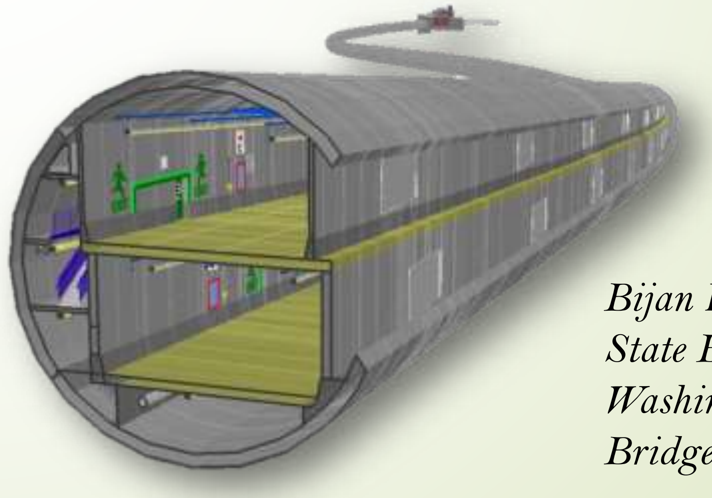
The 3rd International Bridge Seismic Workshop
Seattle, Washington, USA
October 1-4, 2019

Seismic Design Requirements and Construction Challenges of Lifeline Essential and Critical Bridges



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Washington State DOT
Bridge & Structures Office

Post-Earthquake Functionality of Bridges

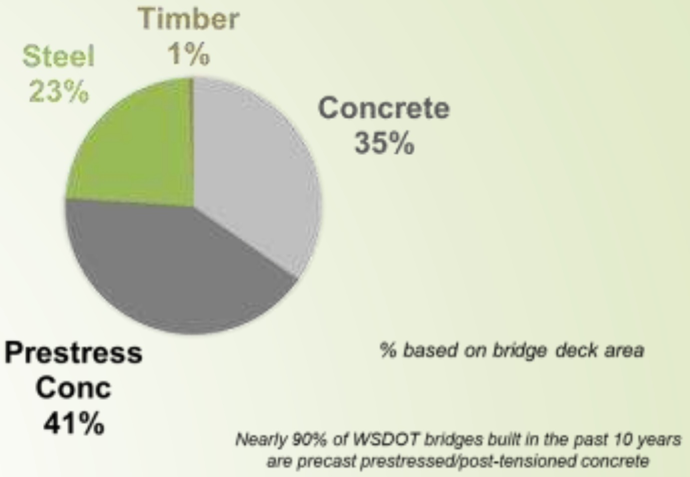
Objectives: Seismic Resilient Bridges

- Seismic Design Challenges of PNW
- Post Earthquake Seismic Performance Requirements - Lifeline
- Challenges of ABC in Seismic Regions
- Innovative in Seismic Resiliency using
  - Self Centering Piers
  - Super Elastic Materials in Bridge Columns
  - Prestressed Bridge Columns
  - Dual Shell Concrete Filled Steel Tubes
- Research and Implementation Projects

Examples of Bridge Earthquake Damages

WSDOT Bridge Inventory


Washington State Map



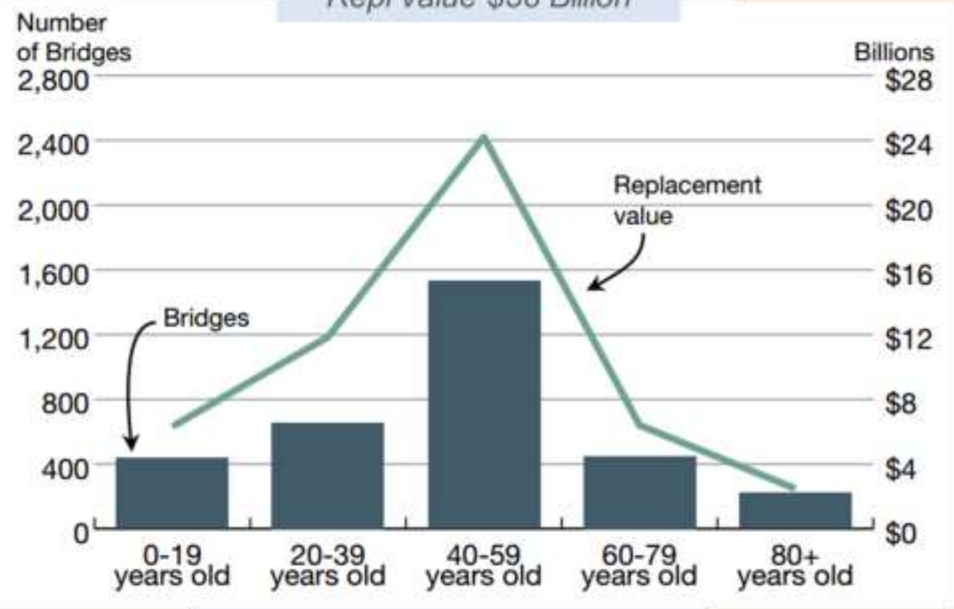
% based on bridge deck area

Nearly 90% of WSDOT bridges built in the past 10 years are precast prestressed/post-tensioned concrete

Ave Age - 48

3,120 bridges (53.5 M SF)
Repl value $58 Billion

Oldest - 1910



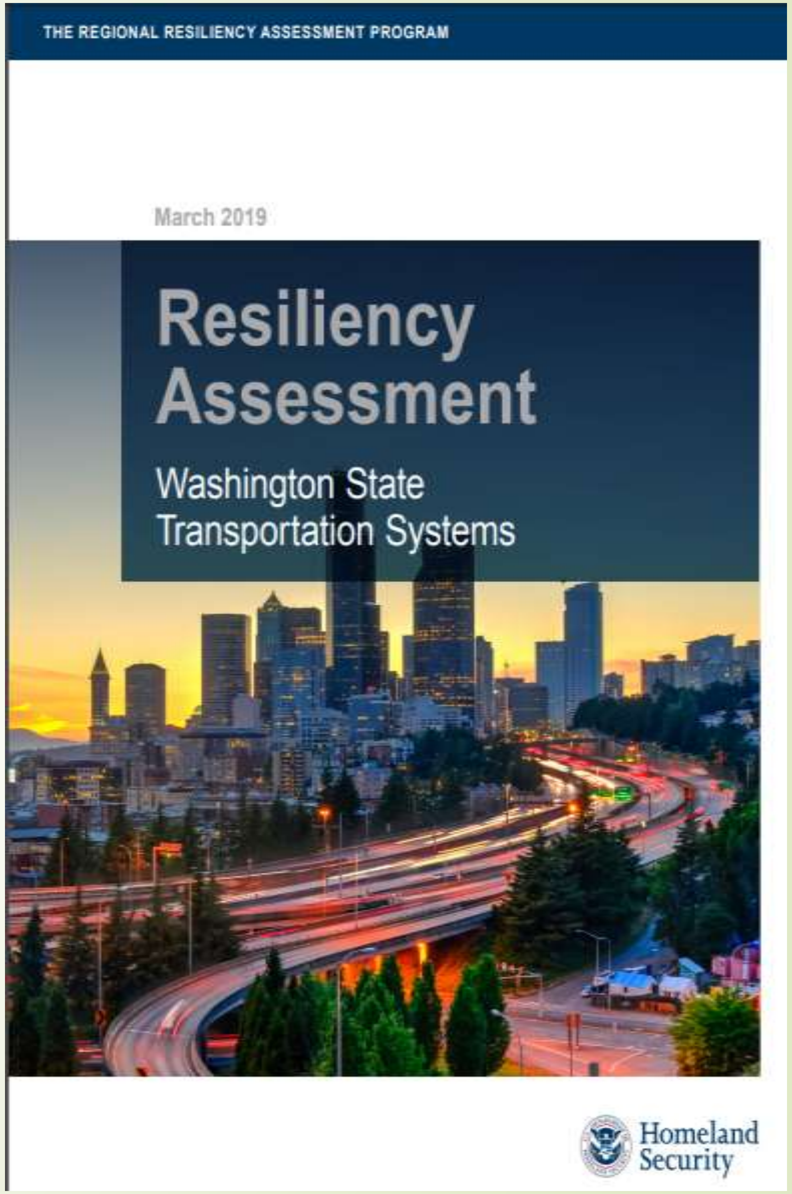
80+ yrs old – 251 bridges ($2.5B)
100+ yrs old – 12 bridges ($55M)

- Total WSDOT bridge structures 3,829
- The average age of WSDOT's bridges is 44 years
- WSDOT has 283 bridges that are 75 years or older
- WSDOT bridge inventory increases by 35 each

Geologic Hazards in Washington State

Risks in Washington State:

- faults and earthquakes,
- tsunamis, landslides,
- volcanic hazards.
- Magnitude 8.0-9.0+
- Shaking felt for 3–6 minutes
- Shaking intensities greatest along coast & where local conditions amplify seismic waves
- Earthquake followed by a major tsunami
- Many large aftershocks



THE REGIONAL RESILIENCY ASSESSMENT PROGRAM

March 2019

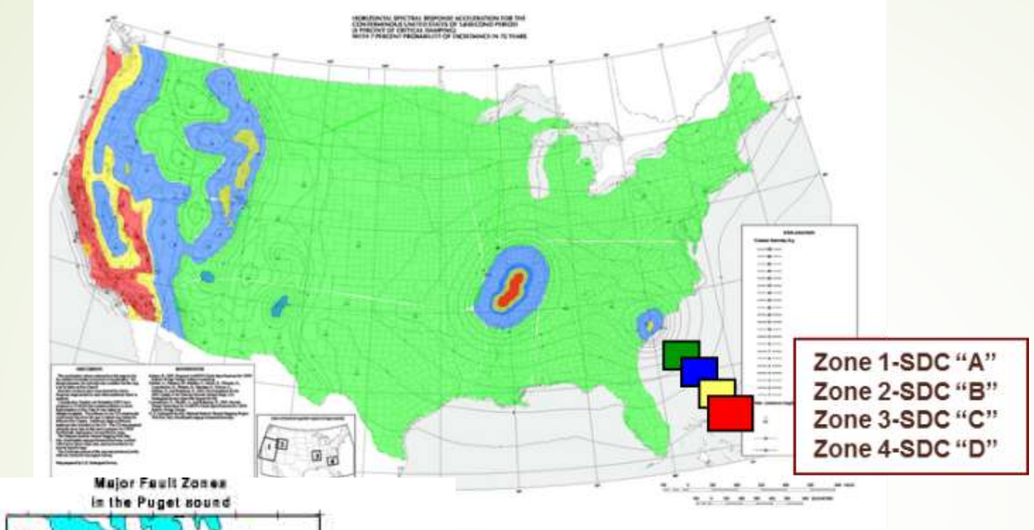
Resiliency Assessment

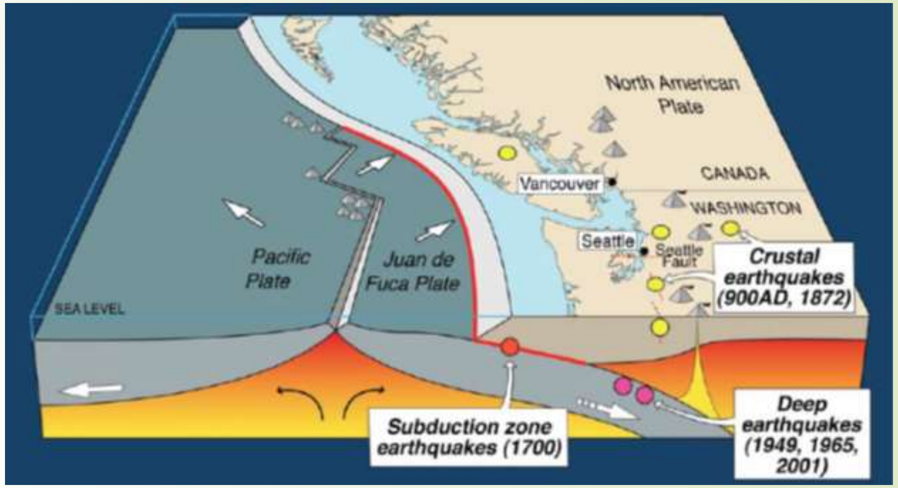
Washington State Transportation Systems

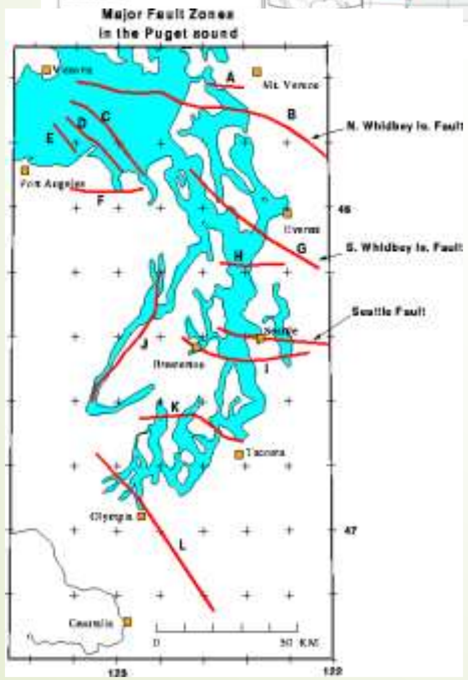
Homeland Security

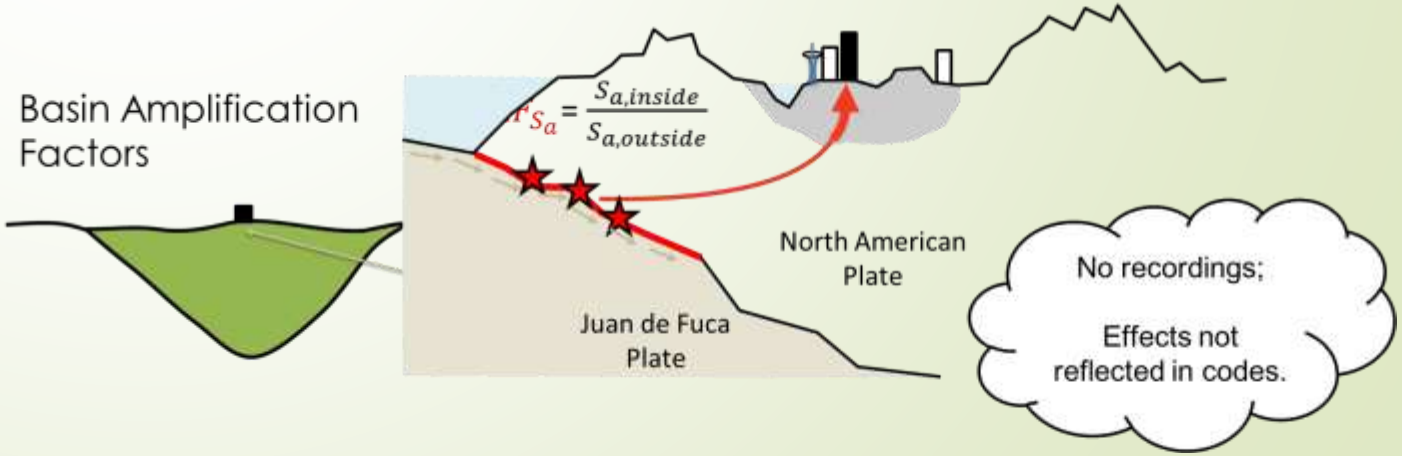
Complexity of PNW Seismic Design

- Cascadia Subduction Zone
- M9 Subduction Mega EQ
- Basin Effect








Basin Amplification Factors

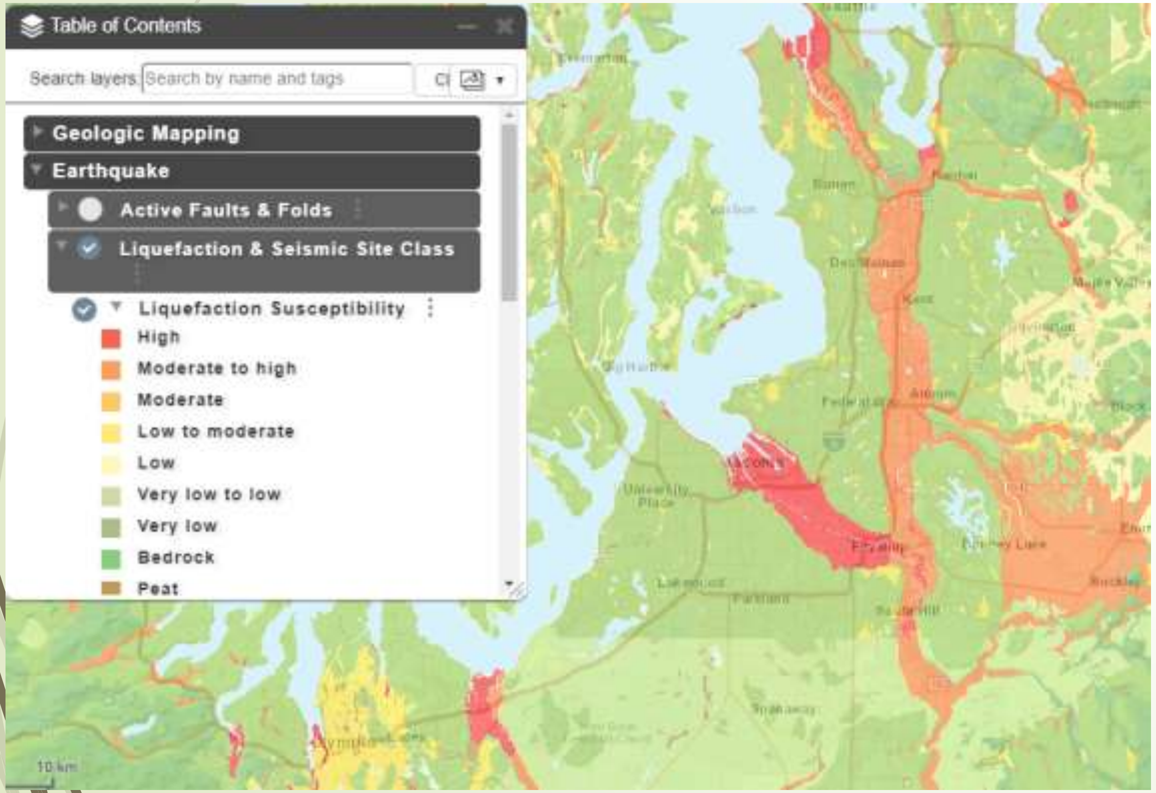
$F_{S_a} = \frac{S_{a,inside}}{S_{a,outside}}$

No recordings;

Effects not reflected in codes.

