American Concrete Institute

Analysis of an Innovative Seismic Resilient Precast Pier System

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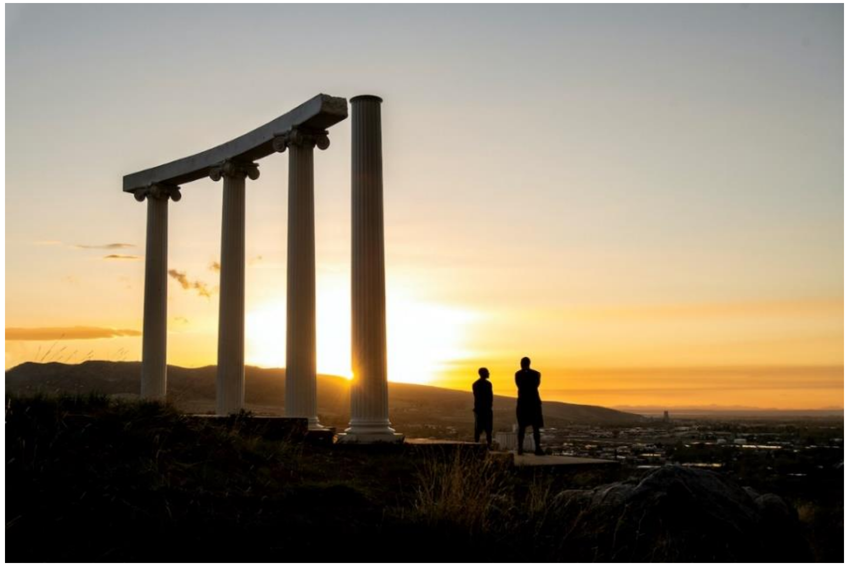
Outline

- Background
- Concept for a Precast Pier System
- Cast-In-Place Cantilever Pier
- Precast Cantilever Pier
- Numerical investigation
- Parametric Case Studies
- Conclusions

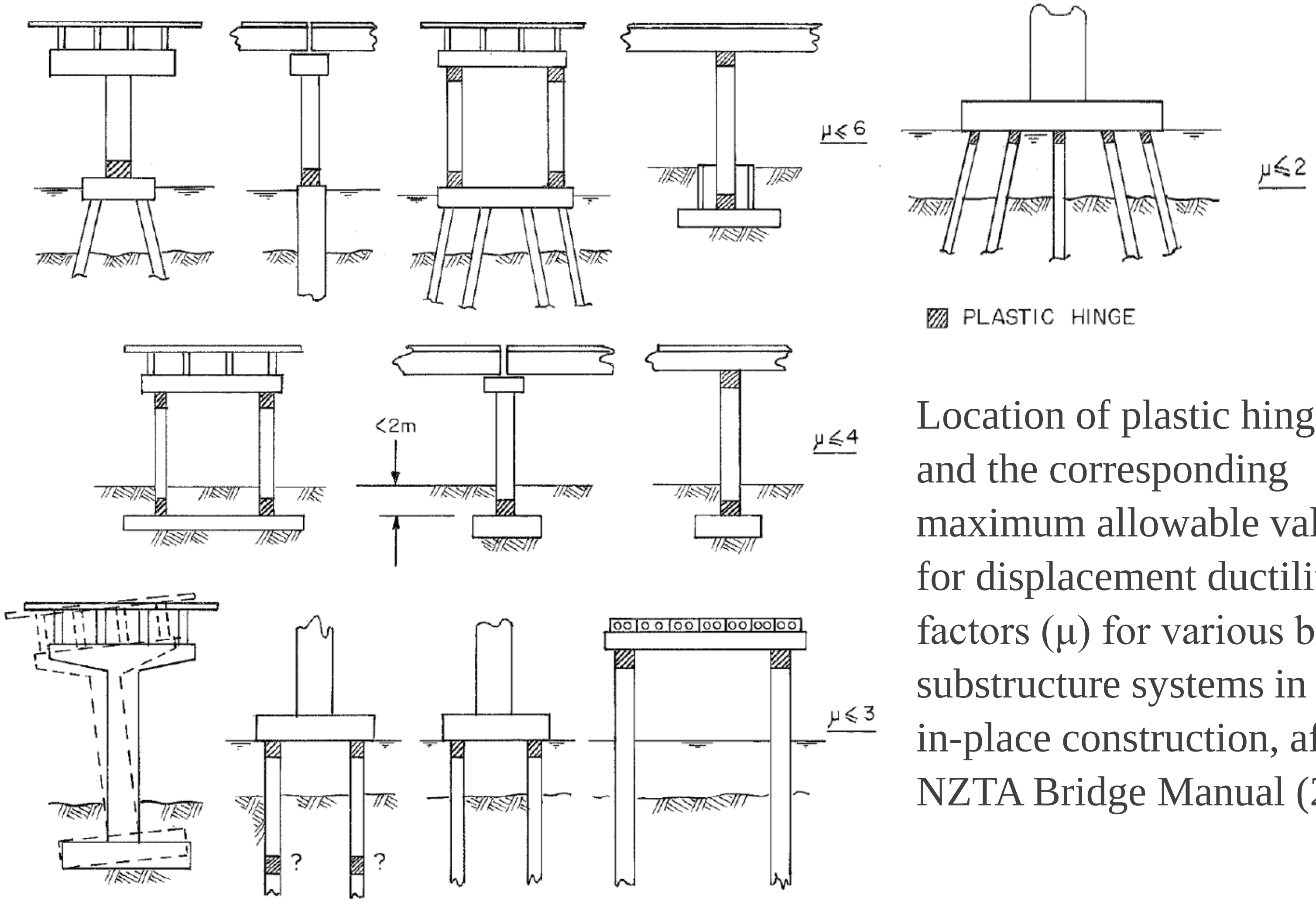


Project information

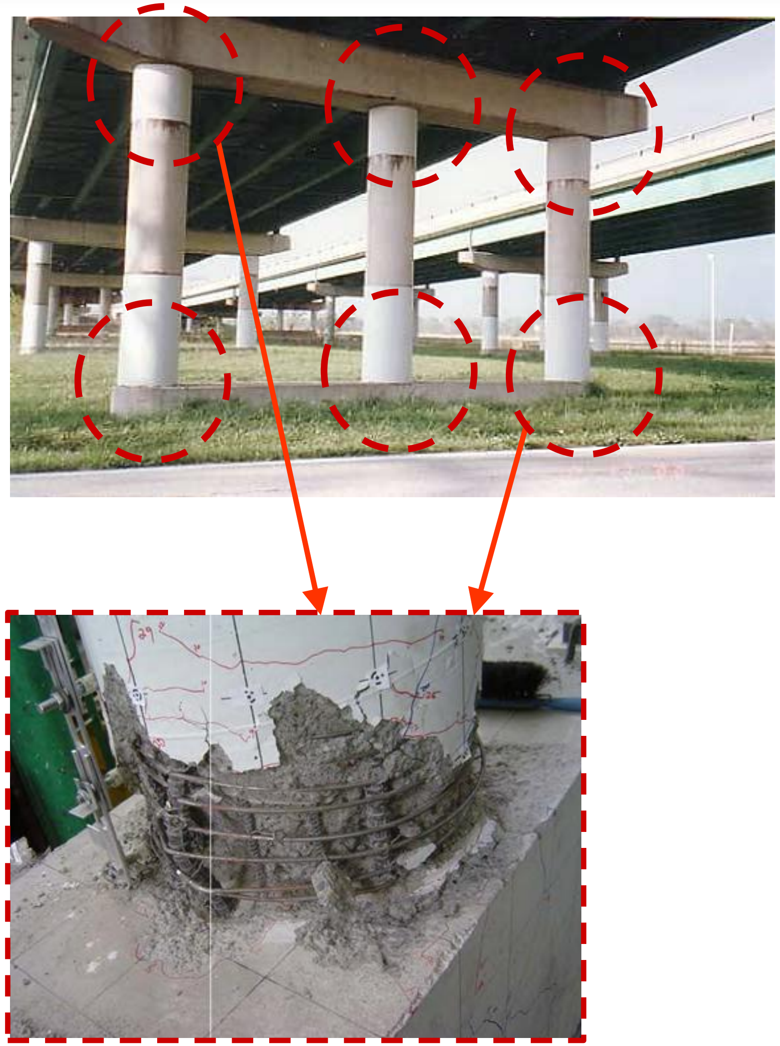
- **Project Title:** A Precast Pier System for ABC in Idaho (ITD Report 281)
- **Project Sponsor:** Idaho Transportation Department
- **Project Duration:** January 2019 – June 2021
- **Project Budget:** $150,000
- **Awarded Institution:** Idaho State University
- **Principal Investigator:** Mustafa Mashal, Ph.D., P.E.
- **Co-Principal Investigator:** Arya Ebrahimpour, Ph.D., P.E.
- **Graduate Students:** Jared Cantrell[1], Corey Marshall, Ali Shokrgozar, Mahesh Acharya, Kathryn Hogarth, Amin Torabi

1. Research Engineer/Lab Manager at ISU

Background



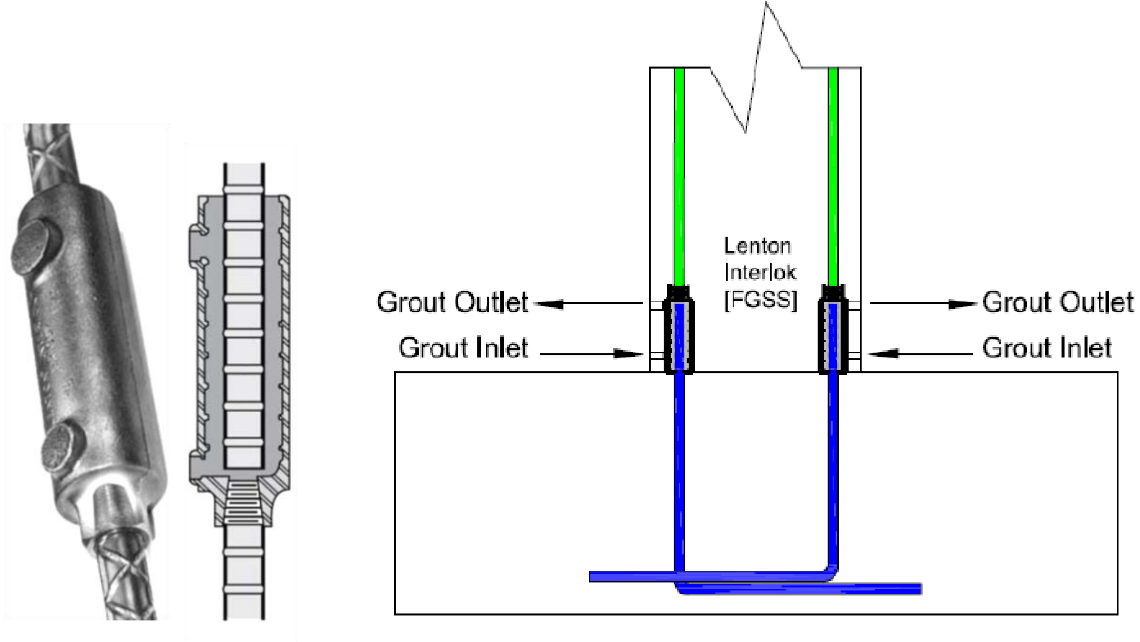
Location of plastic hinges and the corresponding maximum allowable values for displacement ductility factors (μ) for various bridge substructure systems in cast-in-place construction, after NZTA Bridge Manual (2013)



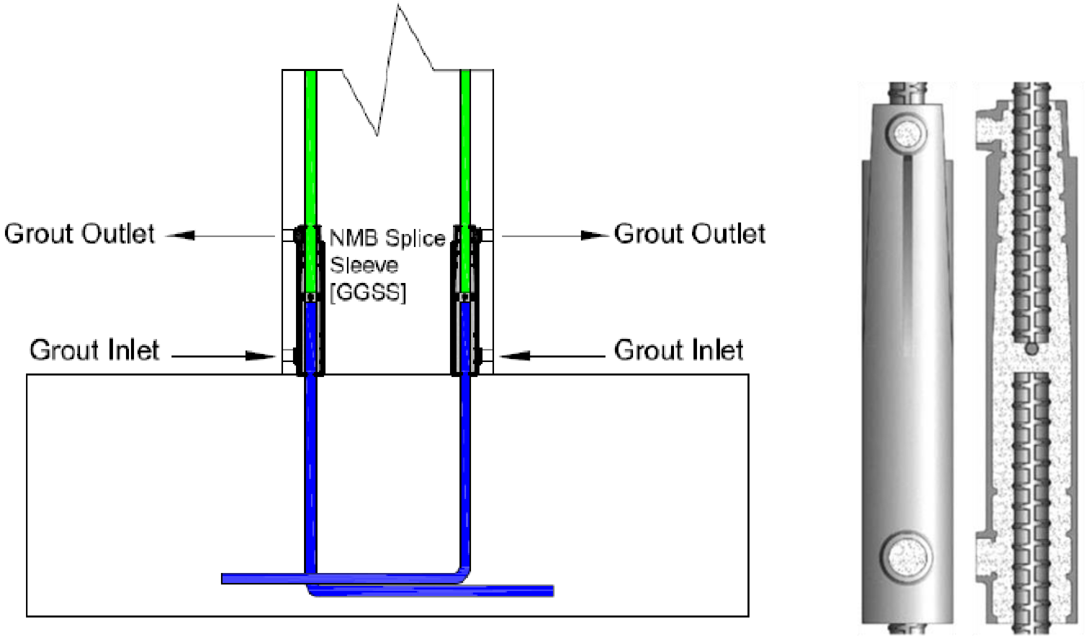
Typical plastic hinge in cast-in-place construction after a large earthquake

Background

Grouted Couplers



Type I. One end grouted, the other threaded



Type II. Both ends grouted

Grouted Couplers (Pantelides et al. 2014)

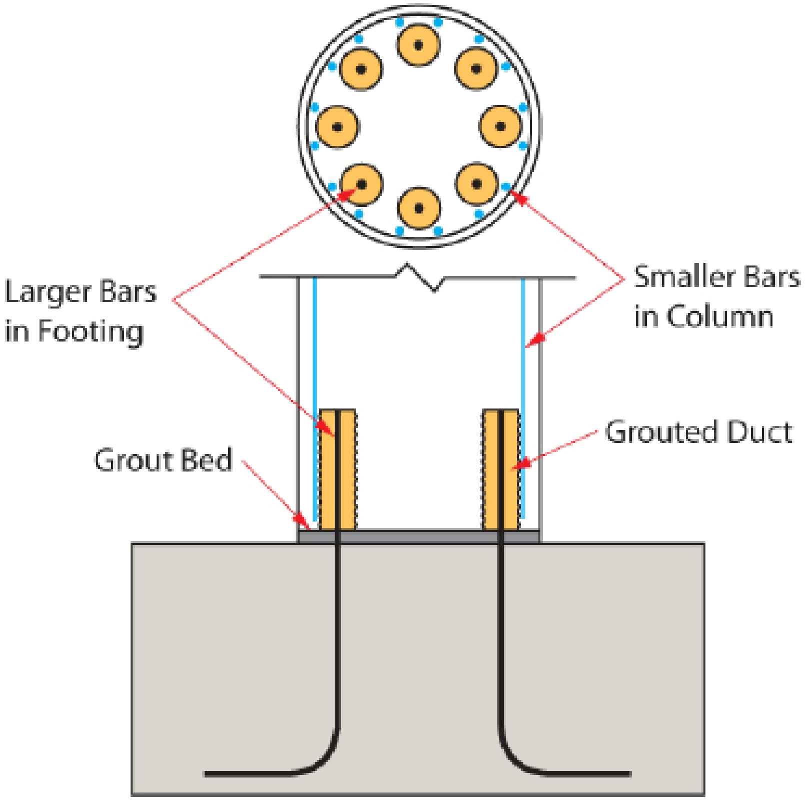
“Seismic Performance of Columns with Grouted Couplers in Idaho Accelerated Bridge Construction Applications”, Ebrahimpour et al. (2016), ITD Report 246.

Background

Grouted Post-Tensioned Ducts

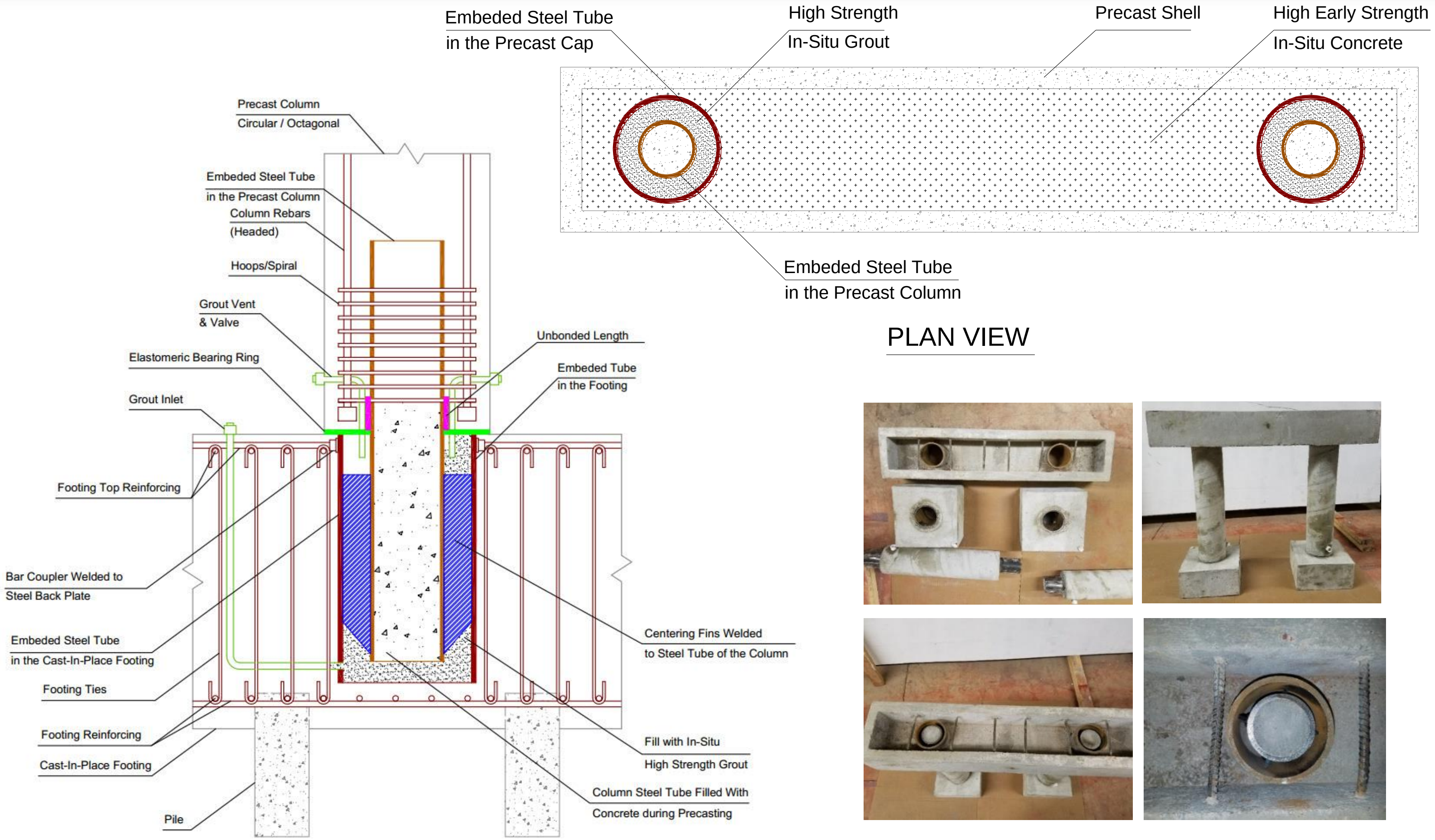
Post-tensioning ducts embedded in precast concrete components used to connect two concrete elements.

