Displacement Capacity SDC D
Material Properties

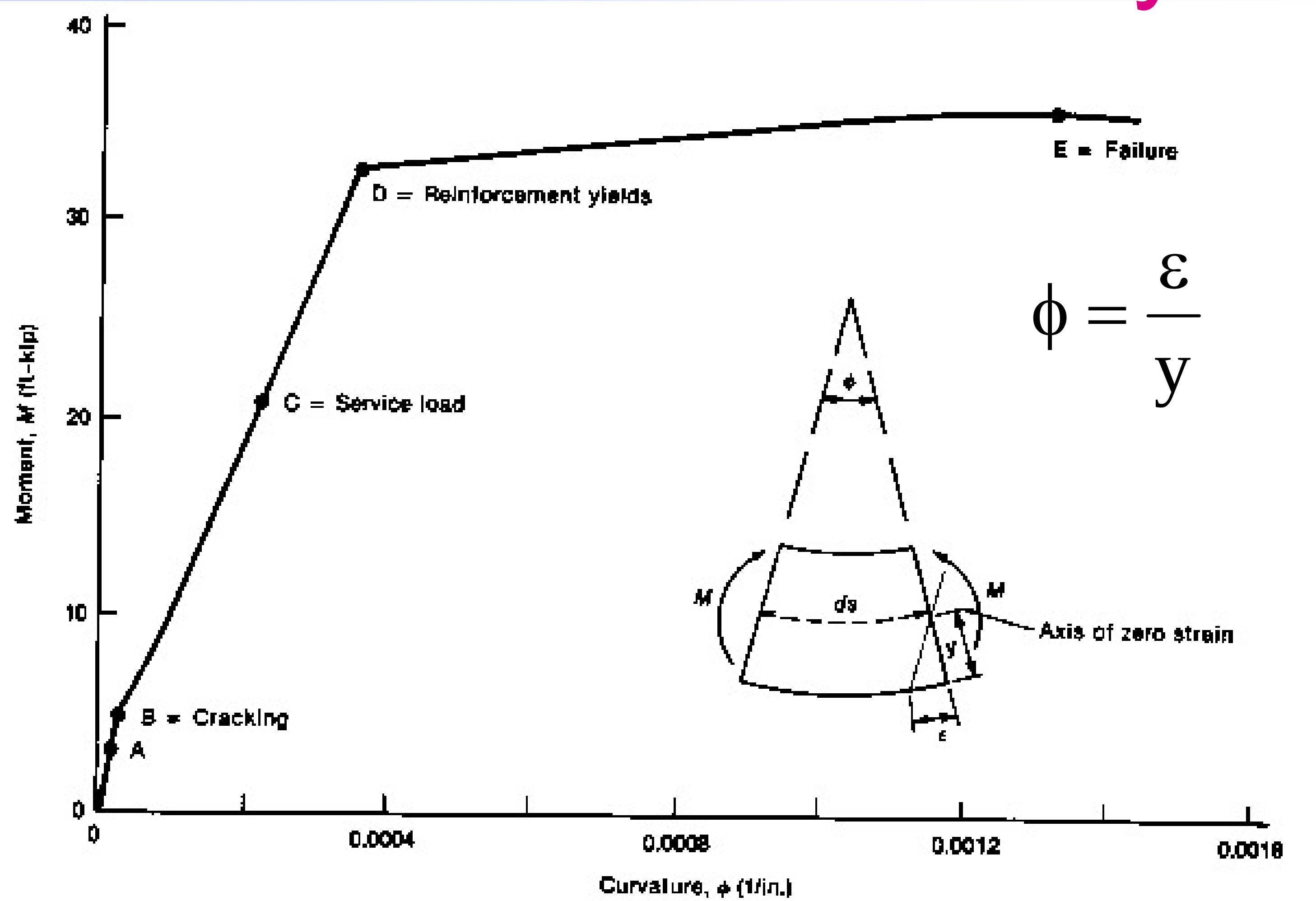


Mander's Concrete Model

Reinforcing Steel Stress-Strain



Displacement Capacity SDC D Moment-Curvature Analysis