WW Liquefaction hazards

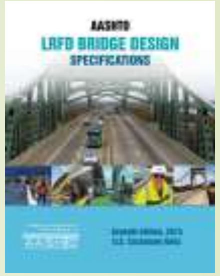
Soil liquefaction and lateral spreading in Tumwater, WA 3 weeks after the 2001 Nisqually Quake. Photo courtesy of UW College of Engineering



LRFD Bridge Seismic and ABC Design Specifications

LRFD Bridge Design Specifications

Bridges shall be designed for specified limit states to achieve the objectives of constructability, safety, and serviceability, with due regard to issues of inspectability, economy, and aesthetics.



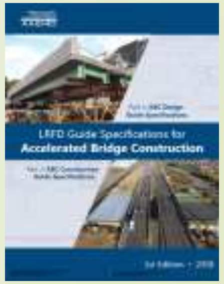
Guide Specifications for LRFD Seismic Bridge Design

The LRFD Guide Specifications apply to the design and construction of conventional bridges to resist the effects of earthquake motions.

LRFD Guide Specifications for Accelerated Bridge Construction

The provisions are for common prefabricated elements and systems for Accelerated Bridge Construction (ABC) projects.

The provisions shall be used in conjunction with the AASHTO LRFD Bridge Design Specifications.



LRFD Guide Specifications for Seismic Isolation Design

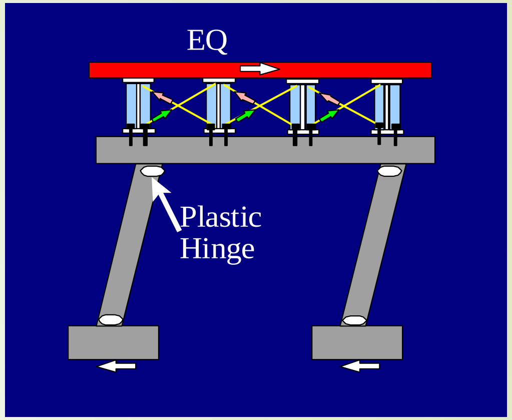
The Guide Specifications apply to the design and construction of conventional bridges supported by isolation bearings to resist the effects of earthquake motions.

AASHTO LRFD Seismic Design Strategies

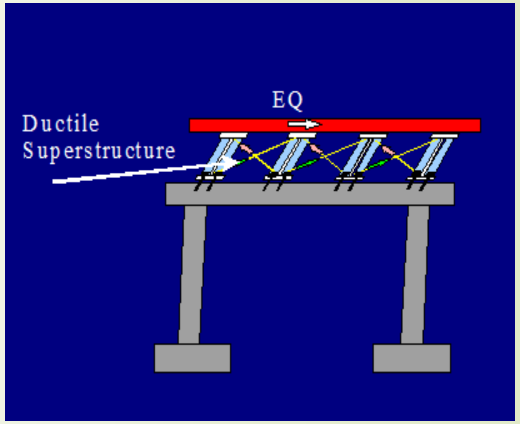
- In general, it is uneconomic to design structures to withstand design level earthquake elastically.

Alternative Approaches:

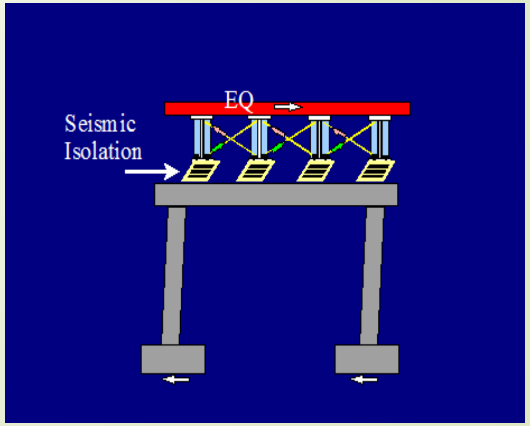
- Type 1 – **Ductile Substructure with Essentially Elastic Superstructure.** (This category includes conventional plastic hinging in columns and walls that limits inertial forces by full mobilization of passive soil resistance)



- Type 2 – **Essentially Elastic Substructure with Ductile Superstructure.** (This category applies only to Steel Superstructures, and ductility is achieved by constructing ductile elements as part of the pier cross-frames)



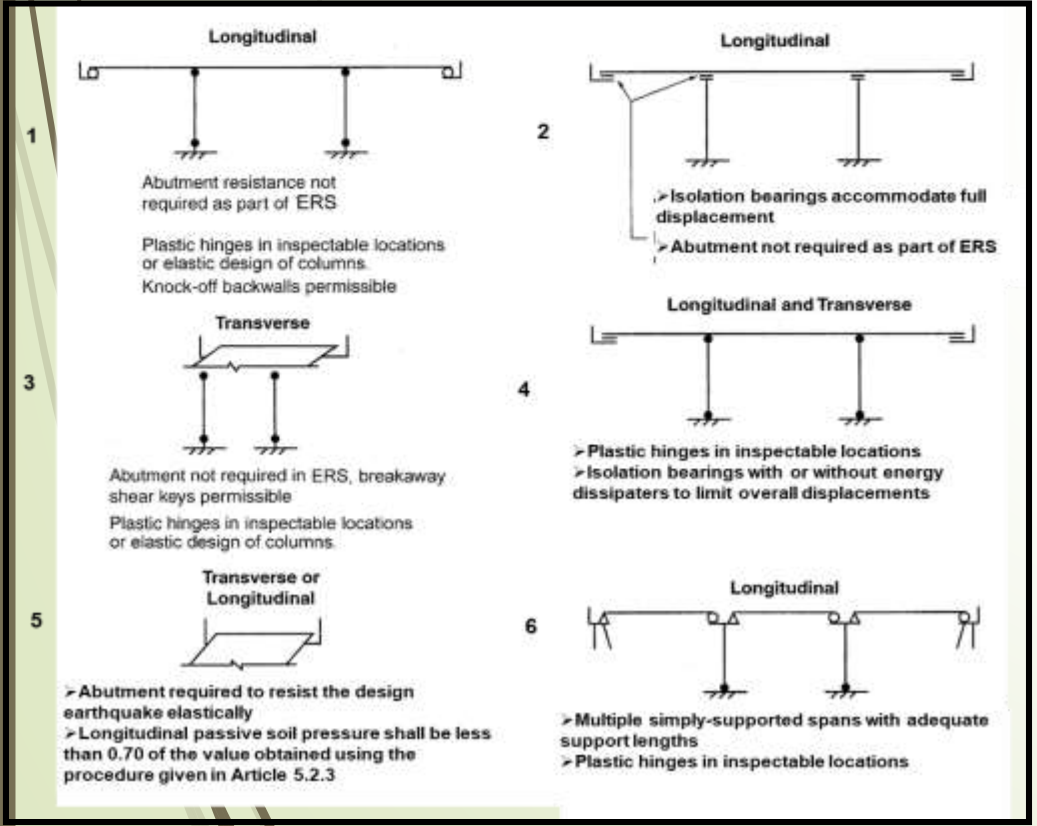
- Type 3 – **Elastic Superstructure and Substructure with a Fusing Mechanism Between The Two.** (This category includes seismically isolated structures)



LRFD SGS: Bridge System ERS and ERE Categories

Use of ERS and ERE to ensure required seismic performance

- Permissible
- Permissible with Approval
- Not Recommended for New Bridge



1: Abutment resistance not required as part of ERS

Plastic hinges in inspectable locations or elastic design of columns.

Knock-off backwalls permissible

2: ➢Isolation bearings accommodate full displacement

➢Abutment not required as part of ERS

3: Abutment not required in ERS, breakaway shear keys permissible

Plastic hinges in inspectable locations or elastic design of columns.

4: ➢Plastic hinges in inspectable locations

➢Isolation bearings with or without energy dissipaters to limit overall displacements

5: ➢Abutment required to resist the design earthquake elastically

➢Longitudinal passive soil pressure shall be less than 0.70 of the value obtained using the procedure given in Article 5.2.3

6: ➢Multiple simply-supported spans with adequate support lengths

➢Plastic hinges in inspectable locations

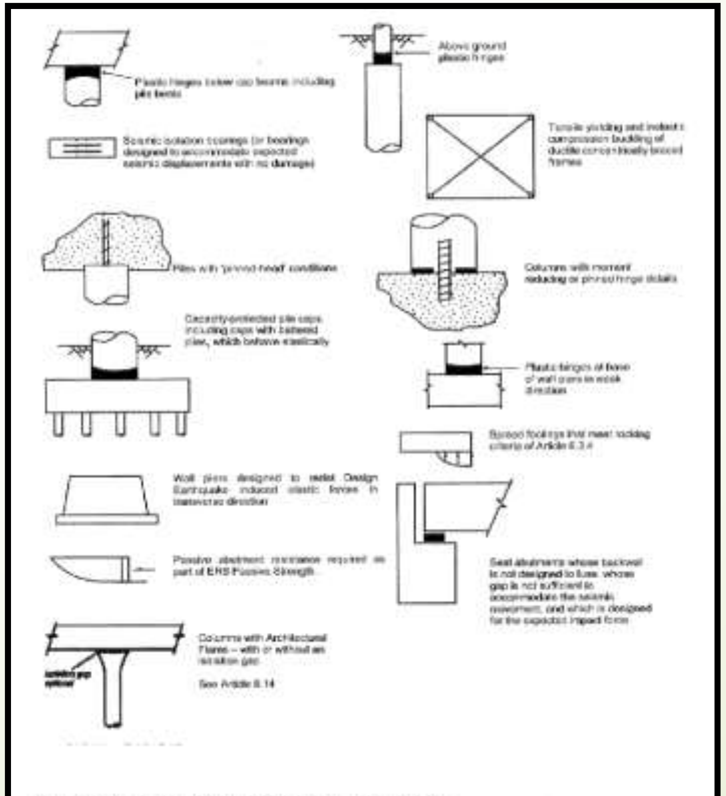
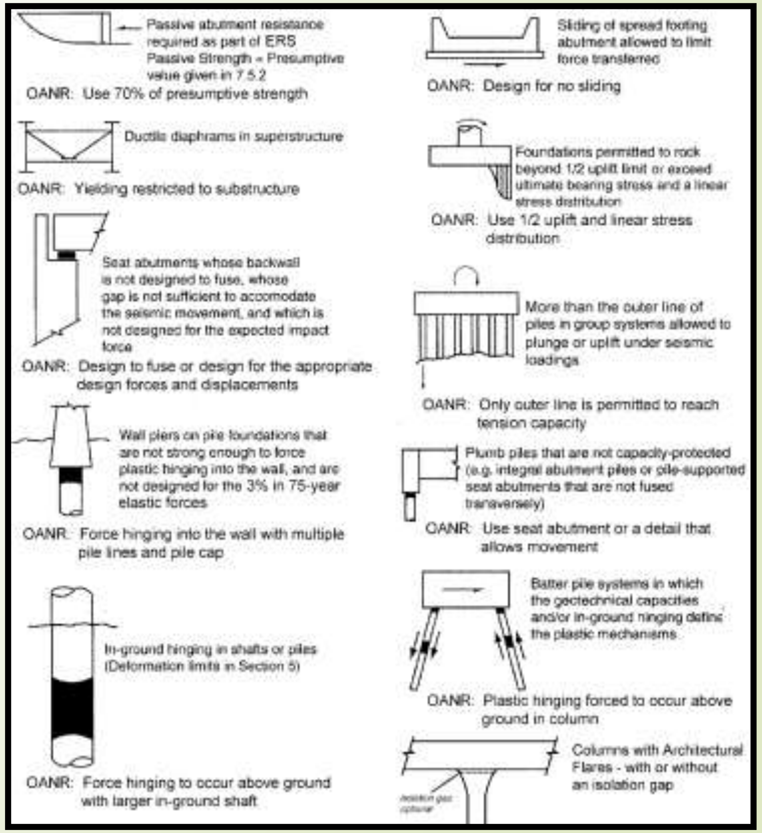


FIGURE 3.3.1b   Permissible Earthquake Resisting Elements (ERE)



Passive abutment resistance required as part of ERS Passive Strength = Presumptive value given in 7.5.2

OANR: Use 70% of presumptive strength

Ductile diaphrams in superstructure

OANR: Yielding restricted to substructure

Seat abutments whose backwall is not designed to fuse, whose gap is not sufficient to accomodate the seismic movement, and which is not designed for the expected impact force

OANR: Design to fuse or design for the appropriate design forces and displacements

Wall piers on pile foundations that are not strong enough to force plastic hinging into the wall, and are not designed for the 3% in 75-year elastic forces

OANR: Force hinging into the wall with multiple pile lines and pile cap

In-ground hinging in shafts or piles (Deformation limits in Section 5)

OANR: Force hinging to occur above ground with larger in-ground shaft

Sliding of spread footing abutment allowed to limit force transferred

OANR: Design for no sliding

Foundations permitted to rock beyond 1/2 uplift limit or exceed ultimate bearing stress and a linear stress distribution

OANR: Use 1/2 uplift and linear stress distribution

More than the outer line of piles in group systems allowed to plunge or uplift under seismic loadings

OANR: Only outer line is permitted to reach tension capacity

Plumb piles that are not capacity-protected (e.g. integral abutment piles or pile-supported seat abutments that are not fused transversely)

OANR: Use seat abutment or a detail that allows movement

Batter pile systems in which the geotechnical capacities and/or in-ground hinging define the plastic mechanisms

OANR: Plastic hinging forced to occur above ground in column

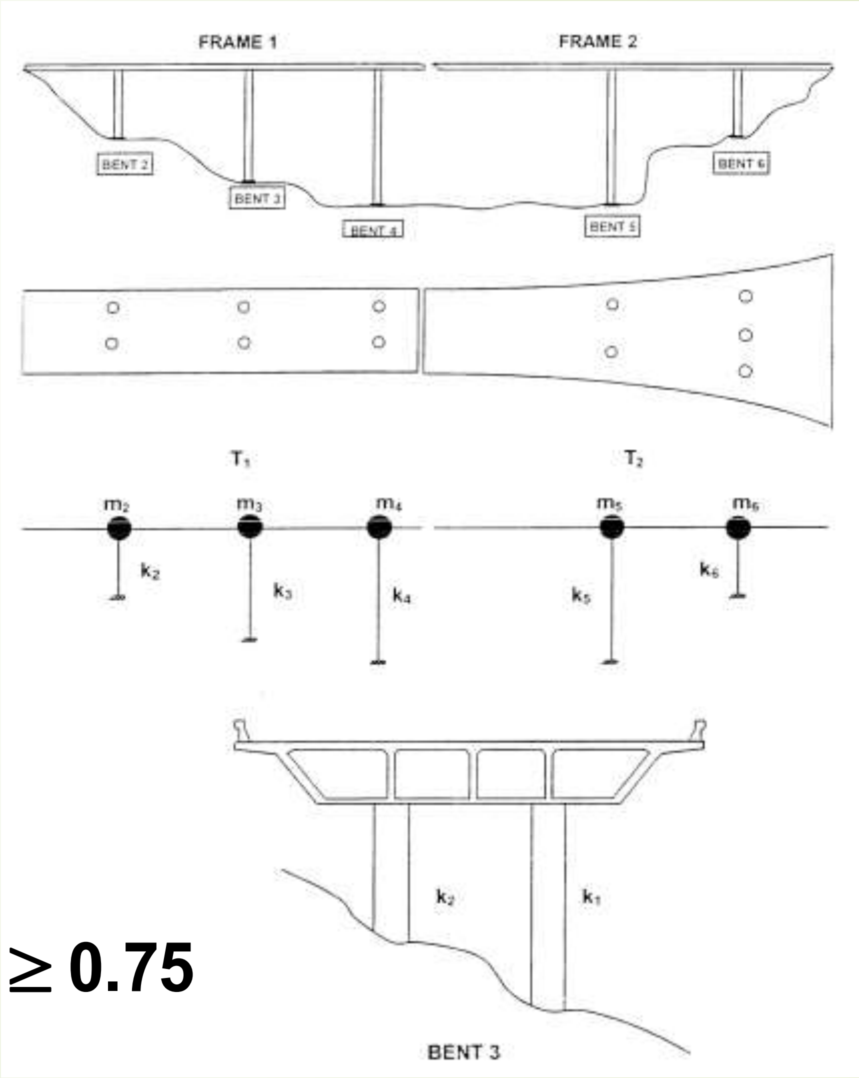
Columns with Architectural Flares - with or without an isolation gap

Seismic Resiliency for Essential/Critical Bridges – Required Balanced Stiffness

Balanced Stiffness Concept for Frames, Bents and Columns

1. Between any two bents within a frame or between any two columns within a bent
2. Between adjacent bents within a frame or between adjacent columns within a bent
3. Balanced Frame Geometry - (ratio of fundamental periods of vibration)

$$\frac{K_i^e \times m_j}{K_j^e \times m_i} \geq 0.50 \qquad \frac{T_i}{T_j} \geq 0.7 \qquad \frac{K_i^e \times m_j}{K_j^e \times m_i} \geq 0.75$$



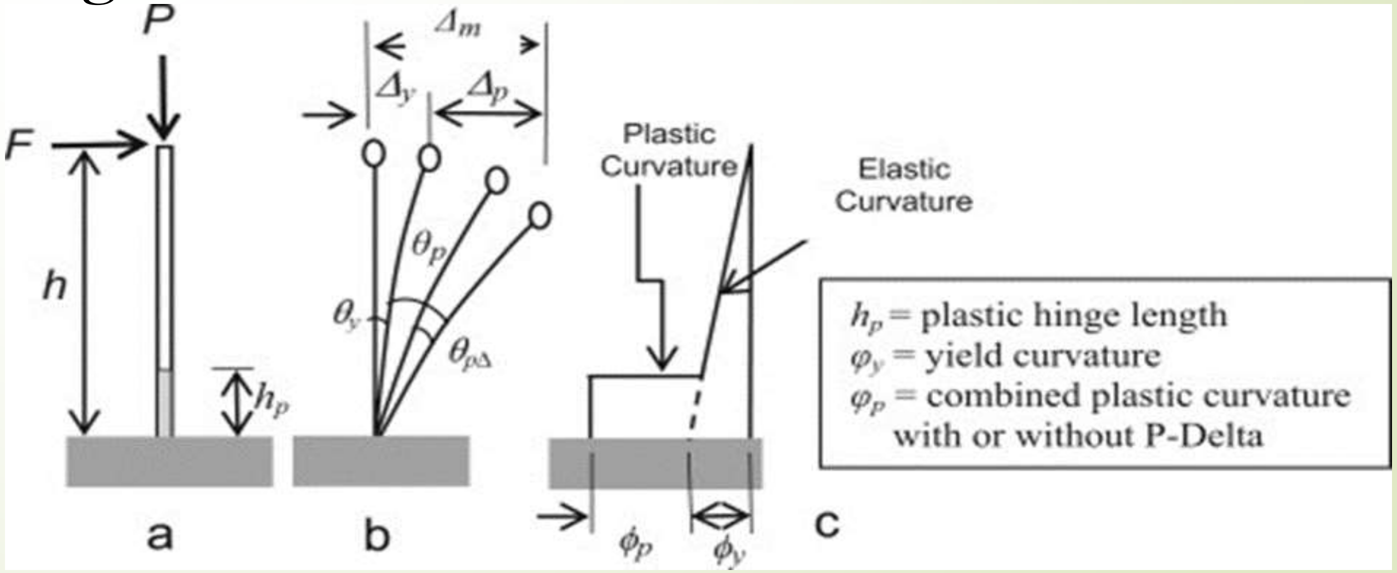
Seismic Resiliency of Essential/Critical Bridges

Limitation on P-Δ and Pu

P-Δ effects may be ignored in the analysis and design of Type 1 structures if the following is satisfied.

