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SEISMIC BEHAVIOR AND DESIGN OF HIGHWAY BRIDGES

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Session 48

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S-8A SEng PRP Training Program

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Outline

- Introduction
- Highway Bridge Performance in Recent EQ
- AASHTO Seismic Design Specifications and Performance Objectives
- Seismic Design Methods: Force and Displacement Based
- Steps for Seismic Design

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Brief Self Introduction

- PhD, University of Michigan, Ann Arbor in 1991
- Bridge Engineer and Instructor, Caltrans, 10/91-6/94
- Licensed Professional Eng in NV, CA and Structural Eng in CA
- UNR Professor of Civil and Env Eng Department, 7/94-Present
- UNR-CEE Department Chair, 7/2013-6/19
- UNR-Associate Vice President for Research; 7/2019-present

Research Interests

– Behavior and design of highway bridges under extreme events
– Large scale structural experiments

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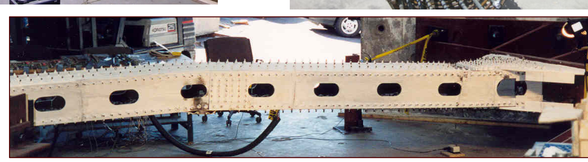

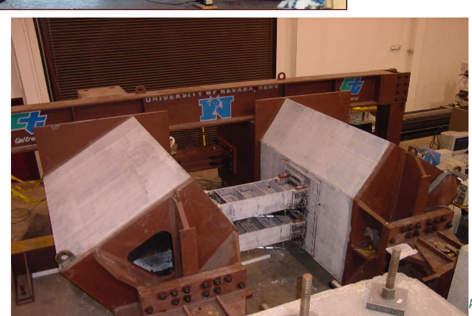

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Development of Seismic Code and Specifications

AASHTO-2012

6.16—PROVISIONS FOR SEISMIC DESIGN

6.16.1—General

The provisions of Article 6.16 shall apply only to the design of slab-on-steel-girder bridge superstructures at the extreme event limit state.

In addition to the requirements specified herein, minimum support length requirements specified in Article 4.7.4.4 shall also apply.

A clear seismic load path shall be established within the superstructure to transmit the inertia forces to the substructure based on the stiffness characteristics of the concrete deck, cross-frames or diaphragms, and bearings. The flow of the seismic forces shall be accommodated through all affected components and connections of the steel superstructure within the prescribed load path, including, but not limited to, the longitudinal girders, cross-frames or diaphragms, steel-to-steel connections, deck-to-steel interface, bearings, and anchor bolts.

C6.16.1

These Specifications are based on the recent work published by Itani et al. (2010), NCHRP (2002, 2006), MCEER/ATC (2003), Caltrans (2006), AASHTO's *Guide Specifications for LRFD Seismic Bridge Design* (2009), and AISC (2005 and 2005b). The Loma Prieta earthquake of 1989, Petrolia earthquakes of 1992, Northridge earthquake of 1994, and the Hyogoken-Nanbu (Kobe) earthquake of 1995 provided new insights into the behavior of steel details under seismic loads. The Federal Highway Administration, Caltrans, and the American Iron and Steel Institute initiated a number of research projects that have produced information that is useful for both the design of new steel-girder structures and the retrofitting of existing steel-girder structures.

This new information relates to all facets of seismic engineering, including design spectra, analytical techniques, and design details. Bridge designers working

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Introduction

- Bridges give the impression that are simple structural systems.
- Historically highway bridges have not performed well.
- Poor performance attributed to design philosophy with lack attention to details.
- Collapse due to structural discontinuity and lack of redundancy.

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Bridge Response to EQ Loading

- EQ loading is a dynamic force generated at the mass: F= m a= (W/g) a=W (a/g)
- Most of the bridge mass is in the superstructure
- Lot of efforts used to estimate “a”
- Forces will flow through the various components of the bridge causing deformations or movements.

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Bridge Performance in Recent EQ

1. Inadequate seismic load path
2. Unseated spans due to insufficient support lengths
3. R/C Column failure in flexure and shear due to inadequate detailing for ductility
4. Damage at expansion joints and at supports (abutments and bents)

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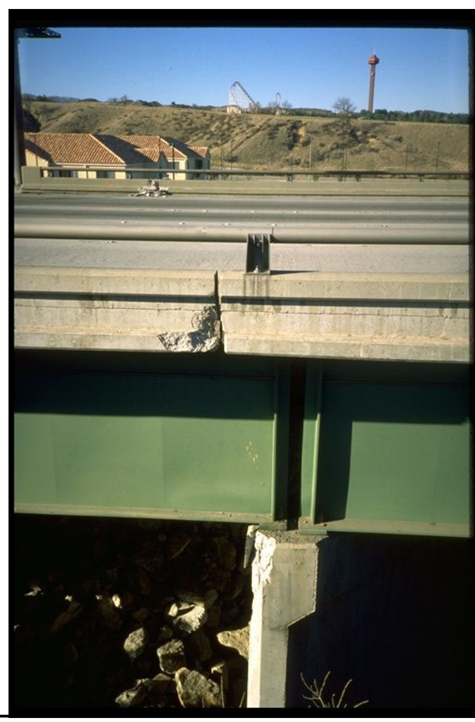

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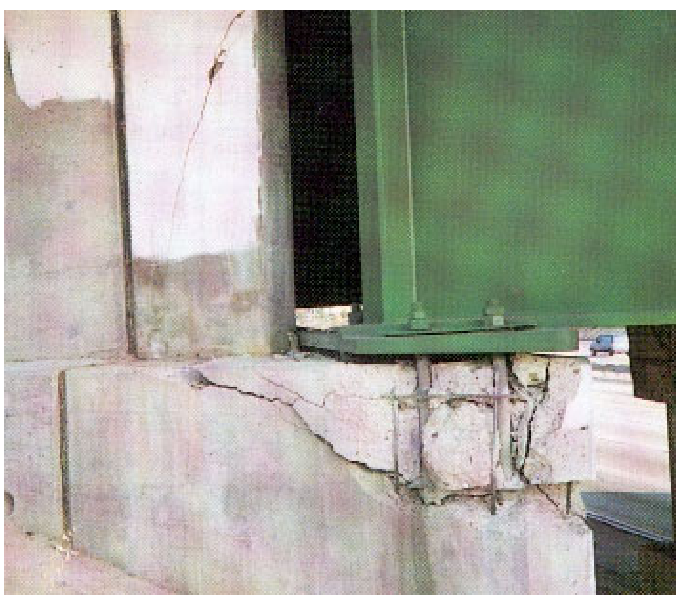

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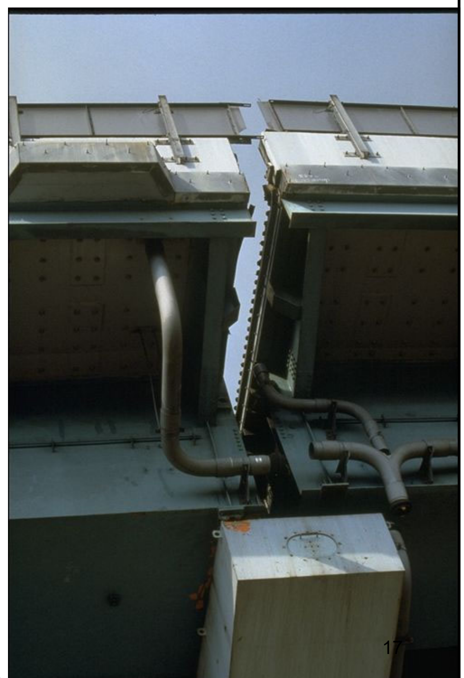

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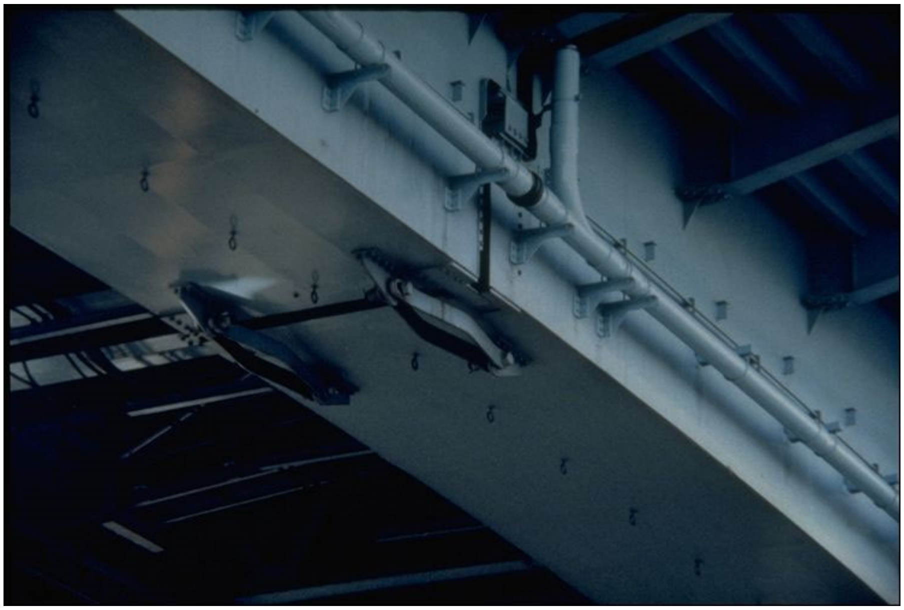

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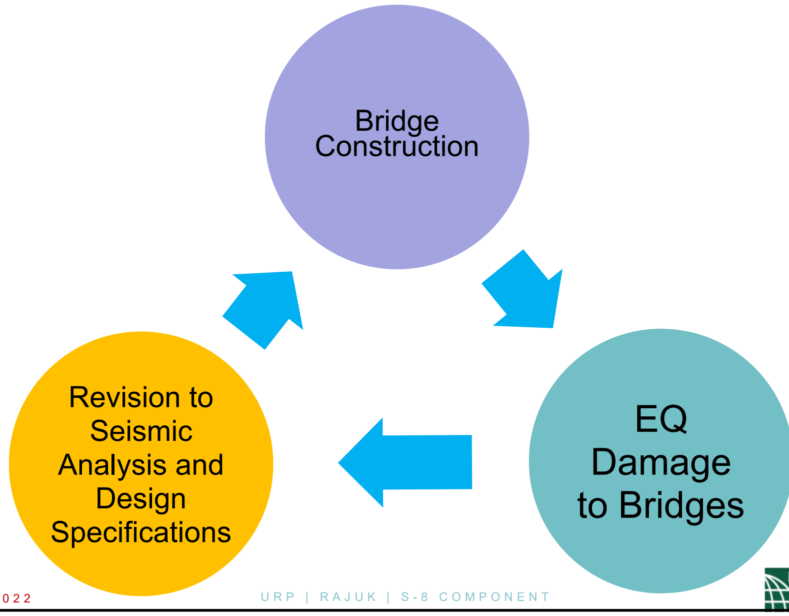
Lesson Learned