Lake Belton Bridge Replacement (FHWA, 2009)



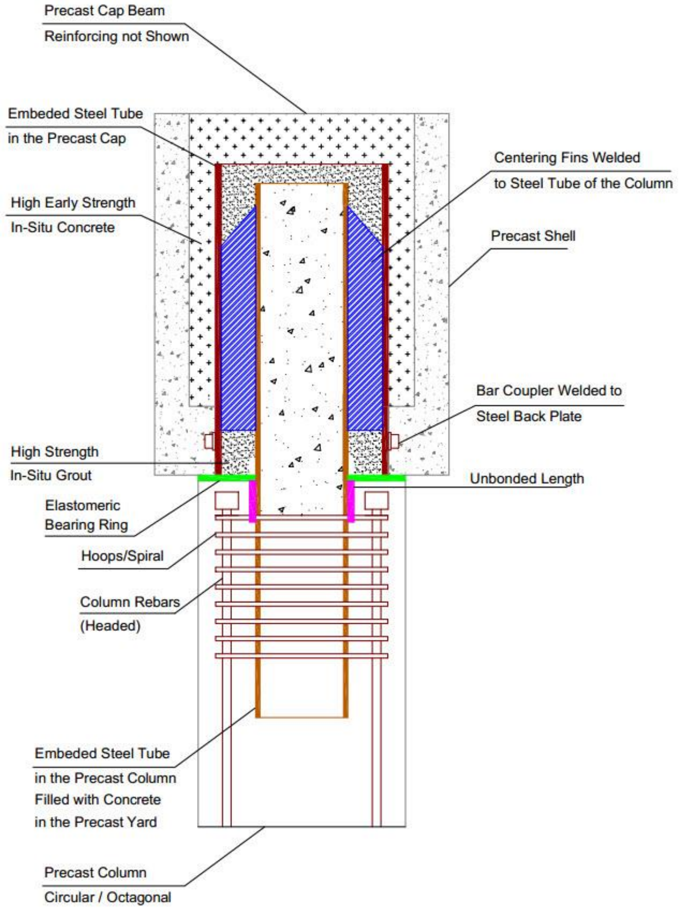
Typical Grouted Duct Connection (NCHRP Report 698)

Concept for a Precast Pier System



Pier-to-footing connection

Demonstration Model of the Concept

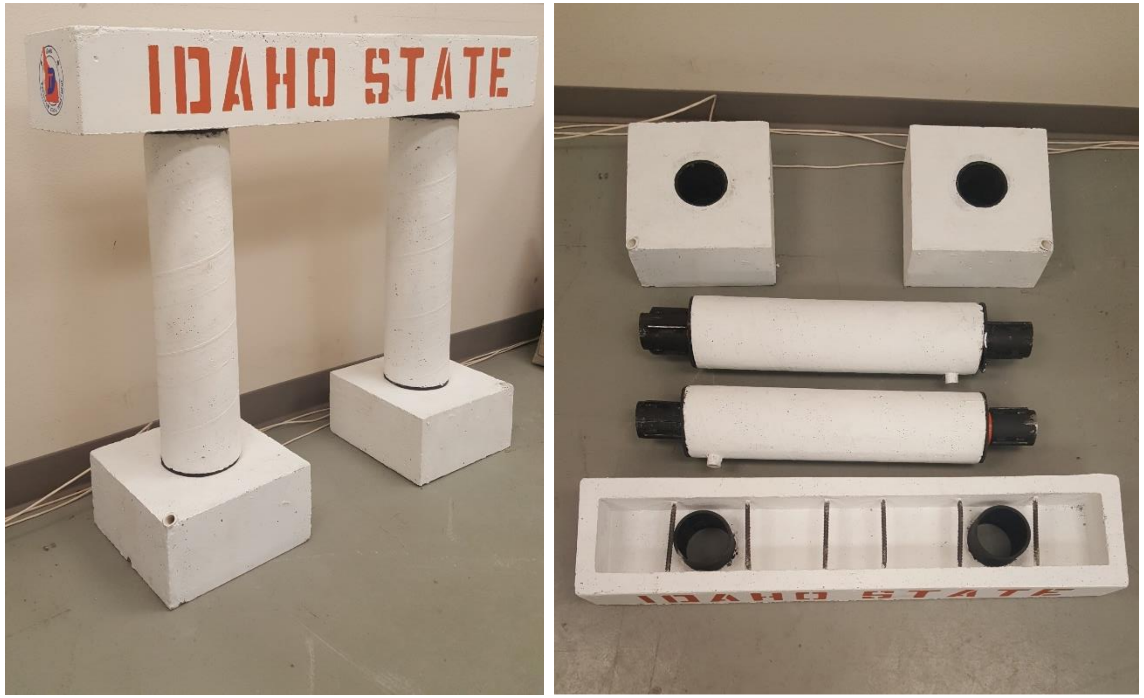


Pier-to-cap beam connection

Concept for a Precast Pier System

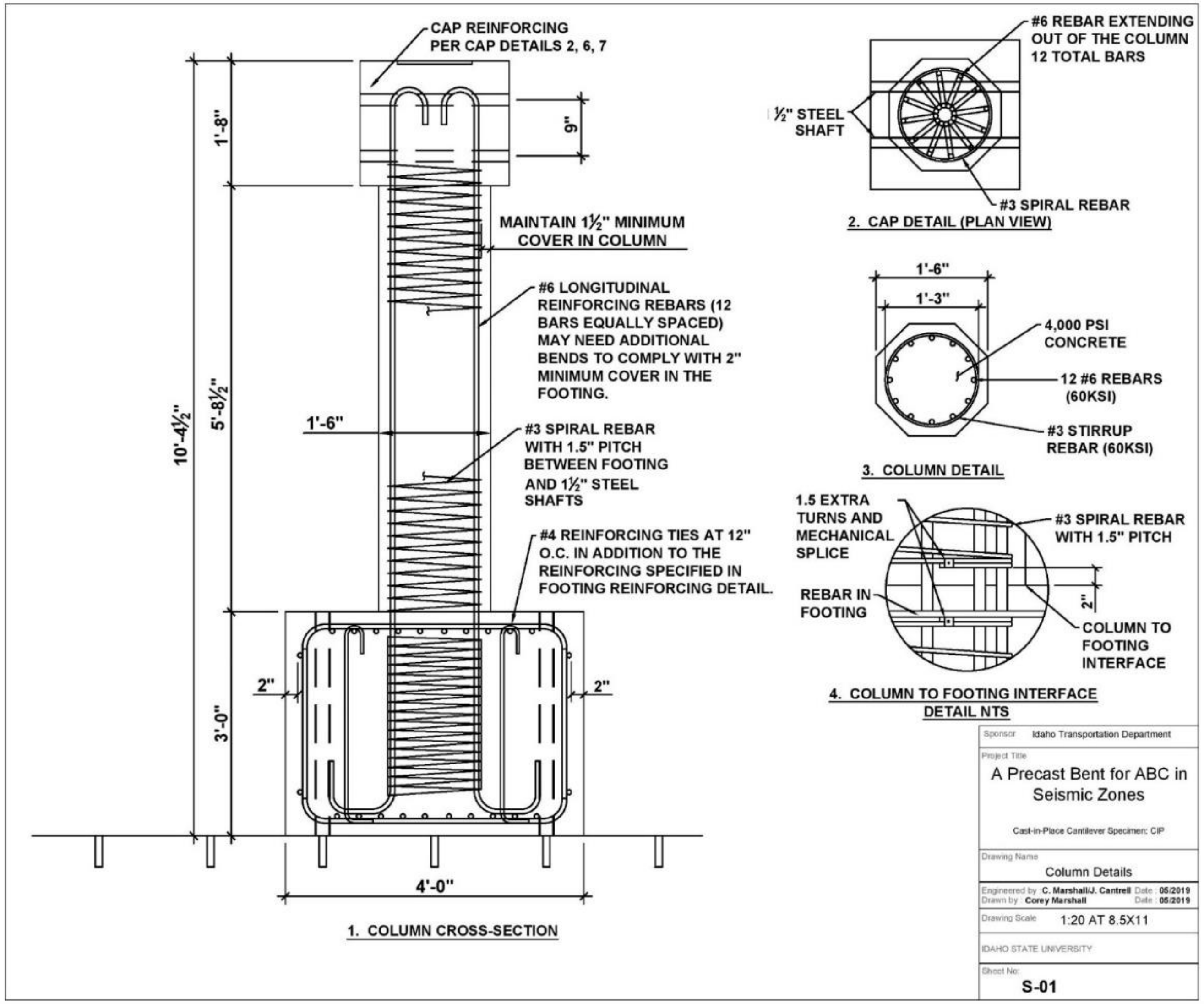
Advantages include:

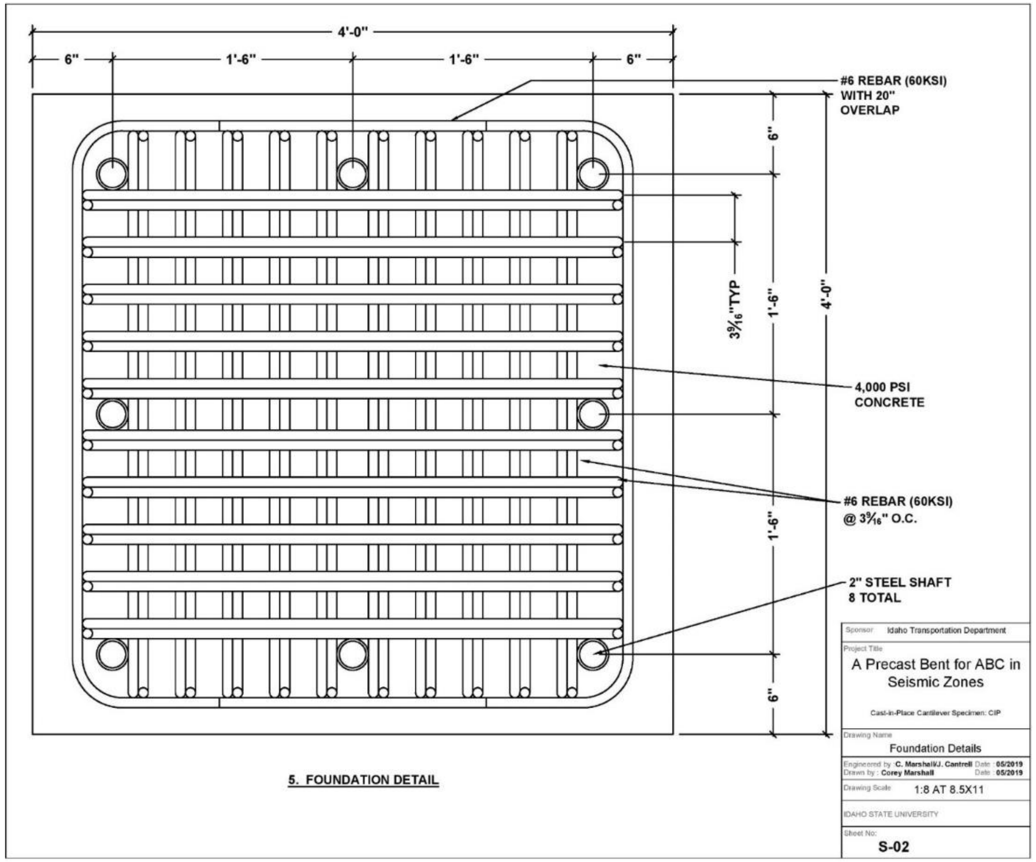
- Fast construction (use of ABC)
- Simple construction
- Ample installation tolerance
- Ease of erection
- Use of hollow precast pier shell
- Option for solid precast pier shell
- Non-proprietary components/materials
- Improved on-site safety
- Faster construction
- Allows deformation during smaller movements without cracking and crushing of concrete