- For reinforced concrete columns: $P_{dl}\Delta_r \le 0.25M_p$
- For steel columns: $P_{dl}\Delta_r \le 0.25M_n$

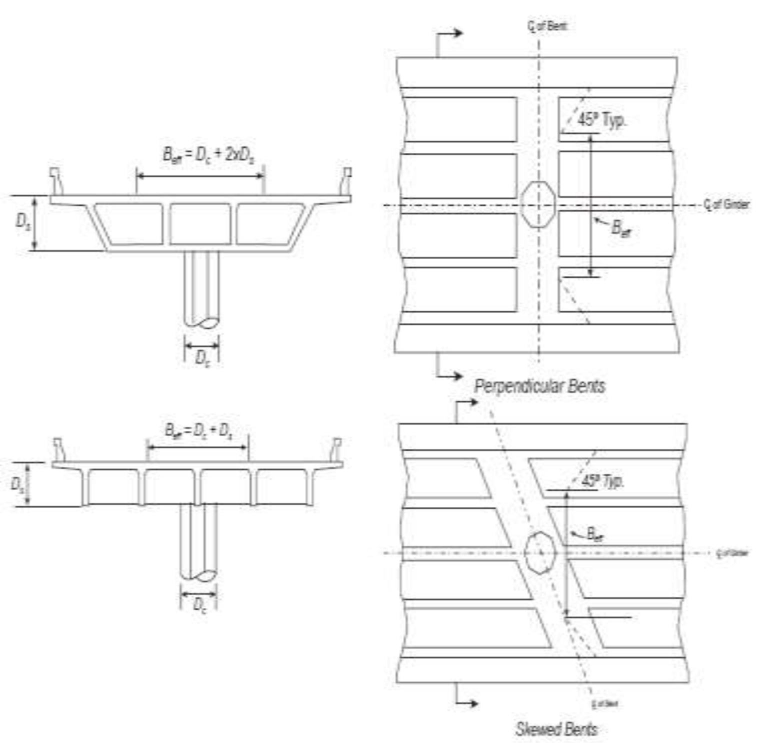
The maximum axial load acting on a column: $Pu < 0.2\, f'_c A_g$



LRFD SGS Capacity Design For Caps for Longitudinal Direction

Capacity Design Requirement for SDCs B, C and D

- Capacity-protected members are designed to remain essentially elastic when the plastic hinge reaches its overstrength moment capacity, **M_{po} = 1.25 times the moment demand**
- Moment-resisting joints is proportioned so that the principal stresses satisfy the requirements below.



- For principal compression, p_c:

$$p_c \le 0.25 f'_c$$

- For principal tension, p_t:

$$p_t \le 0.38\sqrt{f'_c}$$

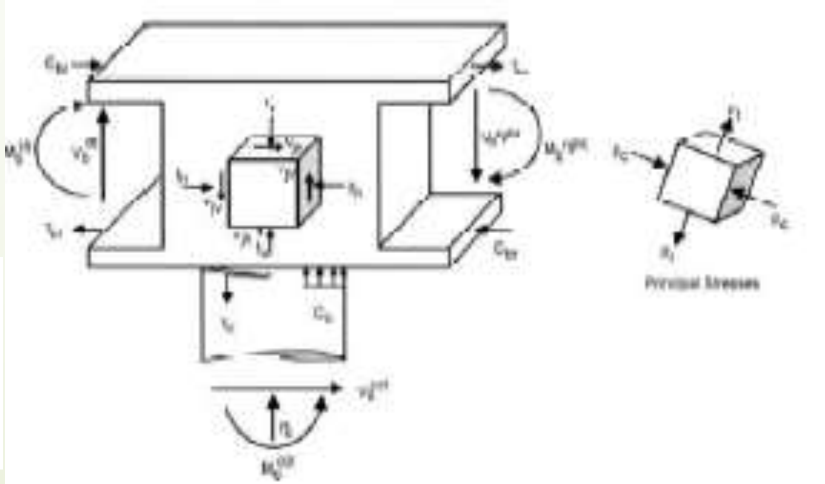
$$p_t = \left|\left(\frac{f_h + f_v}{2}\right) - \sqrt{\left(\frac{f_h - f_v}{2}\right)^2 + v_{jv}^2}\right|$$

$$p_c = \left(\frac{f_h + f_v}{2}\right) + \sqrt{\left(\frac{f_h - f_v}{2}\right)^2 + v_{jv}^2}$$

$$f_h = \frac{P_b}{B_{cap} D_s}$$

$$f_v = \frac{P_c}{(D_c + D_s) B_{cap}}$$

$$v_{jv} = \frac{T_c}{\ell_{ac} B_{eff}}$$



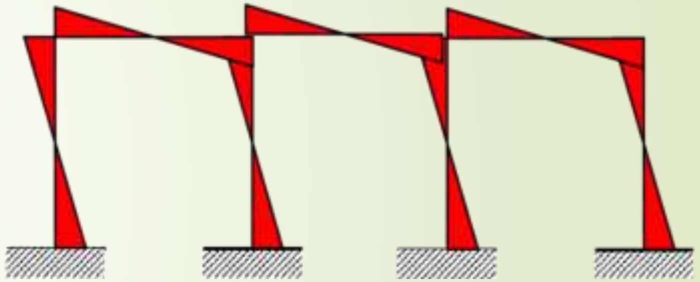
Post-Earthquake Functionality of ABC Bridges

Emulative Construction

- No new concepts to prove.
- Easier acceptance: "performs just like c.i.p."
- Use of precast shortens constructiontime

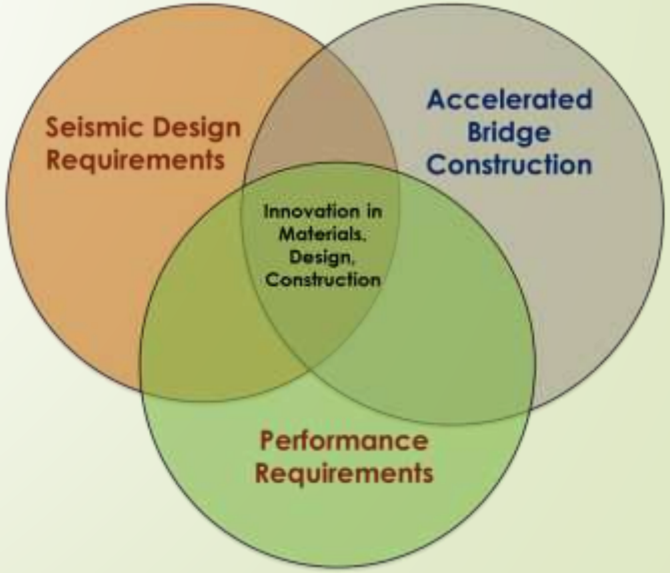
Innovative Connection Types

- Socket and Pocket connections
- Super-Elastic Materials
- Self-Centering



Connections need to be:

- *Constructible*
- *Seismic Resilient*
- *Long term Performance & Longevity*



Seismic Design Requirements

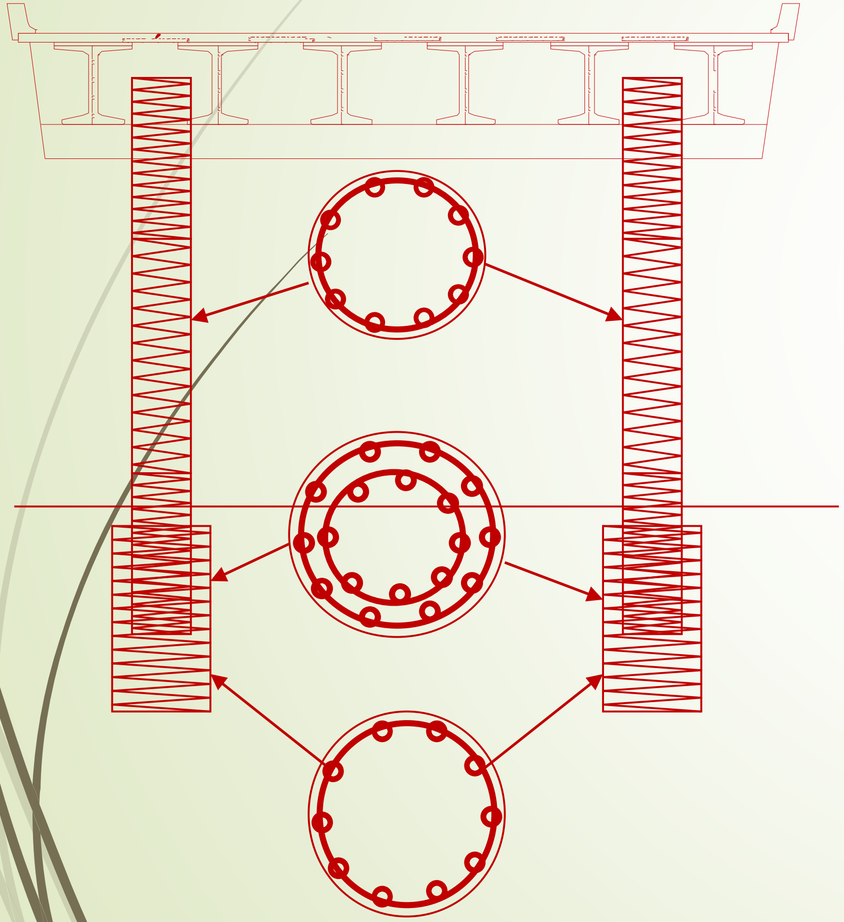
Accelerated Bridge Construction

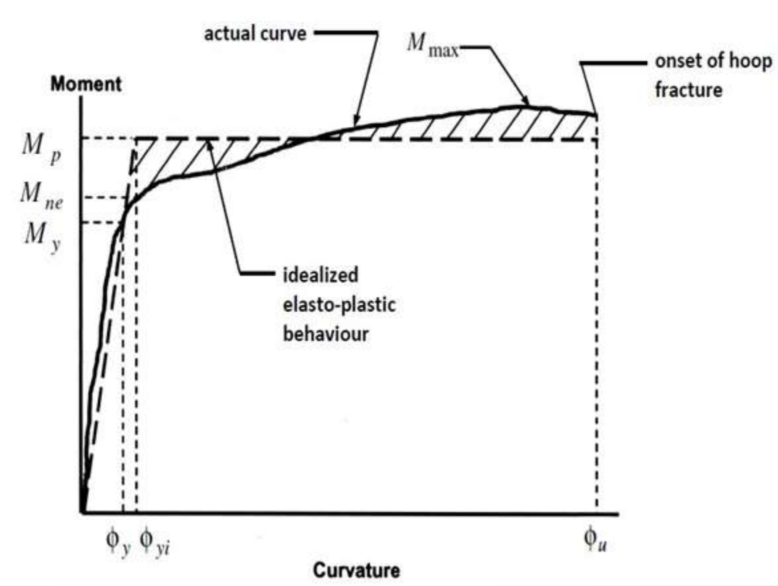
Innovation in Materials, Design, Construction

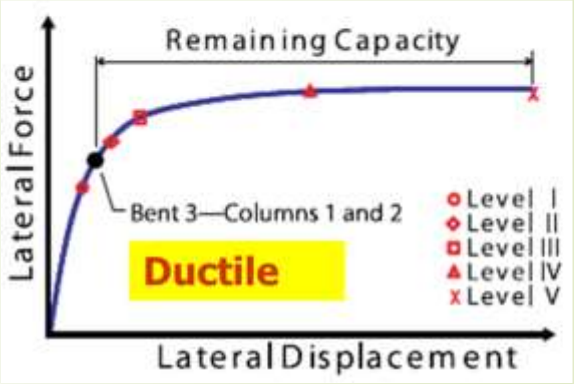
Performance Requirements

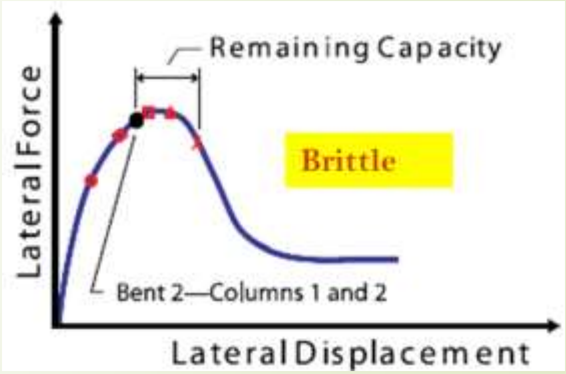
Column Confinement and Performance Curves

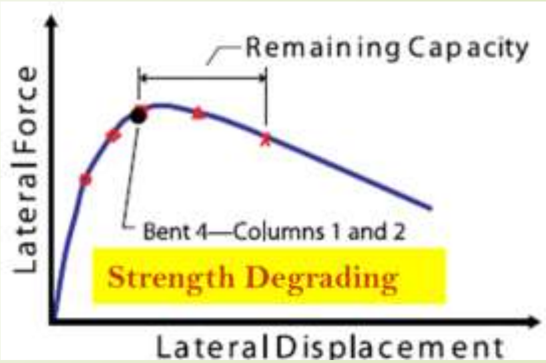
Ductility Performance Curves for Reinforced Concrete Columns in SDCs B, C, and D



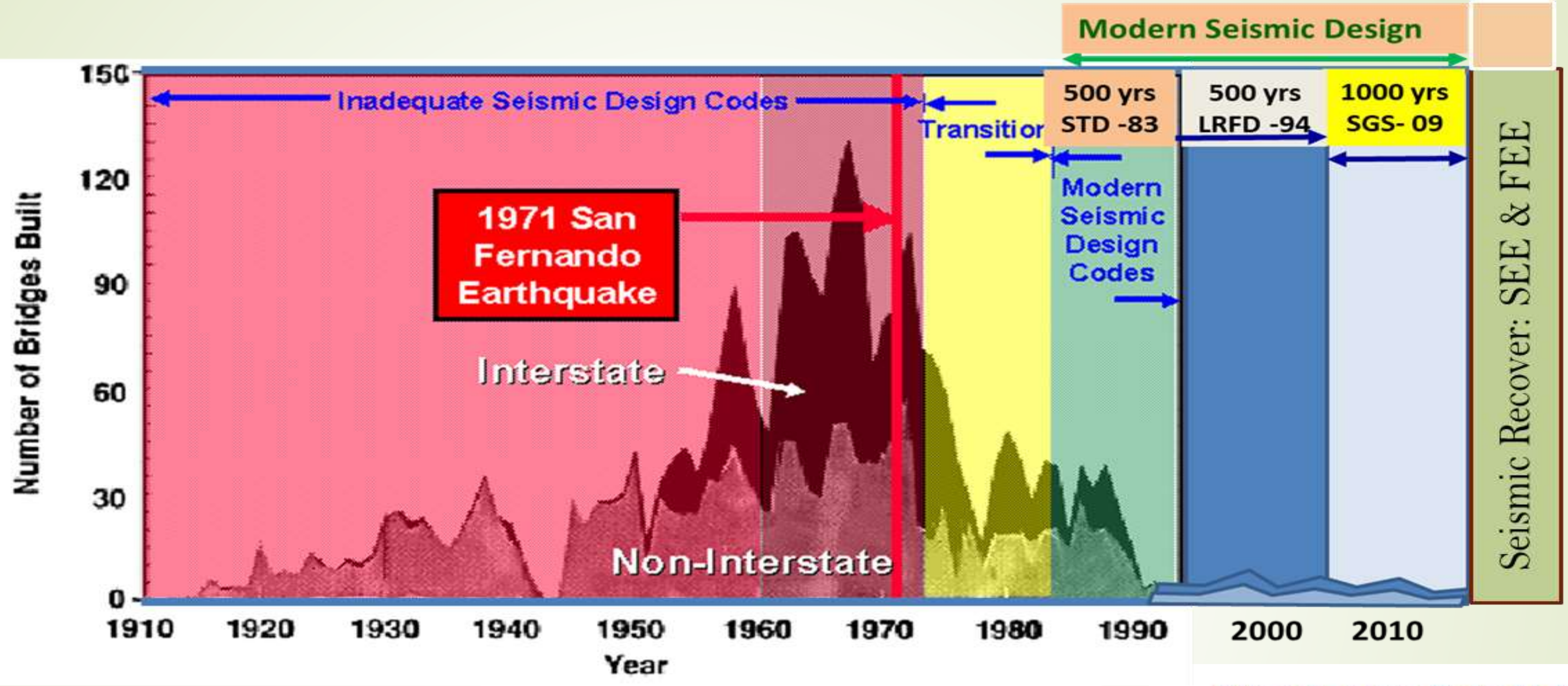


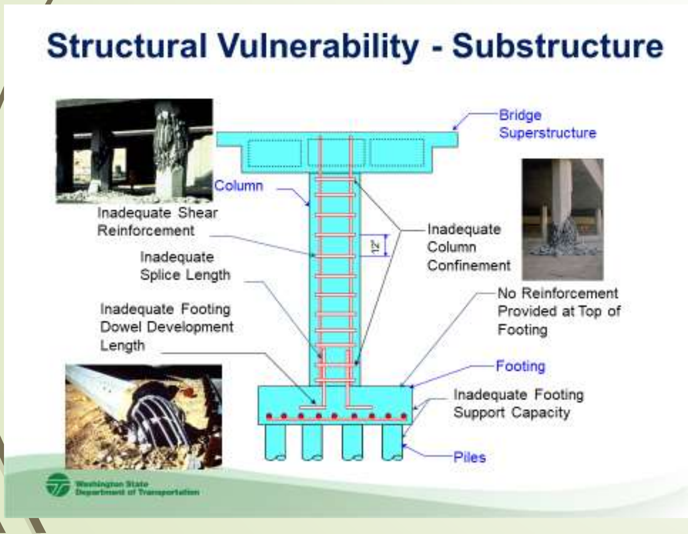






Seismic Resiliency of Existing Bridges





Structural Vulnerability - Substructure

Crossbeam Bolsters

Bolster Reinforcing Steel

Capacity Protection Requirement

Crossbeam Bolster

Other Column Retrofit Techniques

- Steel Jacketing
- Fiber Wrap
- Wire Wrap

Fiberglass & Epoxy Composite Jacket

Fabric & Polyester Resin Jacket

Carbon Fiber Composite Jacket

Research Projects

- **WSU-Performance of Steel Jacket Retrofitted Reinforced Concrete Bridge Columns in Cascadia Subduction Zone Earthquakes**