- Unseating of superstructure at expansion joints and seat type abutments
  - Support Length
- Slippage of main reinforcement-Lap splice at column ends
  - Development lengths
- Crushing of concrete in columns
  - Lateral steel for confinement
- Shear failure in columns
  - Lateral steel for shear resistance

Basic Questions after 1971 EQ

- Is it possible to design a highway bridge to respond elastically due to the maximum credible earthquake?
- Not economically! For a box girder bridge with integral cap and seat type abutment, the column, footing and superstructure size will be large!
- Allowing R/C column to yield during seismic event will lower the seismic forces
- Provide adequate seat width at expansions

Bridge Seismic Specifications



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AASHTO Seismic Specs Timeline

- Pre 1973-Art 1.2.20, EQ=cW (c=2%-6%)
- 1975 Interims of Standard Specs-modified CT Procedures
- 1981 ATC-6 Seismic Design Guidelines
- 1983 AASHTO Seismic Design Guidelines
- 1990 AASHTO Guide Specs into Division IA
- 1994 First Edition AASHTO LRFD Specs

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AASHTO Seismic Timeline

- 2003 ATC/MCEER-49 Recommended LRFD Guidelines
- 2008 Interims to 4th Edition, updated seismic provisions
- 2009 1st Edition, AASHTO Guide Specs for LRFD Seismic Bridge Design
- 2016 7th AASHTO LRFD Edition updated seismic provisions for Steel Bridges
- 2011 2nd Edition, AASHTO Guide Specs for LRFD Seismic Bridge Design

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Seismic Response of Highway Bridges

- Bridge designer controls the seismic response of bridges
- Seismic Performance Objectives
- Computational Modeling and Analysis
- Structural Design and Details

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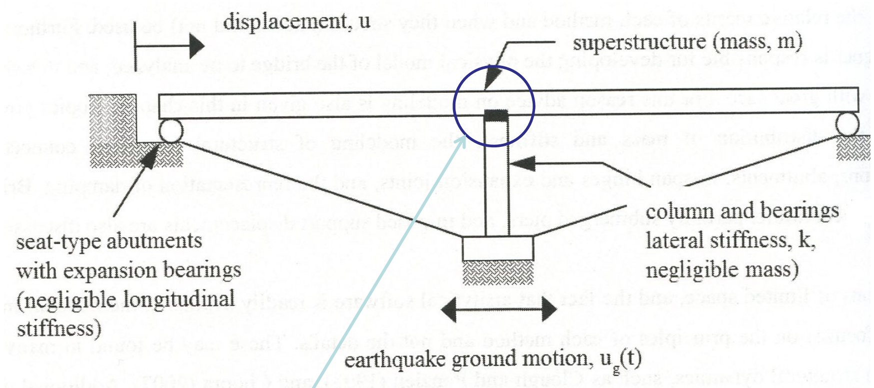
Response to Ground Motion



Integral Cap-monolithic
Dropped Cap-needs for bearings

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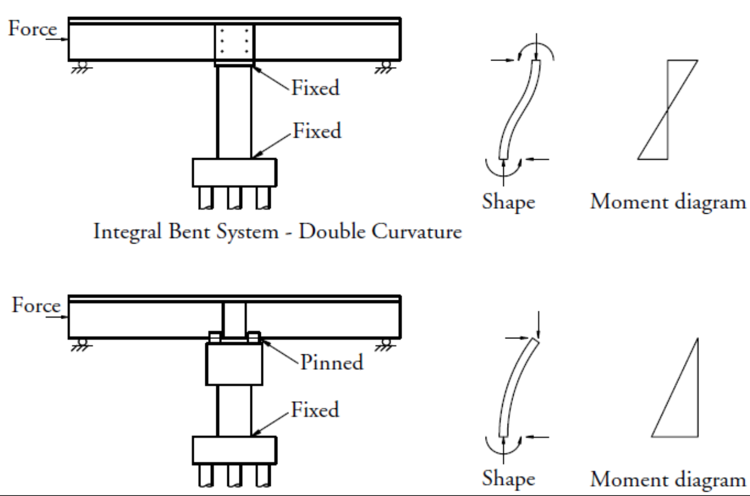
Transverse Direction Integral vs Dropped Cap



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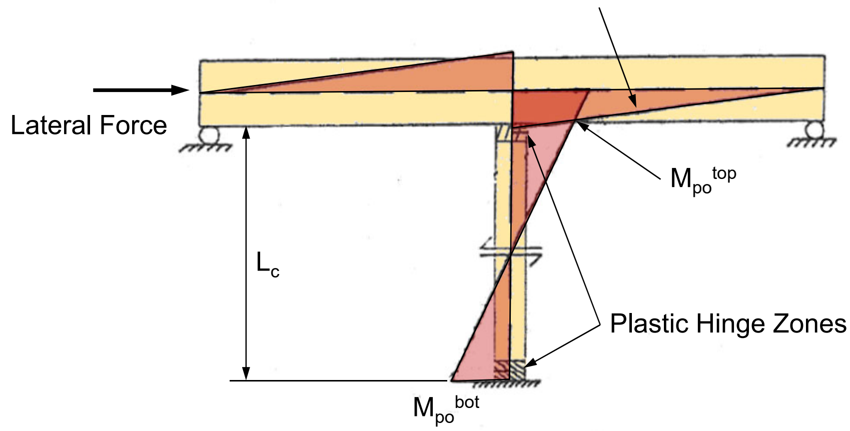
Longitudinal Direction



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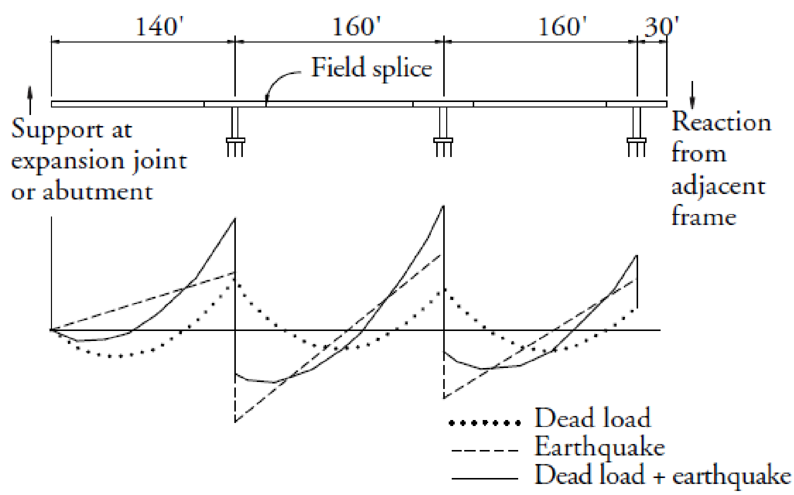
Longitudinal Direction



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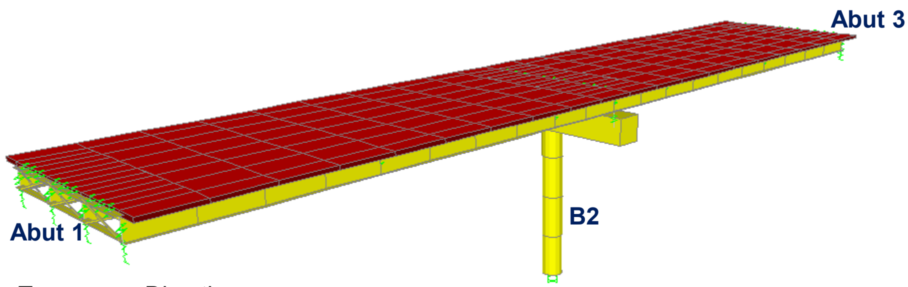
Load Path in Steel Plate Girder Bridges



Transverse Direction

- R/C Deck to Plate Girders through Shear Connectors
  - Shear connectors must be designed for seismic forces, otherwise they will fail and the deck will slide over plate girder
- Cross Frames at supports locations
  - Cross frames must be designed for seismic forces otherwise they will yield and buckle
- Bearings or shear keys

Basic Seismic Concepts

- Capacity Protected Design
- Damage is limited to selected elements Damage must be controlled and limited to ***ductile*** elements
- Damage should be accessible for inspection and repair.
- All other elements must stay essentially elastic

Why Ductile Response

- The internal forces are limited by the yielding elements forming plastic mechanism regardless of the earthquake shaking amplitude.
- However, large earthquakes produce larger deformations, thus proper detailing is required for the yielding element.