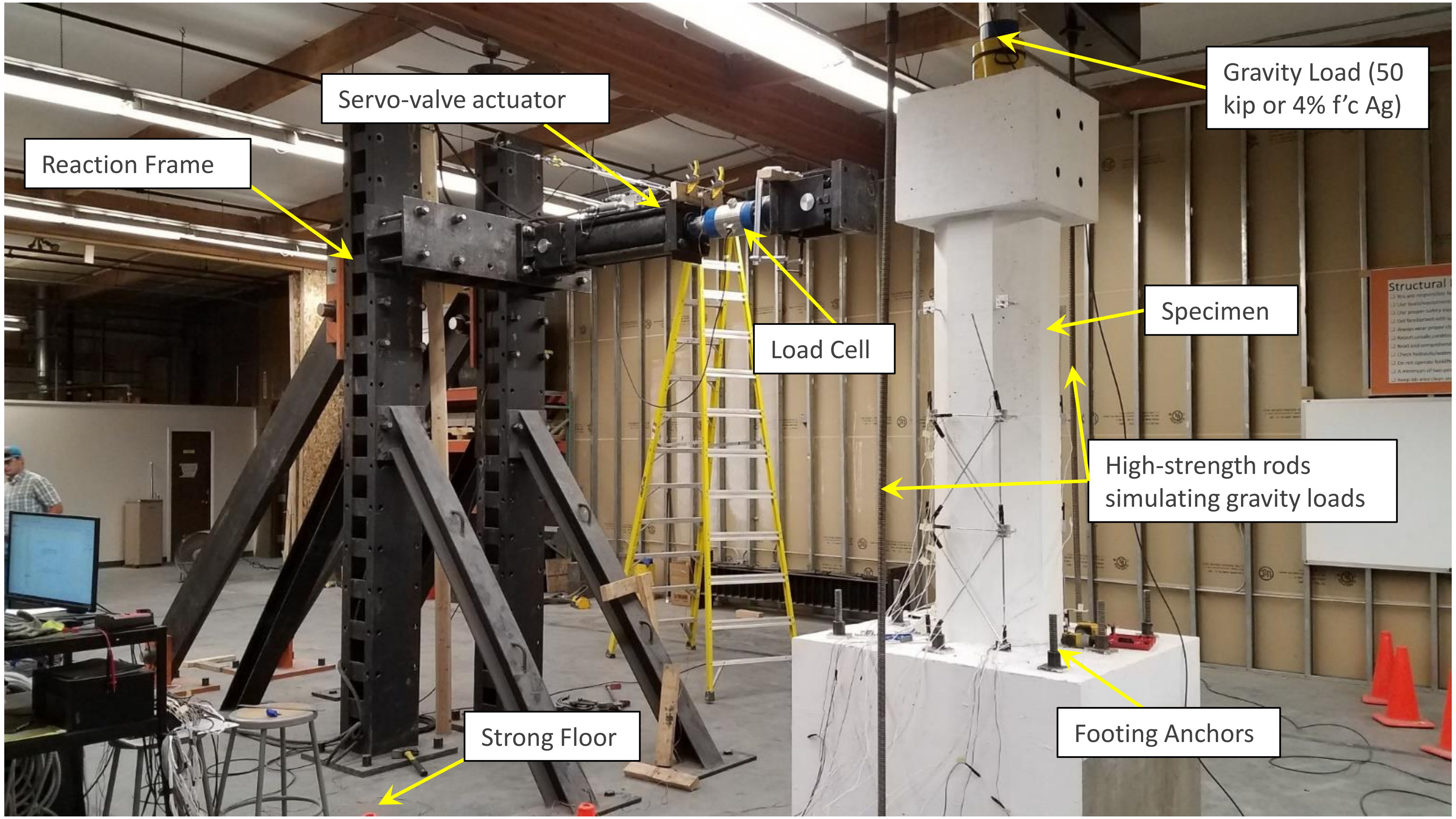
Proposed precast bent

Cast-In-Place Cantilever Pier

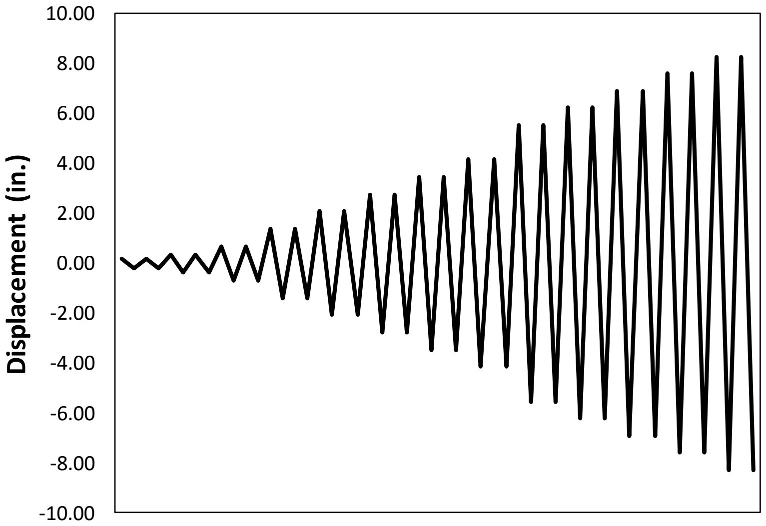




Cast-In-Place Cantilever Pier

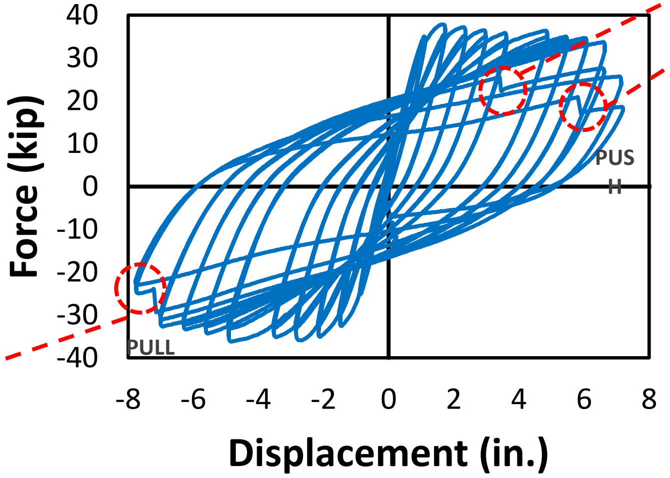


Typical Arrangement for Uni-directional Testing



Quasi-static cyclic loading protocol

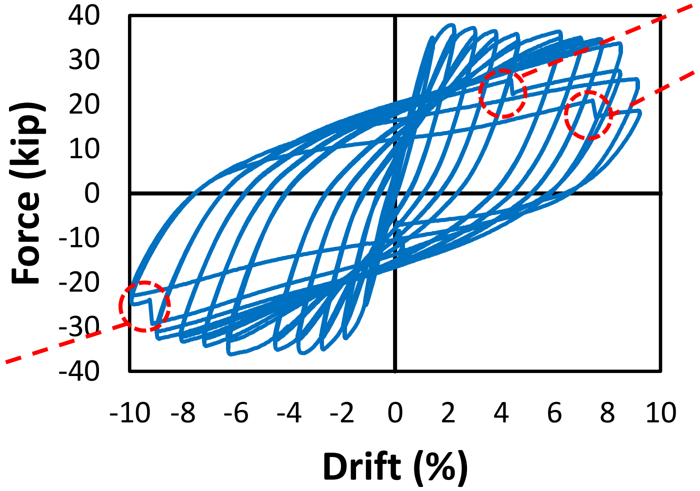
Cast-In-Place Cantilever Pier



First rupture

Third rupture

Second rupture

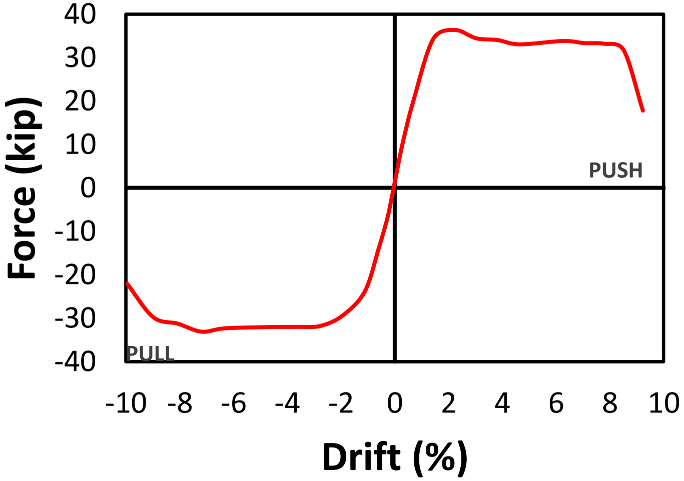


First rupture

Third rupture

Second rupture

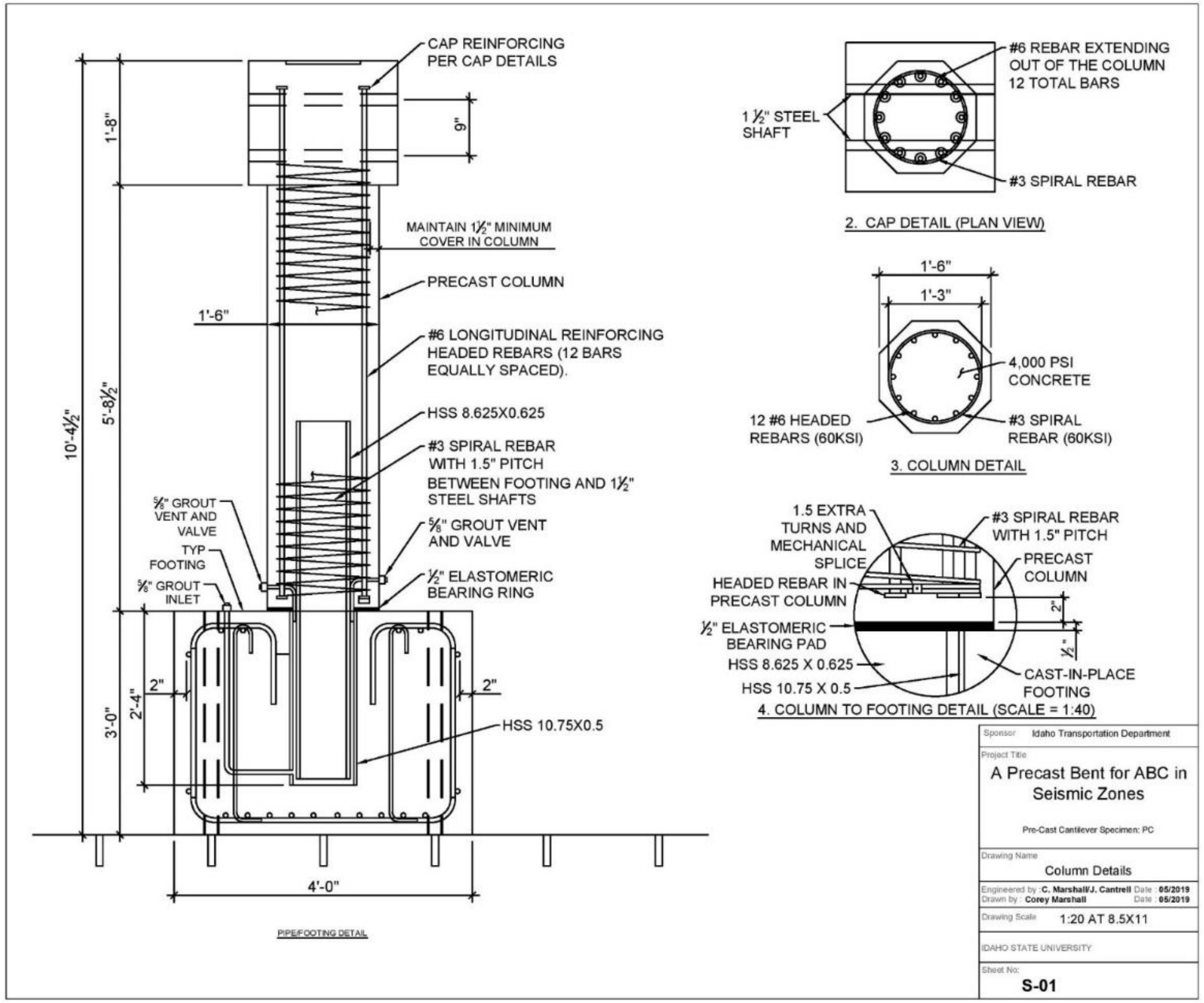
10.0% Drift Ratio (2nd rebar rupture)

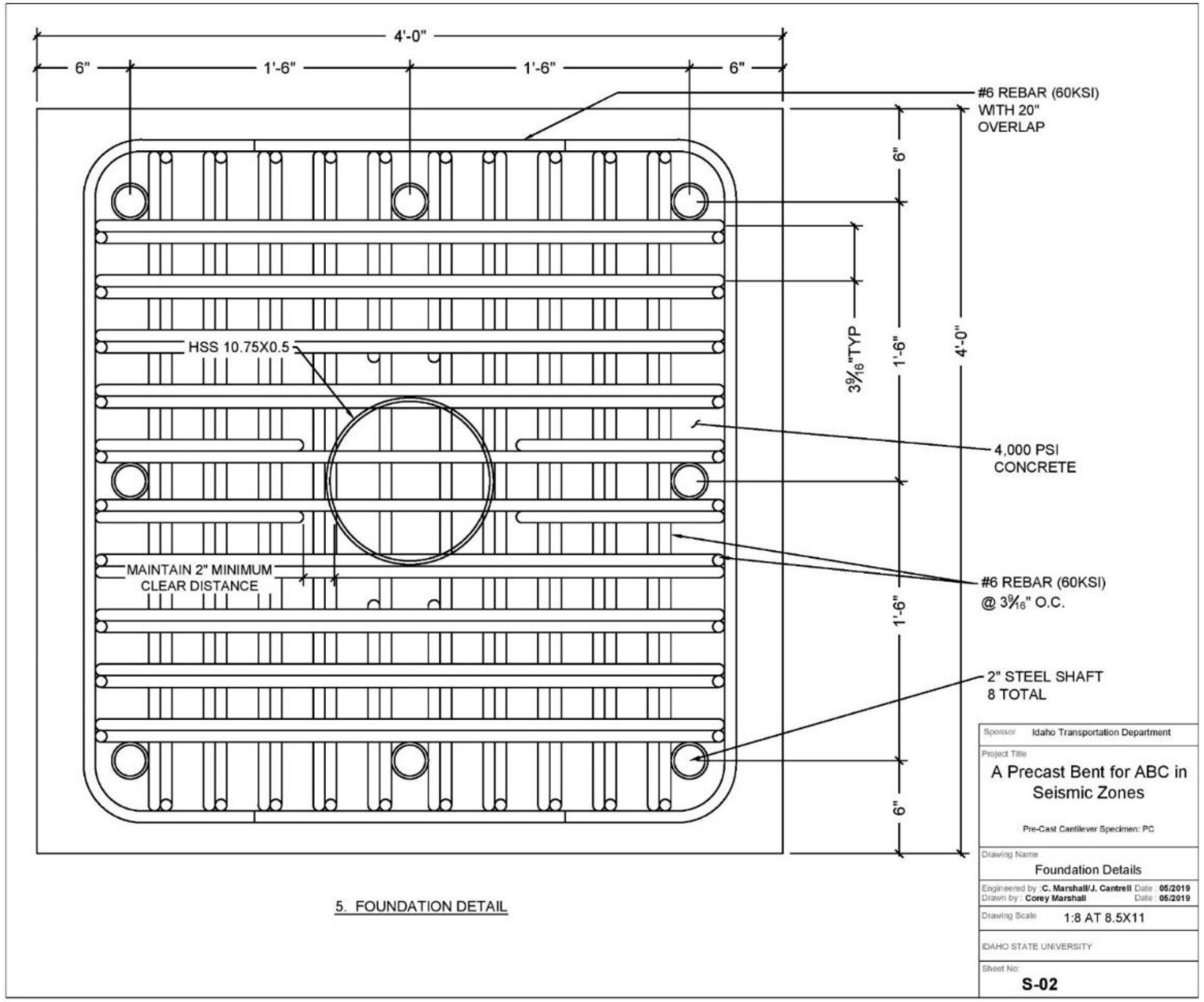


9.0% Drift Ratio (1st rebar rupture)

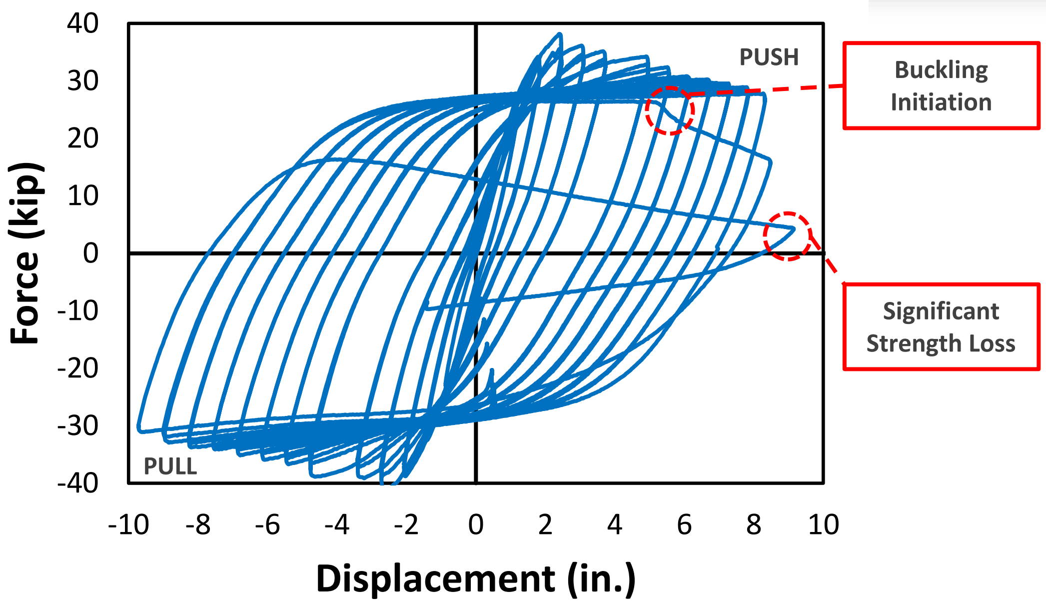
10.0% Drift Ratio (3rd rebar rupture)

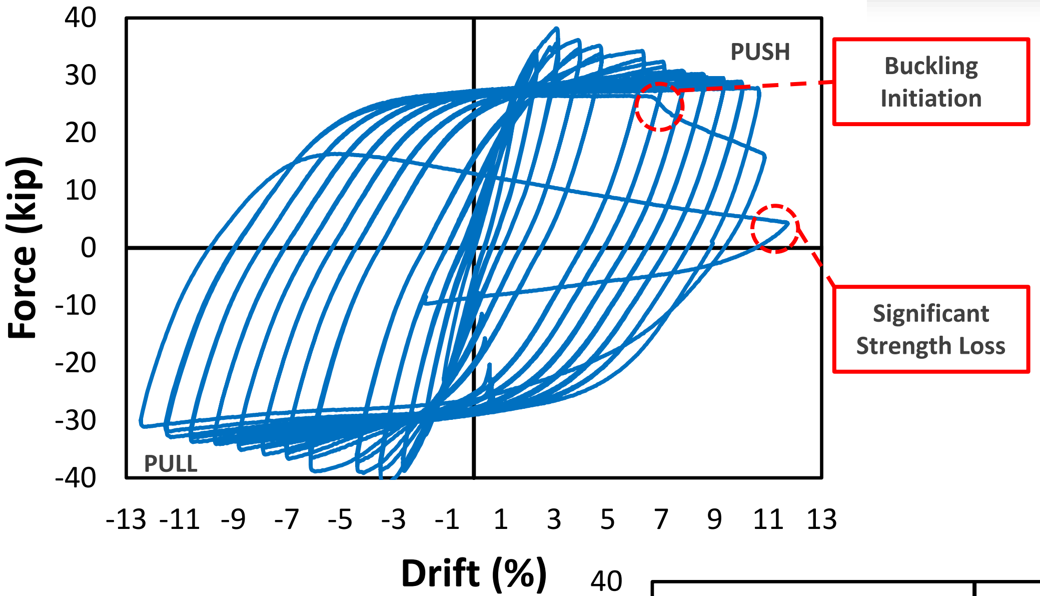
Precast Cantilever Pier



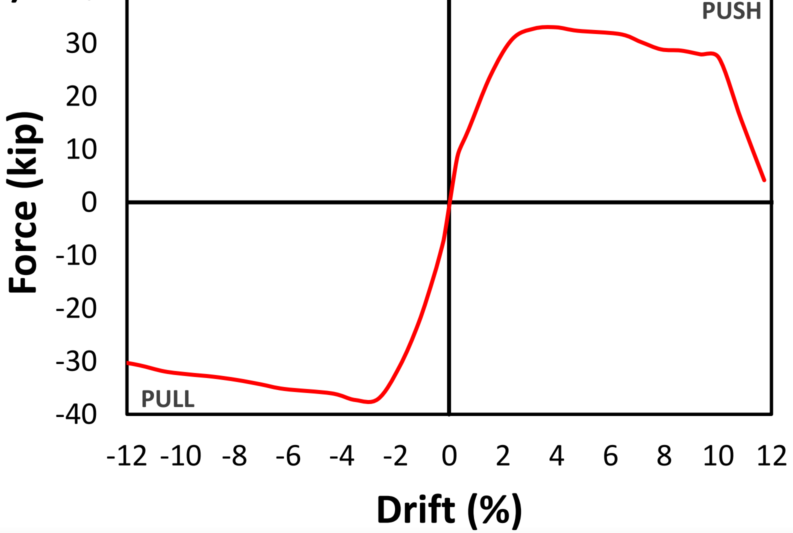


Precast Cantilever Pier

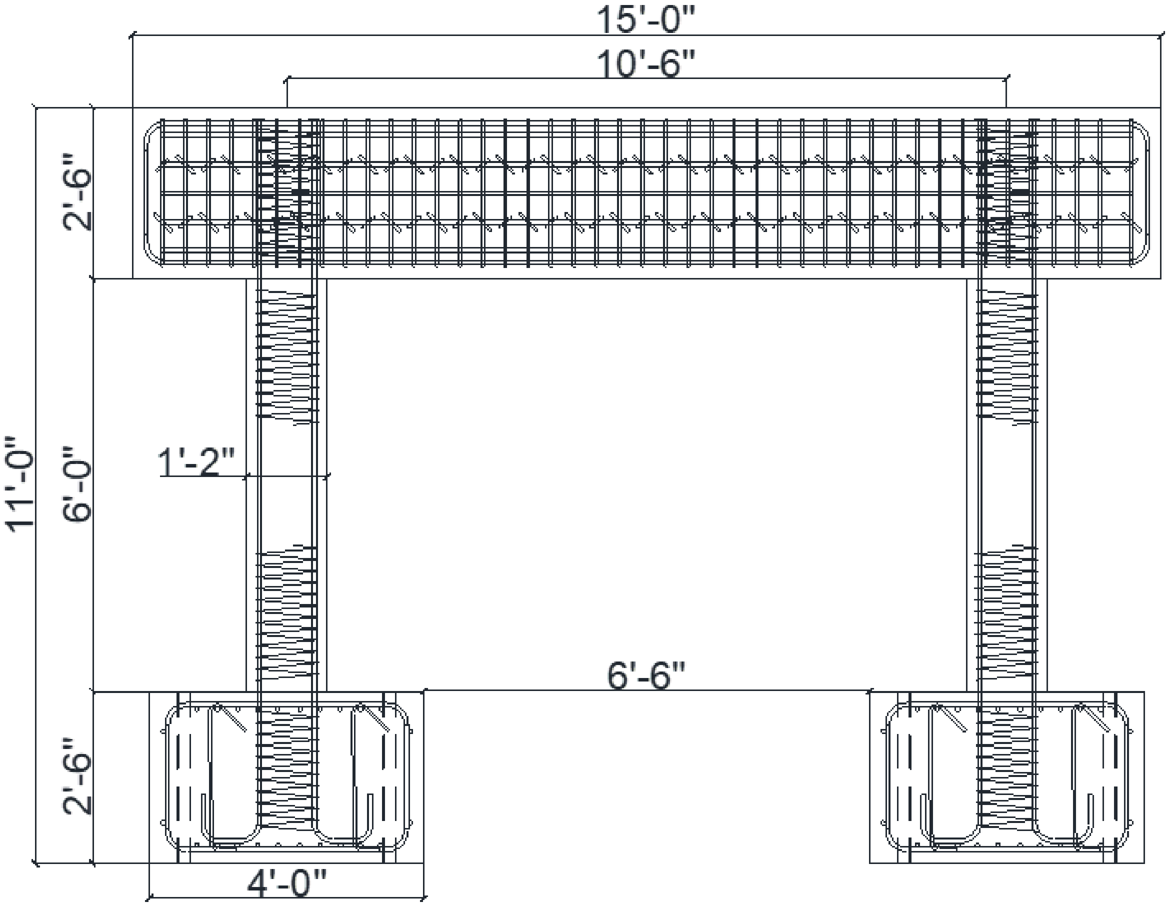


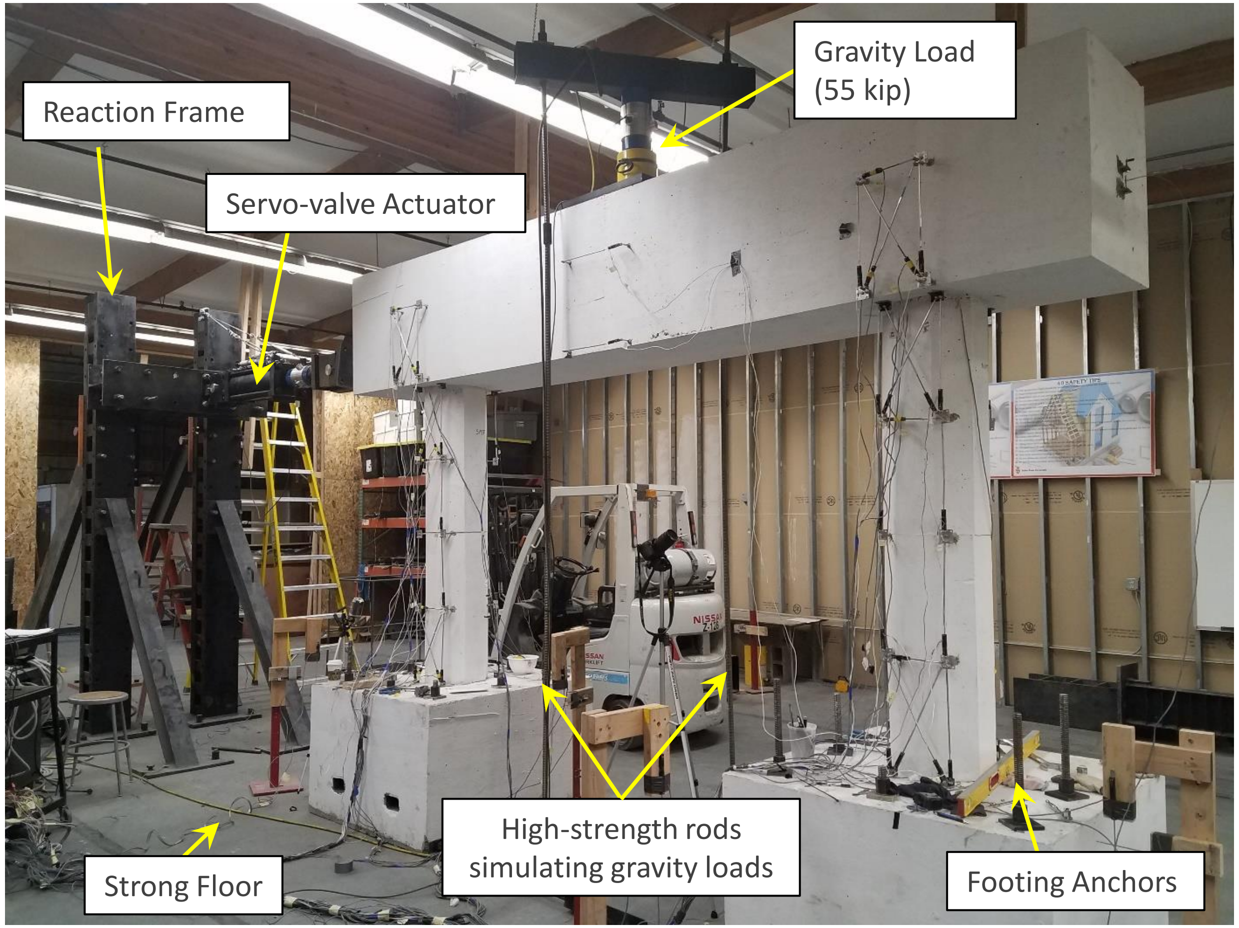


12.45% Drift Ratio (significant buckling of the steel pipe)

