Seismic Behavior of Columns with Grouted Bar Couplers in Idaho ABC Applications

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September 7, 2017
Presentation at the Western Bridge Engineers' Seminar
Portland, Oregon

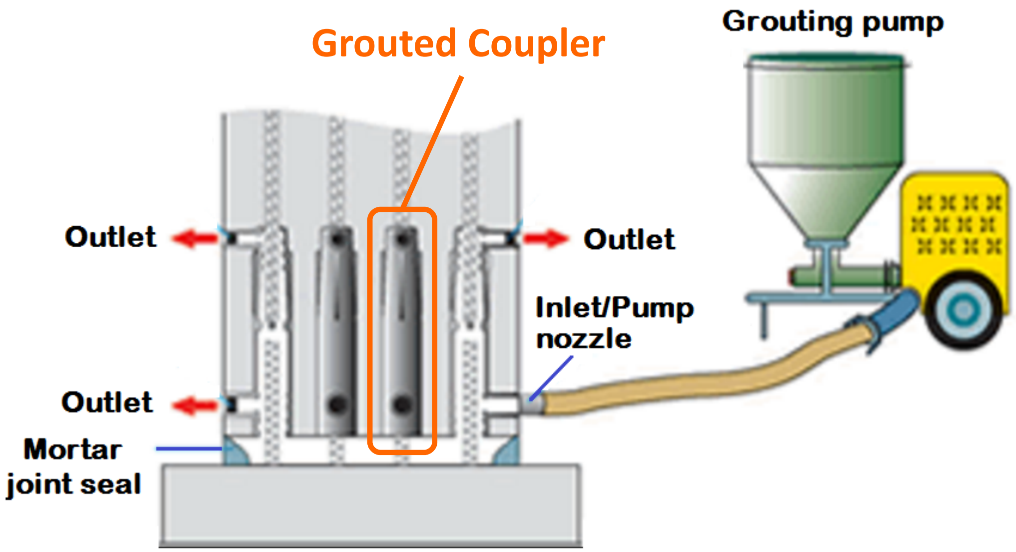
Idaho State UNIVERSITY

Accelerated Bridge Construction (ABC)

- ITD anticipates increased demand for ABC.
  - **Benefits are:** (a) minimizing of inconvenience to the traveling public, (b) increasing safety during construction, (c) reducing construction time, (d) saving costs.

- Installation of grouted couplers:

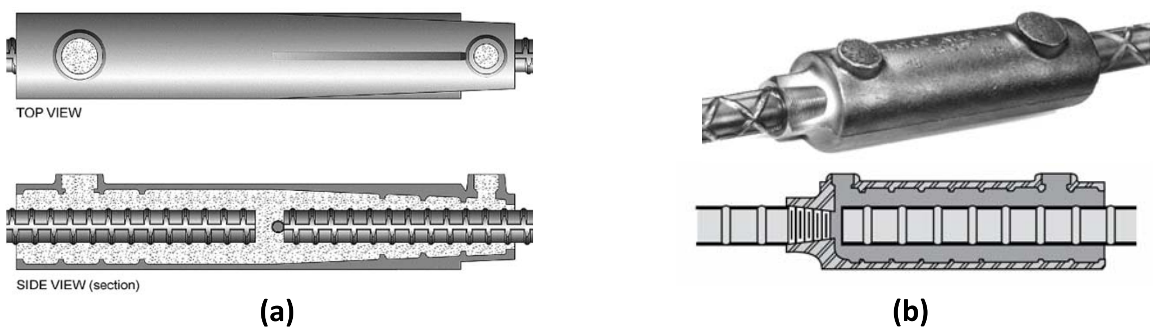
Haber, et al., 2013



http://splicesleeve.com/ssj/assembly.html

Research Statement and Objectives

- Problem Statement: Determine performance of grouted couplers in bridge precast column connections in seismic zones.