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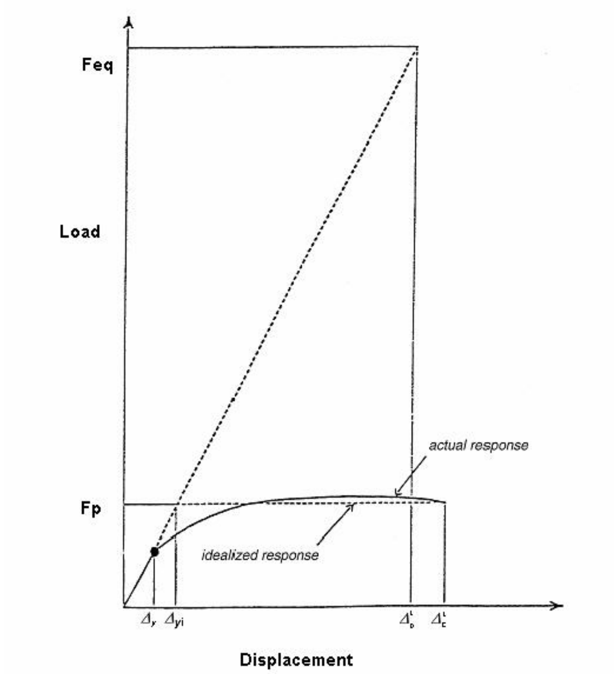

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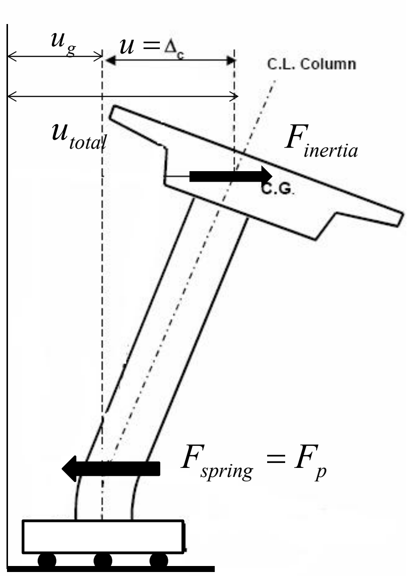
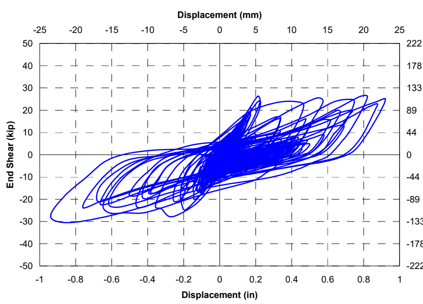


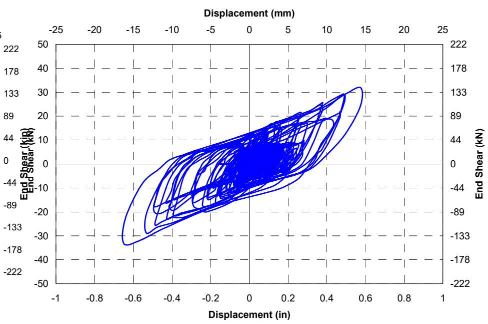
$$m\ddot{u}_{total} + ku = 0$$
$$m(\ddot{u}_g + \ddot{u}) + ku = 0$$
$$F_{inertia} + F_{spring} = 0$$
$$(F_{spring} = V_p) = -F_{inertia}$$

u=relative displacement to ground
u_g=ground displacement

Response of Ductile End X-Frame



Single Angles
X-Frame



BRB
X-Frame

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Effectiveness of Ductile End X-Frame

End X-Frame		V/W	Lateral Displacement (in)
Elastic		1.24	0.21
Ductile	Ductile Angles	0.76	0.80
	BRB	0.86	0.58

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AASHTO Seismic Performance Criteria

- Bridges shall be designed for life safety
- Seismic hazard corresponding to a 7% probability of exceedance in 75 years.
- Implies low probability of collapse.
- Significant damage and disruption to services
- Partial or complete replacement may be required.

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Earthquake Resisting Systems

- Earthquake Resisting System (ERS):
  - Provides reliable and uninterrupted load path for transmitting seismic forces
  - Energy dissipation and/or restraint to control seismic displacements
- Essentials for ERS
  - Simplicity: clear load path
  - Integrity: adequate connection
  - Symmetry: balance in stiffness, mass, strength

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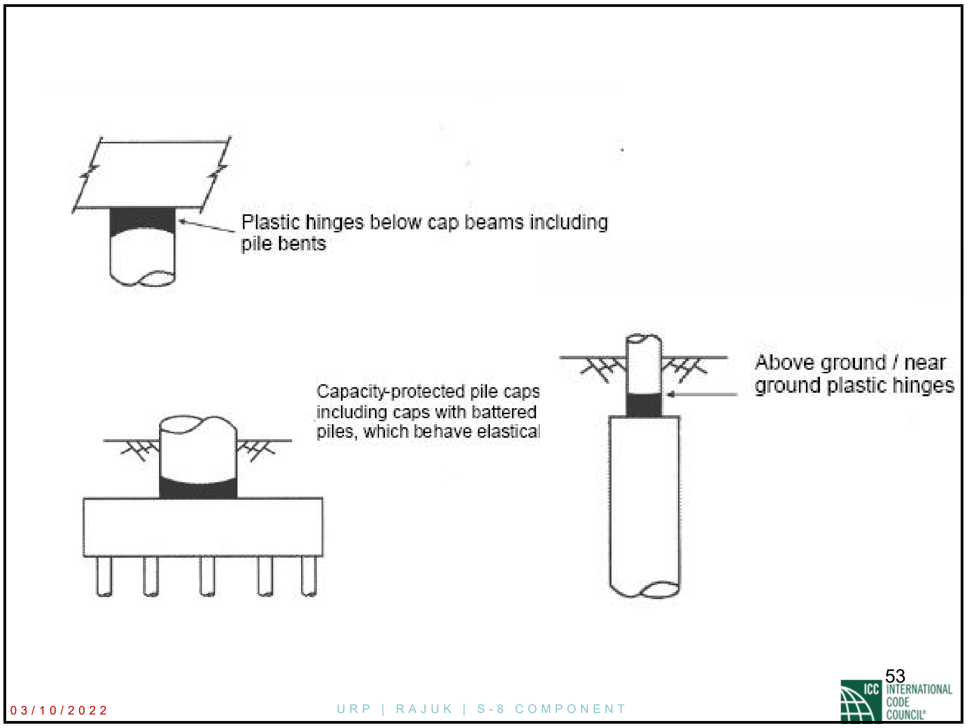
Seismic Design Strategy

- *Type 1*- Ductile Substructure with Essentially Elastic Superstructure
- *Type 2*- Essentially Elastic Substructure with Ductile Superstructure
- *Type 3*- Elastic Superstructure and Substructure with a Fusing Mechanism Between the Two Interface

Longitudinal Response

- Plastic hinges in inspectable locations or elastic design of columns.
- Abutment resistance not required as part of ERS
- Knock-off backwalls permissible


Plastic hinges below cap beams including pile bents
Capacity-protected pile caps including caps with battered piles, which behave elastical
Above ground / near ground plastic hinges
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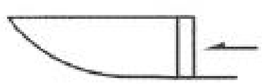
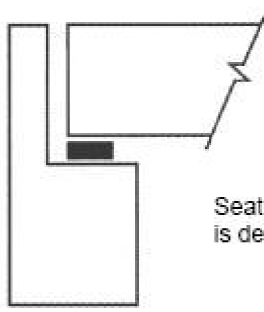
Passive abutment resistance required as part of ERS



Use 70% of passive soil strength designated in Article 5.2.3



Seat abutments whose backwall is designed to fuse

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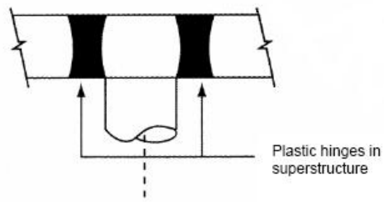

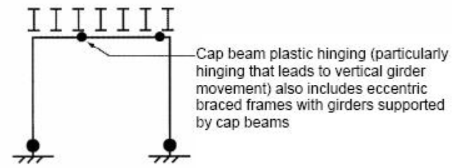

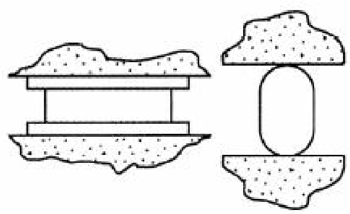

Bearing systems that do not provide for the expected displacements and/or forces (e.g., rocker bearings)

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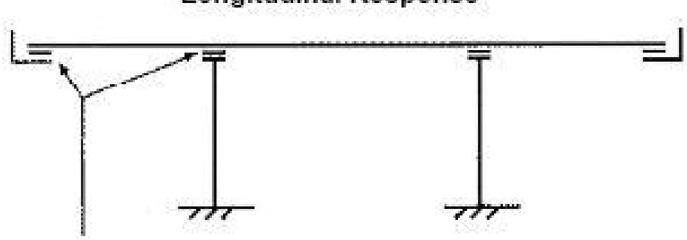
Longitudinal Response



- Isolation bearings accommodate full displacement
- Abutment not required as part of ERS

Seismic isolation bearings or bearings designed to accommodate expected seismic displacements with no damage

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Longitudinal Response

- Plastic hinges in inspectable locations or elastic design of columns
- Isolation bearings with or without energy dissipaters to limit overall displacements

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New Details

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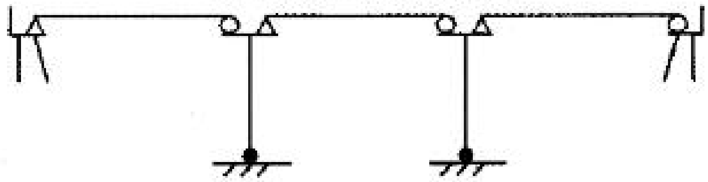
Longitudinal Response



- Multiple simply-supported spans with adequate support lengths
- Plastic hinges in inspectable locations or elastic design of columns

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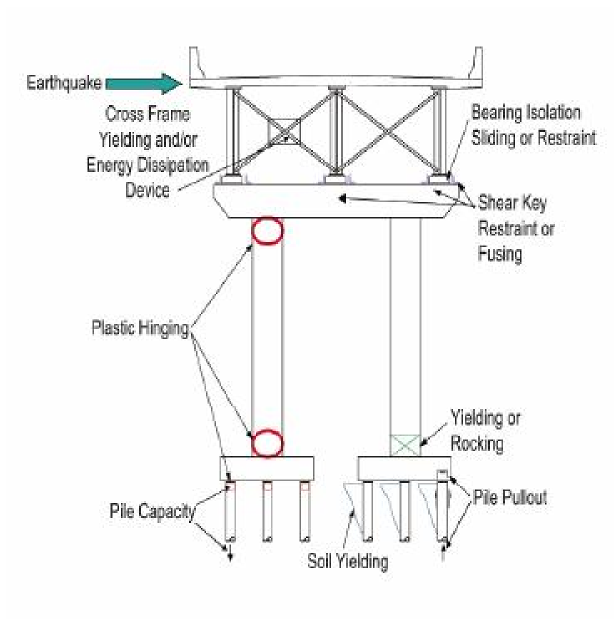