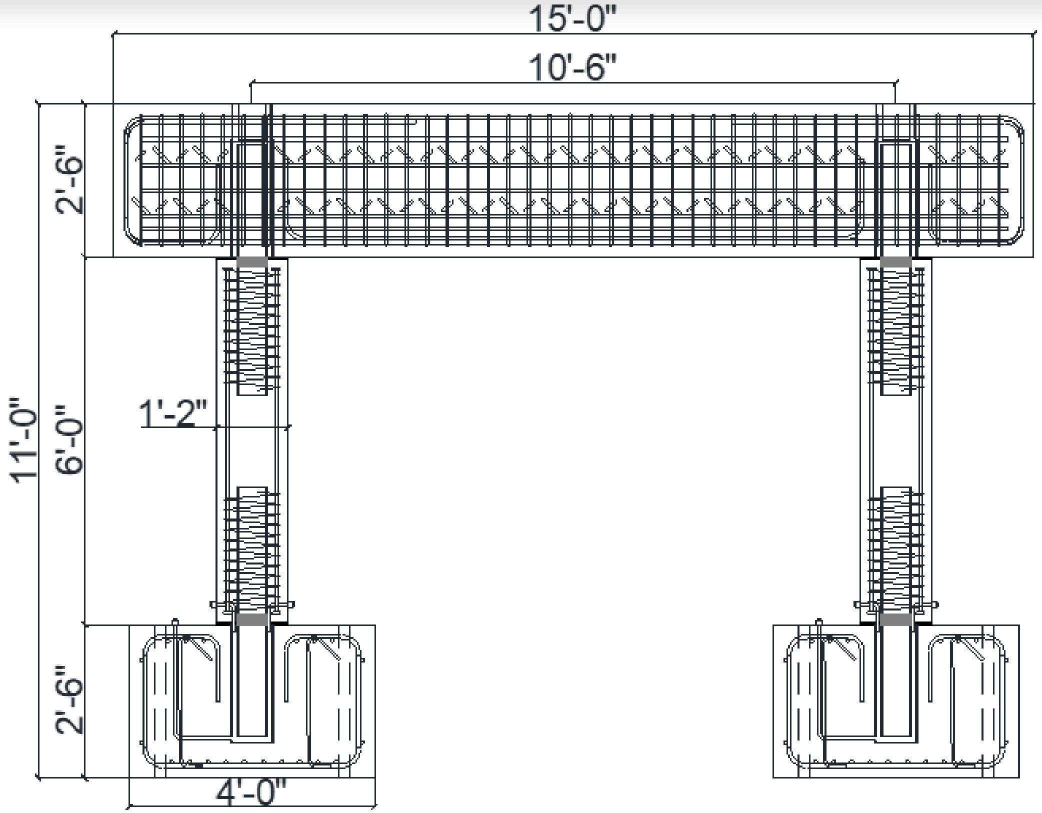


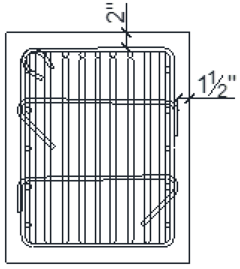
Cast-In-Place Bent



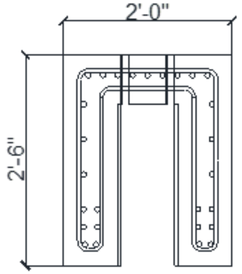


Precast Bent

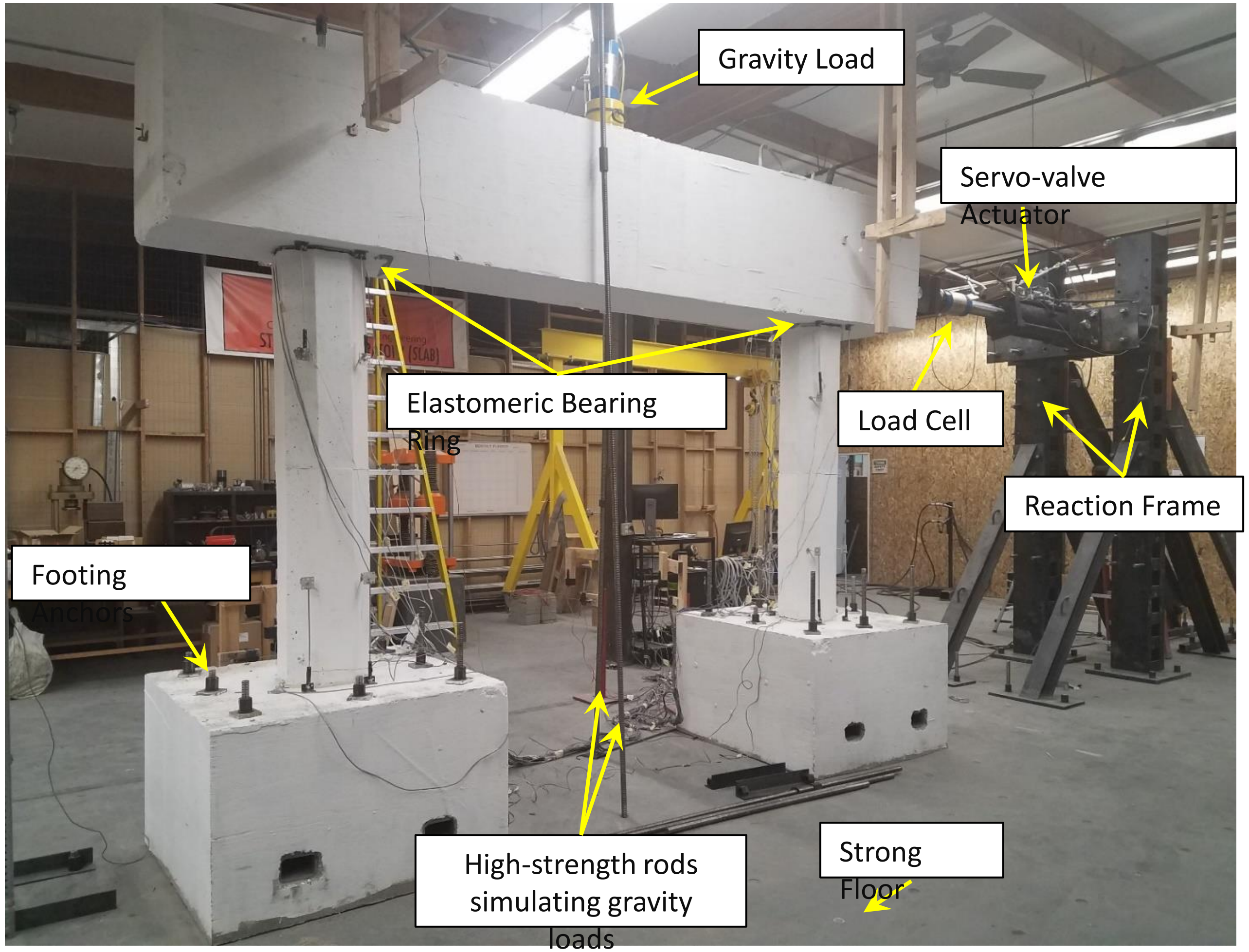




Cap Cross-Section outside of Column



Cap Cross-Section above Column



Gravity Load

Servo-valve Actuator

Elastomeric Bearing Ring

Load Cell

Reaction Frame

Footing Anchors

High-strength rods simulating gravity loads

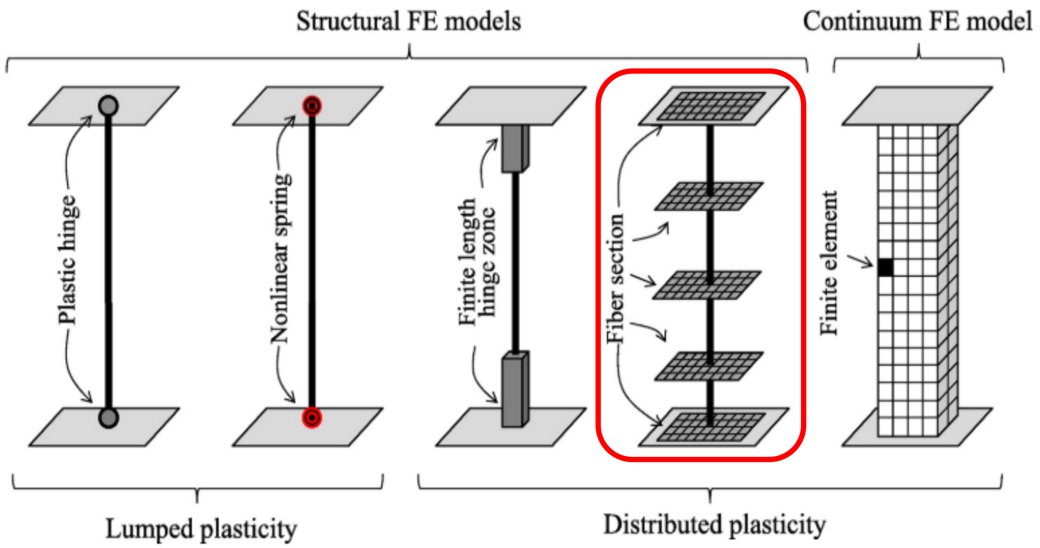
Strong Floor

Numerical Investigation

- Finite Element Analysis of the proposed connection using OpenSees with some input from SAP 2000.
- Calibration of analytical models against experimental data.
- Proposing a back-bone curve and appropriate hysteretic rule for the proposed connection.

Numerical Investigation

- Nonlinear beam-column element with distributed plasticity
  - Permits spread of plasticity along the element.



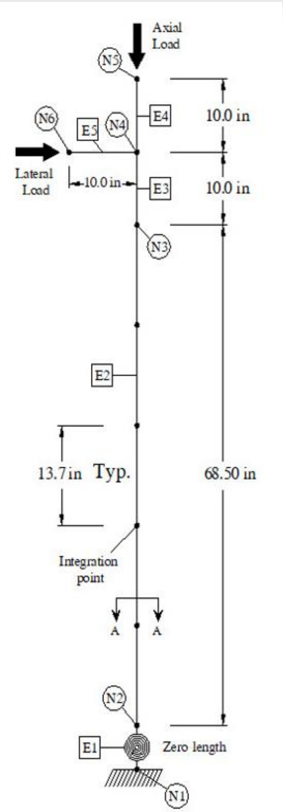
(Astroza, R. et al., 2015)

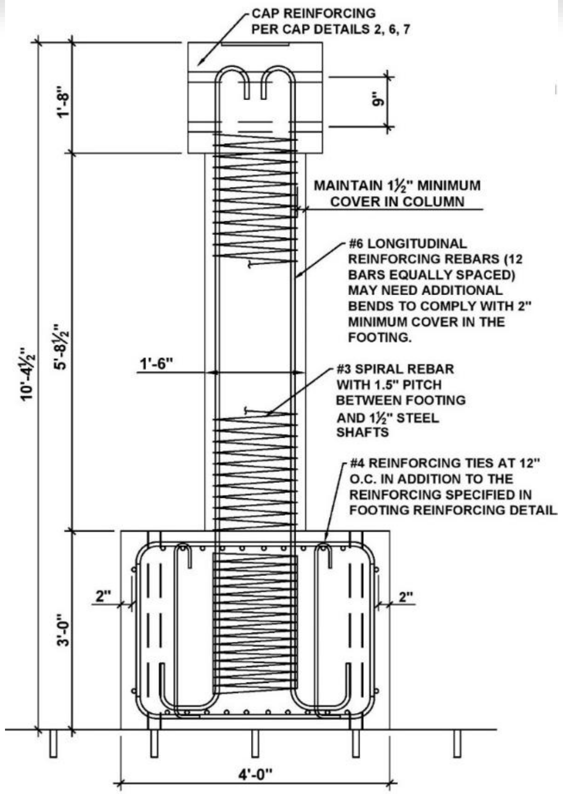
- Material models
  - Unconfined concrete: *Concrete01*
  - Confined concrete: *Concrete04*
  - Reinforcing steel: *Steel02*
- SAP2000 was used to obtain Mander's stress-strain model strength and strain values for confined concrete.

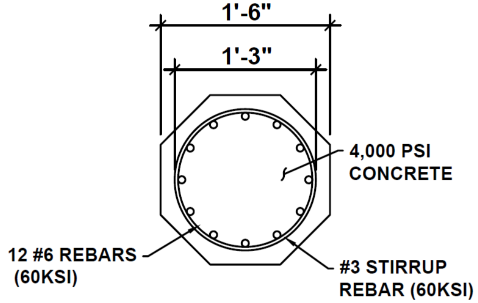
Numerical Investigation

Portion of OpenSees model

```
#Create Model with 3 dimensions and 6 degrees of freedom
model BasicBuilder -ndm 3 -ndf 6
#Create 6 DOF nodes

#       tag    x      y       z
node     1    0.0   0.0     0.0
node     2    0.0   0.0     0.0
node     3    0.0   68.5   0.0
node     4    0.0   78.5   0.0
node     5    0.0   88.5   0.0
node     6    -10   78.5   0.0

#Fix node 1
fix  1  1  1  1  1  1  1
fix  2  1  1  1  0  0  0

#Create uniaxial materials for Concrete and Steel
uniaxialMaterial Concrete01  1  -4.   -0.002  0  -0.005
uniaxialMaterial Concrete04  2  -7.2      -0.0112  -0.0237  2737
uniaxialMaterial Steel02  3  68   29000   0.01   17   0.925   0.15
#Create hysteretic material to model Bond-Slip
uniaxialMaterial Hysteretic 4  2500  .0031  3085. .096  -2500  -.0031   -3085.  -.096    10.5  0.5  0  0.1  0.4
#Create fiber section with defined concrete and rebar
section Fiber  1  {
patch circ 2 16  10  0  0  0  7.125  0  360
layer circ 3 12 0.441 0 0 6.75
patch quad 1 1 1 6.75 0 7.5 0 7.4135 1.4992 6.6203 1.3169
...
}
```