The objective is to characterize the expected performance, ductility capacity, and collapse probability of steel jacket retrofitted bridge columns in Cascadia Subduction Zone earthquakes.

- **UW-Effects of Cascadia Subduction Zone M9 Earthquakes on Bridges in Washington State**

The objective is to quantify the effects of the seismic hazard on (i) the design of new bridges, (ii) the evaluation of existing bridges.

- Prioritization of WSDOT Lifeline Bridges

Lifeline - Seismic Resilient Bridges

Lifeline Objectives:

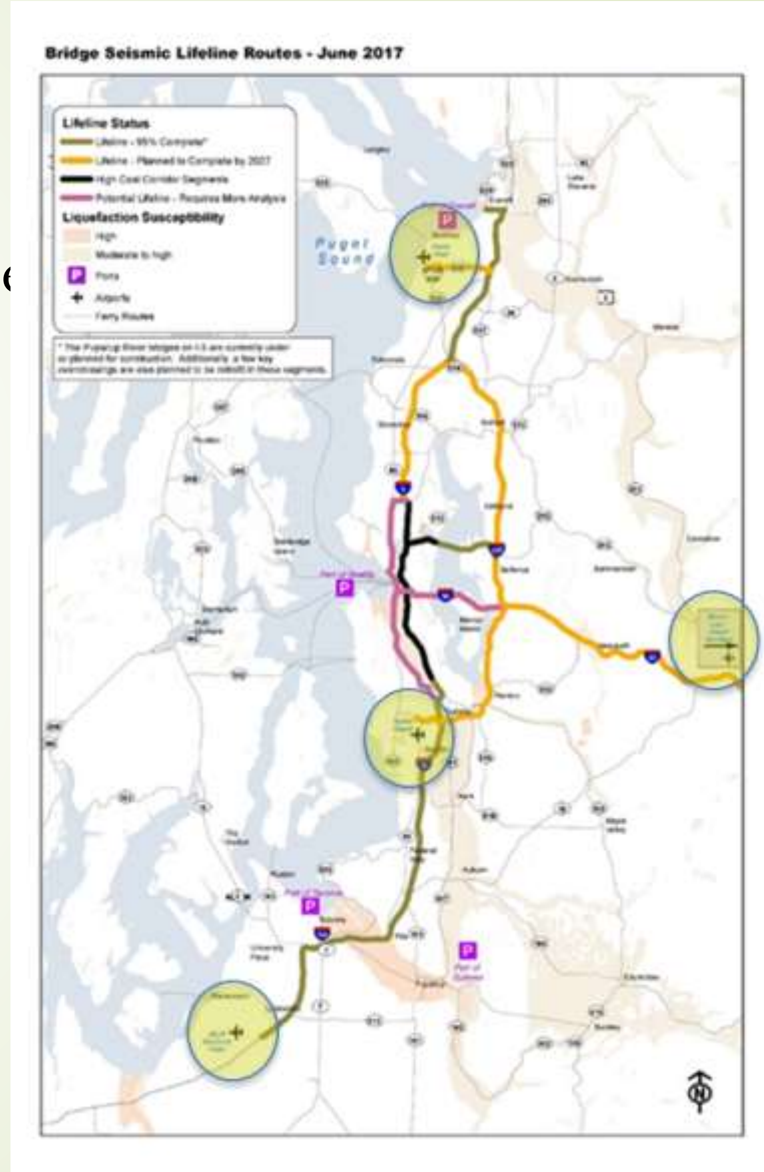
- Provide for public safety in the event of an earthquake
- Reduce the EQ economic impact to the extent reasonabl
- Provide Emergency Response Following the Event

Lifeline Resiliency Requirements:

- Post EQ functionality performance - Functionality
- Seismic Design for Essential and Critical Bridges
- Consideration for Geotechnical Hazards including Liquefaction, Lateral Spread, Landslide, etc.

Lifeline Challenges:

- Current Lifeline: Meets life safety – No Collapse requirements
- New Lifeline: Needs to meet Post EQ functionality for dual level seismic design intended for Essential and Critical Bridges



Seismic Design Functionality Requirements

Expected Bridge Seismic Performance

The seismic hazard evaluation level for designing Normal bridges are Safety Evaluation Earthquake (SEE), and the seismic hazard evaluation level for designing Essential and Critical bridges are both the Safety Evaluation Earthquake and the Functional Evaluation Earthquake (FEE).

Bridge Operational Importance Category	Seismic Hazard Evaluation Level	Expected Post Earthquake Damage State	Expected Post Earthquake Service Level
Normal	SEE	Significant	No Service
Essential	SEE	Moderate	Limited Service
	FEE	Minimal	Full Service
Critical	SEE	Minimal to Moderate	Limited Service
	FEE	None to Minimal	Full Service

Two-level performance criteria are required for design of Essential and Critical bridges.

Revised WSDOT Seismic Design Policy for Post EQ Functionality and Serviceability Requirements

Bridges are considered as Critical, Essential, or Normal for their operational classification as described below:

- **Critical Bridges**

  Critical bridges are expected to provide immediate access to emergency and similar life-safety facilities after an earthquake.

- **Essential Bridges**

  Essential bridges serve as vital links for rebuilding damaged areas and provide access to the public shortly after an earthquake.

- **Normal Bridges**

  All other bridges not designated as either Critical or Essential

Seismic Design Functionality Requirements

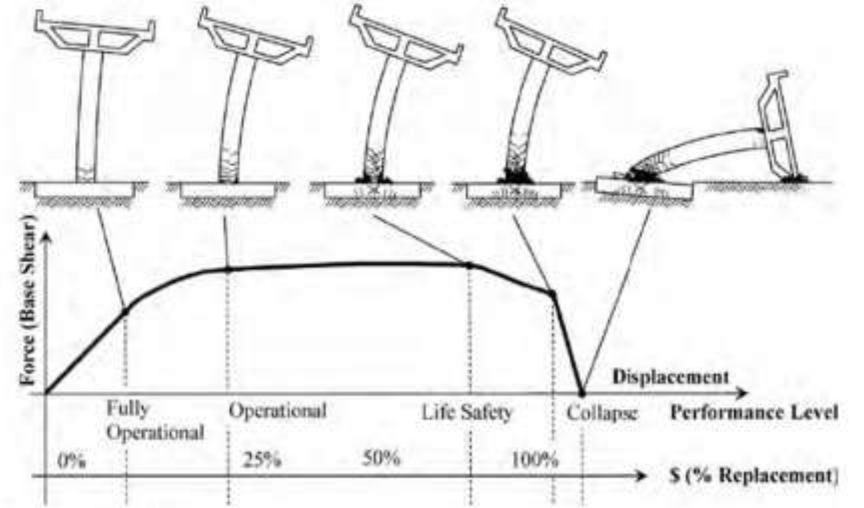
Expected Post Earthquake Damage State

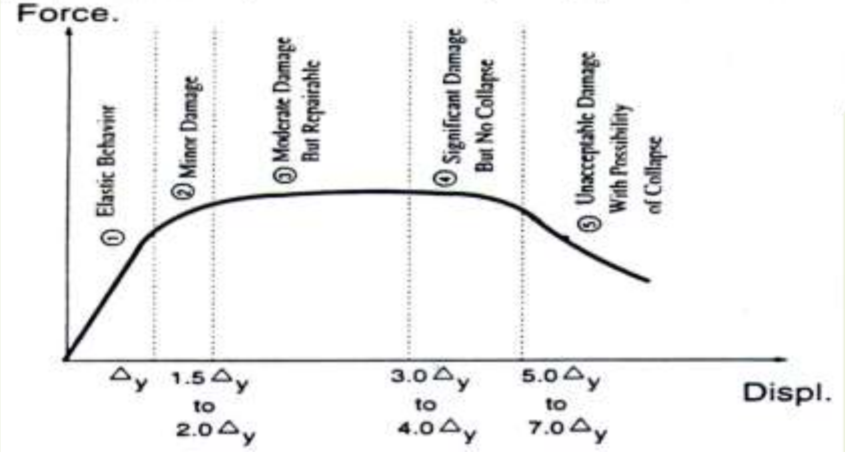
- **Significant** – “imminent failure,” i.e., onset of compressive failure of core concrete. Bridge replacement is likely. All plastic hinges within the structure have formed with ductility demand values.

- **Moderate** – “extensive cracks and spalling, and visible lateral and/or longitudinal reinforcing bars”. Bridge repair is likely but bridge replacement is unlikely

- **Minimal** – “flexural cracks and minor spalling and possible shear cracks”. Essentially elastic performance

- **None** – No damage





Seismic Design Functionality Requirements

- The Design Spectrum for Safety Evaluation Earthquake (SEE) shall be taken as a spectrum based on a 7% probability of exceedance in 75 years (or 975-year return period).
- The Design Spectrum for Functional Evaluation Earthquake (FEE) shall be taken as a spectrum based on a 30% probability of exceedance in 75 years (or 210-year return period).

Seismic Critical Member	Displacement Ductility Demand Limits μ_D				
	Normal Bridges	**Essential Bridges**		Critical Bridges	
		SEE	**FEE**	SEE	FEE
Wall Type Pier in Weak Direction	**5.0**	**2.5**	**1.5**	1.5	1.0
Wall Type Pier in Strong Direction	**1.0**	**1.0**	**1.0**	1.0	1.0
Single Column Bent	**5.0**	**2.5**	**1.5**	1.5	1.0
Multiple Column Bent	**6.0**	**3.5**	**2.0**	1.5	1.0
Pile/Shaft-Column with Plastic above Ground	**5.0**	**3.5**	**2.0**	1.5	1.0
Pile/Shaft-Column with Plastic Hinge Below Ground	**4.0**	**2.5**	**1.5**	1.5	1.0
Superstructure	**1.0**	**1.0**	**1.0**	1.0	1.0

2014 Seismic Hazard Map and Site coefficients

Seismic Design Functionality Requirements

Seismic Critical Member	Displacement Ductility Demand Limits						
	Normal Bridges EW	Normal Bridges WW (Not Lifeline)		Essential Bridges WW (Lifeline)		Critical Bridges	
		SEE	FEE	SEE	FEE	SEE	FEE
Wall Type Pier in Weak Direction	5.0	5.0	1.5	2.5	1.5	1.5	1.0
Wall Type Pier in Strong Direction	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Single Column Bent	5.0	5.0	1.5	2.5	1.5	1.5	1.0
Multiple Column Bent	6.0	6.0	2.0	3.5	2.0	1.5	1.0
Pile Column with Plastic Hinge at Top of Column	5.0	5.0	2.0	3.5	2.0	1.5	1.0
Pile Column with Plastic Hinge Below Ground	4.0	4.0	1.5	2.5	1.5	1.5	1.0
Superstructure	1.0	1.0	1.0	1.0	1.0	1.0	1.0

Seismic Design Requirements *for Bridge Widening and Rehabilitation Projects*

Procedure for Essential/Critical Bridges:

Examples of potential deviations include:

a. Meeting two-level design criteria for the widened portion, but only achieving Normal bridge criteria for the existing bridge.

b. Meeting two-level design criteria for the above-ground portions of the composite structure, but not achieving this for the below-ground portions (foundations).

c. Performing a two-level design, but requiring deviations from the displacement ductility demand limits identified in BDM.

d. Only achieving Normal criteria for the composite structure.

Example of Projects on Lifeline –I-5 Ship Canal

Bridge Built – 1962 (57 yrs)

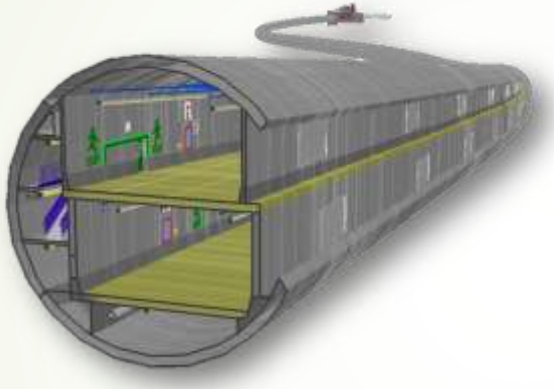
Length – 3,620 feet Center Spans Steel Deck Truss 6 spans 2,293 feet

Width – 52 feet

Replacement Value - $1 Billion

Example of Projects on Lifeline, Alaskan Way Viaduct Replacement

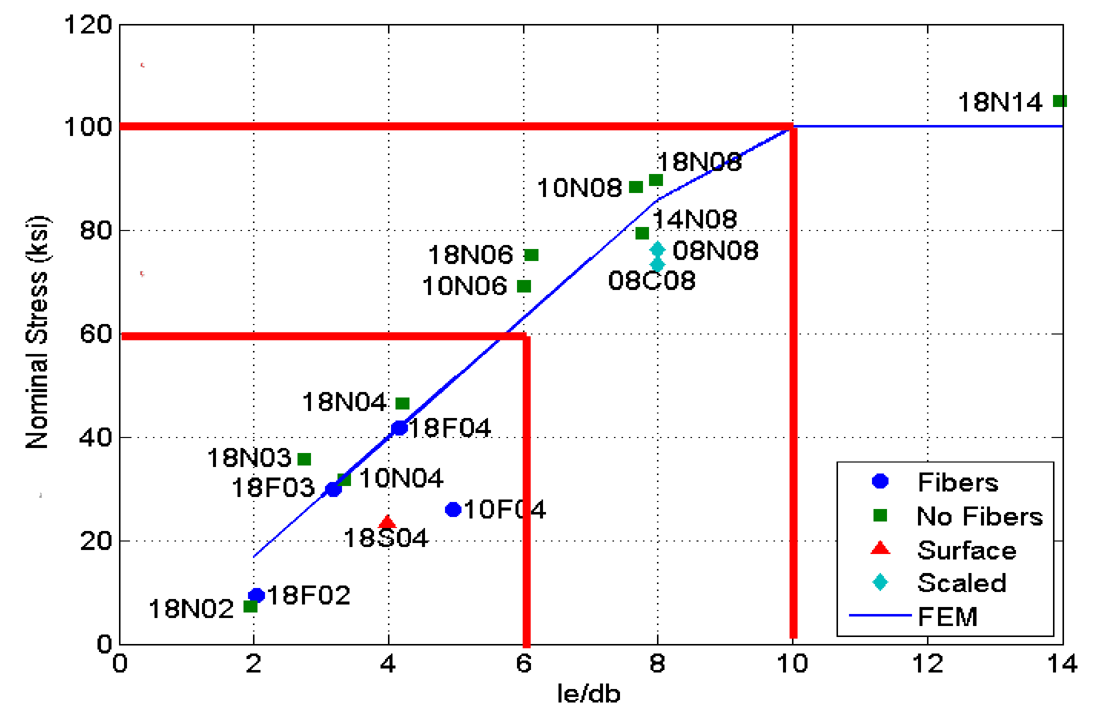
Alaskan Way Viaduct
REPLACEMENT
PROGRAM



Demolition:

- Removes the Alaskan Way Viaduct.
- Closes and fills the Battery Street Tunnel.