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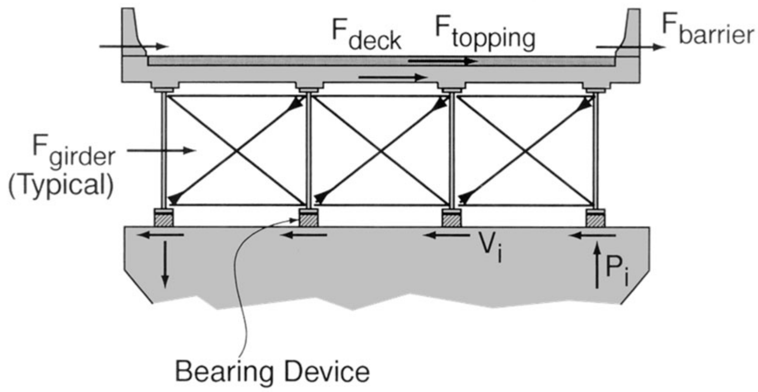
Steel Plate Girder

Pier / Cross Frame / Superstructure



Steel Plate Girder Bridge during EQ

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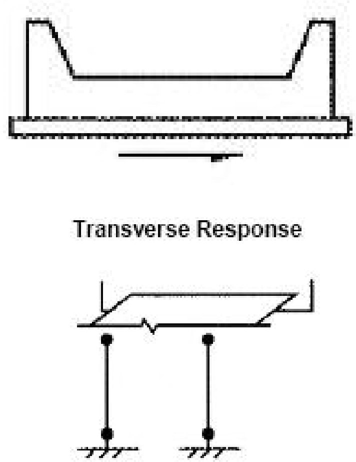

- Plastic hinges in inspectable locations or elastic design of columns
- Abutment not required in ERS, breakaway shear keys permissible

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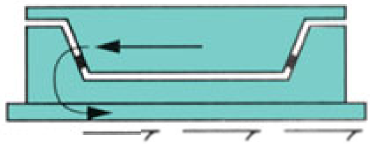

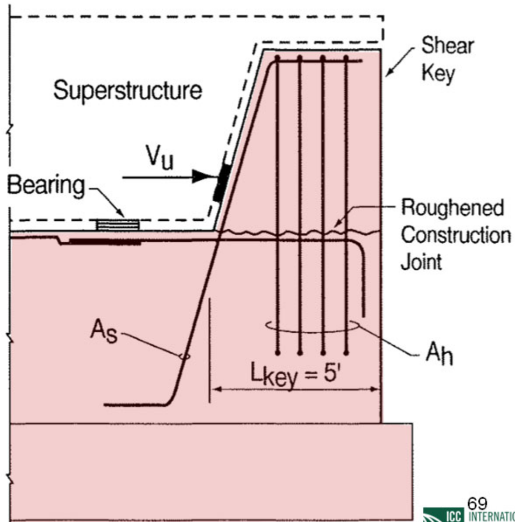

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Seismic Hazard

- Seismic Hazard is the hazard associated with potential earthquakes in a particular area.
- The seismic hazard level at a bridge site is determined by the intensity of ground shaking in the rock below the site and the amplification of this motion by the overlaying soil.

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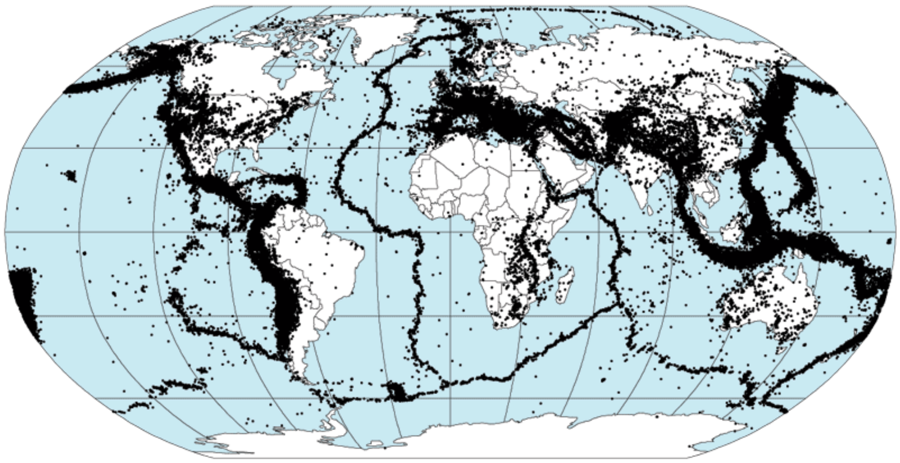
Preliminary Determination of Epicenters
358,214 Events, 1963 - 1998



AASHTO/USGS Design Hazard Maps

- AASHTO adopted a 1,000 year return period in 2007 for no-collapse design limit state.
- The Hazard Maps show the distribution of earthquake ground shaking that have 7% Probability of Exceedance (PE)
- The goal of Hazard Map is to predict the potential of shaking hazard from future earthquake

Probability Poisson Law

- Probability of an event is related to the annual frequency of ground motion γ and the exposure time t

$$P=1-e^{(-\gamma t)}$$

$$\gamma=-[\ln(1-P)]/t$$

- Probability of 10% of exccedance in 50 years, P=0.1 and t=50, γ=0.002107 which is 1/475 years
- Probability of 7% of exceedance in 75 years, P=0.07 and t=75, γ=0.001 which is 1/1033 years (1000 years)

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AASHTO/USGS Hazard Maps

- Provide a uniform margin against collapse at the design ground motion.
- Ground Motion Hazard are defined in terms of **D**esign **E**arthquake motion.
- Three Sets of Hazard Maps for rock spectral acceleration
  - Peak Acceleration **PA** (PGA)
  - 0.2 sec $\mathbf{S_s}$ **Map**
  - 1 sec $\mathbf{S_1}$ **Maps**

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AASHTO Seismic Coefficient Spectra

- Shorter period range: deterministic cap on probalistically-derived spectrum
- Longer period range: smoothed and assumed to be inversely proportional to the modal period, T

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AASHTO Seismic Coefficient Spectra

- Plot is NOT acceleration response spectrum. Modified for design purposes. AASHTO refers to it as 'seismic coefficient'.
- Similar to AASHTO NEHRP and IBC modify acceleration Spectrum.
- Pre 2007 PGA was assumed to be equal to 0.4 times spectral acceleration at 0.2 sec.

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Seismic Parameters

- S_s Mapped spectral response, acceleration at short periods for site Class B (California rock).
- S_1 Mapped spectral response acceleration at 1.0 second period for site Class B (rock).
- Need to modify these values to account for local sites

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Effect of Local Soil

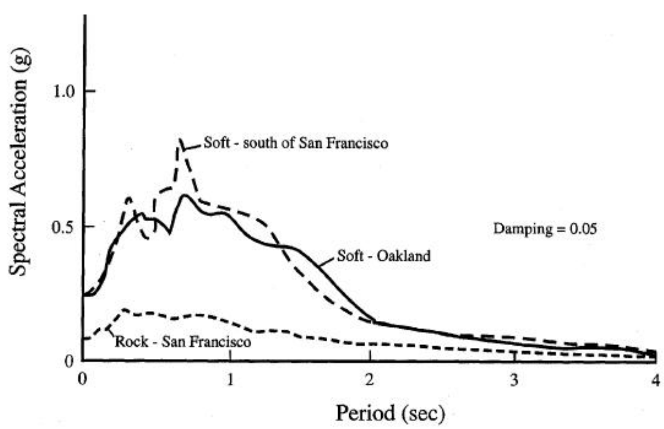

Figure C3.3.2-1. Average spectra recorded during the 1989 Loma Prieta earthquake in San Francisco Bay area at rock sites and soft soil sites (modified after Housner, 1990).

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AASHTO Site Class Definition

- Sites are classified by their stiffness as determined by shear wave velocity in the upper 100 ft (30m-V_{s30}), SPT, blow counts and undrained shear strength, s_u
- Site Classes
  1. Class A: Hard Rock
  2. Class B: Rock
  3. Class C: Very dense soil and soft rock
  4. Class D: Stiff Soil
  5. Class E: Soft Soil
  6. Class F: Soils require site-specific evaluations

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Site Factors

- Three values approach to account for local soil conditions
- Anchoring spectral acceleration for design spectrum are modified by site response factors F_{pga}, F_a, F_v

$$A_s = F_{pga}\,PGA$$
$$S_{DS} = F_a\,S_S$$
$$S_{D1} = F_v\,S_1$$

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Elastic Seismic Response Coefficient

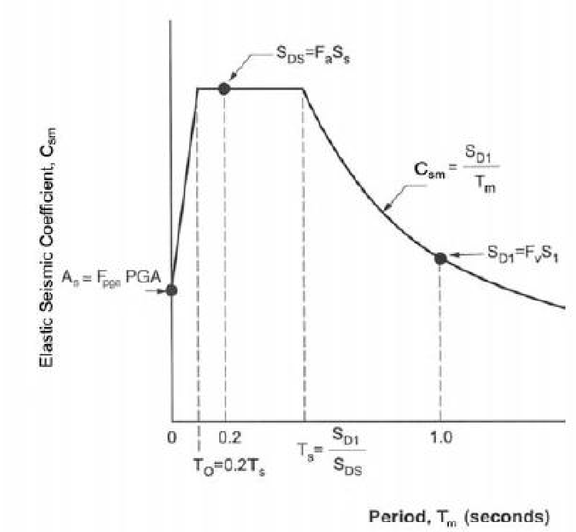

Figure 3.10.4.1-1—Design Response Spectrum

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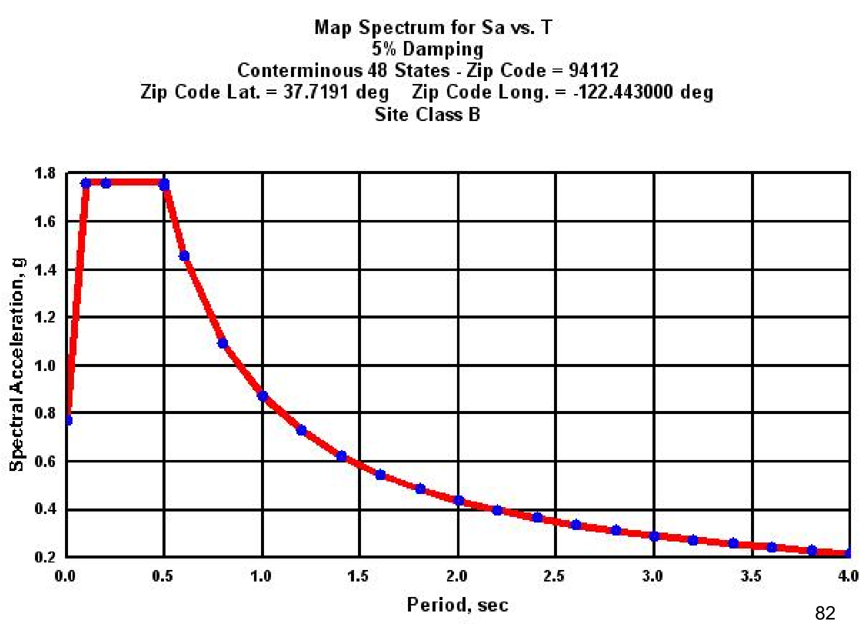