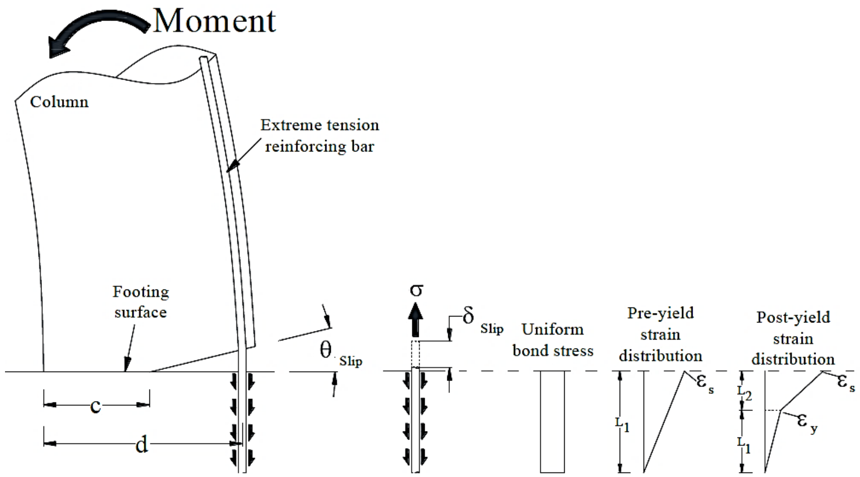






Numerical Investigation

Bond-slip at the footing



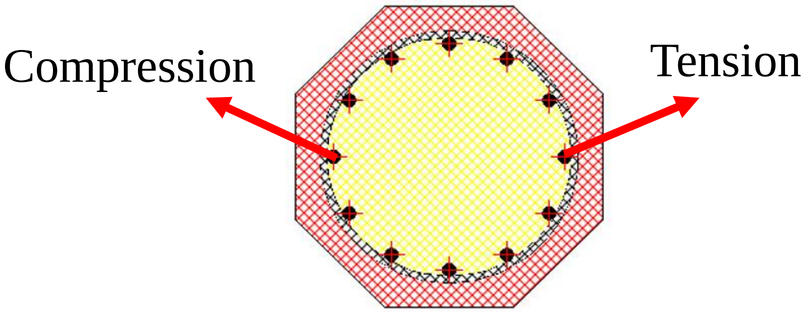
$$L_1 = \frac{f_s d_b}{4u}$$

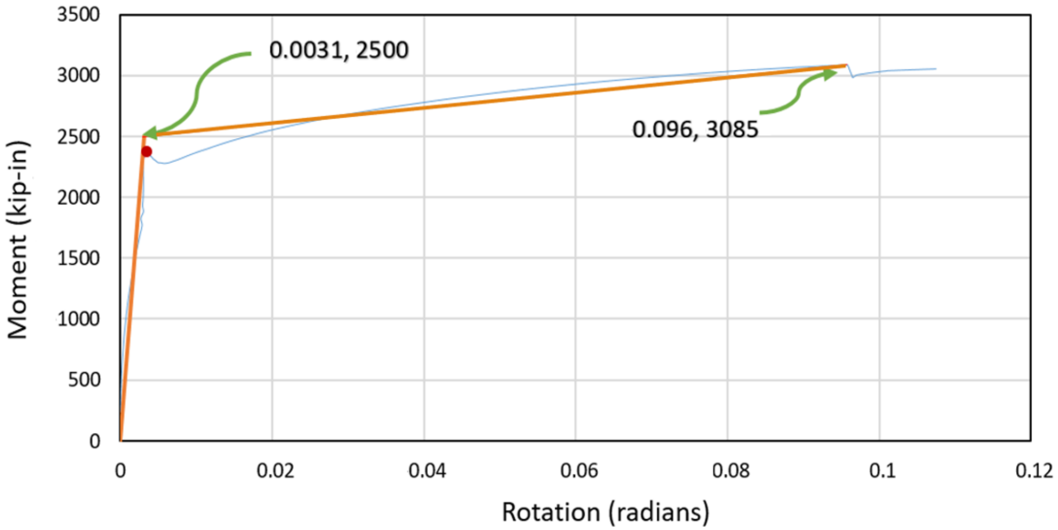
$$L_2 = \frac{(f_s - f_y)\, d_b}{4u}$$

$$u = \frac{9.5\sqrt{f_c'}}{d_b} \leq 800\ psi$$

$$\theta_{slip} = tan^{-1}\left(\frac{\delta_{slip}}{c-d}\right)$$

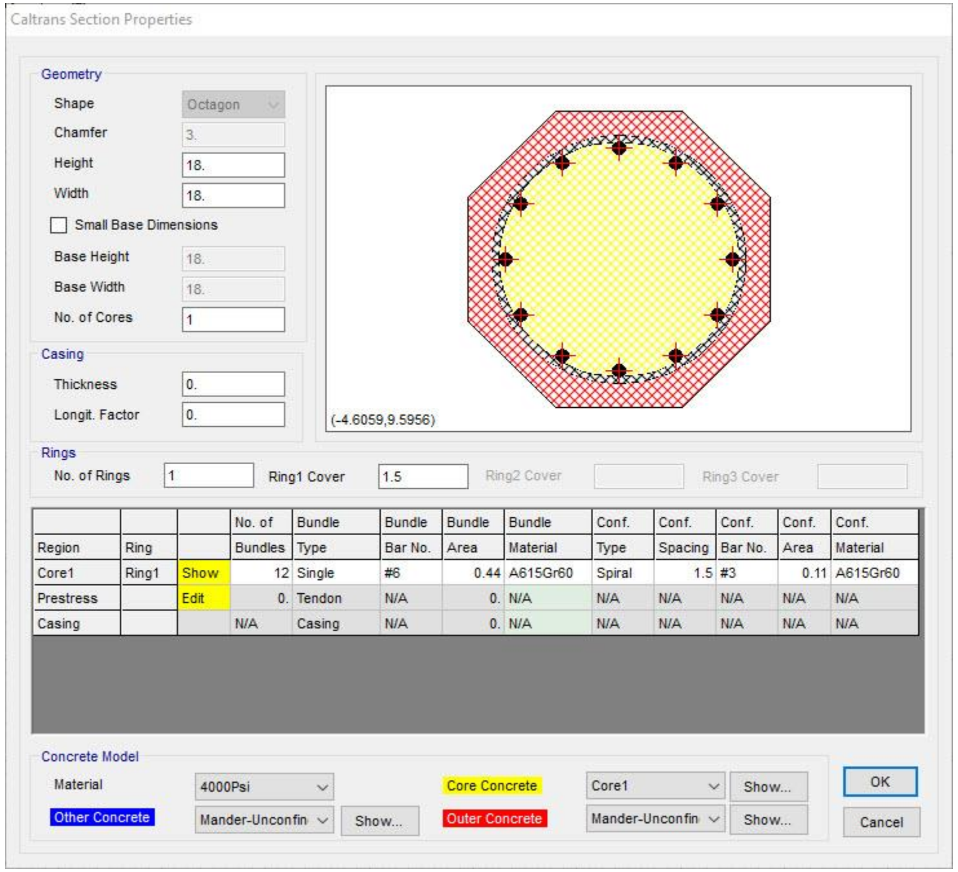
$$c = 2.65 + \frac{|\varepsilon_c|}{(\varepsilon_t - \varepsilon_c)}(18.37)\ in.$$





Numerical Investigation

Confined concrete stress-strain from SAP2000, Mander’s model



Caltrans Section Properties

Geometry
Shape: Octagon
Chamfer: 3.
Height: 18.
Width: 18.
☐ Small Base Dimensions
Base Height: 18.
Base Width: 18.
No. of Cores: 1

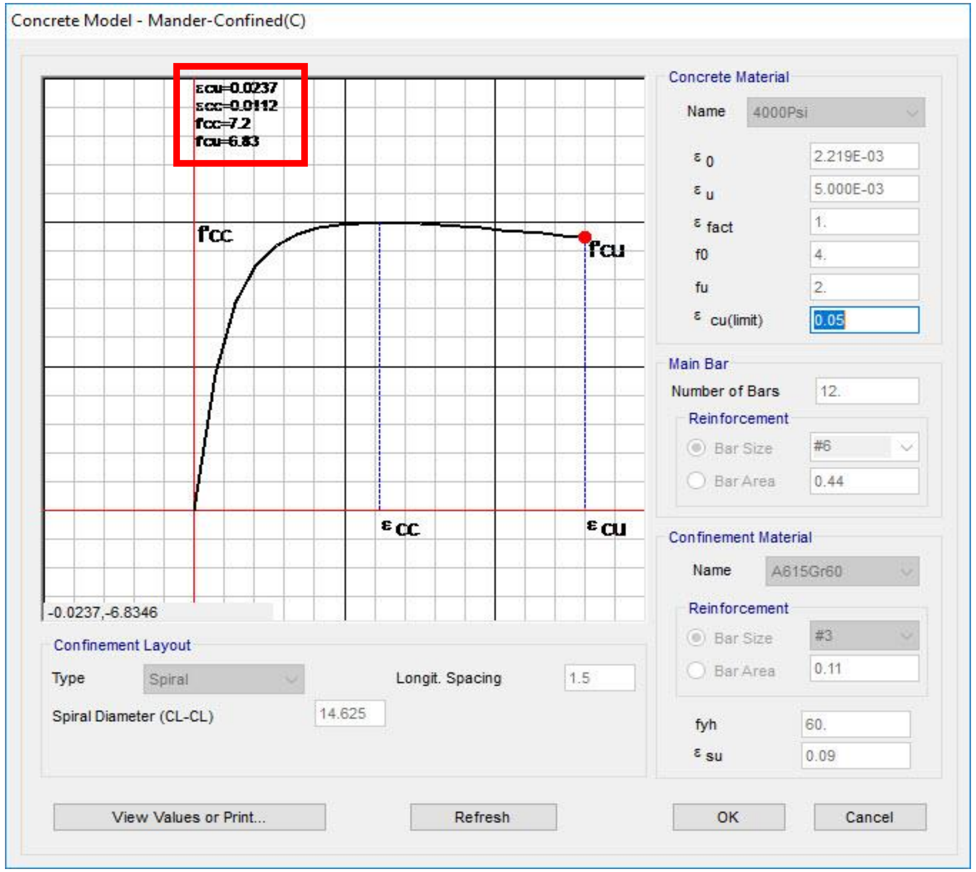
Casing
Thickness: 0.
Longit. Factor: 0.

(-4.6059,9.5956)

Rings
No. of Rings: 1
Ring1 Cover: 1.5
Ring2 Cover:
Ring3 Cover:

Region	Ring		No. of Bundles	Bundle Type	Bundle Bar No.	Bundle Area	Bundle Material	Conf. Type	Conf. Spacing	Conf. Bar No.	Conf. Area	Conf. Material
Core1	Ring1	Show	12	Single	#6	0.44	A615Gr60	Spiral	1.5	#3	0.11	A615Gr60
Prestress		Edit	0.	Tendon	N/A	0.	N/A	N/A	N/A	N/A	N/A	N/A
Casing			N/A	Casing	N/A	0.	N/A	N/A	N/A	N/A	N/A	N/A

Concrete Model
Material: 4000Psi
Other Concrete: Mander-Unconfin
Core Concrete: Core1
Outer Concrete: Mander-Unconfin



Concrete Model - Mander-Confined(C)

εcu=0.0237
εcc=0.0112
fcc=7.2
fcu=6.83

-0.0237,-6.8346

Confinement Layout
Type: Spiral
Longit. Spacing: 1.5
Spiral Diameter (CL-CL): 14.625

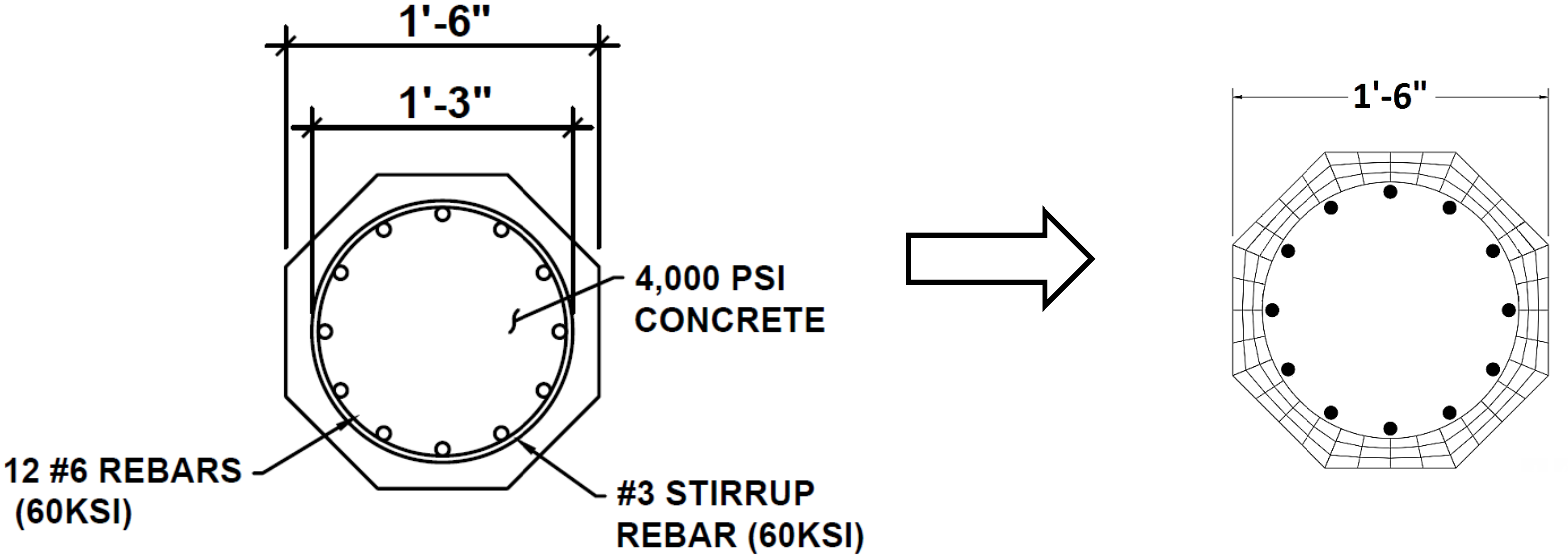
Concrete Material
Name: 4000Psi
ε_0: 2.219E-03
ε_u: 5.000E-03
ε_{fact}: 1.
f0: 4.
fu: 2.
$\varepsilon_{cu(limit)}$: 0.05

Main Bar
Number of Bars: 12.
Reinforcement
● Bar Size: #6
○ Bar Area: 0.44

Confinement Material
Name: A615Gr60
Reinforcement
● Bar Size: #3
○ Bar Area: 0.11
fyh: 60.
ε_{su}: 0.09

Numerical Investigation

- **Octagonal cross-section model in OpenSees**



  - Circular patch for confined concrete
  - Quadrilateral patches for unconfined concrete
  - Reinforcing bars generated with the circular arc layer command

Numerical Investigation

- **Low-cycle fatigue**

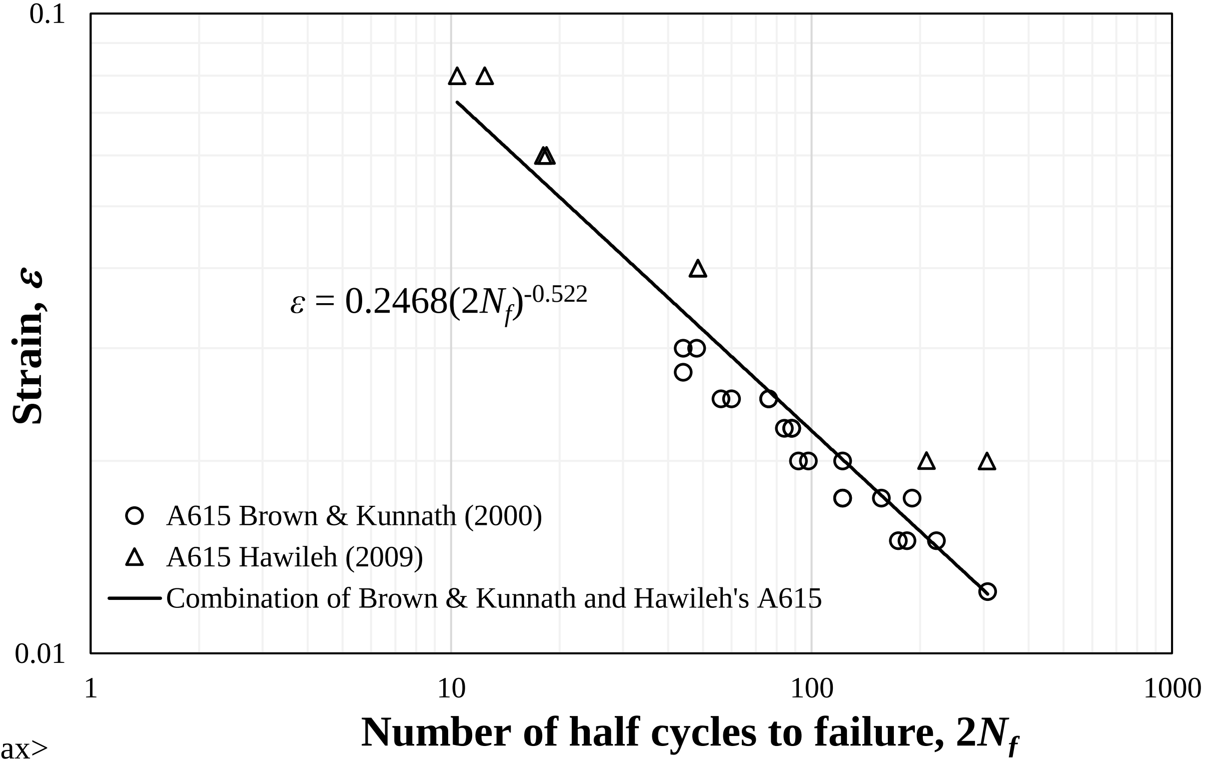
  - The relation for the strain versus number of half-cycles to failure for ASTM A615:

$$0.2468(2N_f)^{-0.522}$$

In order to introduce low-cycle fatigue in OpenSees, the appropriate parameters for the Coffin-Manson curve needed to be introduced.

  - OpenSees code added lines:

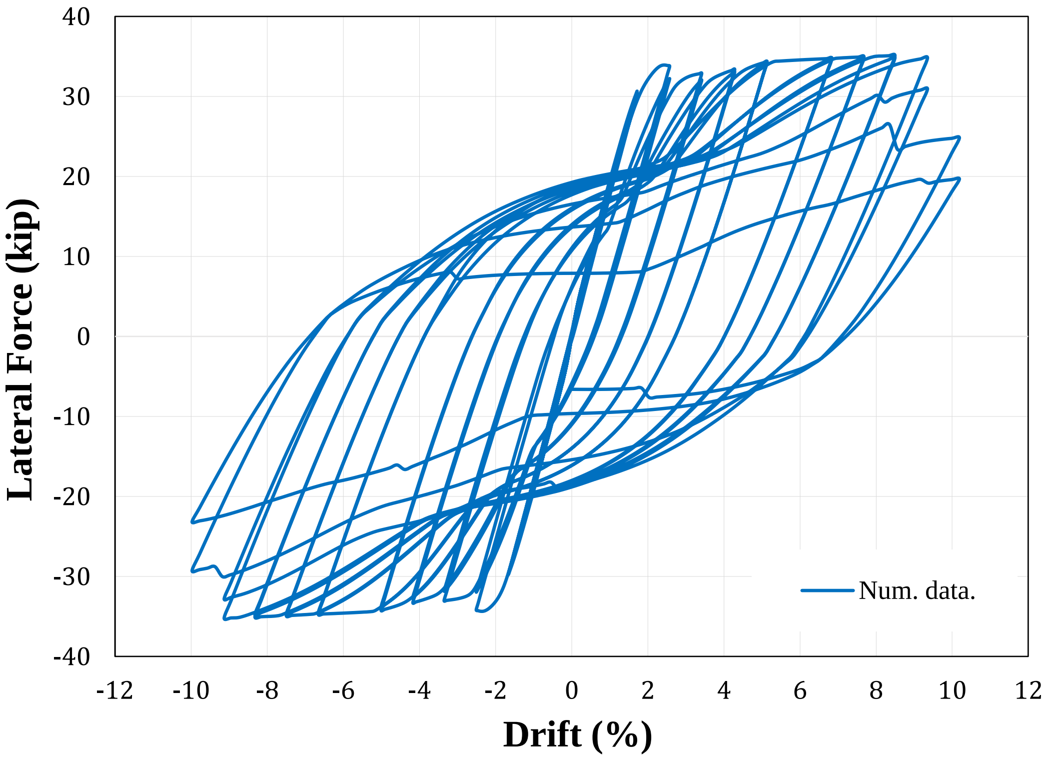
```
#uniaxialMaterial Fatigue $matTag $tag <-E0 $E0> <-m $m> <-min $min> <-max $max>
uniaxialMaterial Fatigue 3 100  -E0 0.17 -m -0.522
```



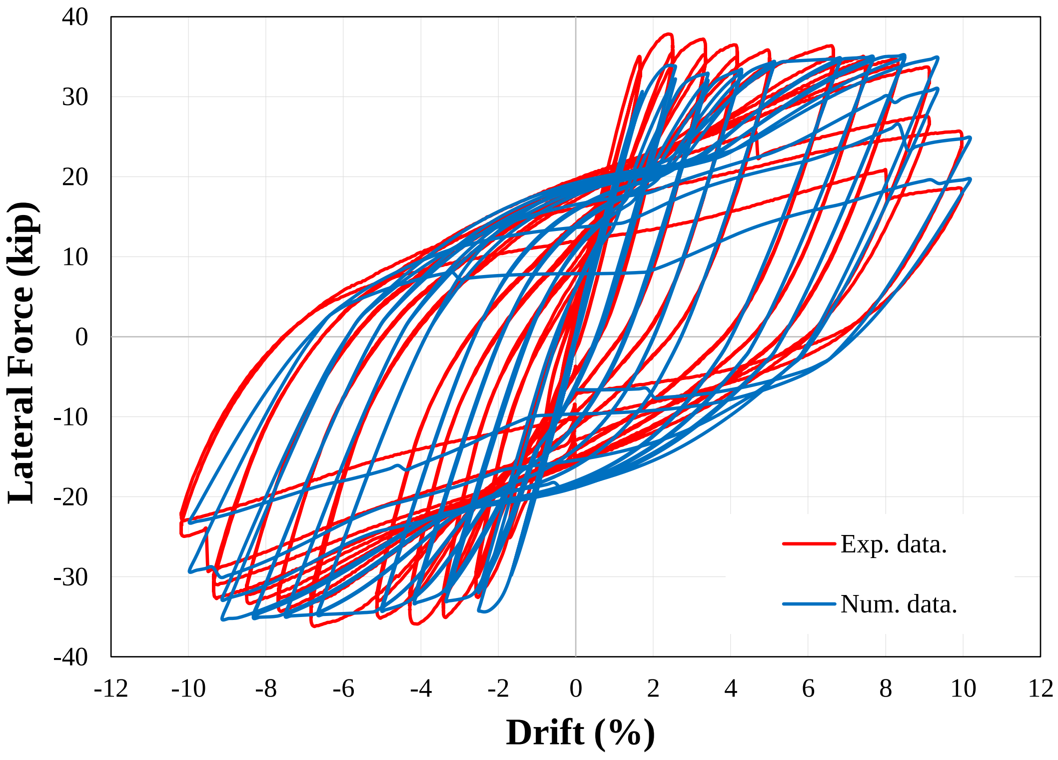
Combined Strain vs Number of Half Cycles to Failure plot for ASTM A615 (Plot based on data by Brown & Kunnath 2000 and Hawileh, et al. 2009).