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

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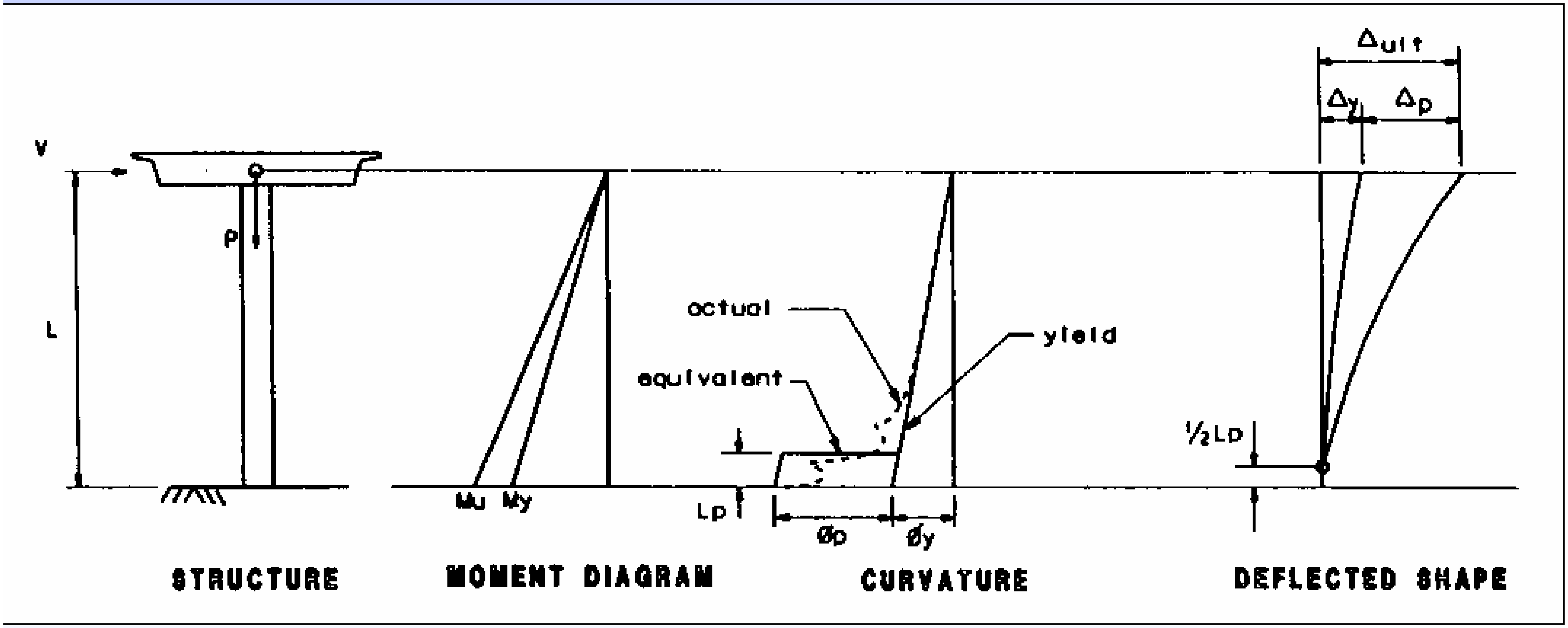
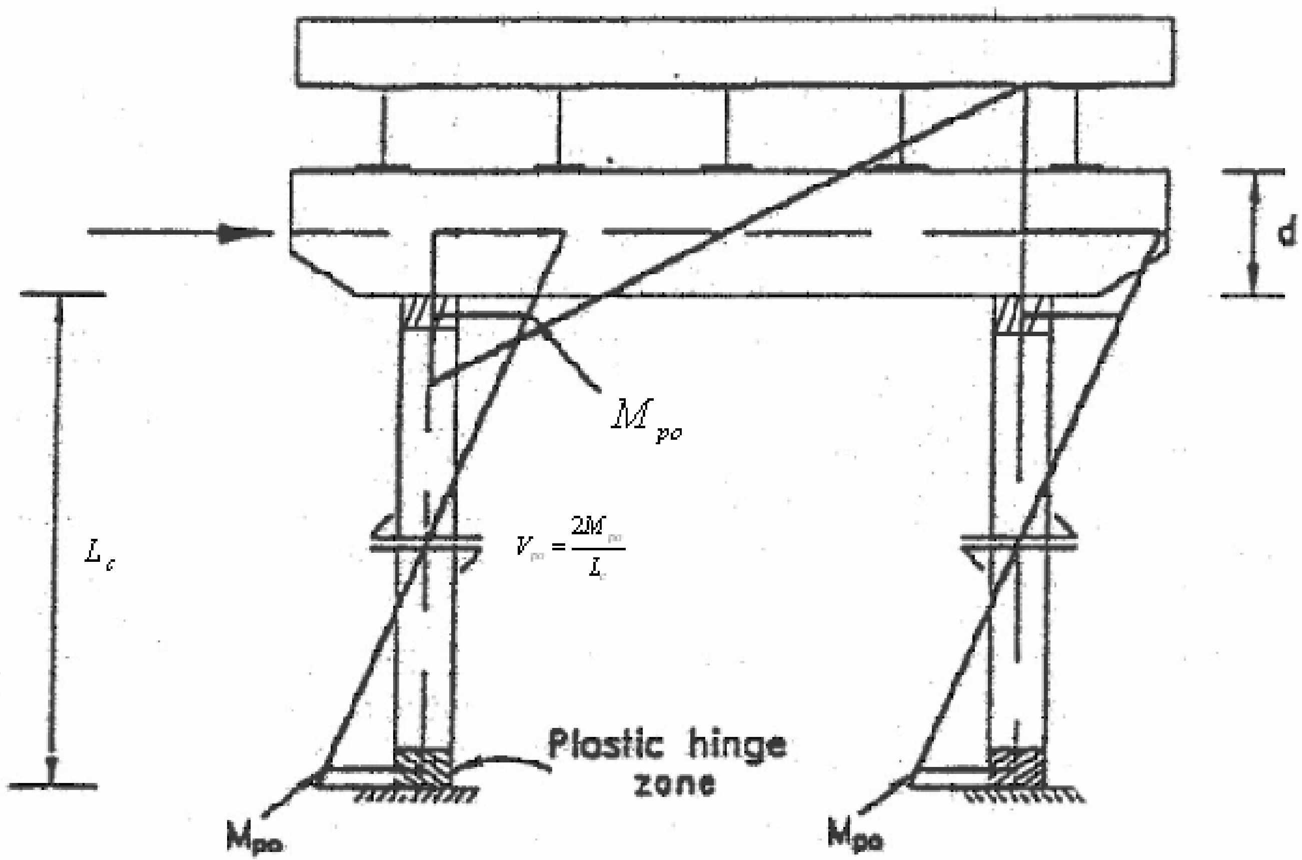
Elastic-Plastic Displacement of a Column Pushover Analysis for SDC D