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Seismic Performance Zones

Table 3.10.6-1—Seismic Zones

Acceleration Coefficient, S_{D1}	Seismic Zone
$S_{D1} \leq 0.15$	1
$0.15 < S_{D1} \leq 0.30$	2
$0.30 < S_{D1} \leq 0.50$	3
$0.50 < S_{D1}$	4

- Analysis methods of analysis
- Minimum support lengths
- Column design details
- Foundation and abutment design procedure

Seismic Design Methodology

- Force Based Method (FBM)
- Displacement Based Method (DBM)
- Both methods seek the same objective: "collapse prevention"
- Both methods relay on ductility and load path to resists EQ larger than the design level.

Force Based Method

- Used in AASHTO LRFD Specifications.
- Develop seismic demand **forces** for the yielding elements by dividing the elastic seismic forces by appropriate Response Modification Factor (R).
- Perspective details are followed in these elements to ensure adequate ductility.
- Provide adequate load path and displacement for other bridge elements.

Operational Classification

- Bridge Operational Categories
- Critical
  - Operational to all traffic (3% PE-2,500 year return period)
- Essential
  - Operational to emergency vehicles
- Other

Table 3.10.7.1-1—Response Modification Factors—Substructures

Substructure	Operational Category		
	Critical	Essential	Other
Wall-type piers—larger dimension	1.5	1.5	2.0
Reinforced concrete pile bents			
• Vertical piles only	1.5	2.0	3.0
• With batter piles	1.5	1.5	2.0
Single columns	1.5	2.0	3.0
Steel or composite steel and concrete pile bents			
• Vertical pile only	1.5	3.5	5.0
• With batter piles	1.5	2.0	3.0
Multiple column bents	1.5	3.5	5.0

Table 3.10.7.1-2 Response Modification Factors—Connections

Connection	All Operational Categories
Superstructure to abutment	0.8
Expansion joints within a span of the superstructure	0.8
Columns, piers, or pile bents to cap beam or superstructure	1.0
Columns or piers to foundations	1.0

Displacement Based Method

- Used in AASHTO Guide Specifications for LRFD Seismic Design.
- Proportion the yielding system to ensure the demand **displacement** is less than displacement capacity of the yielding element-adjust element detailing
- Provide adequate strength for other elements based on the ultimate capacity of the yielded element.

Design Methods Comparison

- FBM, R values are prescribed and used to size yielding element. No verification of the actual displacement or ductility demand is made and prescribed detailing is used to ensure adequate ductility
- DBM, displacement capacity of each yielding element is evaluated and compared with the displacement demand on the elements. Detailing can be customized to improve required ductility.

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Elements of Capacity Design

- Select the location where damage is preferred
- Design these elements to be ductile
- Protect all other elements from failure

- Designer control the behavior and response of the bridge!

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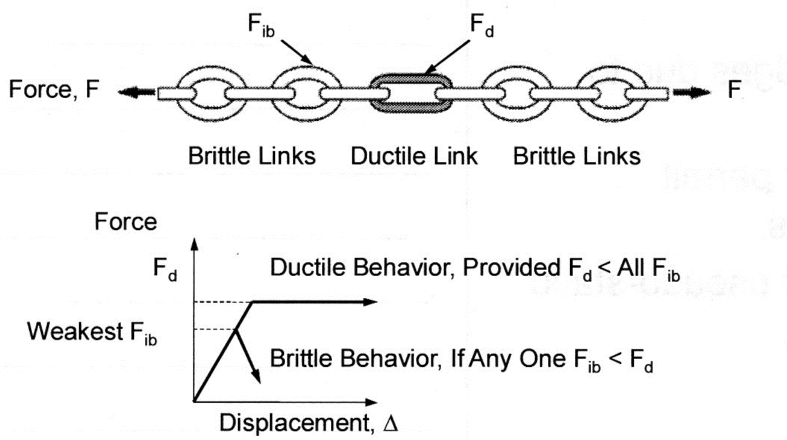
Capacity Protection Concept



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What Elements Need Capacity Protection

- Column Shear
- Column Joint at the footing and bent cap
- Footing
- Superstructure

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Steps for Seismic Design

1. Determine Seismic Input
   a) Seismic Hazard
   b) Site Classification
   c) Response Spectra
2. Establish Design procedures
   a) Seismic Zone
   b) Importance
   c) Analysis Procedure
   d) Foundation Modeling

3. Identify Earthquake Resisting System and Global Design Strategy
   a) Where yielding will be accepted
   b) What system of deformation will be used?
   c) Participation of abutments
4. Demand Analysis
   a) Bridge modeling
   b) Analysis method (linear, nonlinear, etc)
5. Design and Check Earthquake Resisting Elements
   a) FBM or DBM
   b) Detail ductile elements

6. Capacity Protect Elements

a) Shear in ductile earthquake resisting elements

b) Bent Caps

c) Foundations and Abutments

d) Superstructures, connections, bearings, support lengths.

Seismic Design of Highway Bridges- Accelerated Bridge Construction (ABC) and Innovative Materials

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NCHRP

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1

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TOPICS

1. **Next generation of bridge columns for accelerated bridge construction (ABC)- Caltrans**
2. **Seismic design of ABC column connections in the 2020 proposed AASHTO guidelines- NCHRP**
3. **Seismic resistance of columns with CFRP tendons- USDOT**
4. **Deconstructible bridges w/ advanced materials- NSF**

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1- Next generation of bridge columns for ABC

- What is "Next generation?"
- Prefabricated columns, **including connections,** that
  - Meet seismic performance requirements
  - Constructible
  - Do not introduce unusual durability, maintenance, or inspectability issues
- Resilient- minimum damage; serviceable after EQ
- Conform to current ban on splices in plastic hinges

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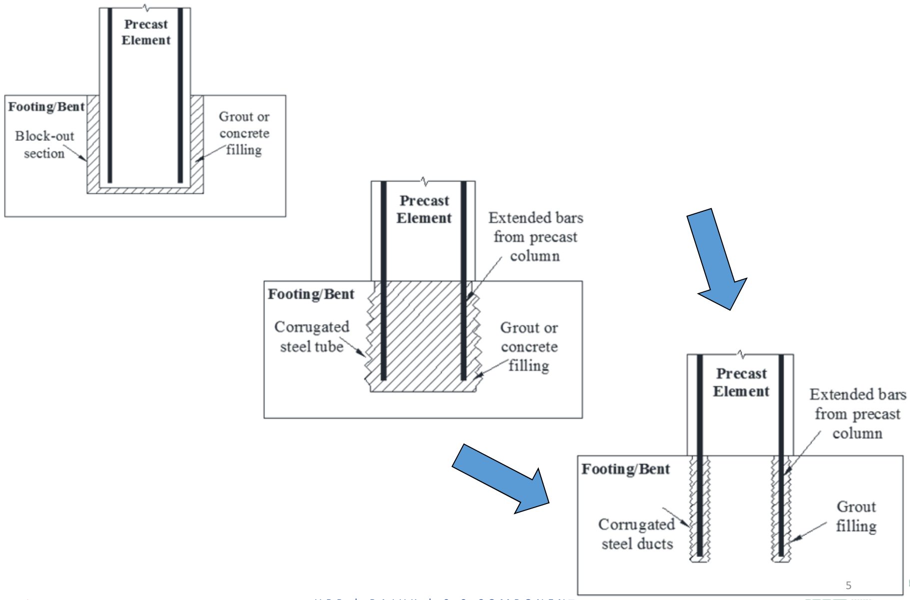
OPTIONS W/ NO-COUPLERS



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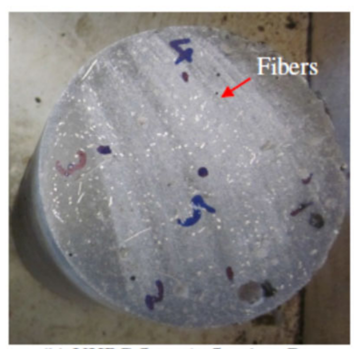
Ultra High Performance Concrete, UHPC

(a) Steel Fibers



(b) UHPC Sample Section Cut

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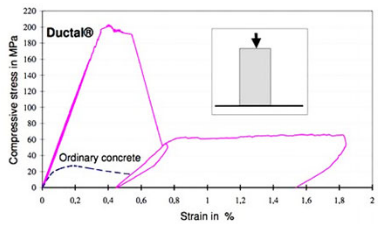
UHPC Materials

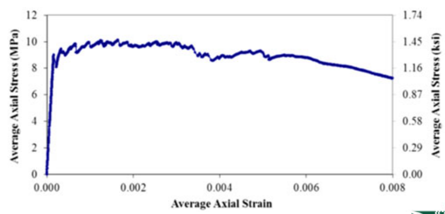
- Ultra-high Performance Concrete (UHPC)
  - Significantly higher compressive and tensile ductility

Compared to Conventional Concrete



Courtesy: Lafarge.com

Compression



Tension

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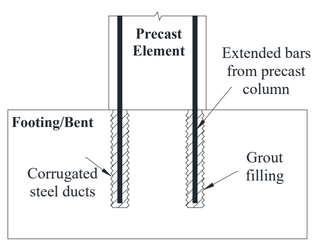
ABC Connections w/ UHPC