Numerical Investigation

Force-displacement for revised cast-in-place model



Numerical hysteretic force-displacement

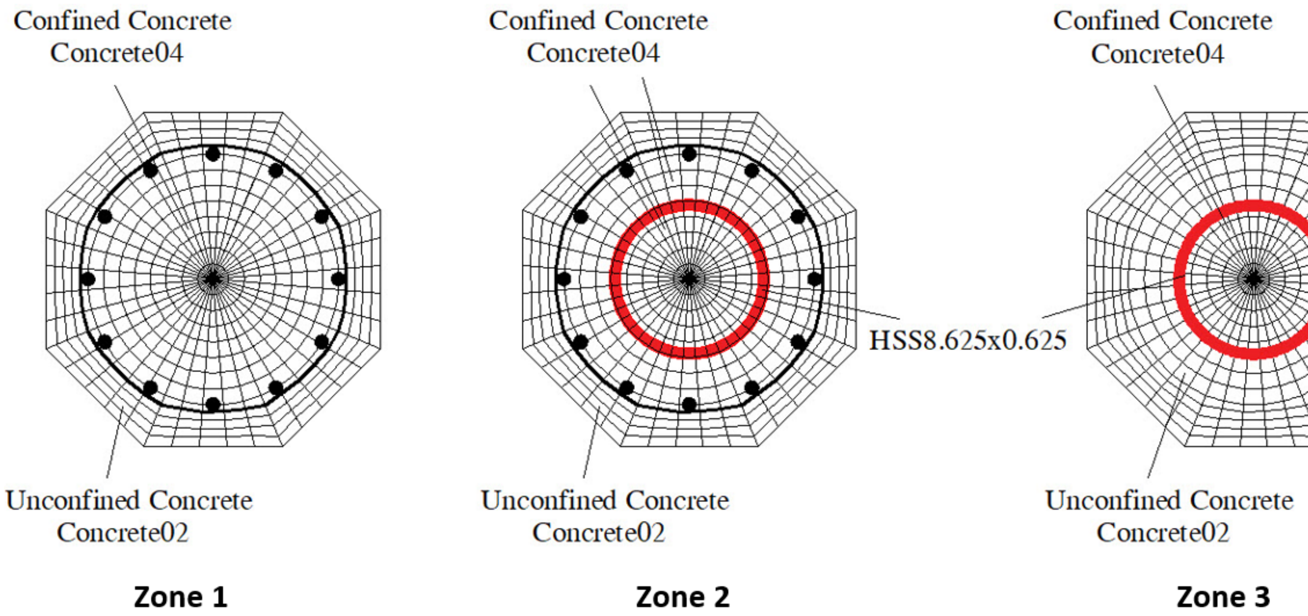


Numerical and experimental hysteretic force-displacement

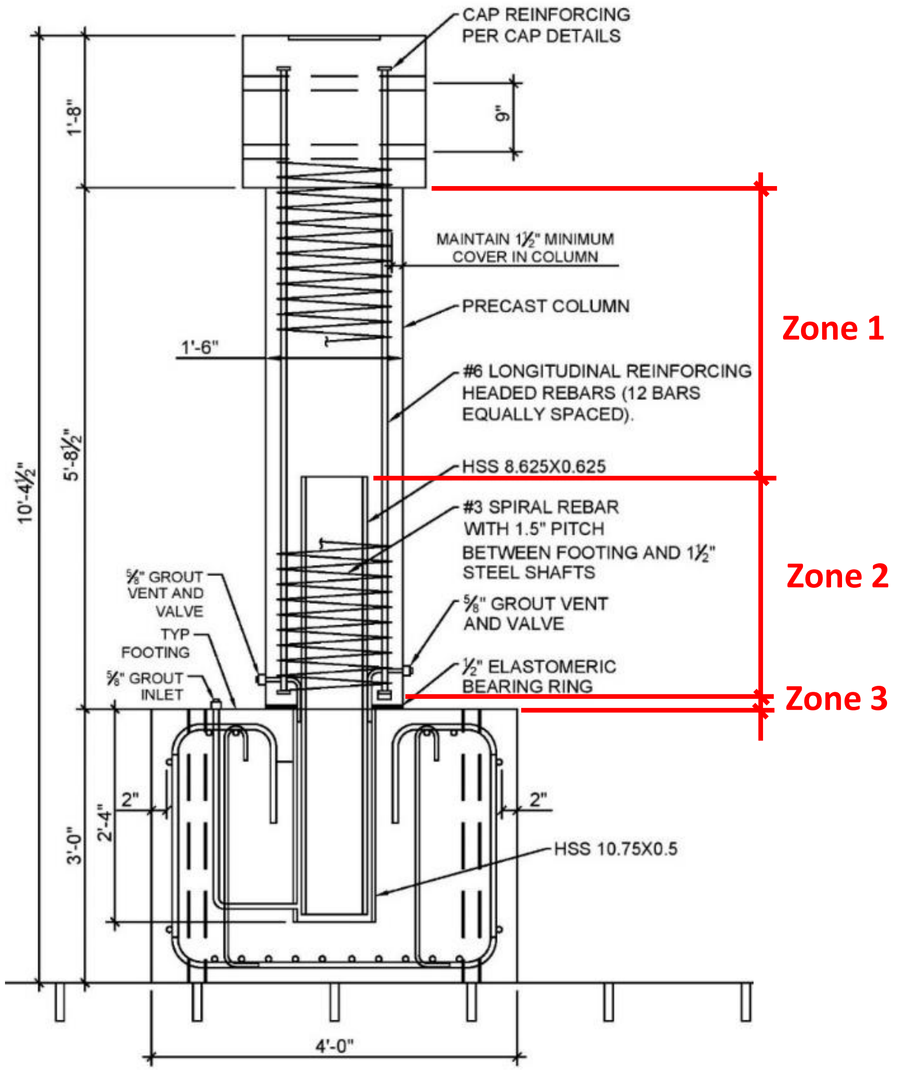
Numerical Investigation

Precast Pier

Octagonal cross-section model in OpenSees

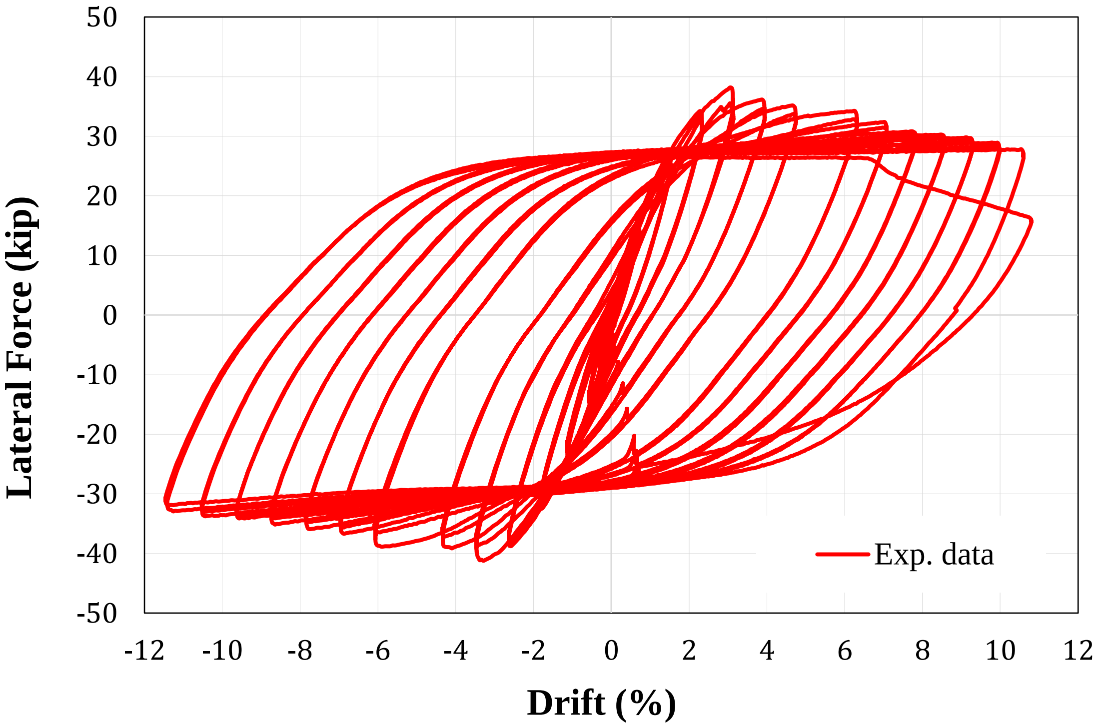


Detailed Sections of the Model for Precast Column:
(a) Zone 1, (b) Zone 2, and (c) Zone 3

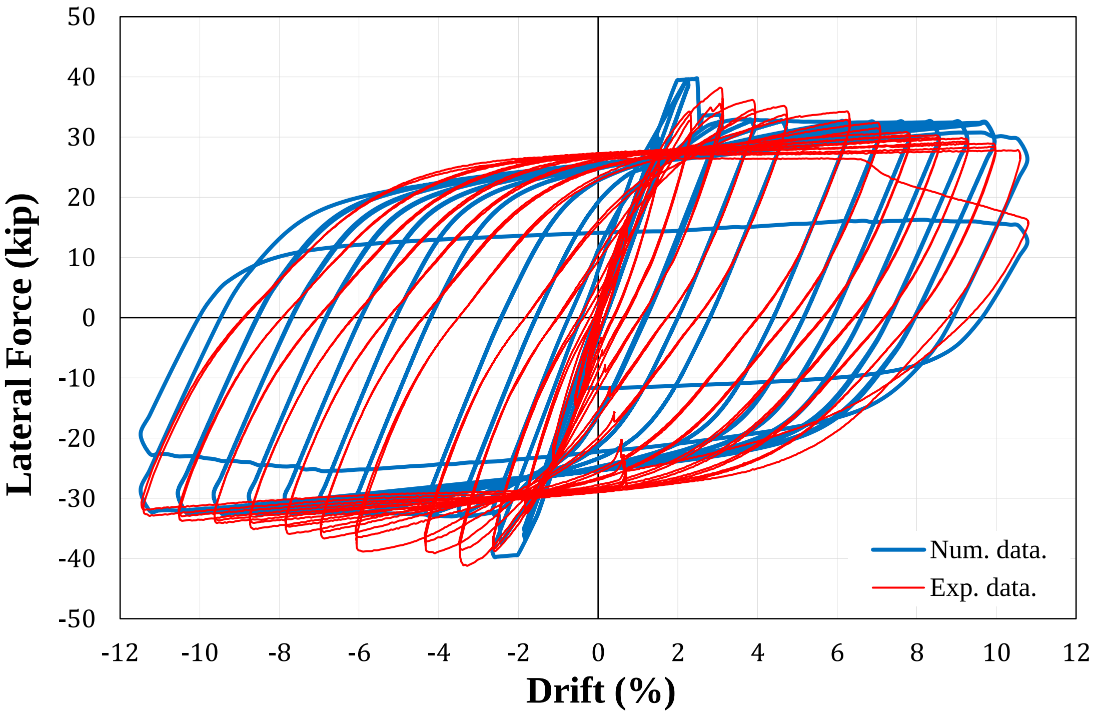


Numerical Investigation

Precast column force-displacement



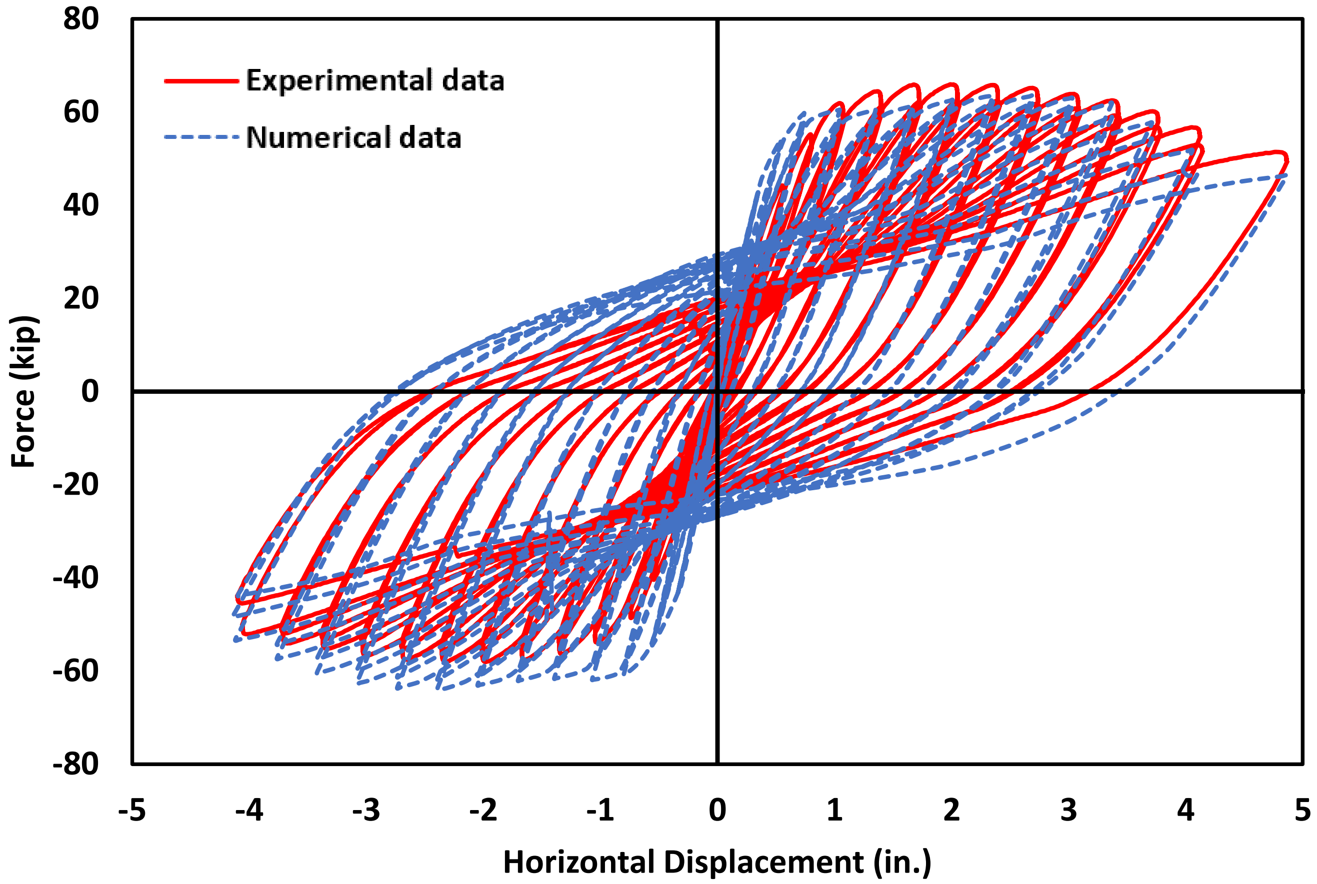
Experimental hysteretic force-displacement



Numerical and experimental hysteretic force-displacement

Numerical Investigation

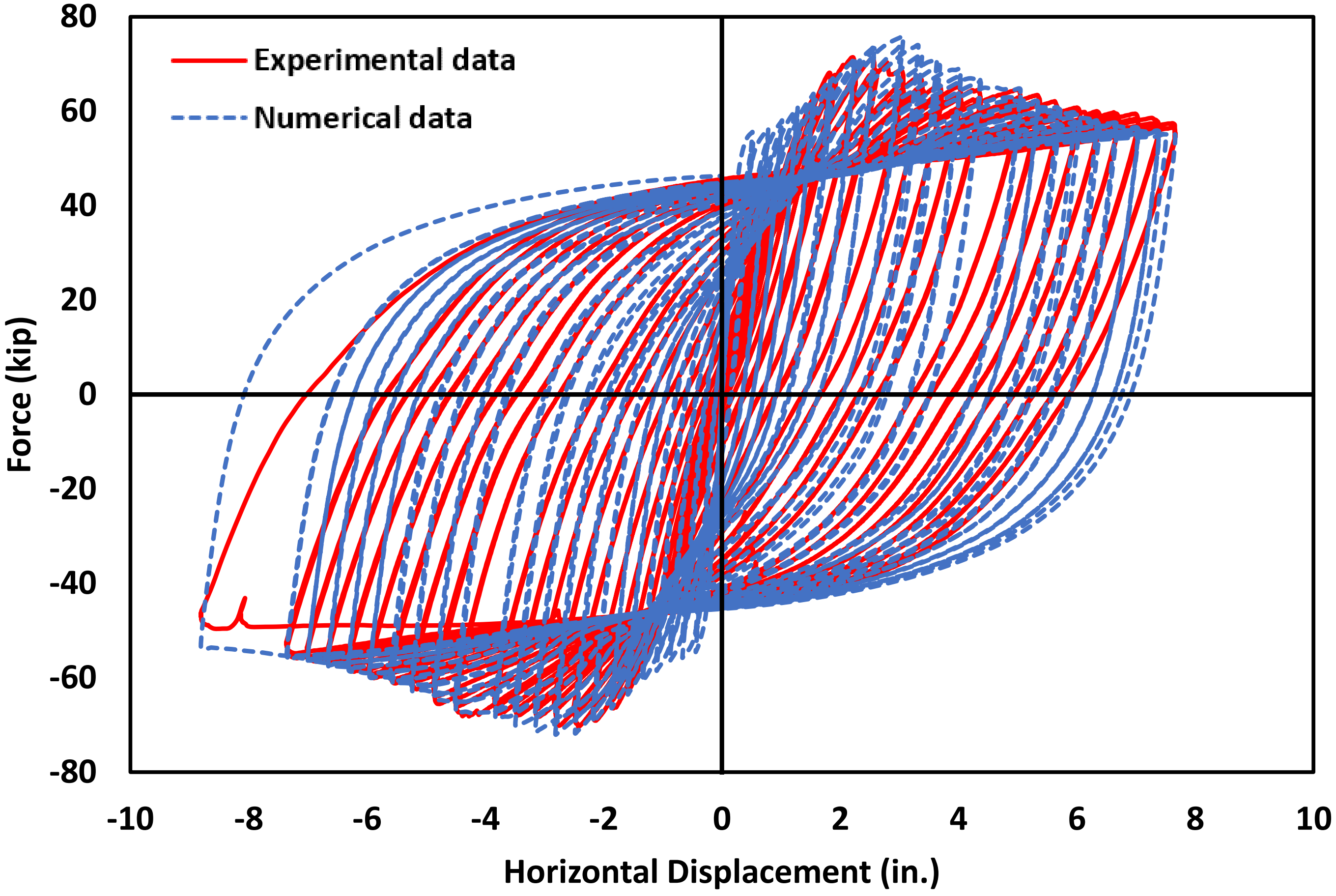
Cast-In-Place Bent Pier



Numerical and Experimental Hysteresis Force-Displacement for CIP Bent Pier

Numerical Investigation

Precast Bent Pier



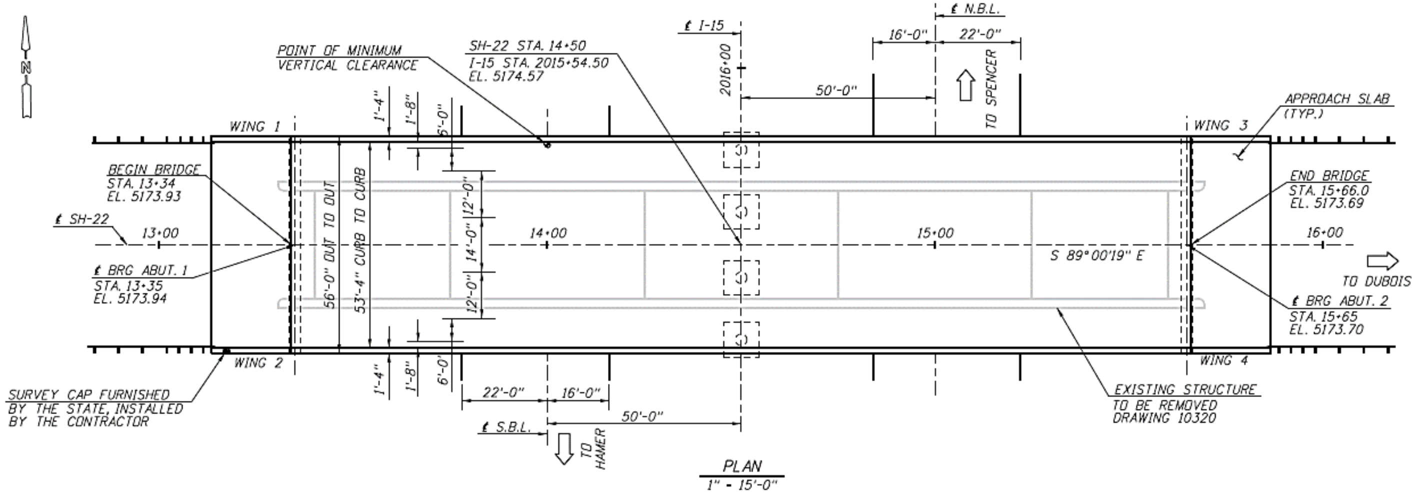
Numerical and Experimental Hysteresis Force-Displacement for Precast Bent Pier