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



San Fernando Earthquake

Route 210/5 Interchange

Northridge Earthquake

Gavin Canyon Undercrossing – Collapsed Spans

Eureka Earthquake

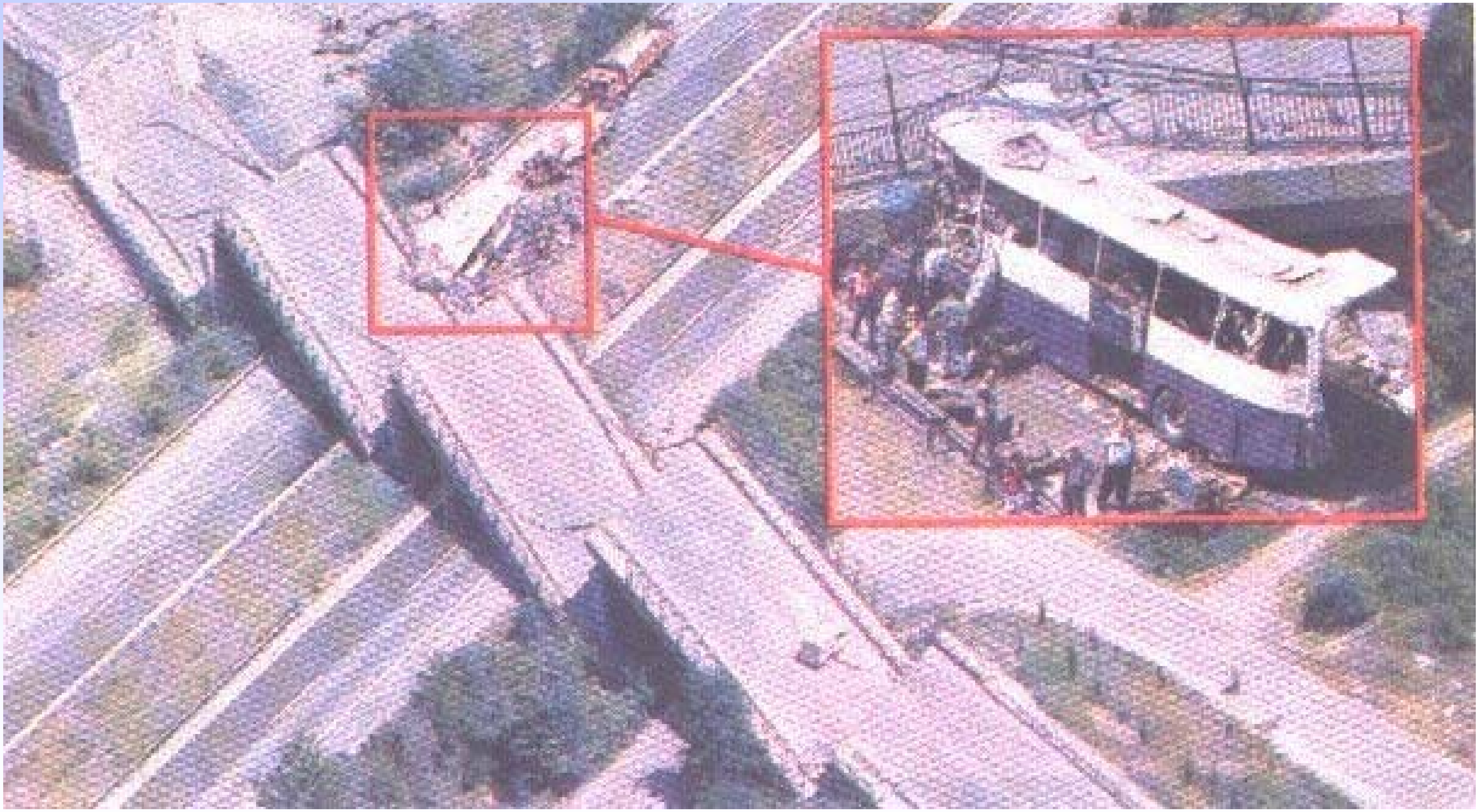
Fields Landing Spans 1 and 2 Collapsed

Guatemala Earthquakes