Connections: Recommended Duct Size & Embedment Length



Seismic Performance

Pull out Test
Large Bar – Grouted Duct

$$l_{ac} = \frac{0.67 d_{bl} f_{ye}}{\sqrt{f'_{g}}}$$

Precast Column Grouted Ducts and Pocket/Socket Connections

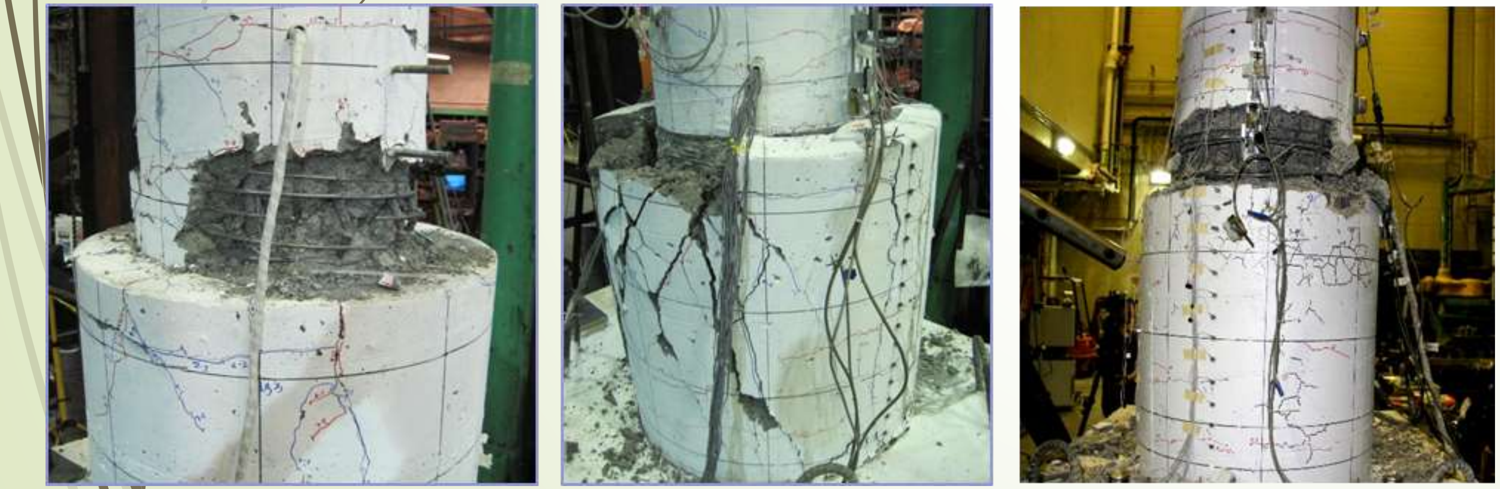
Implementation Examples

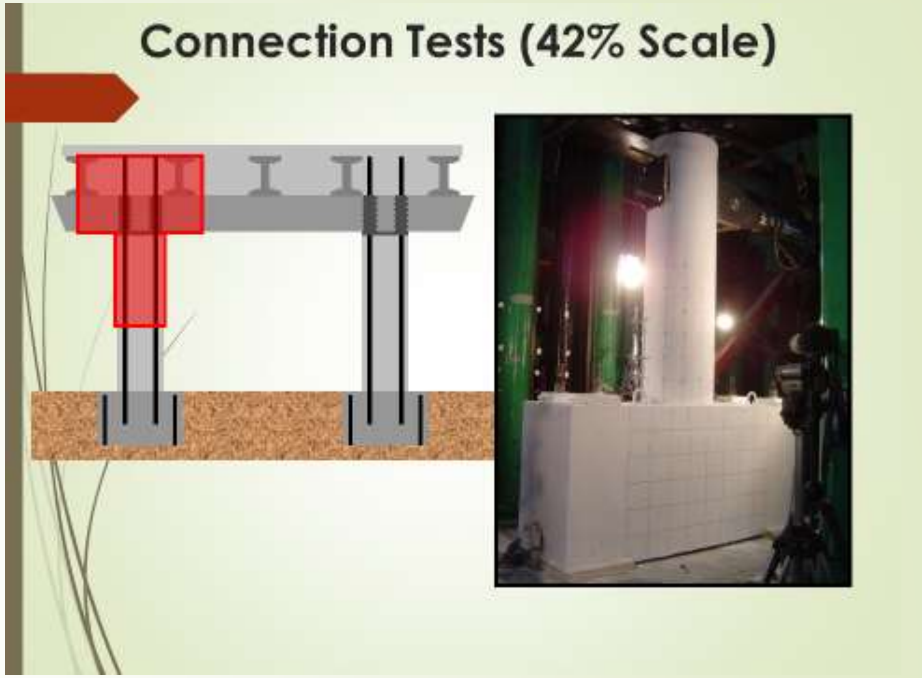
Minimum thickness of corrugated steel pipe:

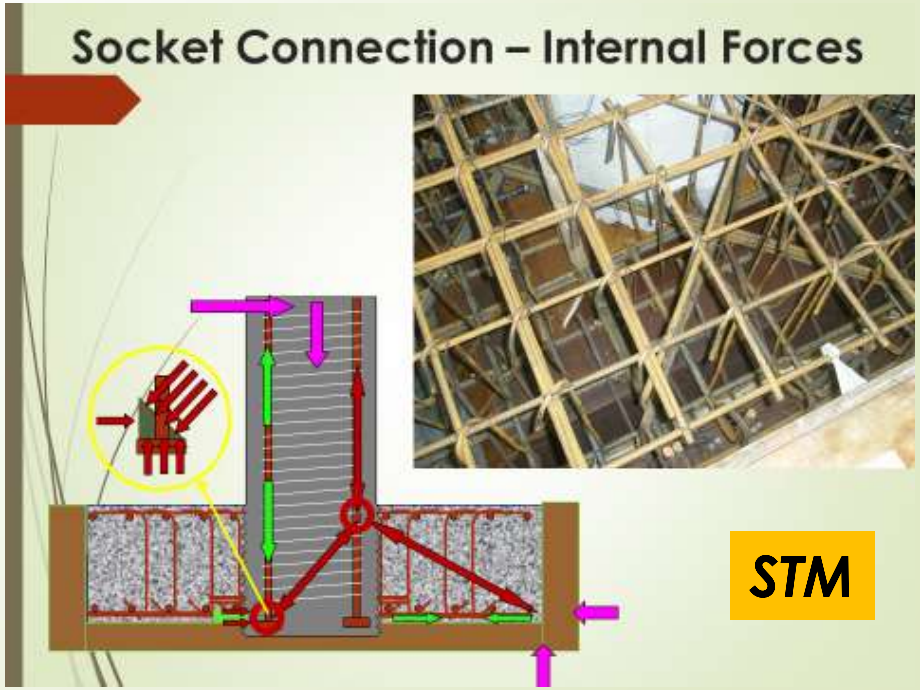
$$t_{pipe} \geq \max \left| \begin{array}{l} 0.04 \dfrac{\sqrt{f'_c}\, D'_{cp}}{f_{yp} \cos \theta} \\ 0.0598 in \end{array} \right.$$

Highways For Life Project
Fully Precast Bridge

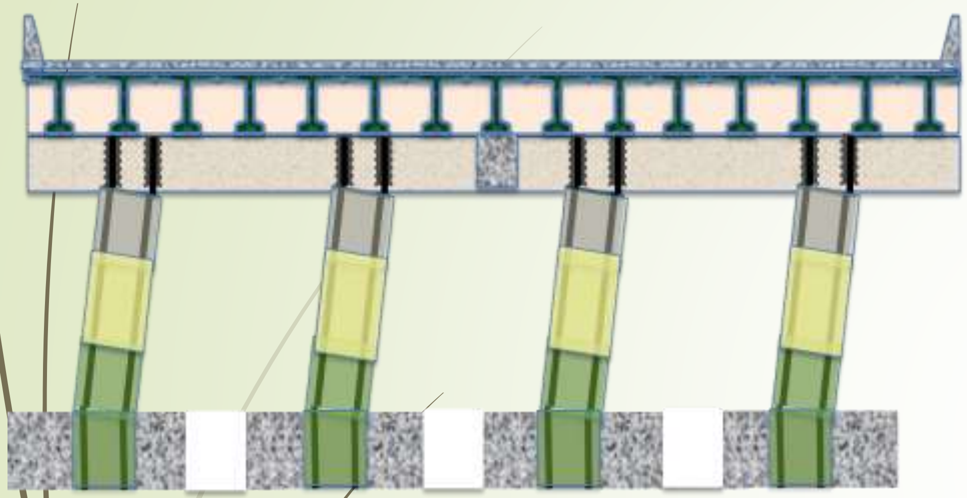
The purpose of **Highways for LIFE** was to advance **L**onger-lasting highway infrastructure using **I**nnovations to accomplish the **F**ast construction of **E**fficient and safe highways and bridges

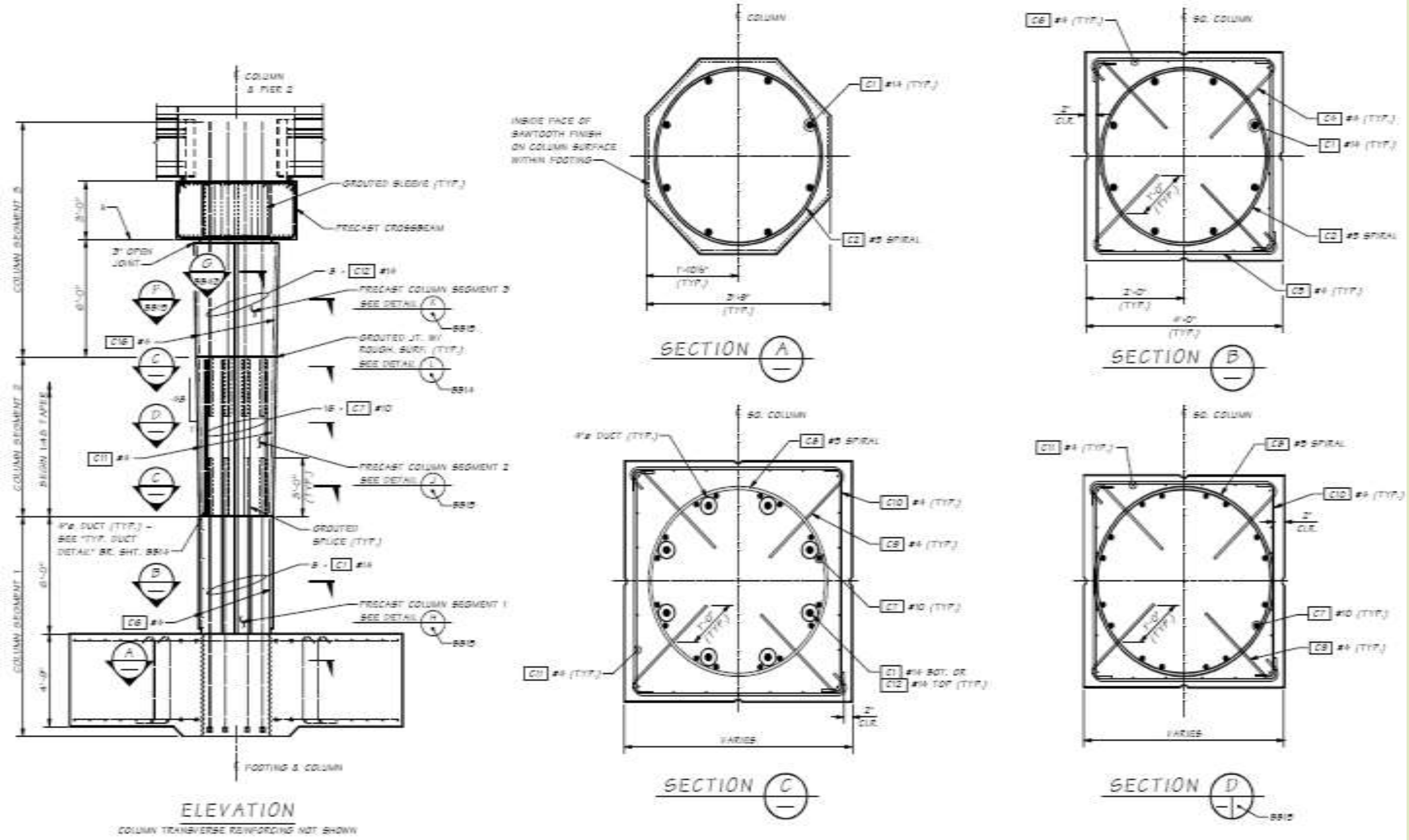



Connection Tests (42% Scale)


Socket Connection – Internal Forces

Fully Precast Bent with Dropped Bent Cap

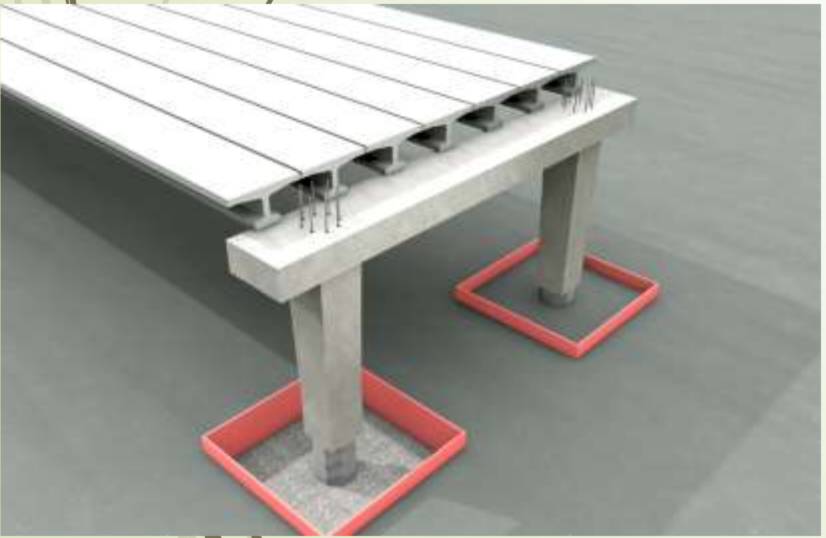


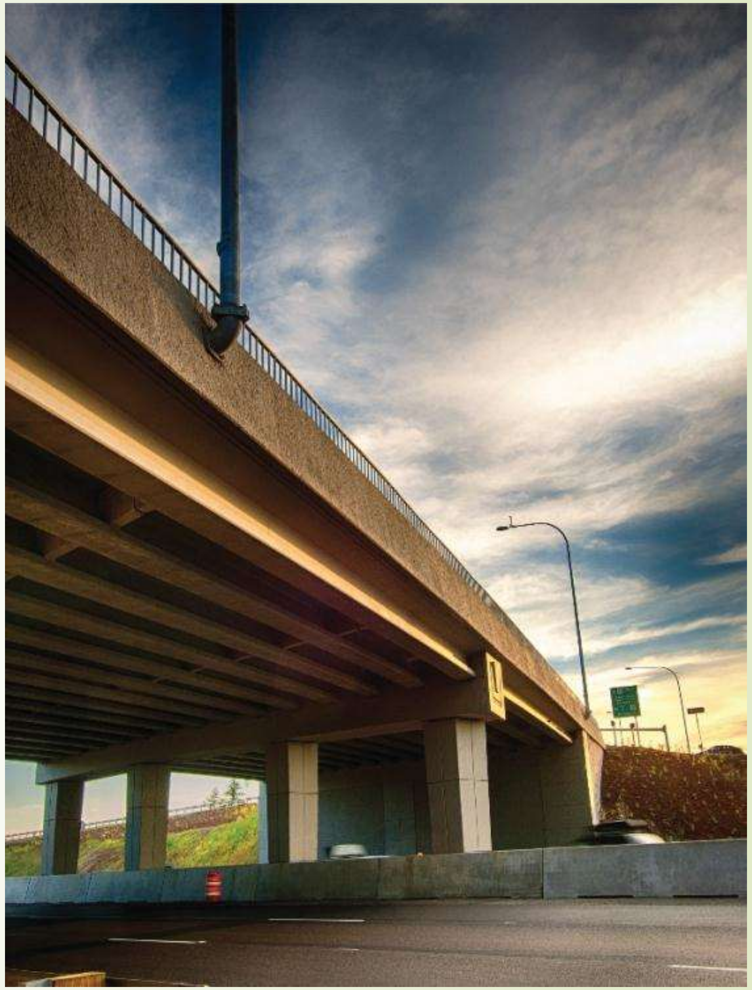


HFL Bridge Feature:

- 12 Precast Column Segments
- 2 Precast Pretensioned Bent Cap
- 30 Precast Pretensioned DBT Girders
- 96 Grouted Duct Connections
- 4 Pocket/Socket Connections

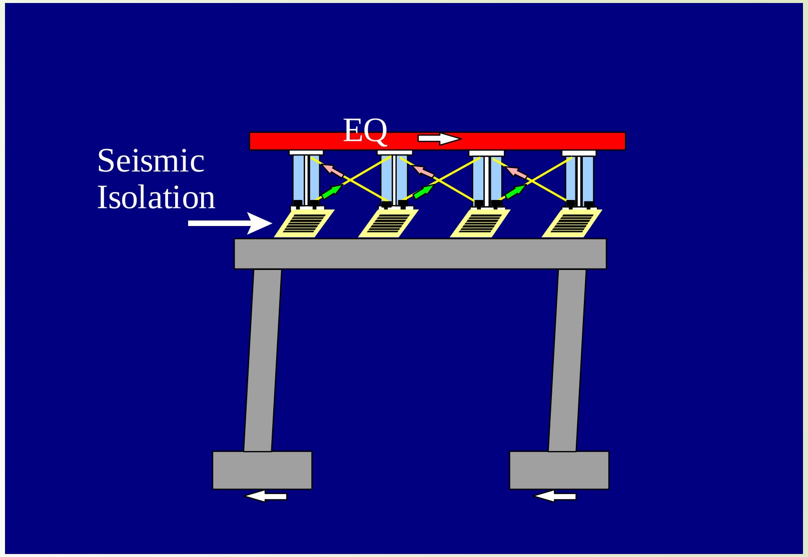
WSDOT HFL - Fully Precast Bridge





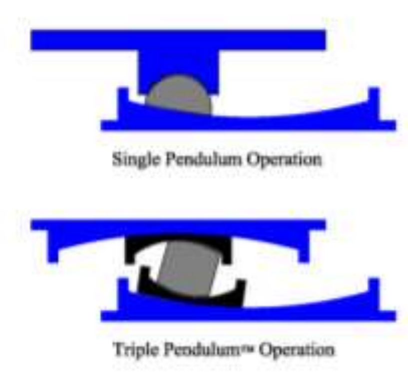
From Research to Implementation

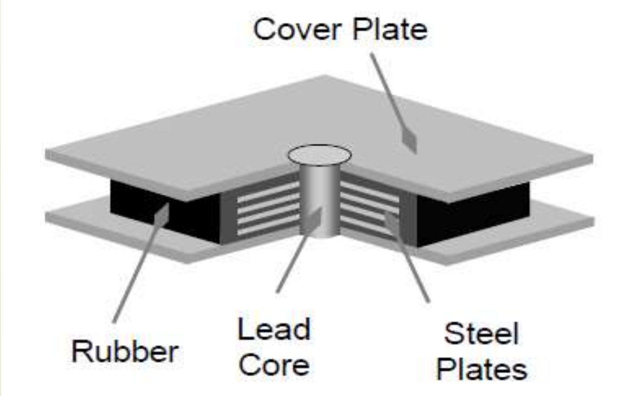
Isolation Bearings for Seismic Resiliency and Energy Dissipation