Parametric Case Studies

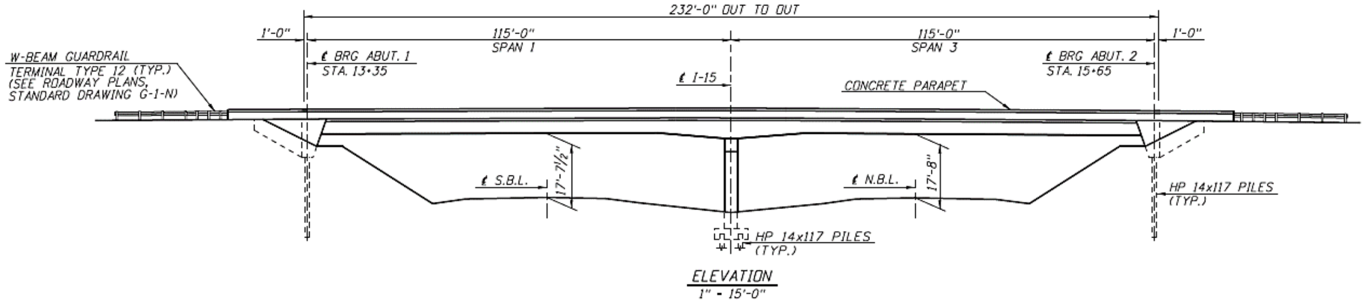
- Building analytical models of full bridge structure in OpenSees. The models are to reflect the type of bridges constructed in Idaho. Two types of connections will be implemented in the models: the cast-in-place and the proposed connection.
- Running nonlinear static (pushover) and nonlinear dynamic (time-history analysis) on the models and comparing the global seismic response of the bridge structures (e.g., formation of plastic hinges, ductility, strength, force-displacement response etc.)
- Comparing capacity versus demand curves for high seismicity for the proposed connection and cast-in-place construction.
- Summarizing findings from global seismic analysis of the bridge structures

Parametric Case Studies

Nonlinear Dynamic Analysis



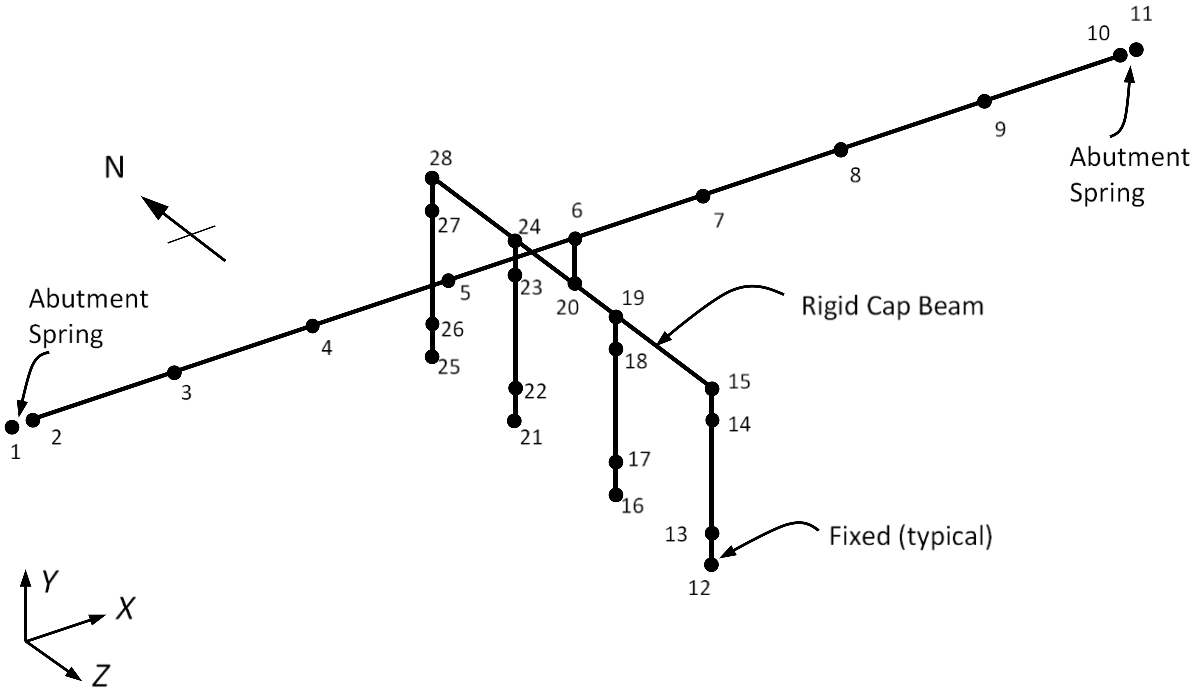
Plan View of the SH-22 over I-15 Bridge at Dubois (NTS)



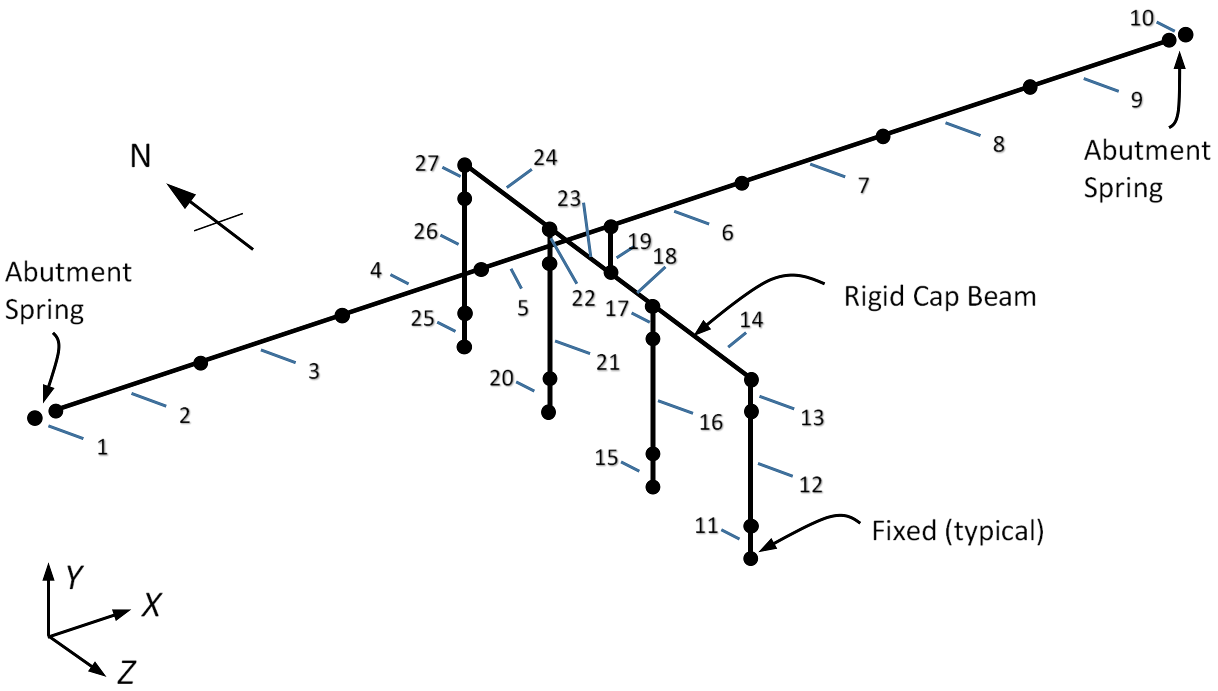
Elevation View of the SH-22 over I-15 Bridge at Dubois (NTS)

Parametric Case Studies

Nonlinear Static & Dynamic Analyses



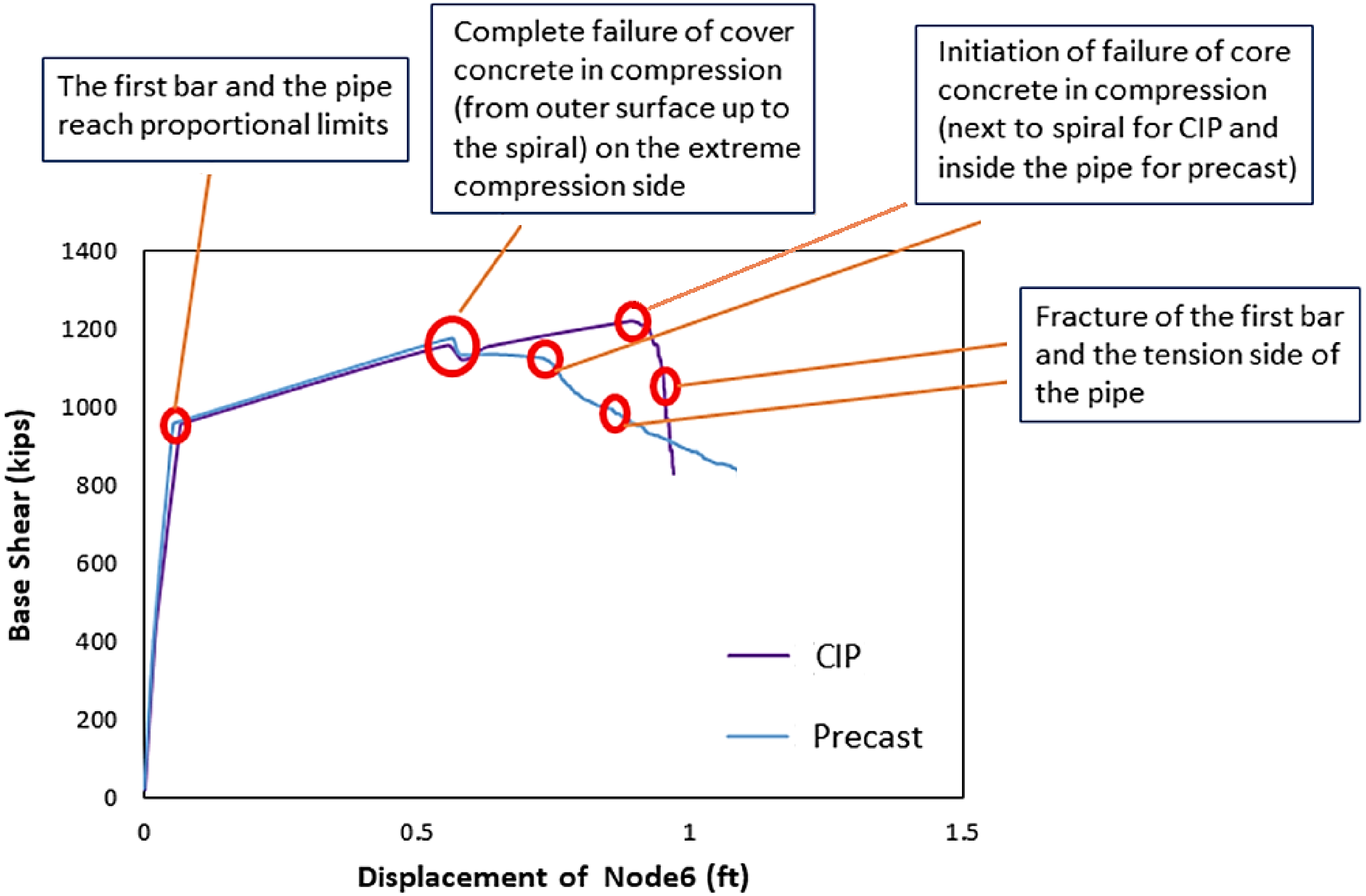
Dubois Bridge Model with Node Numbers



Dubois Bridge Model with Element Numbers

Parametric Case Studies

Nonlinear Static (Pushover) Analysis



The first bar and the pipe reach proportional limits

Complete failure of cover concrete in compression (from outer surface up to the spiral) on the extreme compression side

Initiation of failure of core concrete in compression (next to spiral for CIP and inside the pipe for precast)

Fracture of the first bar and the tension side of the pipe

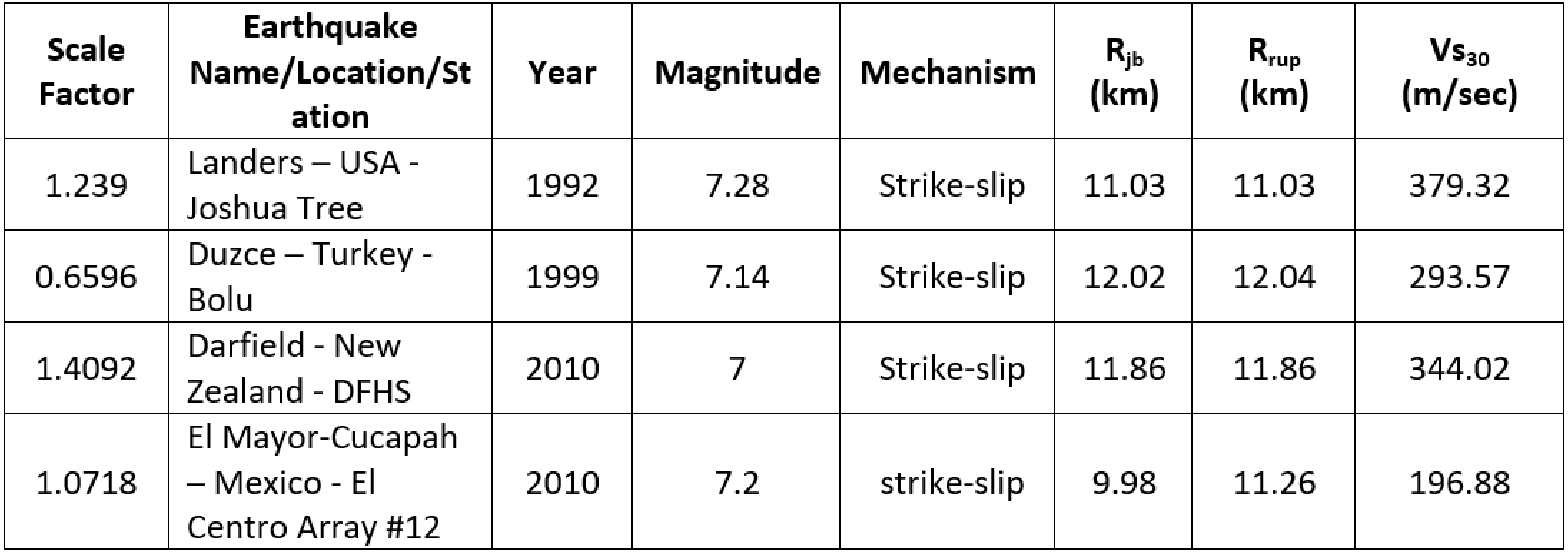
Base Shear vs. Displacement for both CIP and Precast Columns in the Transverse Direction