Rio Agua Caliente Bridge

Kocaeli, Turkey Earthquake

Overpass at Arifiye Junction



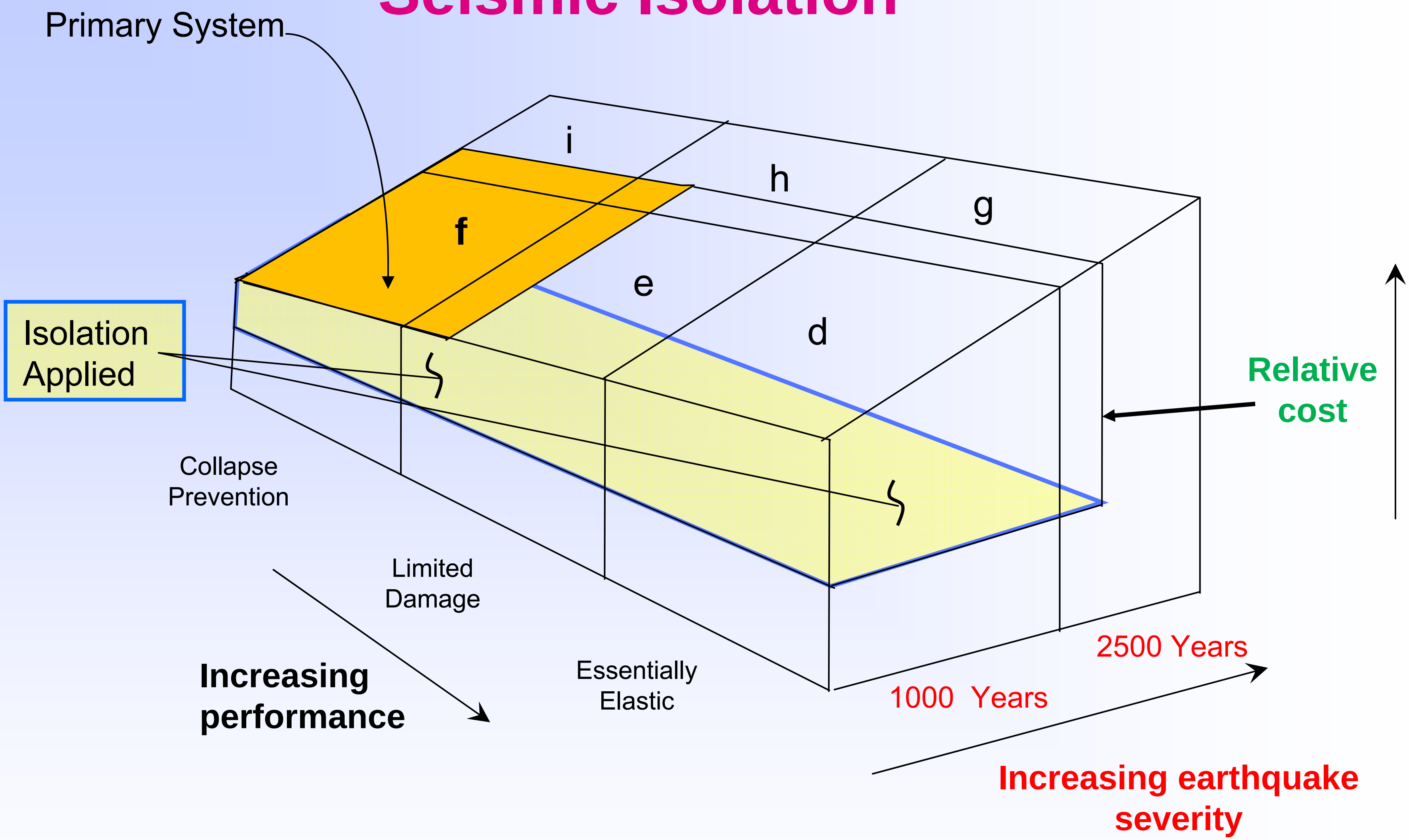
Highway Collapse, Kobe Japan 1995

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

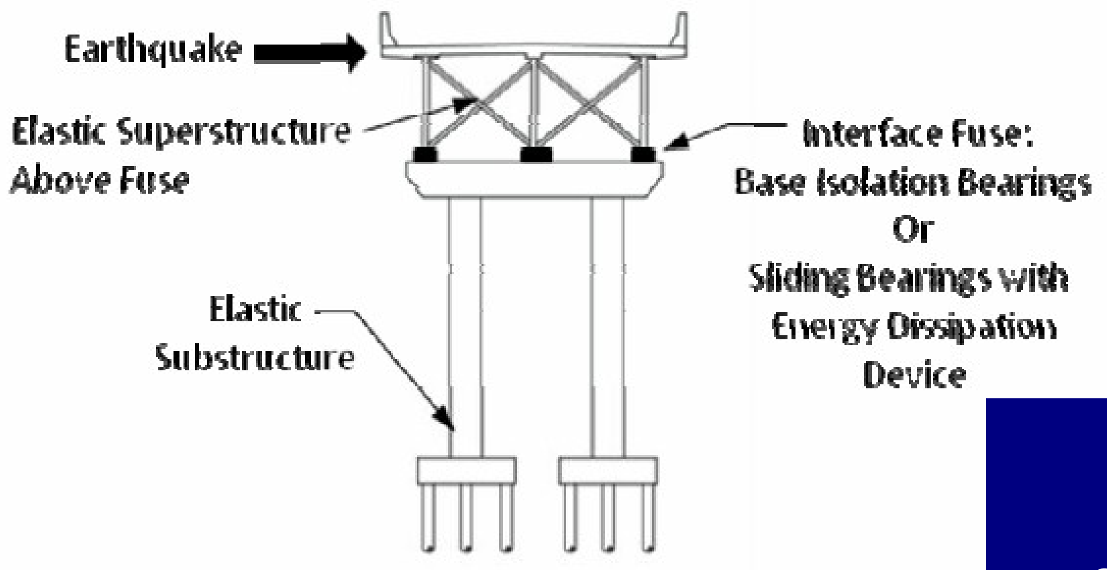
Seismic Isolation

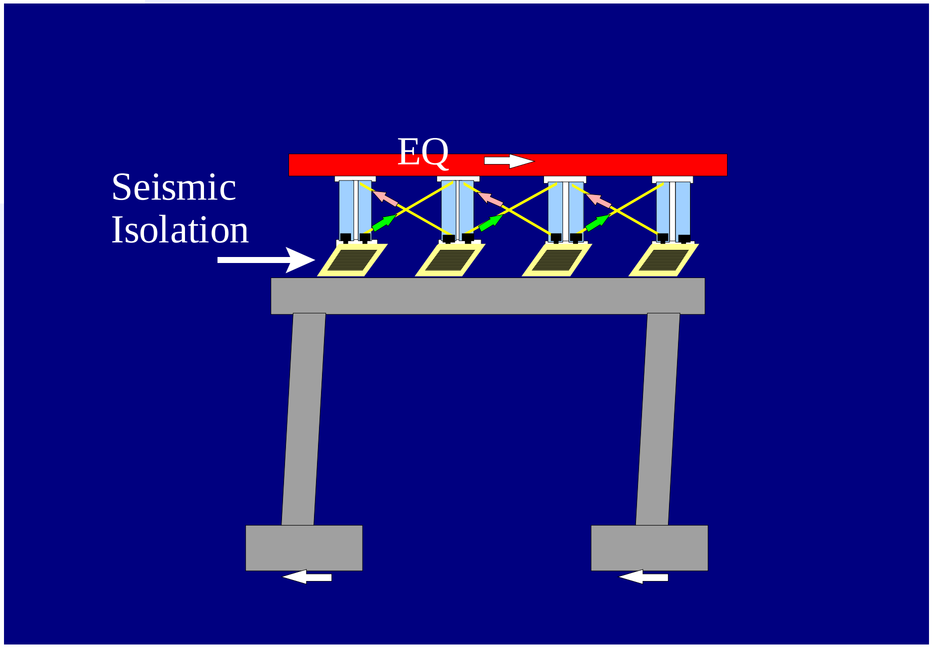