Considerations:

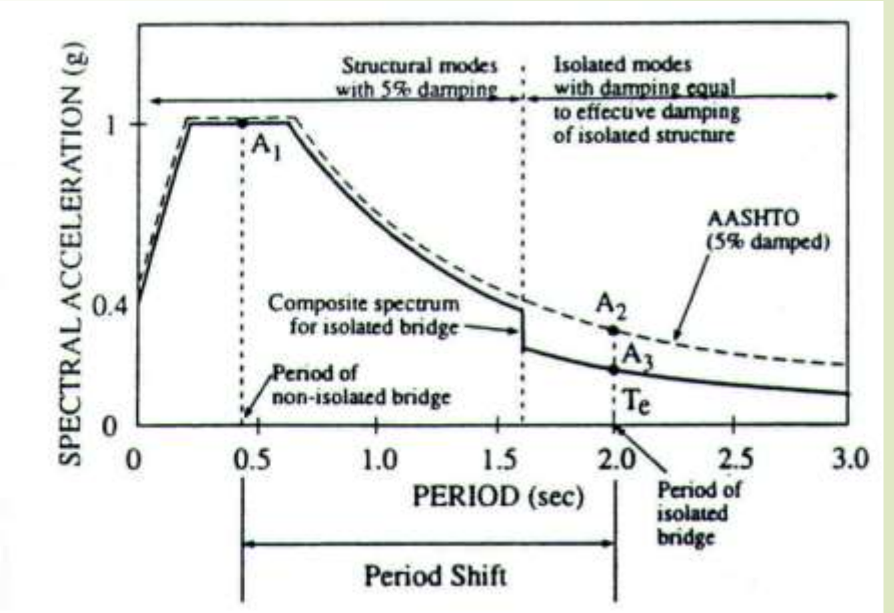
- Durability & Long-term Performance of Bearings
- Expansion joints to accommodate seismic movements for bearings to function properly.
- Adequate clearance for the seismic displacement between the girders and abutment back wall.
- Bearings type Combinations not allowed.





$$T_D = 2\pi\sqrt{\frac{W}{k_{D\min} g}}$$

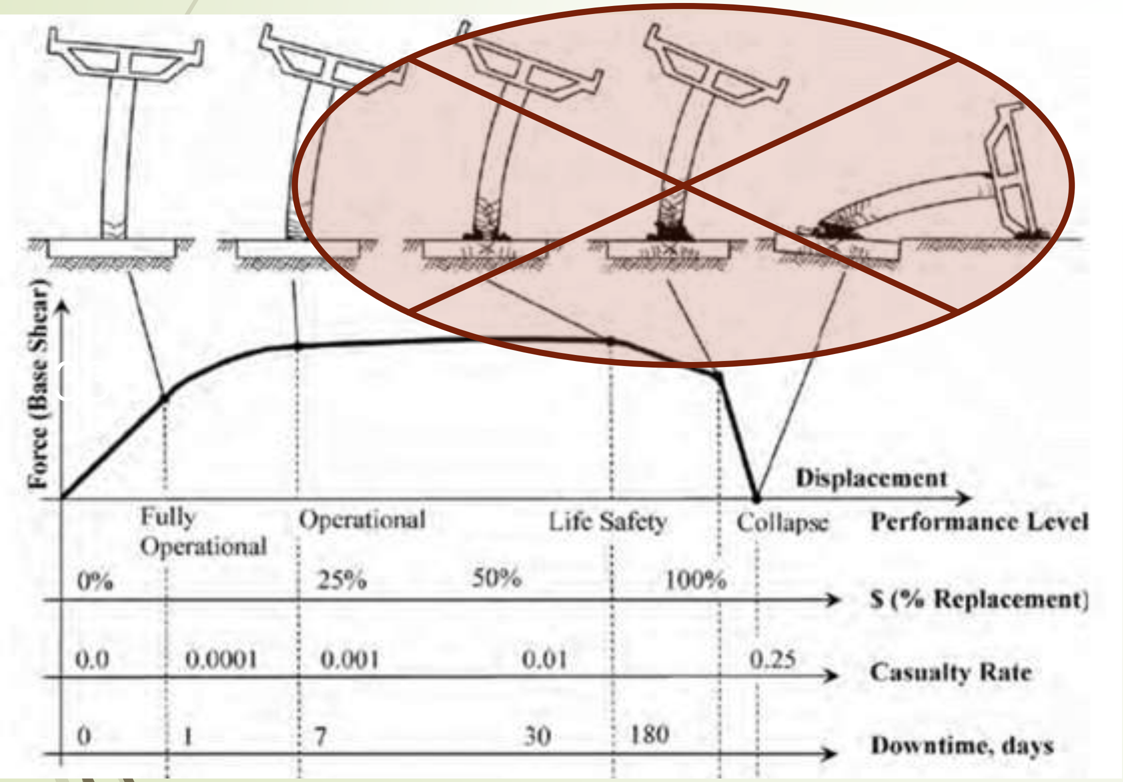
$$D_M = \frac{g S_{M1} T_M}{4\pi^2 B_M}$$

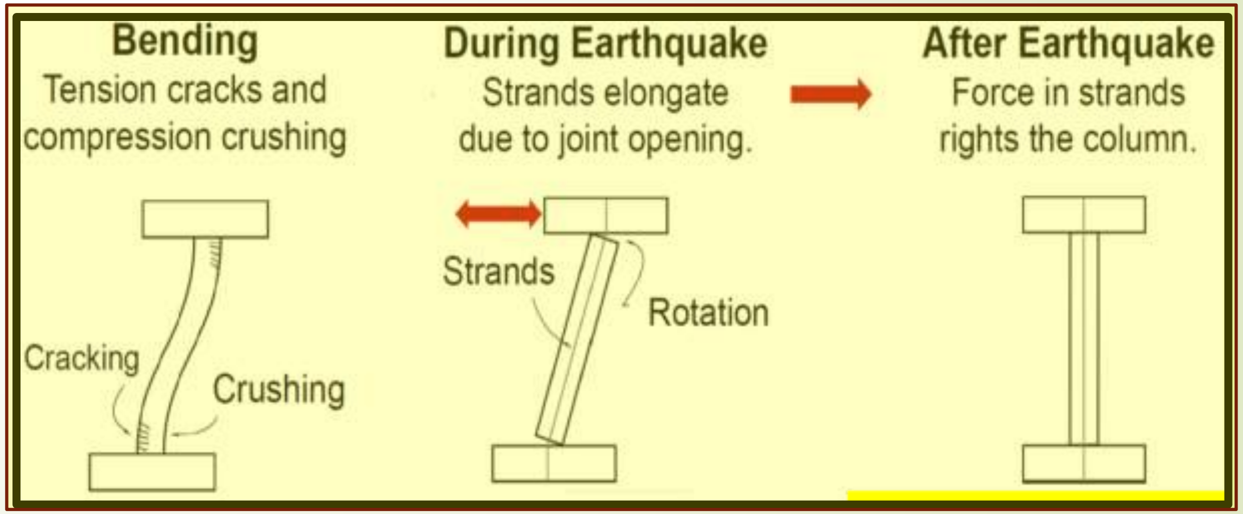


Innovative Designs for Seismic Resiliency

Seismic Resiliency with use of Innovative Designs, Materials, and construction:

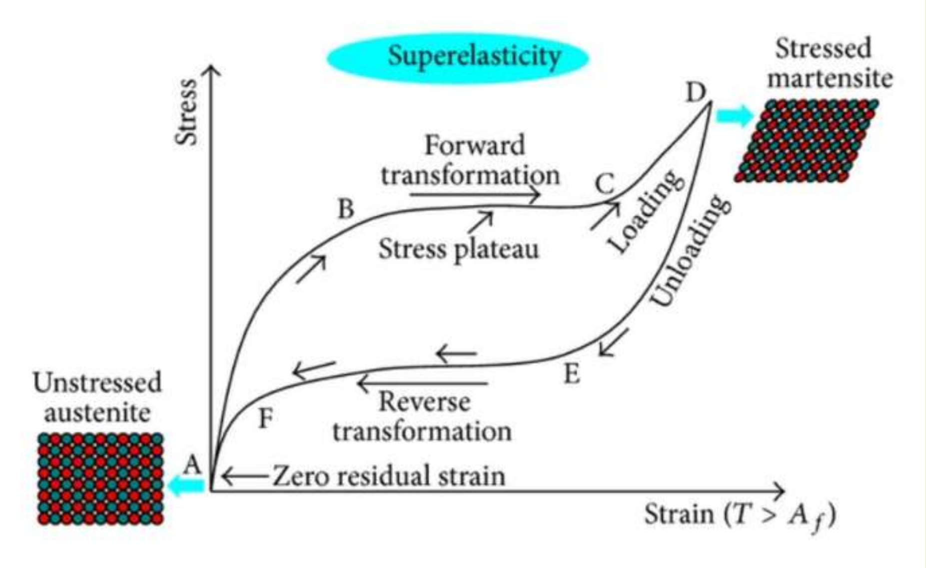
- Use of super-elastic materials in columns
- Use of prestressing in columns
- Other innovative designs

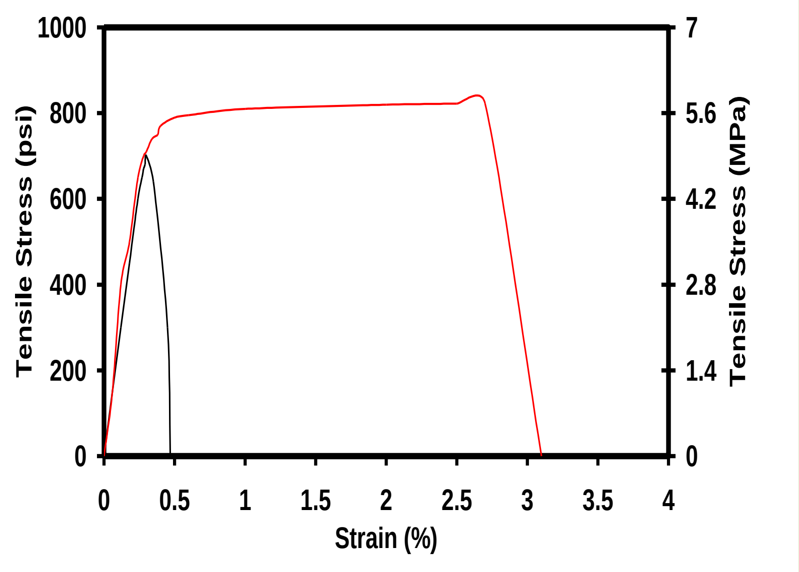




Self Centering Piers using Super Elastic Materials for Bridge Columns

- Shape Memory Alloy (SMA)
- Engineered Cementitious Composite (ECC)
- Three - 0.4 Scale Columns (2 SMA/ECC, 1 RC)





Super-Elastic Materials in Bridge Columns

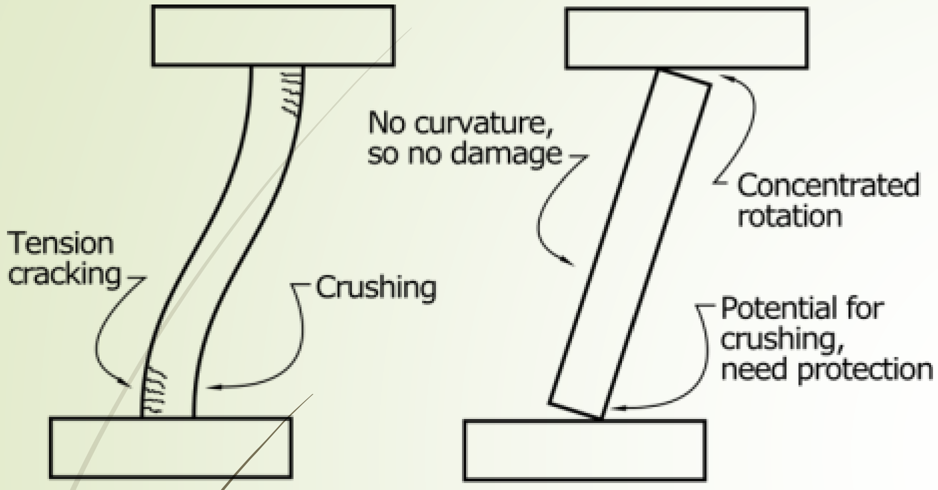
Shape Memory Alloys & Engineered Cementitious Concrete

From Research to Implementation – **1st use**

The Goal of Innovative Bridge Research and Deployment (**IBRD**) **Program** was to promote innovative designs, materials, and construction methods.

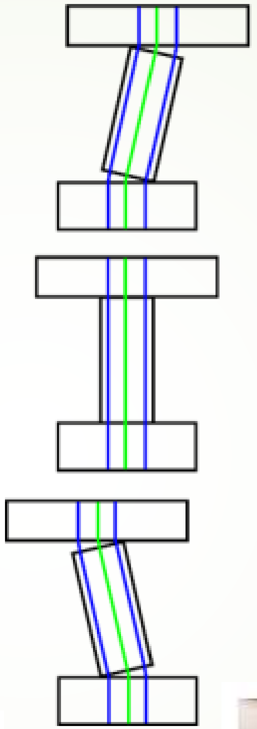
New Generation of Super-elastic Materials!