Grouted Ducts w/ UHPC

Two parts:
1- Bond strength studies
2- Implementation in large-scale columns tested under cyclic loading

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UHPC-Filled Duct Connections

- 14 Pullout Tests
- Variables:
  - Embedment Length: $3d_b$, $5d_b$, $8d_b$, and $12d_b$
  - Bar Size: #8 (Ø25 mm) and #11 (Ø36 mm)
  - Duct Size: nominal 3 in. (75 mm), 4 in. (100 mm) and 5 in. (125 mm)
  - Bundled Bar: a pair of bars in a connection
  - Multiple Ducts: two ducts in a connection

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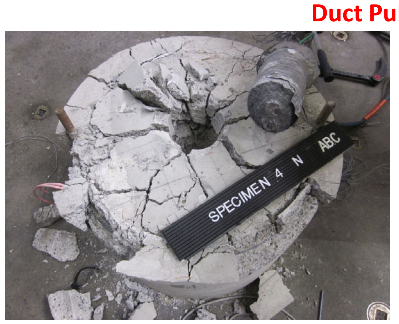
UHPC-Filled Duct Connections

Connection Bond performance: *Test Results*

Duct Pullout



SP4- Group I
Bundled #8 Bars
Emb. Length: $8d_b$

SP11- Group I
Single #11 Bar
Emb. Length: $8d_b$

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UHPC-Filled Duct Connections

Bond performance: *Test Results*

- Bond strength of bar in UHPC was eight times higher than that in conventional concrete
- Design Development Length:

$$L_d = \max\left(L_{d,duct},\ L_{d,bar}\right)$$

$$L_{d,duct} = \frac{d_b^2 \cdot f_s}{27 d_d \cdot \sqrt{f'_c}}$$

$$L_{d,bar} = \frac{d_b \cdot f_s}{120\sqrt{f'_{UHPC}}}$$

(*psi, in*)

Compared to conventional connections designed according to:

- ACI 318
- AASHTO LRFD Grout-Filled Ducts

At least 50% Reduction in Required Embedment Length

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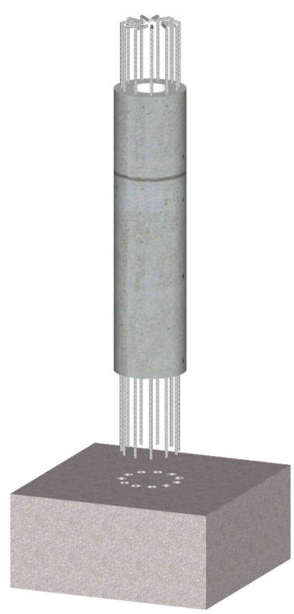
UHPC-Filled Duct Column Connections

- **Two Column Models**
  - Conventional Materials in Plastic Hinge ("PNC")
  - SMA-ECC in Plastic Hinge ("HCS")
- **Connection to Footing**
  - UHPC-Filled Duct Connections
- **Column Geometry**
  - Half-Scale; Hollow; Filled SCC after connectin
  - Height: 9 *ft* (2.74 *m*)
  - Diameter: 24 *in*. (610 *mm*)
  - 11-#8 (Ø25 *mm*) Longitudinal Bars (ρ_l=1.92%
  - Spiral, ρ_s=1.03%
  - Axial Load Index: 10% (200-kip axial load on specimens)



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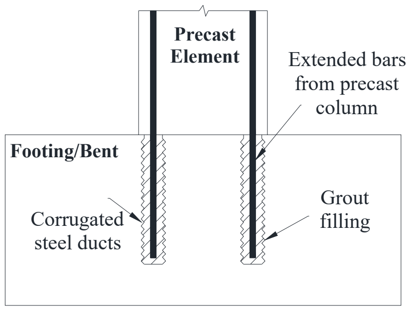
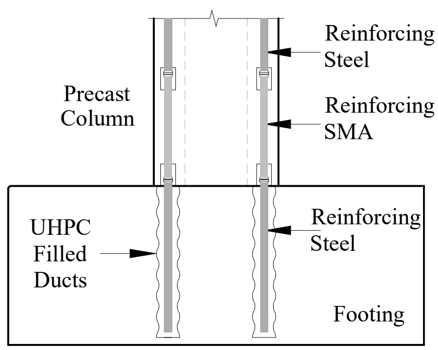
Column ABC Connections w/ UHPC Grouted Ducts





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UHPC-Filled Duct Columns Connections - Construction

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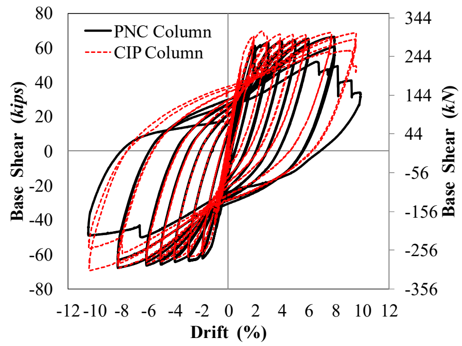
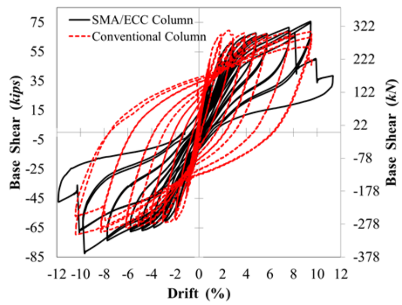
UHPC-Filled Duct Column Connections - Performance





9% Drift Capacity

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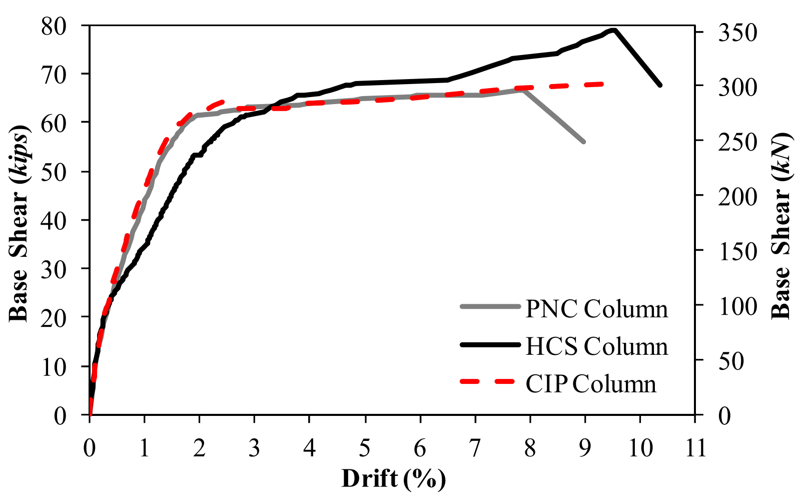
UHPC-Filled Duct Column Connections- Test Results

PNC, HCS, and CIP Test Average Envelopes



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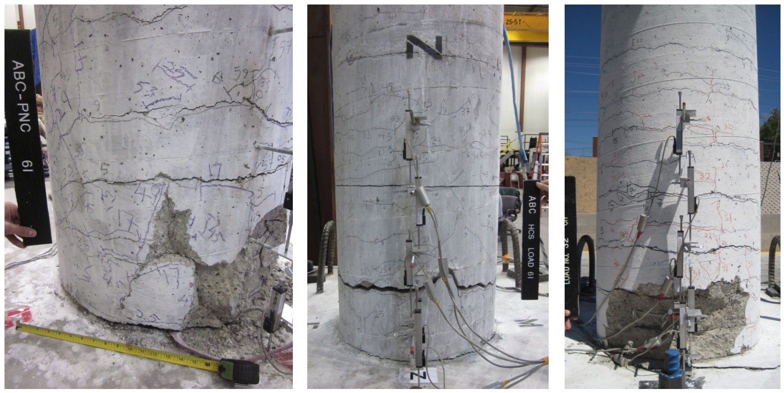
UHPC-Filled Duct Connections

@ 5% Drift Ratio

Columns w/ UHPC-Filled Duct Connections

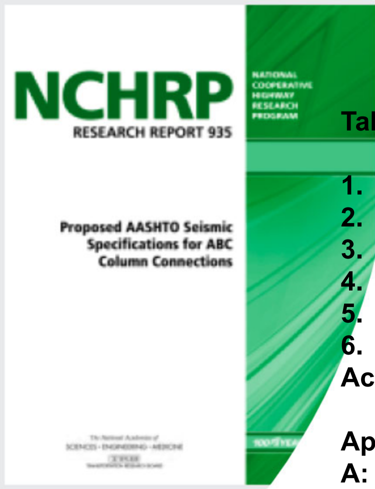


PNC **HCS** **CIP**

TOPIC 2-
Seismic design of ABC column connections in the 2020 proposed AASHTO guidelines- NCHRP

- **PI: M. Saiid Saiidi**
- **Co-PIs: A. Itani, D. Sanders, UNR; M. Tazarv, S. Dakota State U.; T. Murphy, Modjeski & Masters; M. Reno, Quincy**

NCHRP University of Nevada, Reno South Dakota State University Quincy Engineering Modjeski and Masters



Published April 2020

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2. State-of-the-Art Literature Review
3. Experimental Programs
4. Analytical Programs
5. Proposed Specifications and Examples
6. Summary and Conclusions
Acronyms

Appendices
A: Survey of State Departments of Transportation
B: Proposed AASHTO/ASTM Standard Test Method for Bar Couplers
C: Proposed AASHTO Specifications ABC Columns
D: Detailed Design Examples

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Objectives of NCHRP 12-105

- Develop proposed AASHTO displacement-based design and construction specifications for ABC column connections in moderate and high seismic regions.

- Include mechanical bar couplers, grouted ducts, pocket, and socket connections.