Calibration Objectives with Isolation

Global Design Strategies

Type 3 Design



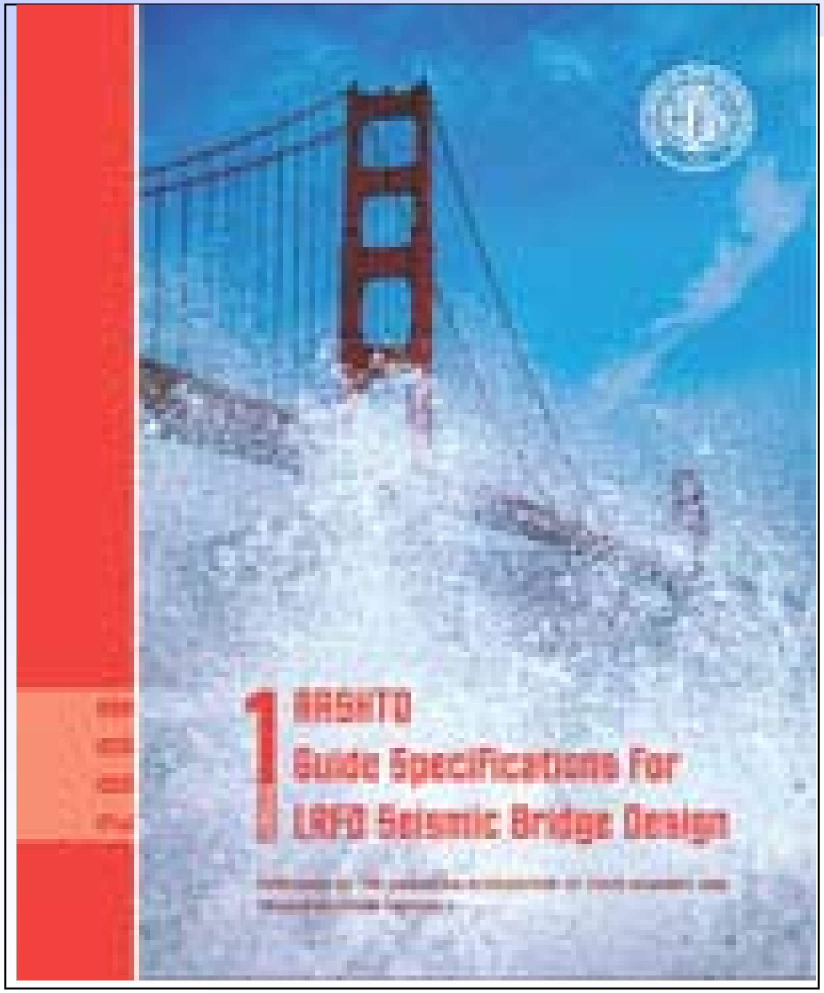


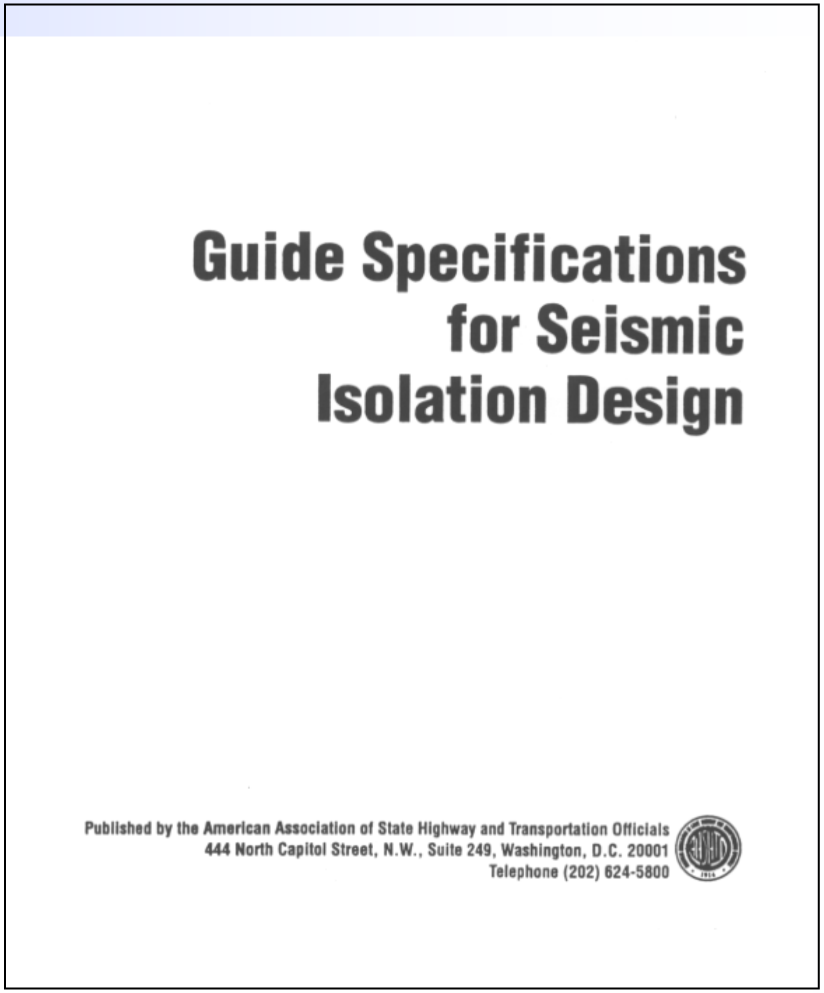
ype 3 - Design an elastic superstructure and substructure with a fusing (e.g., isolation) mechanism at the interface.