Seismic Resiliency – PS Self Centering



Bending: Tension cracks and compression crushing inevitable

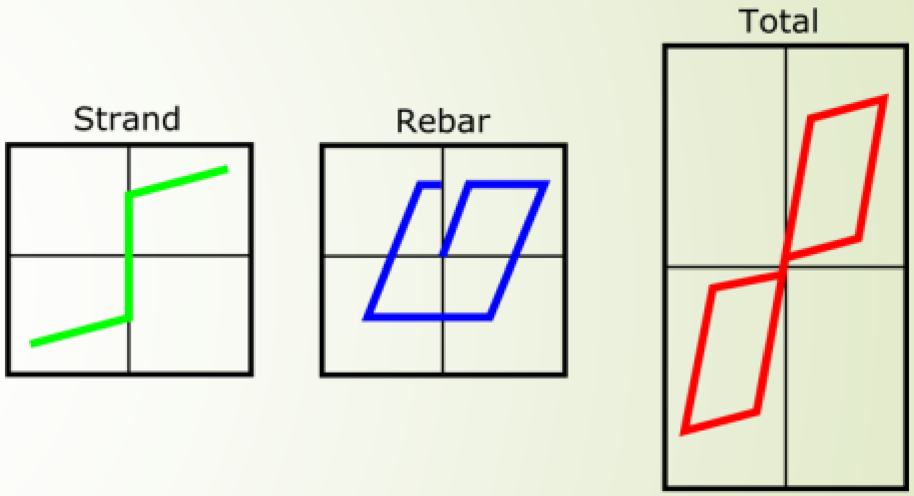
Rocking: High contact stresses

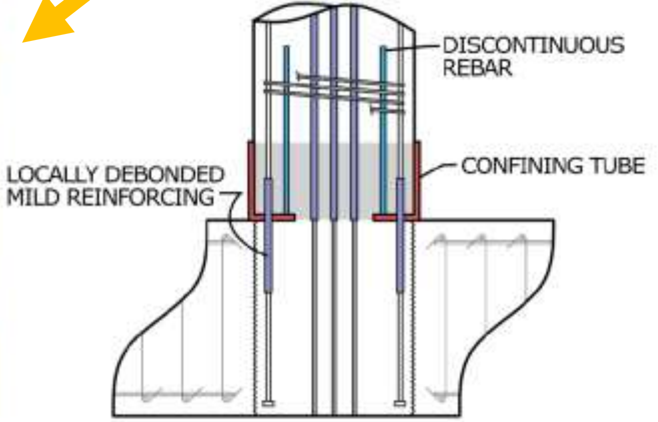


Strand: **Stays elastic, provides re-centering force**

Rebar: **Yields and dissipates energy**

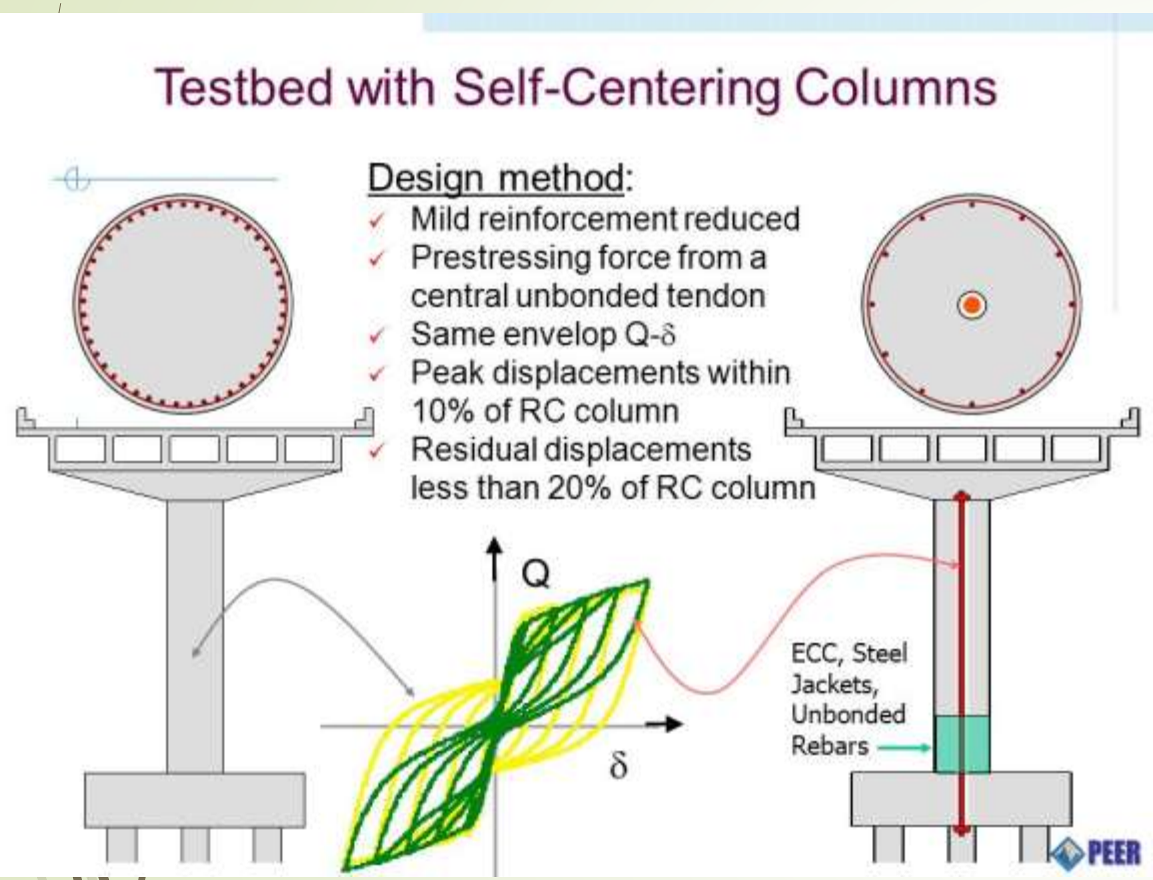
30-50% f_{pu}





Wigram-Magdala Bridge in New Zealand

Seismic Resiliency PS Self-centering



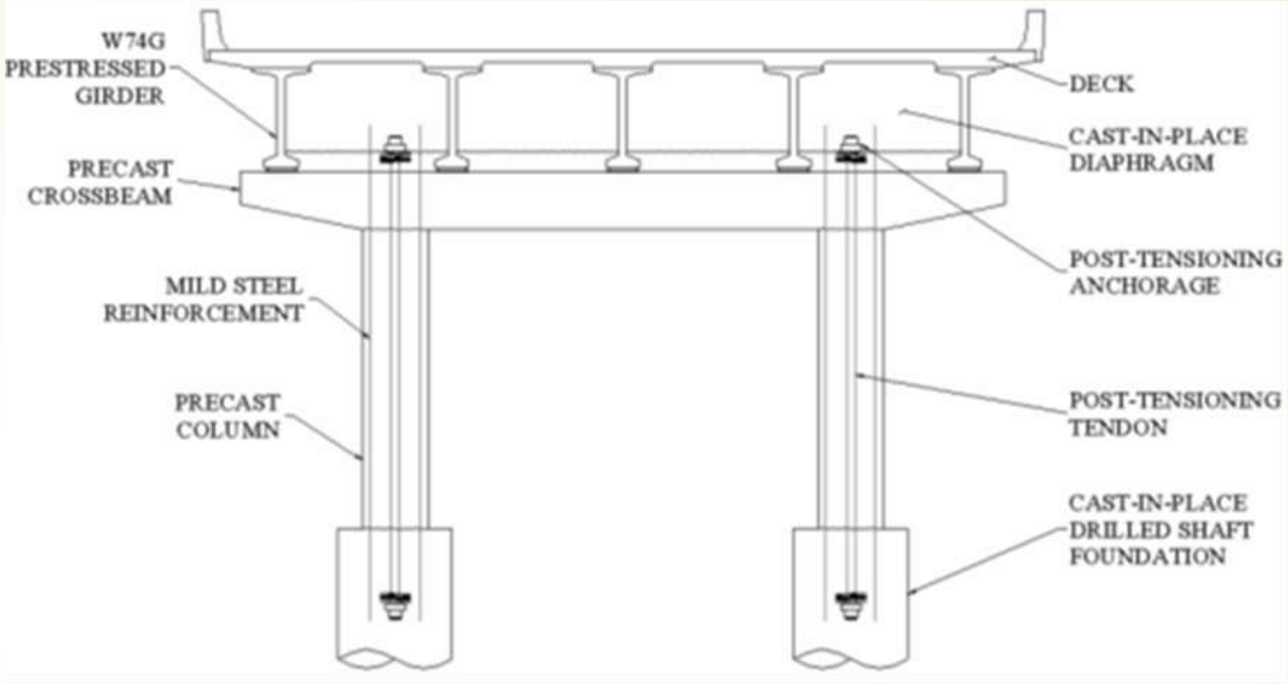
Testbed with Self-Centering Columns

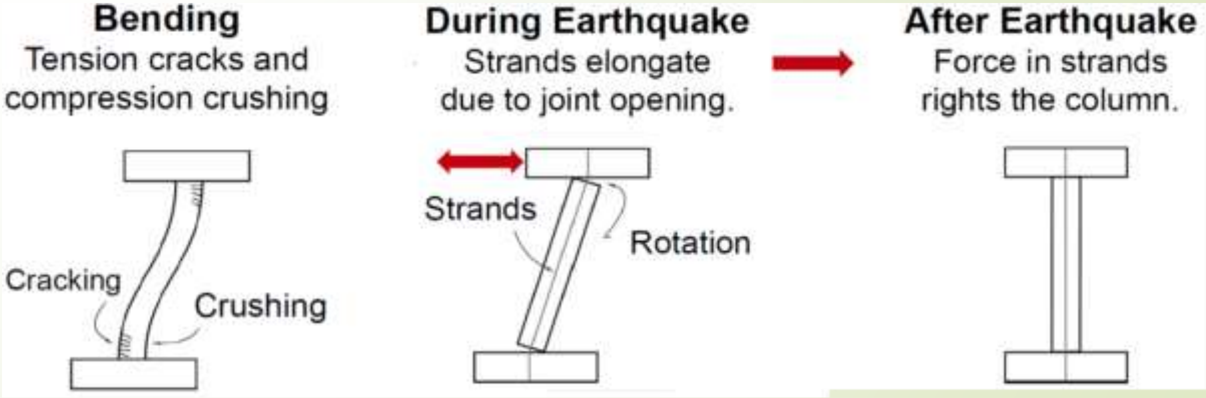
Design method:

- ✓ Mild reinforcement reduced
- ✓ Prestressing force from a central unbonded tendon
- ✓ Same envelop Q-δ
- ✓ Peak displacements within 10% of RC column
- ✓ Residual displacements less than 20% of RC column

RC

Self Centering - ECC
Steel Jacket, Unbonded PS





Bending
Tension cracks and compression crushing

During Earthquake
Strands elongate due to joint opening.

After Earthquake
Force in strands rights the column.

Improving *Seismic Resiliency for Essential/Critical Bridges*

Foundation Flexibility on Structural Response

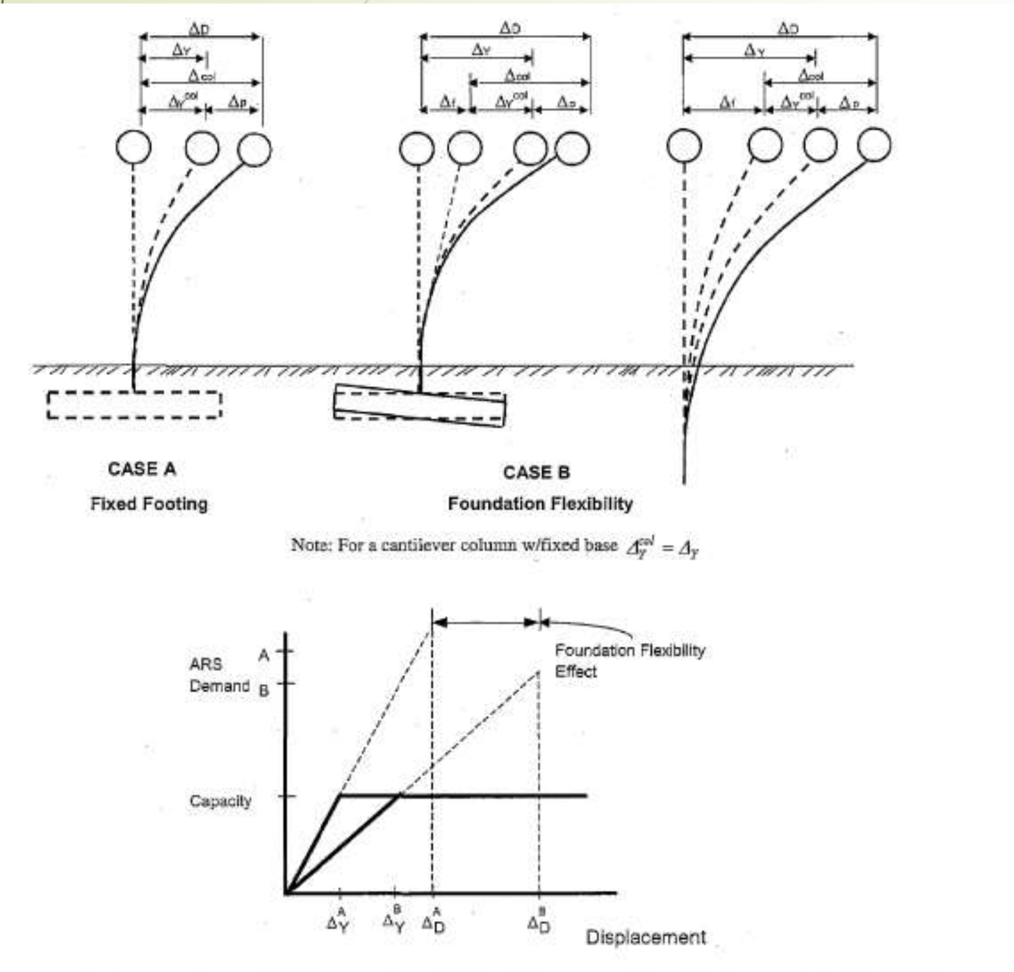
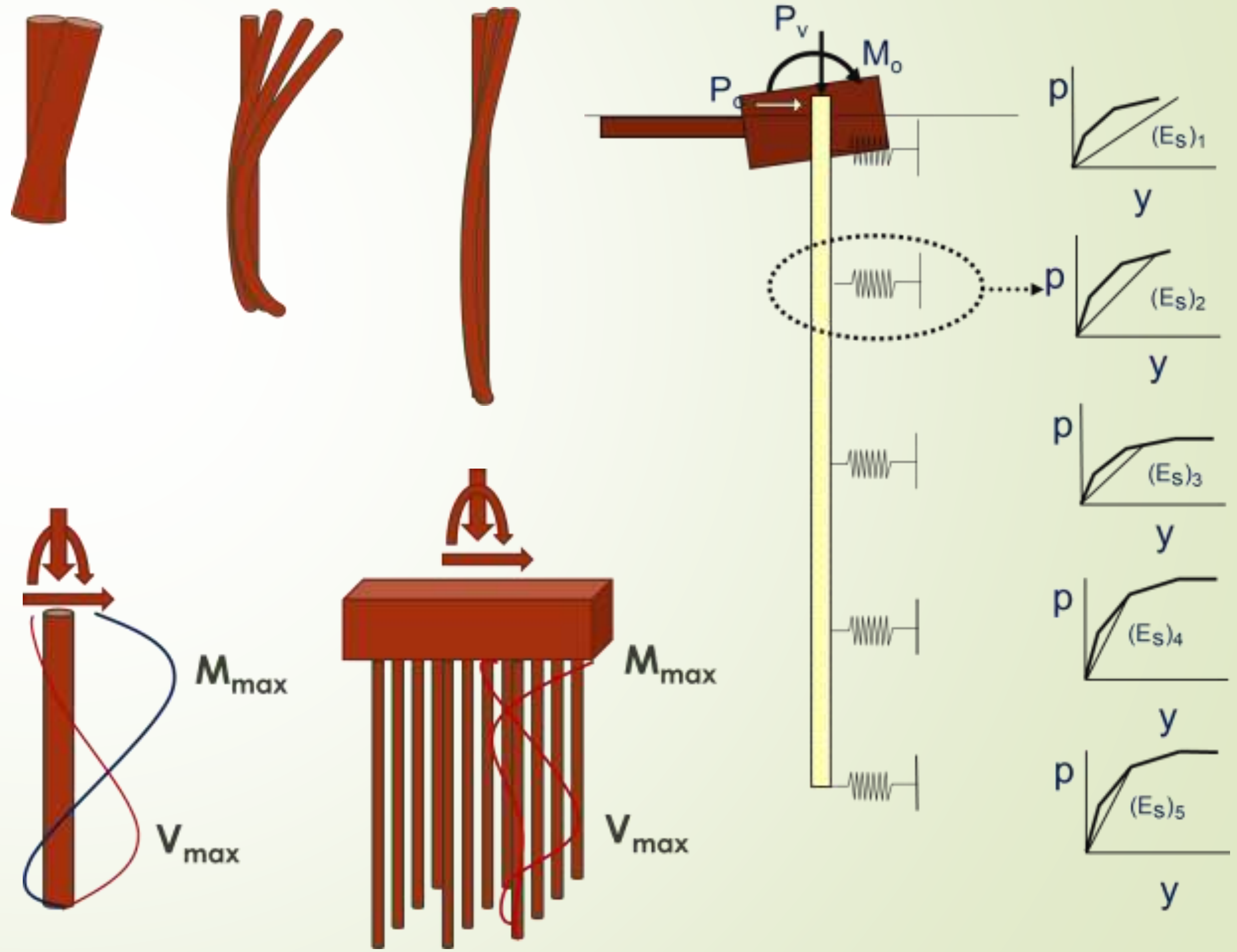
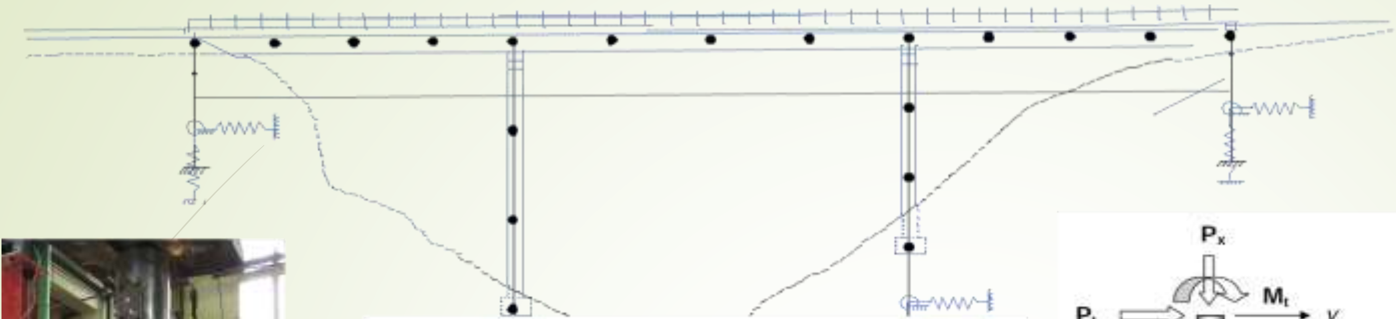


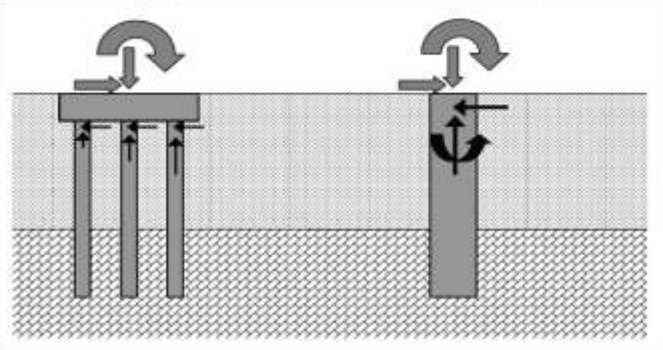
Figure 4.8-1—Effects of Foundation Flexibility on the Force-Deflection Relation for a Single Column Bent (Caltrans, 2006)



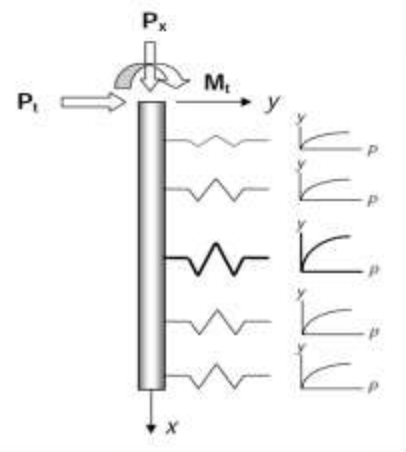
Seismic Design and Resiliency of CFST Foundation