Include analytical and experimental studies

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Task 13.1

Seismic Design of Columns with ABC Connections

Task 13.2

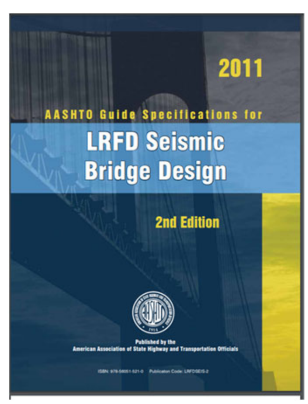
AASHTO Standard Test Methods for Seismic Couplers

Task 13.3 – Examples

Design Examples for ABC Column Seismic Connections

Guidelines as Appendix to "SGS"

- Additional requirements for seismic connections using ABC details
- Does not supplant the requirements of the Seismic Guide Specifications – **adds to them**
- Three main sets of provisions
  - Bar couplers
  - Grouted duct connections
  - Pocket/socket connection details



Mechanical Bar Splices (Couplers)

Current Bridge Seismic Design: Couplers are banned in plastic hinges in moderate and high seismic zones

[ancon.co.uk] (a) Shear Screw Coupler

[hrc-usa.com] (b) Headed Bar Coupler

[splicesleeve.com] (c) Grouted Sleeve Coupler

[erico.com] [armaturis.com] (d) Threaded Coupler

[barsplice.com] (e) Swaged Coupler

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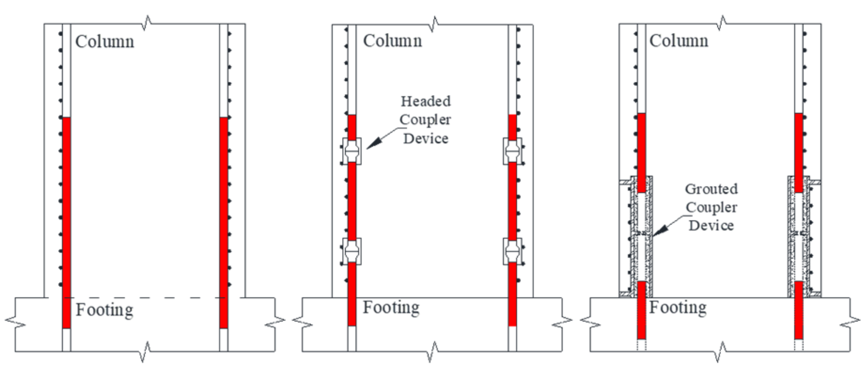
Reason?



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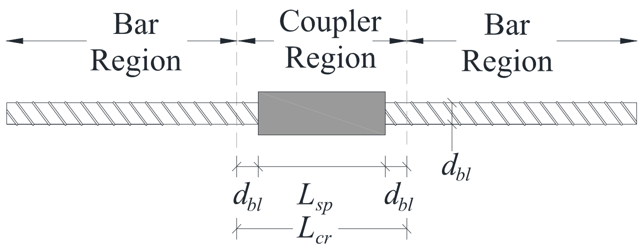
Couplers

- **Coupler length definition**:

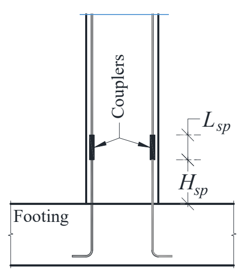
$$L_{cr} = L_{sp} + 2d_{bl}$$



Plastic Hinge Length

- Presence of couplers accounted for by using altered plastic hinge length

$$L_p^{\ sp} = L_p - \left(1 - \frac{H_{sp}}{L_p}\right)\beta L_{sp} \le L_p$$



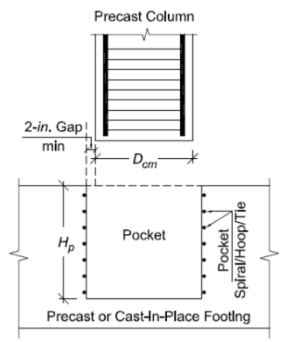
- Strain adjustment for section analysis:

$$\frac{\varepsilon_{sp}}{\varepsilon_s} = \frac{L_{cr} - \beta L_{sp}}{L_{cr}}$$

Pocket/Socket Connections

- Pocket filler material requirements
  - Concrete, SCC, or grout
  - Footings and fully precast columns require grout
- Corrugated pipe material requirements
- Gaps and surface preparation requirements
- Pocket depth requirement:

$$
\begin{cases}
H_p \geq D_{cm} \\
H_p \geq 0.79 d_{bl} \dfrac{f_{ye}}{\sqrt{f'_c}} \\
H_p \geq 24 d_{bl}
\end{cases}
$$



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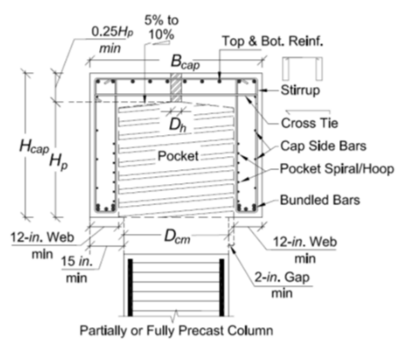
Bent Cap Details

- **Minimum cap depth**
- **Minimum cap width**
- **Vent hole size and top surface slope**
- **Pocket reinforcing requirements**
- **Bent cap longitudinal reinforcing**



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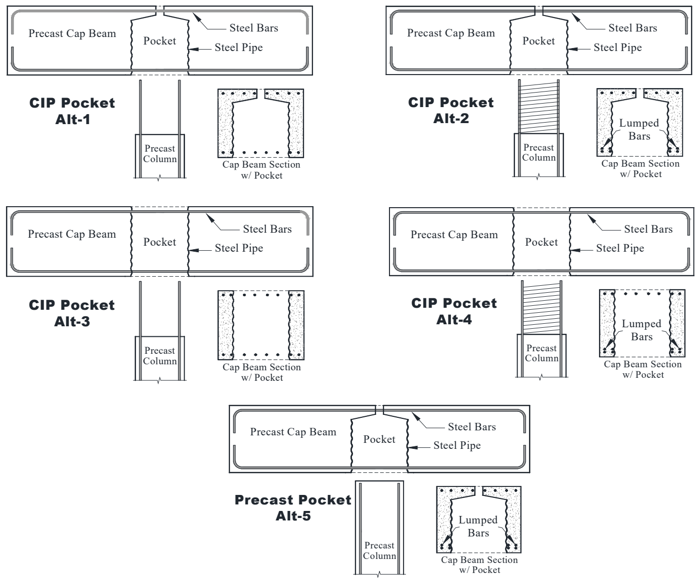
Detailing Alternatives for Pocket/Socket Connections



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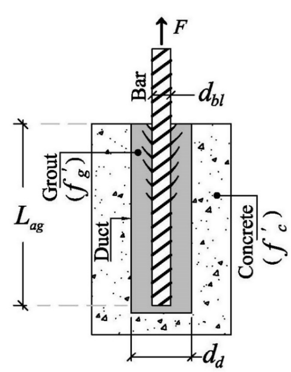
Grouted Ducts

- Requirements for duct material
- Duct size and spacing requirements
- Requirements for length of embedment in grouted ducts
  - Bar-to-grout bond
  - Duct-to-concrete bond

$$L_{ag} = \text{Max} \begin{cases} l_{ab} = \dfrac{0.68 d_{bl} f_{ye}}{\sqrt{f'_g}} \\ l_{ad} = \dfrac{2.25 d^2_{bl} f_{ye}}{d_d \sqrt{f'_c}} \end{cases}$$



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1/3rd Scale Concrete Bridge Model w/ Grouted Duct Connections- 200% Design- Overview

Bridge System Seismic Research for Accelerated Bridge Construction (ABC) - Calt-Bridge 1
Bridge Overview SW

20/9/2017
Run 8 – 1.070 x Sylmar
(PGATRANS=0.66g PGALONG=0.98g)

PI: Dr. M. 'Saiid' Saiidi
Co-PI: Dr. Ahmad Itani
Graduate Assistant: José Benjumea, Ph.D. Student

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1/3rd Scale Concrete Bridge Model w/ Grouted Duct Connections- 200% Design- Closeup

Bridge System Seismic Research for Accelerated Bridge Construction (ABC) - Calt-Bridge 1
Bent North View

20/9/2017
Run 8 – 1.070 x Sylmar
(PGATRANS=0.66g PGALONG=0.98g)

PI: Dr. M. 'Saiid' Saiidi
Co-PI: Dr. Ahmad Itani
Graduate Assistant: José Benjumea, Ph.D. Student

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1/3rd Scale Steel Bridge Model w/ Grouted Duct & Base Pocket Connections and Pocket- 200% Design- Closeup

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1/3rd Scale Concrete Bridge Model w/ Pocket Connections- 200% Design- Closeup

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3- Seismic Evaluation of a Precast PT/UHPC Bridge Column with Pocket Connection

- Evaluate seismic response of a precast square column connected to a precast footing using a pocket connection subjected to earthquakes simulated on a shake table.
- Determine the effectiveness of ultra-high performance concrete (UHPC) in the plastic hinge zone in minimizing column damage,
- Investigate effectiveness of unbonded carbon fiber reinforced polymer (CFRP) tendons in recentering columns under strong earthquakes.