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

The Synergy for Increased Seismic Protection of Bridges




Guide Specifications for Seismic Isolation Design

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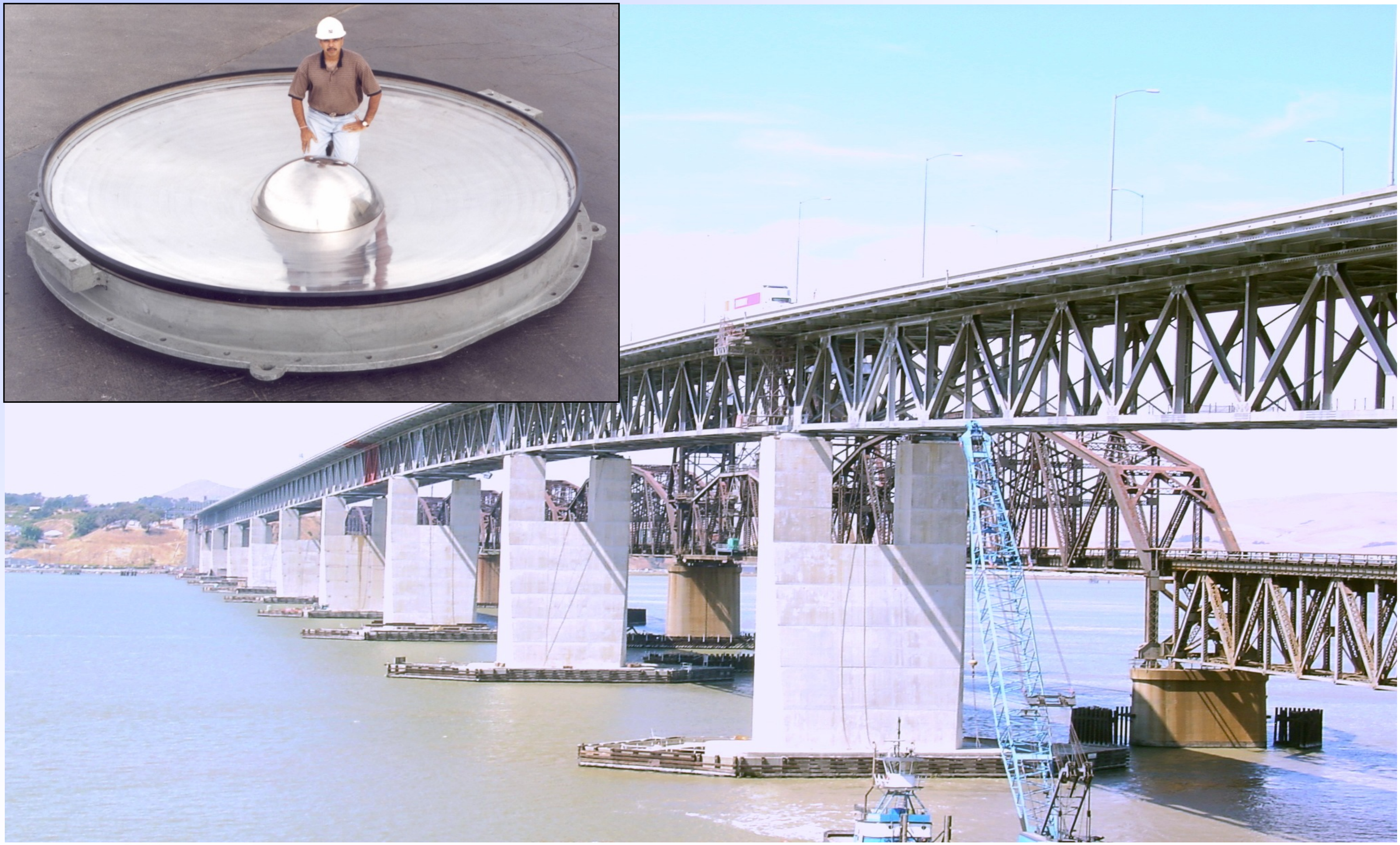
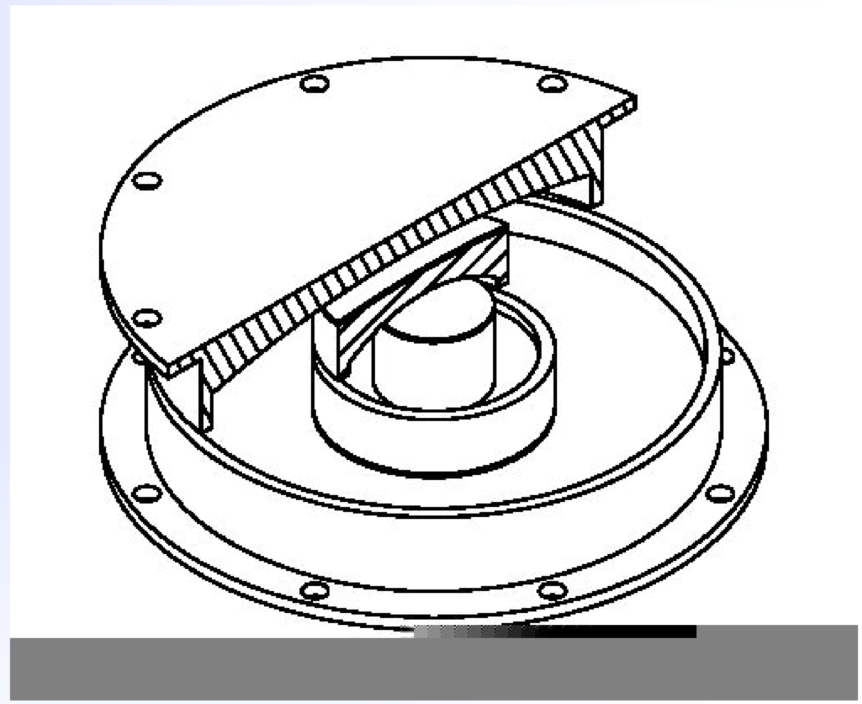
Telephone (202) 624-5800