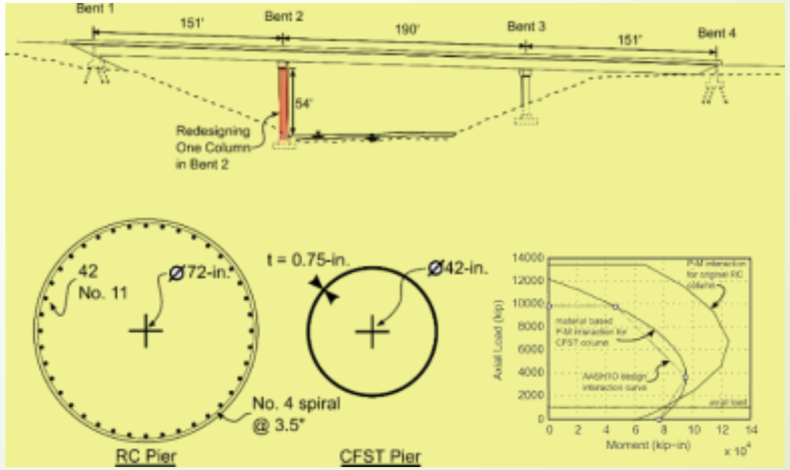
Ductility



Deep Foundation



Lateral EQ Load



CFST Column Connections

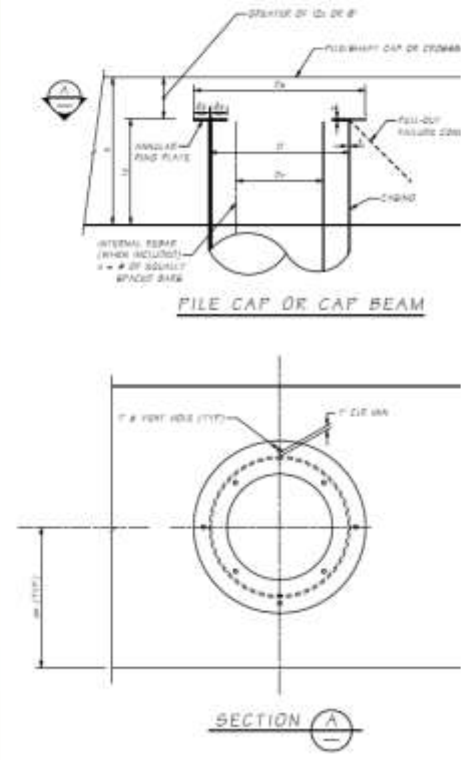
Embedment: $l_e \geq \sqrt{\frac{{D_o}^2}{4} + \frac{5.27DtF_u}{\sqrt{f'_{cf}}}} - \frac{D_o}{2}$

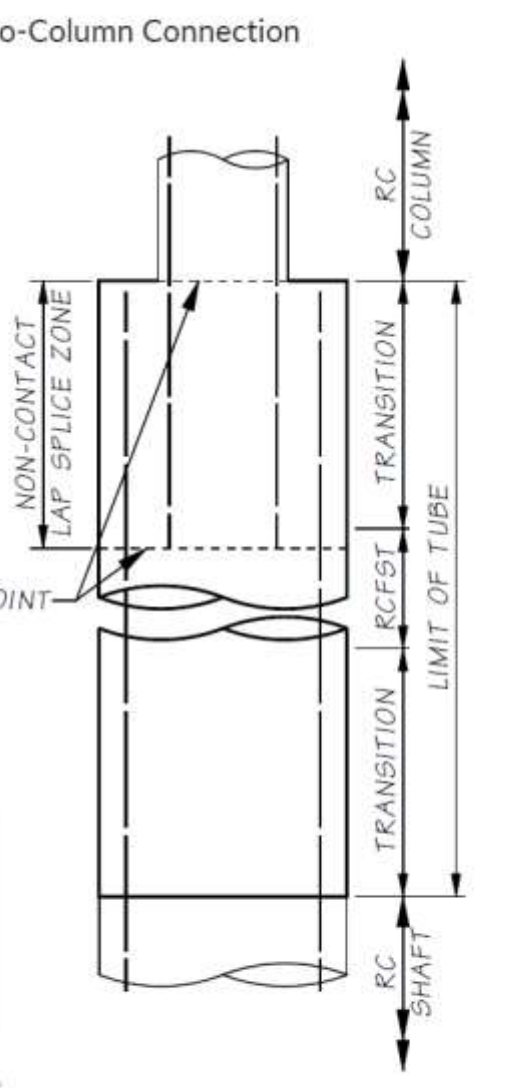
Punching Shear: $h \geq \sqrt{\frac{D^2}{4} + \frac{1.68C_{max}}{\sqrt{f'_{cf}}}} - \frac{D}{2}$

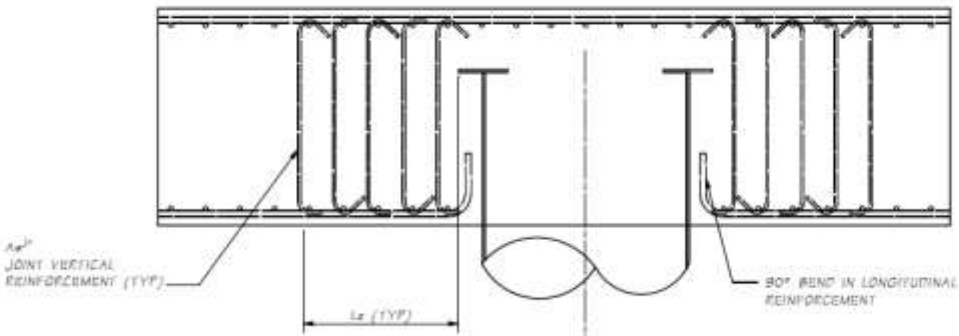
Compressive Force: $C_{max} = C_c + C_s$

Corrosion 0.001 to 0.004 inch per year

Joint Reinf.: ${A_s}^{jv} = 0.65A_{st}$

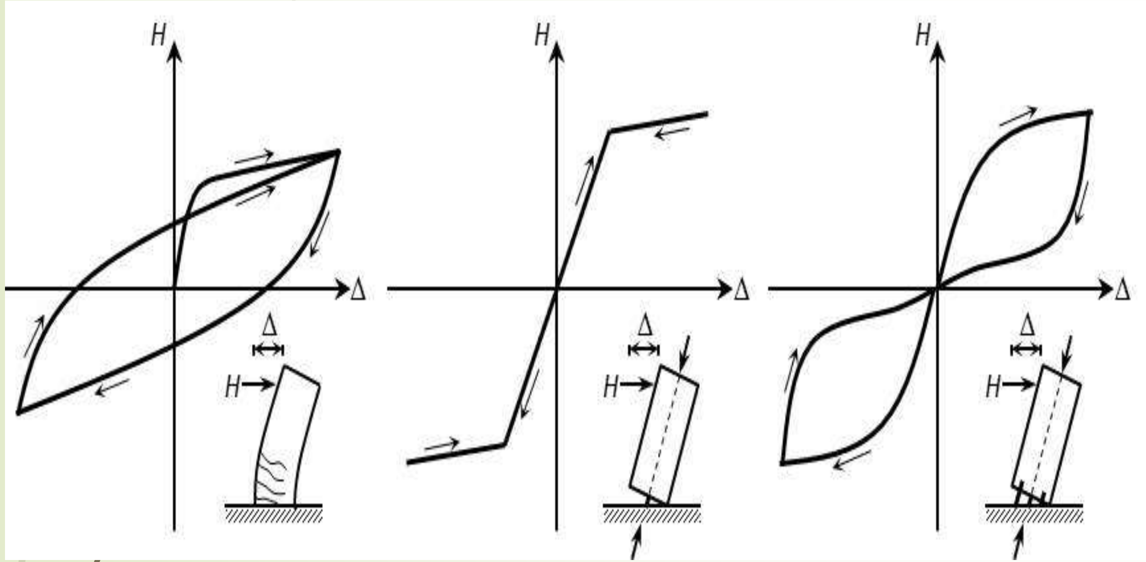




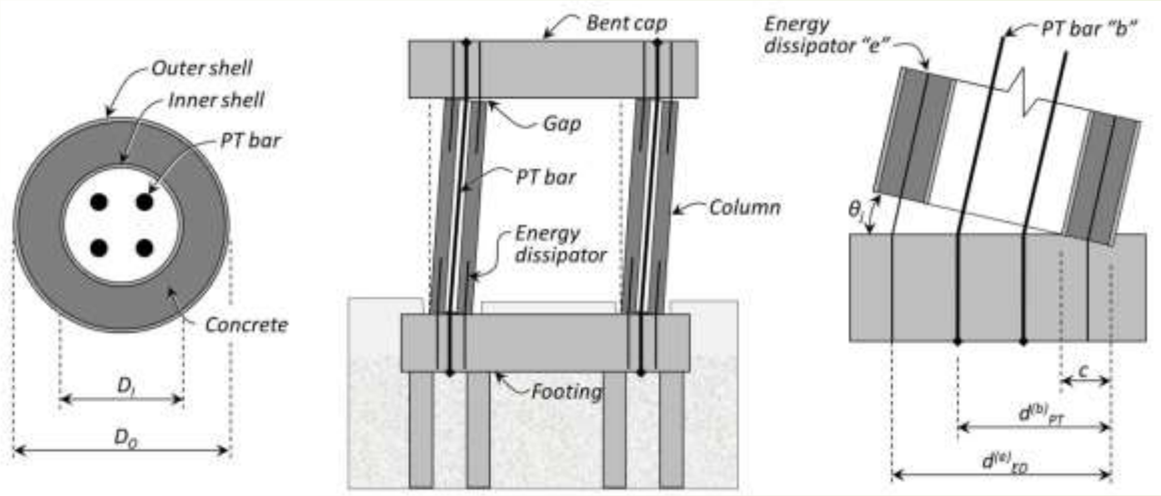


Dual Shell CFST Self-Centering Capability

Self-Centering Precast Concrete Dual-Steel-Shell Columns for Accelerated Bridge Construction



Hysteretic response: (a) conventional ductile system; (b) purely rocking system; and (c) hybrid rocking system.

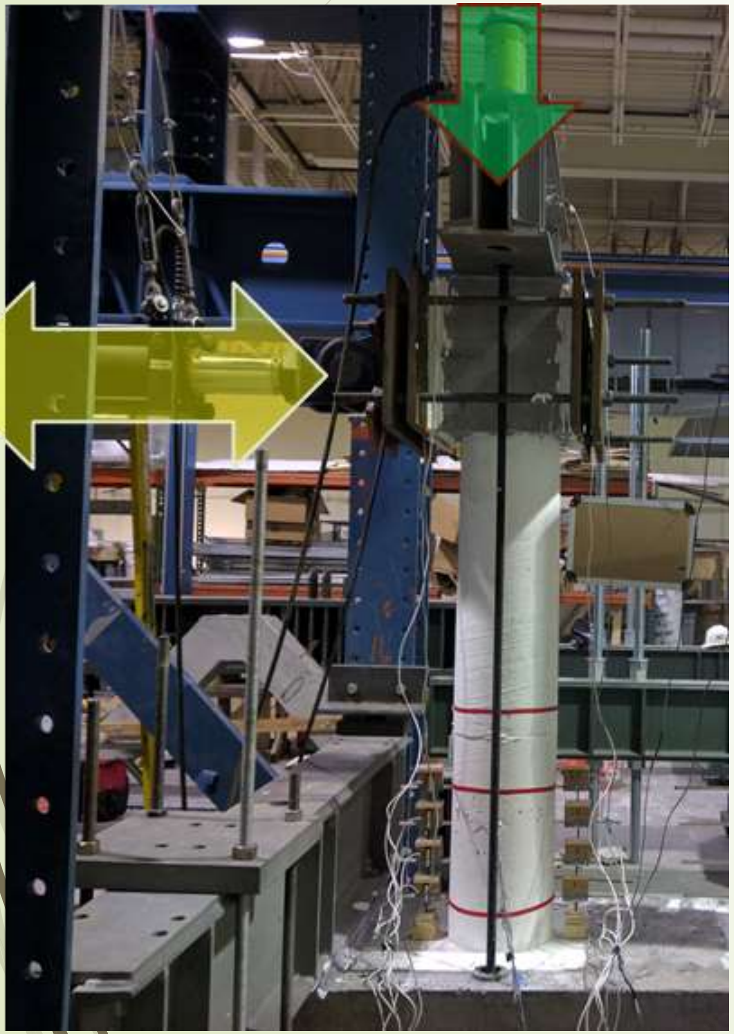


(a) (b) (c)

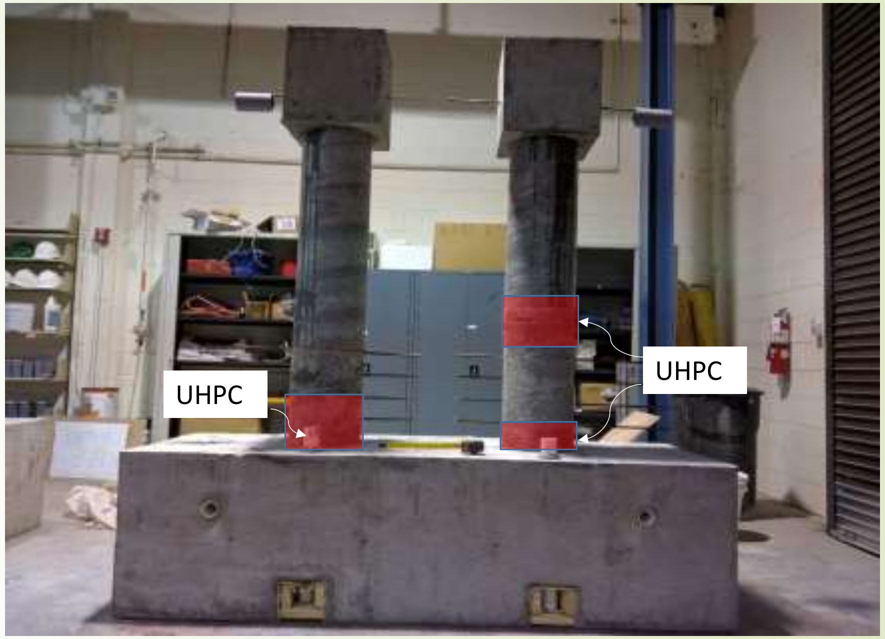
Figure: Schematics of the proposed system:

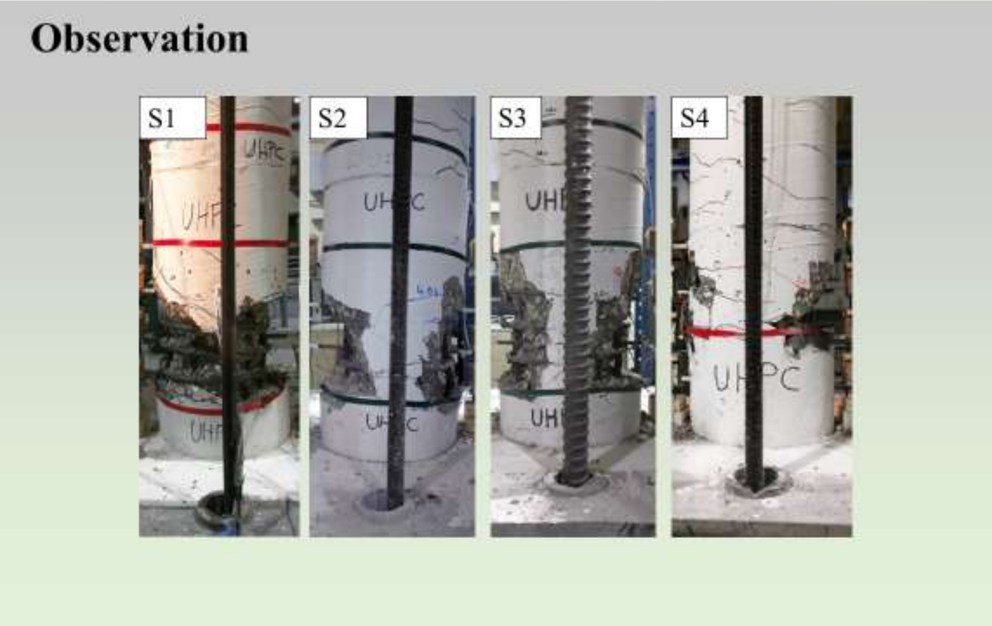
(a) column typical cross-section;
(b) bent components and rocking kinematics; and
(c) joint rotation.

ABC-UTC: UHPC Connection for Seismic Performance

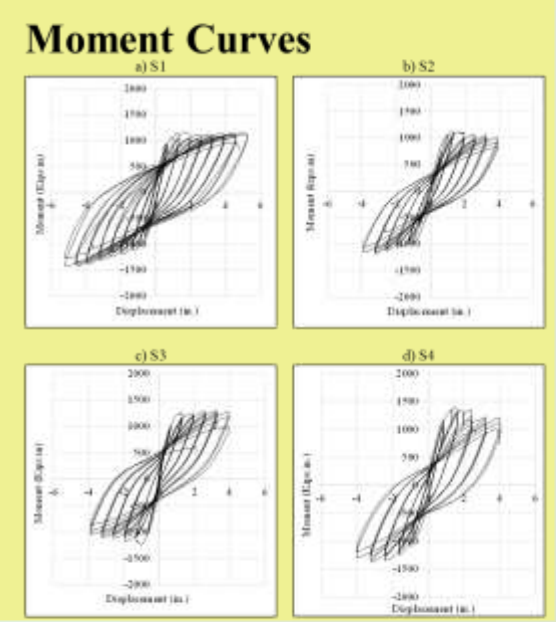


FIU Research: UHPC Connections + SMA or Self Centering PS





Observation



Moment Curves

Concluding Remarks:

- Post-Earthquake seismic resiliency is achievable using innovative design and construction methods
- Bridge Piers with Self Centering Capability (SMA, PS, etc.) are suited for Seismic Resiliency and post EQ Functionality
- Self Centering Super-elastic materials are suited for seismic resiliency
- CFST facilitate rapid construction and offers greater seismic resiliency
- UHPC Pier Connections provides improved seismic performance
- **Need for Further Implementation of Proven Innovative Technologies to Facilitate:**
  - **Designers/Owners/Contractors Familiarity,**
  - **Materials Availability and Costs,**
  - **Construction Experience,**
  - **Research, etc.**

Thanks for Your Attention

Available Reports/Documents:

- WSDOT Bridge Design Manual
- Webinars: ABC-UTC, TRB, WSDOT
- Precast concrete spliced-girder bridge in Washington State using super-elastic materials in bridge columns to improve seismic resiliency: From research to practice
- Shear Design Expressions For Concrete Filled Steel Tube And Reinforced Concrete Filled Tube Components
- https://www.wsdot.wa.gov/Research/publications.htm
- https://www.wsdot.wa.gov/publications/manuals/fulltext/M23-50/BDM.pdf

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