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ABC UTC

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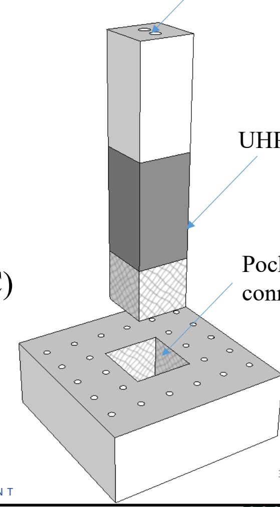
Novel Concepts

- Precast column and footing with pocket connection
- Post-tensioning using unbonded Carbon Fiber Reinforced Polymer (CFRP) tendons
- Ultra-High Performance Concrete (UHPC) in plastic hinge



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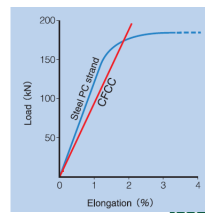
CFRP Tendons

CFRP main features:

- High tensile strength (~300 ksi, effective area=0.88 in^2)
- High tensile modulus (~21,030 ksi)
- Noncorrosive



(Tokyo Rope)

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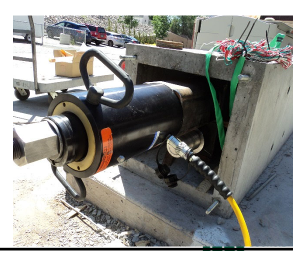
Precast Column

Concrete UHPC



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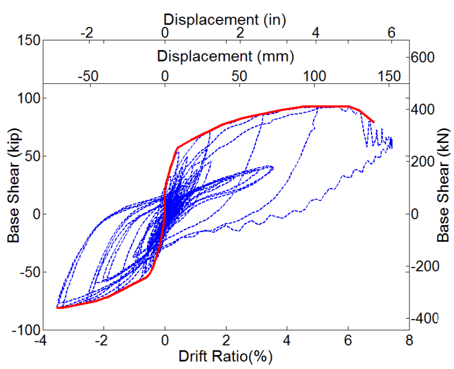
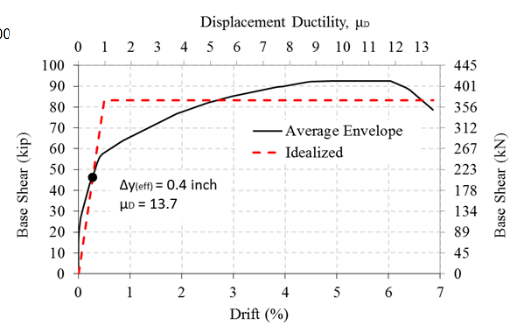
Pocket Connection

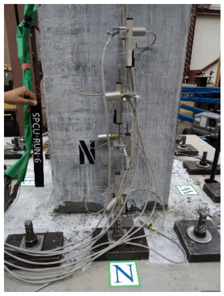
Hysteresis and Pushover Reponse





Damage

Run #6
Max. Drift: 6.82%



UHPC Plastic Hinge

Conventional Concrete Plastic Hinge

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4- Deconstructible bridges w/ advanced materials

Objectives:

Develop bridge columns that
1- Withstand strong earthquakes with no or minor damage so they are useable after earthquakes.
2- Can be disassembled and reused.

5% of CO_2 emission in the world is from cement factories.

NSF

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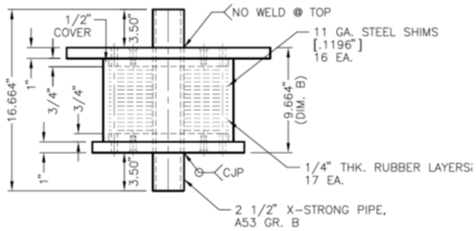
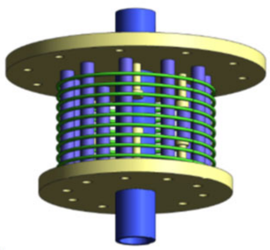
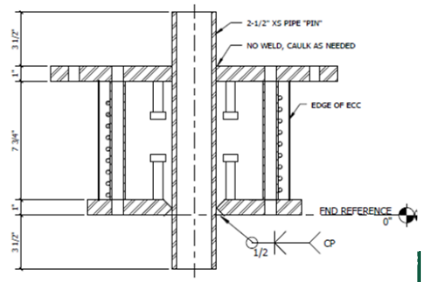
Plastic Hinge Elements







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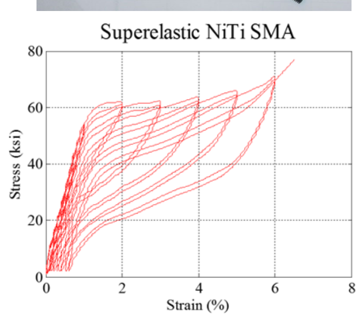
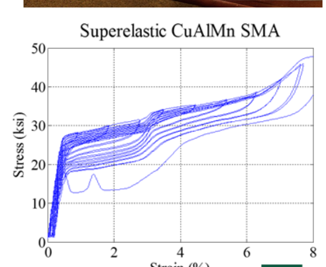
Longitudinal Reinforcement in PH Shape Memory Alloys (SMA)

Ni-Ti



Cu-Al-MN



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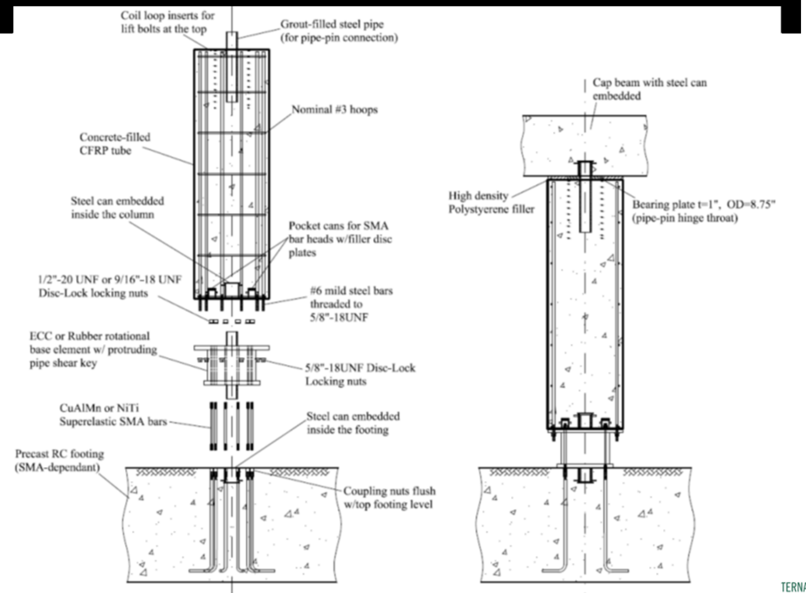
Capacity-protected column outside PH



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ECC; NiTi; Copper Based SMA; Rubber; CFRP Shell
(Patent Filed)

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[redacted]

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Reassembled Bridge

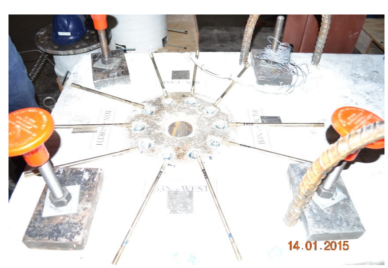
Overview - Shake table test of a reassembled precast modular 2-span bridge model with innovative materials (Bridge #2)

2/6/2015
Run 7 - 1.225 x Rinaldi (PGA=1.2 g)

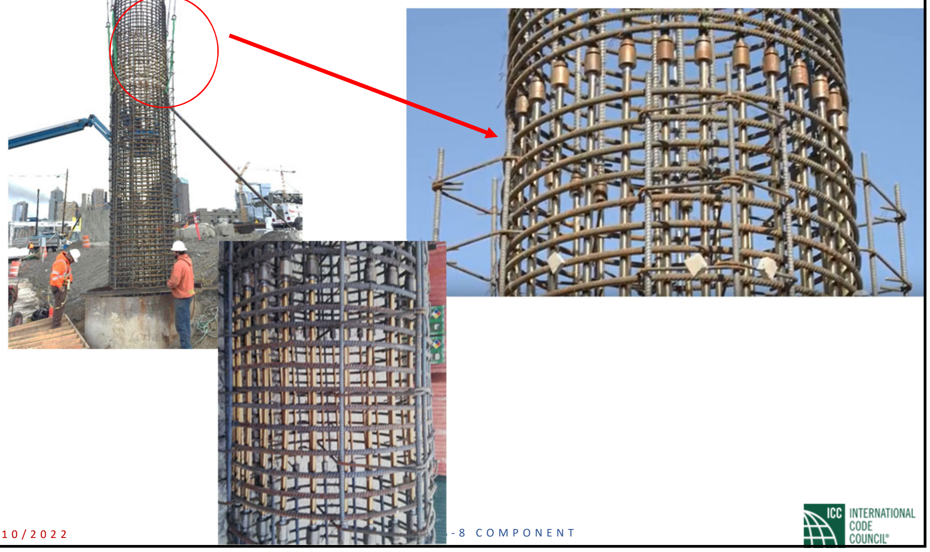
PI: Dr. M. 'Saiid' Saiidi
Graduate Assistant: Sebastian Varela, PhD student
University of Nevada, Reno

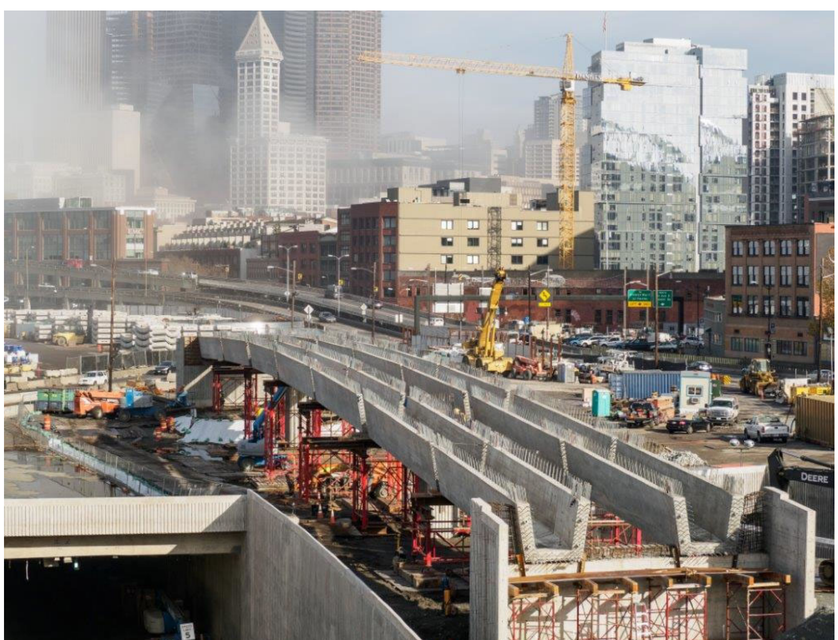
After disassembly





Implementation of SMA/ECC in Showcase Bridge (J. Bingle, B. Khaleghi, T. Moore, M. Saiidi)





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Message

- Recent research enabled the development of ABC seismic design connection guidelines with confidence.
- The proposed guidelines expand the current SGS provisions to cover ABC as an appendix.
- Precast column connections without using couplers are feasible and being implemented.
- Superelastic SMAs are being considered as an alternative to improve seismic performance of structures.
- Unbonded CFRP tendons present a good alternative to steel tendons to reduce permanent drifts without concern about corrosion.

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