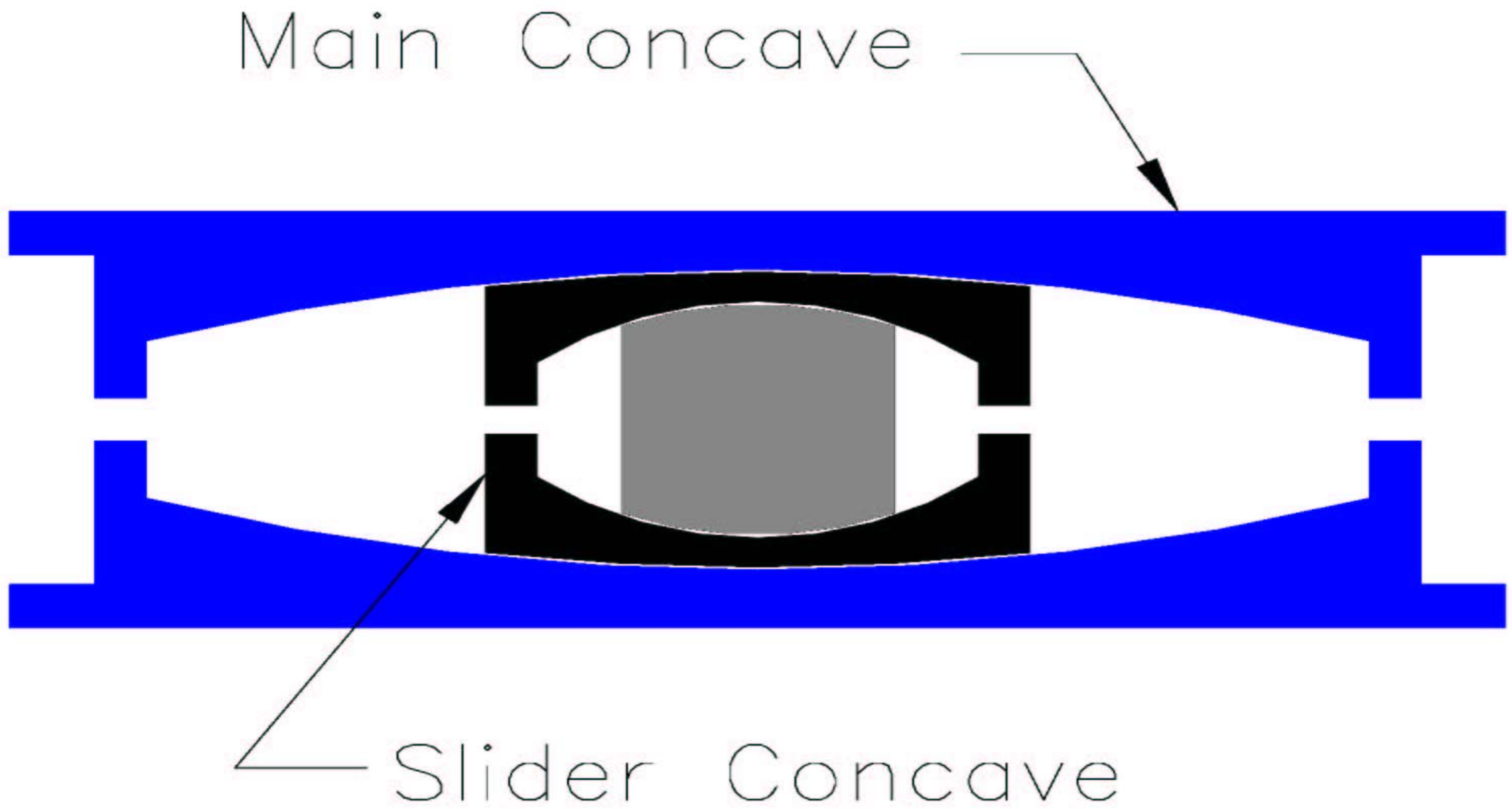
Benicia-Martinez Bridge



Triple Pendulum Bearing

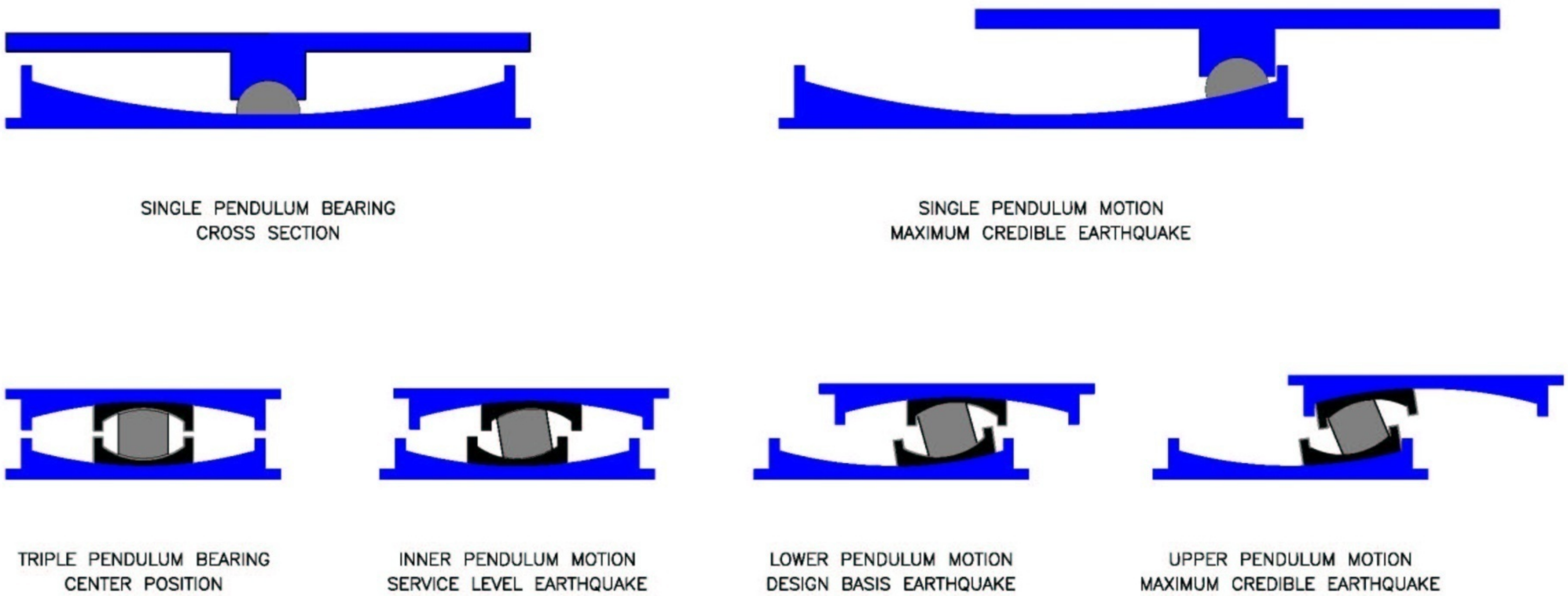


Triple Pendulum Bearing



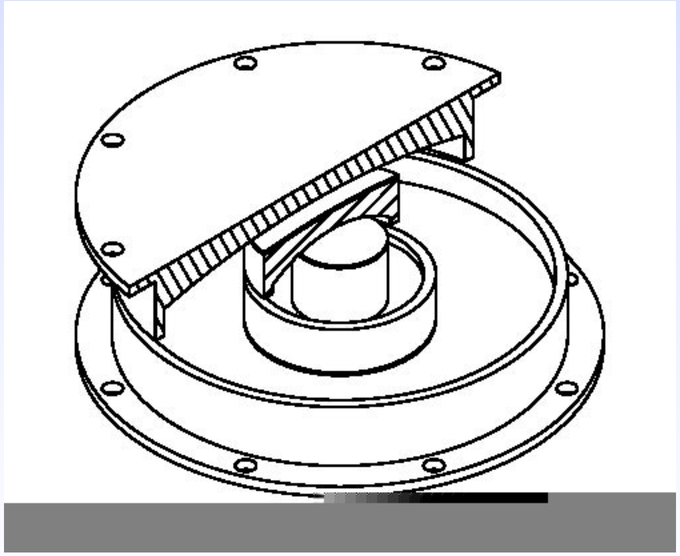
Section of Triple Pendulum Bearing

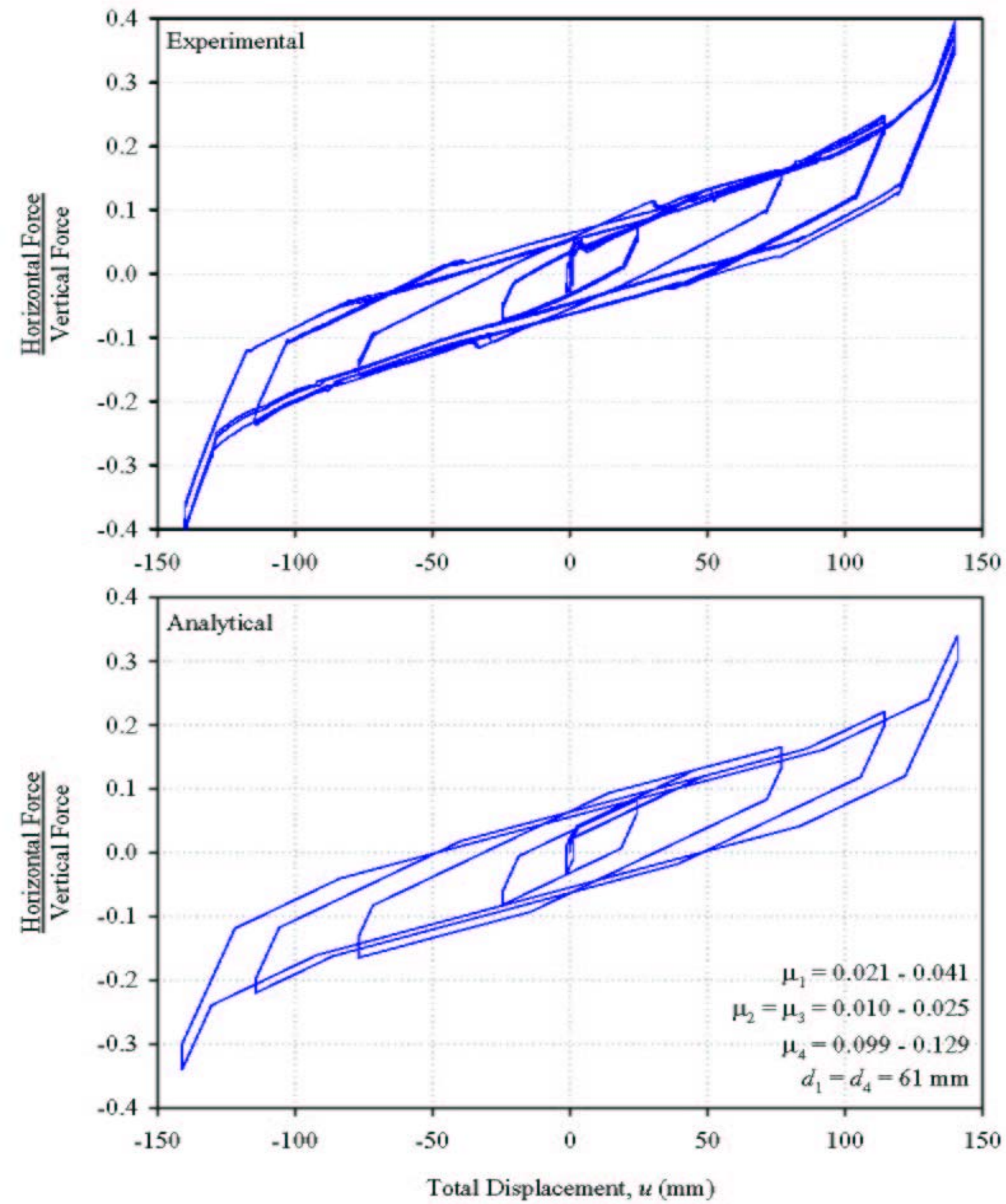
Triple Pendulum Bearing



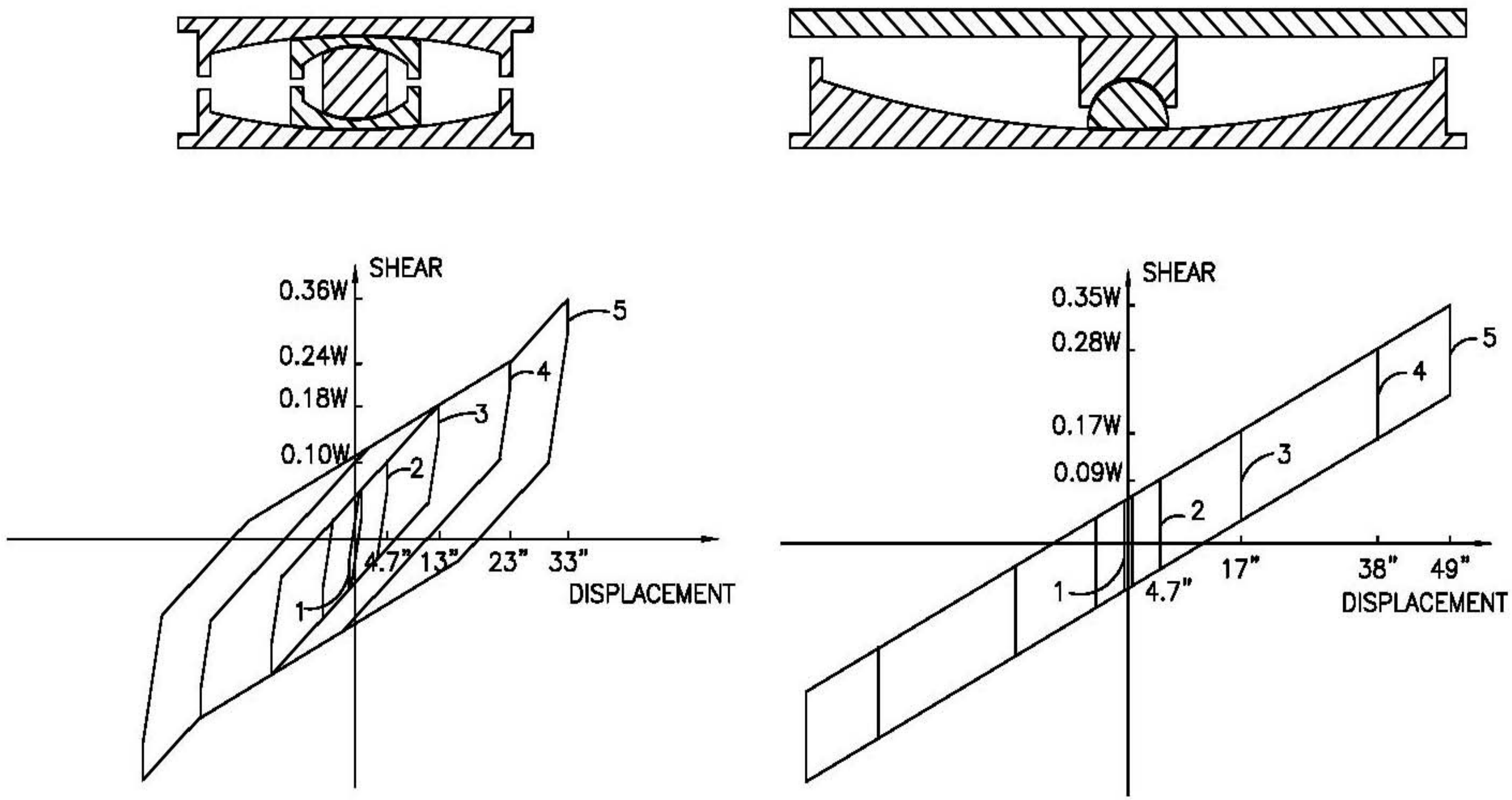
COMPARISON OF BEARING SIZES AND RESPONSE TO EARTHQUAKE MOTIONS

Component Testing Of Triple Pendulum Bearing At MCEER, Suny Buffalo





Advantages Of Triple Pendulum Bearing



TRIPLE PENDULUM BEARING

SINGLE PENDULUM BEARING

TESTING OF TRIPLE PENDULUM BEARING

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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.

Concluding Remarks

- Single Level Hazard for 1000 year return period applicable to all regions of the U.S.
- 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.
- Partition of Seismic Design Category (SDC) into four groups (A,B,C & D) with increasing levels of design requirements.

Concluding Remarks (continued)

- Identification of Global Design Strategy, an Earthquake Resistant System and Load Path.
- Displacement Based Approach with design factors calibrated to prevent collapse.
- 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.
- Both the Guide Specifications and Isolation Guide Specifications are Displacement Based Design.

Concluding Remarks (continued)

- 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.
- Capacity Protection of all components and joints.
- Steel Superstructure Design Option based on Force Reduction Factors including the use of ductile end-diaphragms.
- New Isolation/Energy Dissipation Concepts will be developed in the future.