Parametric Case Studies

Nonlinear Dynamic Analysis

Earthquake Records from Different Regions from PEER Website

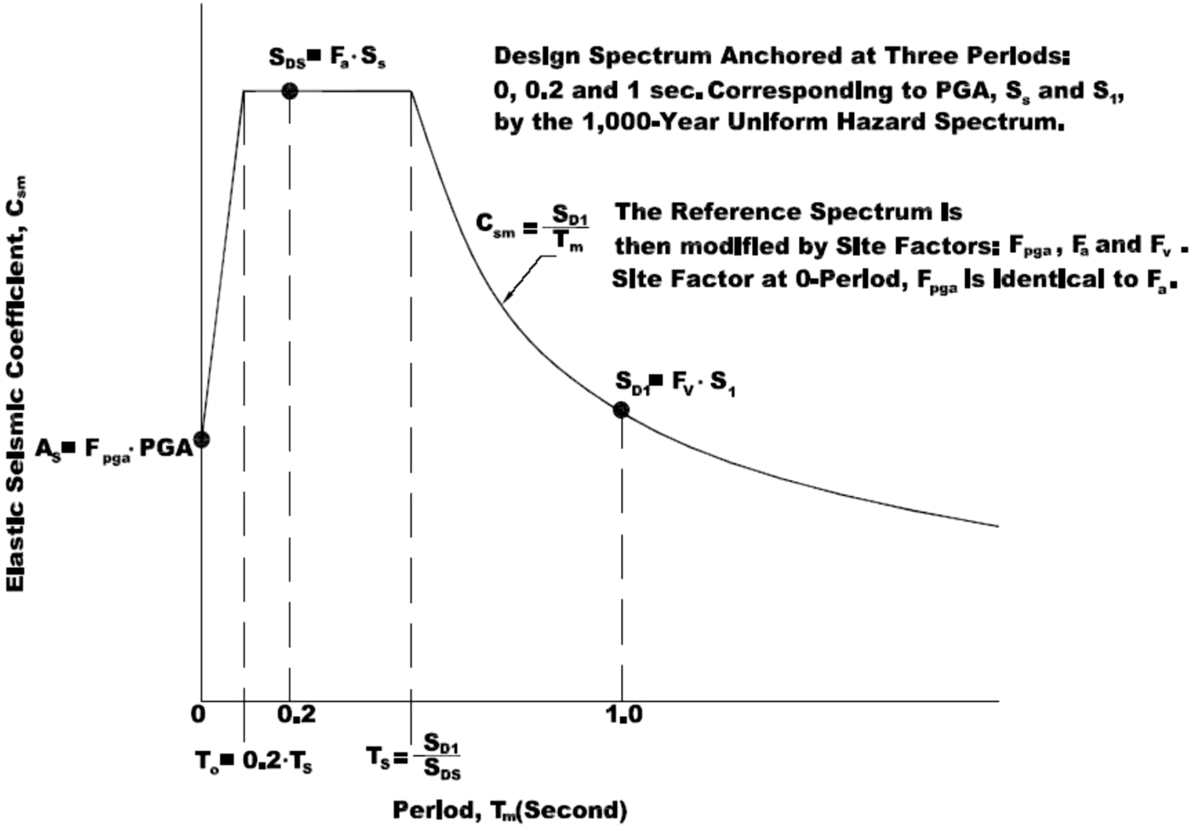
https://ngawest2.berkeley.edu/



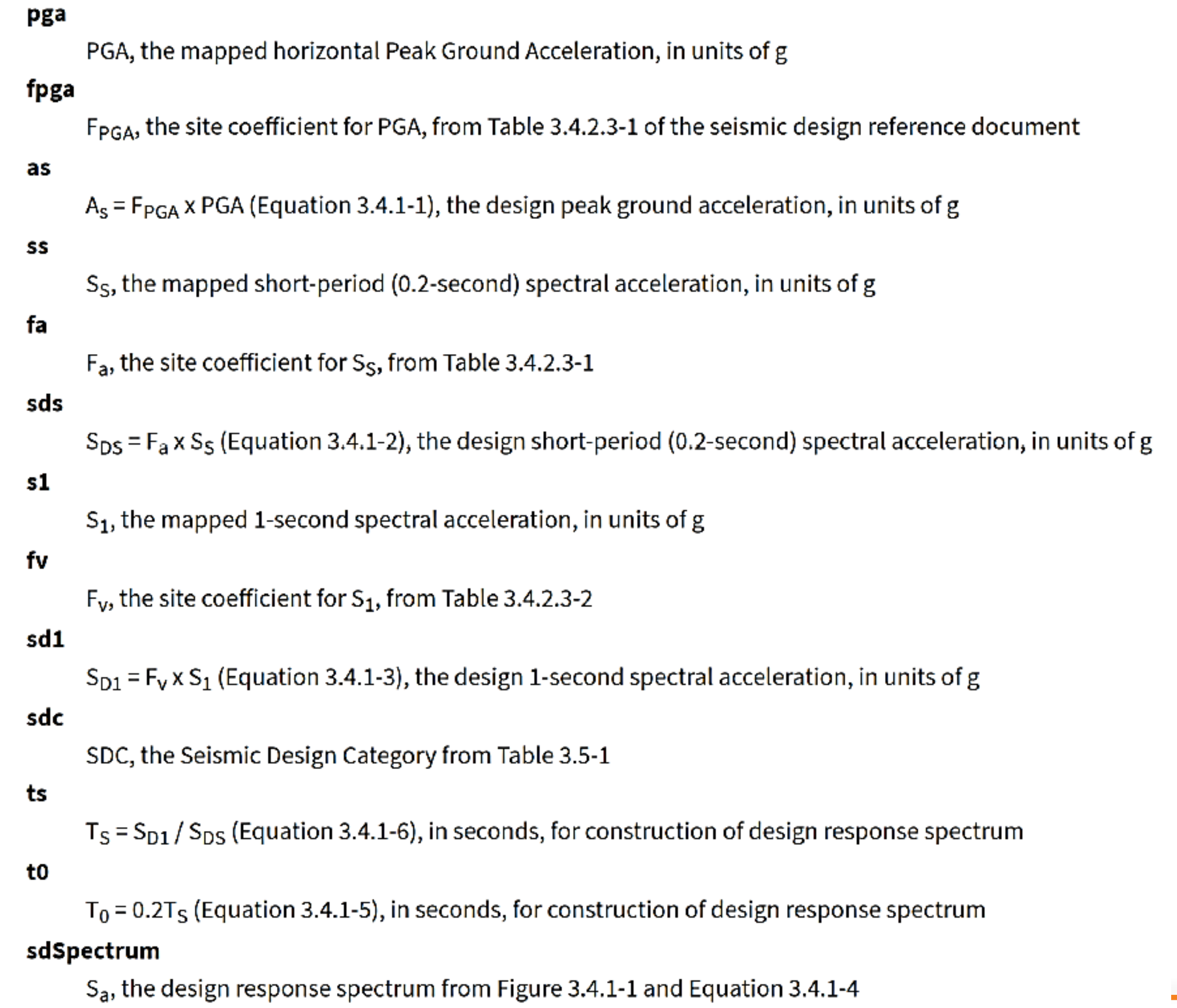
Scale Factor	Earthquake Name/Location/Station	Year	Magnitude	Mechanism	R_{jb} (km)	R_{rup} (km)	Vs_{30} (m/sec)
1.239	Landers – USA - Joshua Tree	1992	7.28	Strike-slip	11.03	11.03	379.32
0.6596	Duzce – Turkey - Bolu	1999	7.14	Strike-slip	12.02	12.04	293.57
1.4092	Darfield - New Zealand - DFHS	2010	7	Strike-slip	11.86	11.86	344.02
1.0718	El Mayor-Cucapah – Mexico - El Centro Array #12	2010	7.2	strike-slip	9.98	11.26	196.88

Parametric Case Studies

Nonlinear Dynamic Analysis



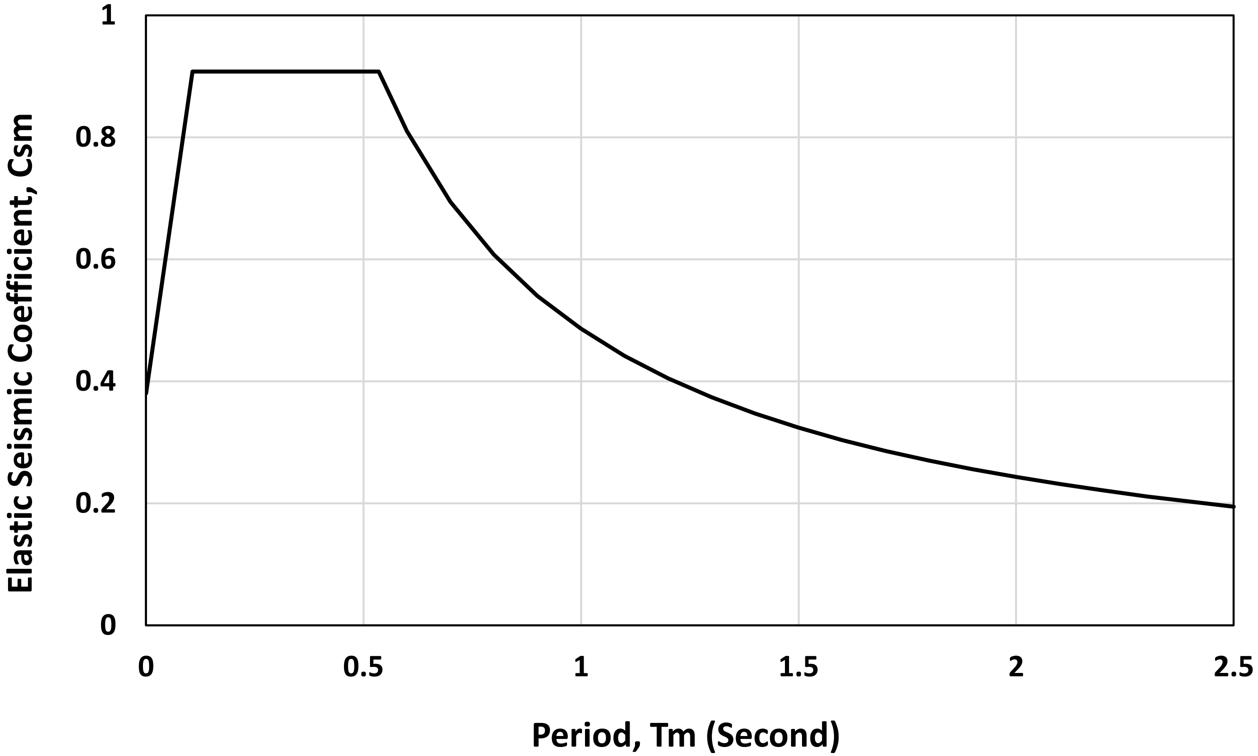
AASHTO Seismic Coefficient Design Spectrum
Constructed with the Three-Point Method



pga	PGA, the mapped horizontal Peak Ground Acceleration, in units of g
fpga	F_{PGA}, the site coefficient for PGA, from Table 3.4.2.3-1 of the seismic design reference document
as	$A_S = F_{PGA}$ x PGA (Equation 3.4.1-1), the design peak ground acceleration, in units of g
ss	S_S, the mapped short-period (0.2-second) spectral acceleration, in units of g
fa	F_a, the site coefficient for S_S, from Table 3.4.2.3-1
sds	$S_{DS} = F_a$ x S_S (Equation 3.4.1-2), the design short-period (0.2-second) spectral acceleration, in units of g
s1	S_1, the mapped 1-second spectral acceleration, in units of g
fv	F_V, the site coefficient for S_1, from Table 3.4.2.3-2
sd1	$S_{D1} = F_V$ x S_1 (Equation 3.4.1-3), the design 1-second spectral acceleration, in units of g
sdc	SDC, the Seismic Design Category from Table 3.5-1
ts	$T_S = S_{D1} / S_{DS}$ (Equation 3.4.1-6), in seconds, for construction of design response spectrum
t0	$T_0 = 0.2T_S$ (Equation 3.4.1-5), in seconds, for construction of design response spectrum
sdSpectrum	S_a, the design response spectrum from Figure 3.4.1-1 and Equation 3.4.1-4

Parametric Case Studies

Nonlinear Dynamic Analysis

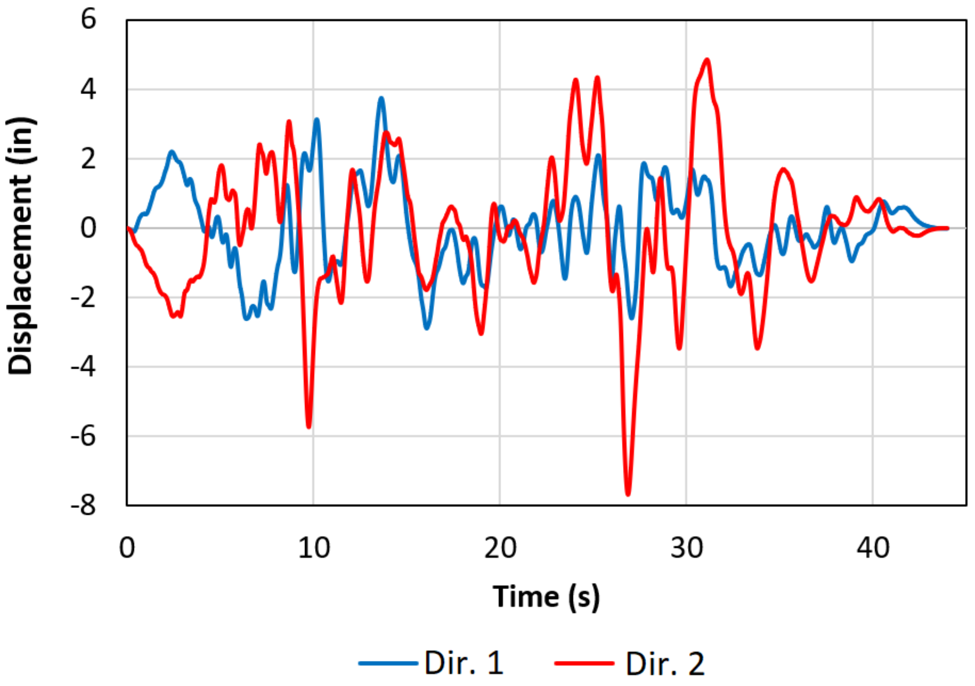


Period, Tm (second)	Elastic Seismic Coefficient, Csm
0	0.38
0.1072	0.908
0.2	0.908
0.535	0.908
0.6	0.81
0.7	0.694285714
0.8	0.6075
0.9	0.54
1	0.486
1.1	0.441818182
1.2	0.405
1.3	0.373846154
1.4	0.347142857
1.5	0.324
1.6	0.30375
1.7	0.285882353
1.8	0.27
1.9	0.255789474
2	0.243

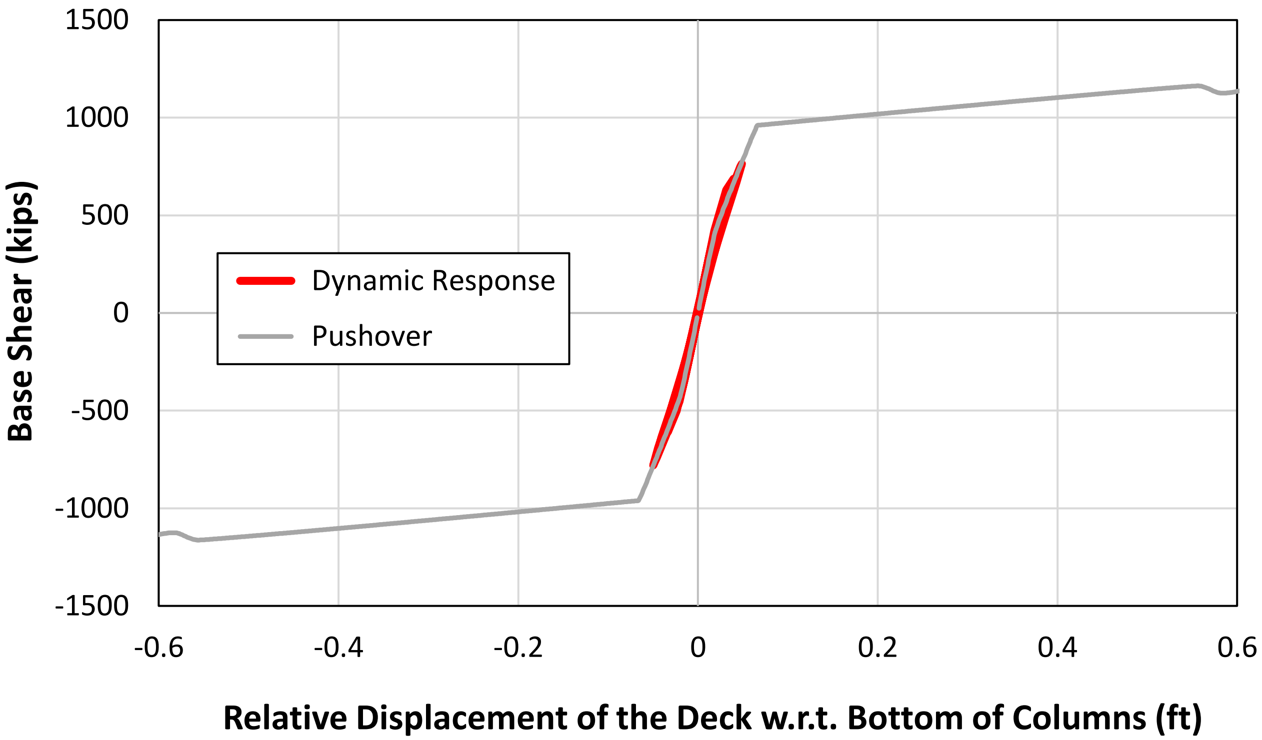
Uniform Hazard Spectrum Data Points for Montpelier, Idaho

Project information

Typical Dynamic Input and Response



Displacement vs. Time for Landers Earthquake



Pushover vs. Dynamic Response for Landers Earthquake for the Bridge with CIP Columns in the Transverse Direction (Dir. 1 Long., Dir. 2 Transv.)

Project information

Cast-In-Place Bridge

Maximum Base Shear and Displacement for CIP Bridge (Absolute Values Shown)

EQ	Direction of EQ	Max. Long. Base Shear (kips)	Max. Trans. Base Shear (kip)	Max. Long. Displ. (ft)	Max. Trans. Displ. (ft)	Max. Base Shear Orth. Comb. (kips)	Max. Displ. Orth. Comb. (ft)	Push over Yield Force (kips)
Landers	Dir1-Long, Dir2-Trans	296	780	0.02	0.05	869	0.056	940
	Dir1-Trans, Dir2-Long	413	749	0.025	0.047	873	0.055	940
Duzce	Dir1-Long, Dir2-Trans	530	657	0.03	0.04	816	0.05	940
	Dir1-Trans, Dir2-Long	315	974	0.021	0.098	1067	0.1	940
Darfield	Dir1-Long, Dir2-Trans	972	966	0.094	0.082	1262	0.12	940
	Dir1-Trans, Dir2-Long	714	978	0.051	0.11	1192	0.05	940
El Mayor	Dir1-Long, Dir2-Trans	622	770	0.043	0.049	957	0.062	940
	Dir1-Trans, Dir2-Long	648	931	0.044	0.067	1125	0.08	940

AASHTO requirement for finding maximum base shear and displacement load combination:

$$(1.0A + 0.3B)$$

Where,

A = Larger displacement or base shear between two directions (longitudinal and transverse)

B = Smaller displacement or base shear between two directions (longitudinal or transverse)

Project information

Precast Bridge

Maximum Base Shear and Displacement for Precast Bridge (Absolute Values Shown)

EQ	Direction of EQ	Max. Long. Base Shear (kips)	Max. Trans. Base Shear (kip)	Max. Long. Displ. (ft)	Max. Trans. Displ. (ft)	Max. Base Shear Orth. Comb. (kips)	Max. Displ. Orth. Comb. (ft)	Push over Yield Force (kips)
Landers	Dir1-Long, Dir2-Trans	315	872	0.02	0.047	967	0.053	960
	Dir1-Trans, Dir2-Long	421	761	0.024	0.04	887	0.047	960
Duzce	Dir1-Long, Dir2-Trans	544	696	0.029	0.037	860	0.05	960
	Dir1-Trans, Dir2-Long	340	975	0.02	0.083	1077	0.09	960
Darfield	Dir1-Long, Dir2-Trans	977	973	0.088	0.08	1269	0.11	960
	Dir1-Trans, Dir2-Long	788	984	0.05	0.1	1220	0.12	960
El Mayor	Dir1-Long, Dir2-Trans	661	965	0.043	0.061	1163	0.07	960
	Dir1-Trans, Dir2-Long	755	952	0.047	0.054	1179	0.07	960

AASHTO requirement for finding maximum base shear and displacement load combination:

$$(1.0A + 0.3B)$$

Where,

A = Larger displacement or base shear between two directions (longitudinal and transverse)

B = Smaller displacement or base shear between two directions (longitudinal or transverse)

Conclusion

- A new precast pier system for ABC in seismic zones has been proposed. The concept aims for an emulative cast-in-place or better performance for the bridge.
- The proposed system offers advantages that are not associated with some common emulative cast-in-place connections such as ample installation tolerance, ease of erection, and limiting cracking to the pier during smaller earthquakes.
- Uni-directional quasi-static cyclic tests were conducted on a large-scale pier specimen to validate the concept and compare performance with cast-in-place construction.
- Compared to an equivalent cast-in-place pier, the precast pier with moment pipe connection achieved higher strength and ductility.
- The analytical modeling is aimed to provide a practical tool for bridge engineers when considering new connection details.

Conclusion

- Analytical models were created for the CIP column and precast column using the Open System for Earthquake Engineering Simulation (OpenSees) software
- To predict the experimental results, low-cycle fatigue data must be included in the OpenSees models.
- Predicted hysteresis force-displacements for single column (CIP and precast) and CIP bent agreed with the experimental results.
- Predicted force-displacement for the precast bent had the same peak forces but did not follow the experimental results in the last few cycles.
- Both bridge models had almost the same pushover base shear yield values.
- In some simulations, the maximum dynamic base shear values exceeded the yield values. This is to be expected since the design seismic accelerations for Dubois (the actual bridge location) are approximately half those of Montpelier.

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Idaho State Board of Education

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Thank You!

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