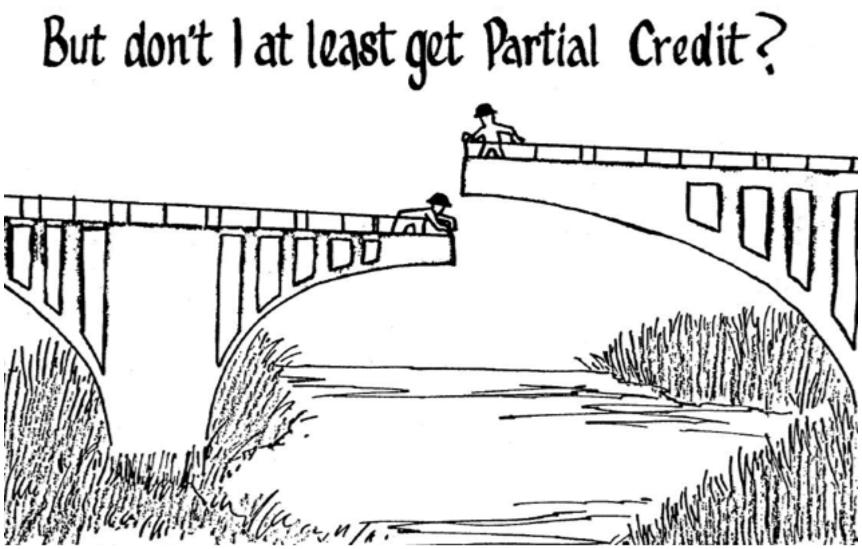


Grouted Couplers: (a) Both Ends Grouted and (b) One End Grouted and the Other End Threaded (ACI Committee 374, 2013)

- Objectives:
  - Assess the performance of grouted couplers in column connections under Idaho seismic conditions.
  - Develop recommendations on the use of columns with grouted couplers.

Tasks/Presentation Outline

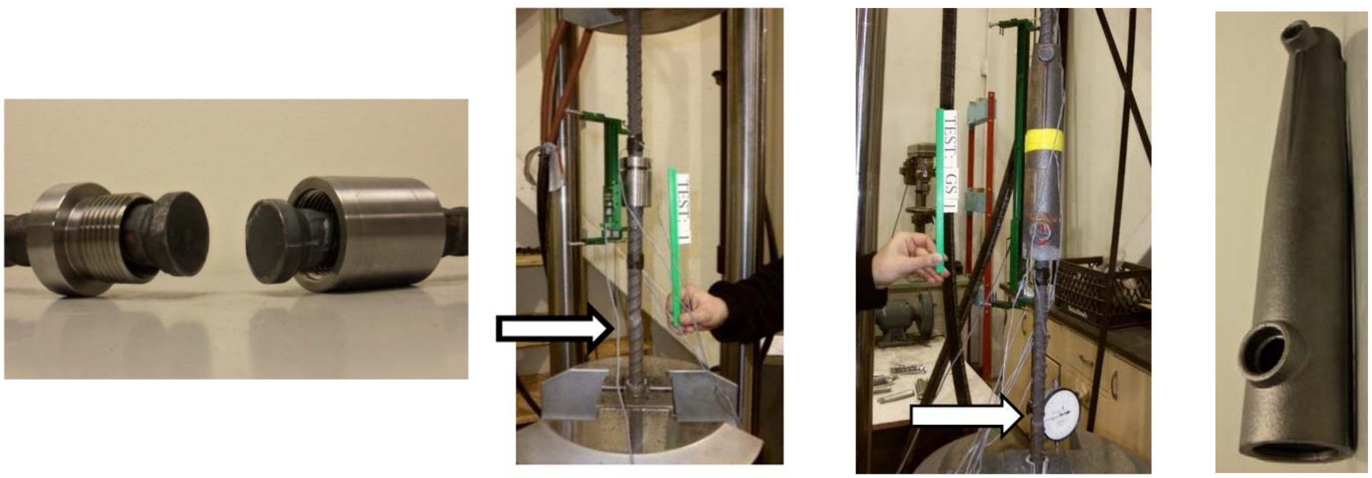
- Task 1: Literature Review
- Task 2: Computer Models of Univ. of Nevada, Reno Columns
- Task 3: Analysis of Representative Bridges in Idaho
- Task 4: Recommendations for Idaho Bridge Manual



https://www.reddit.com/r/space/comments/16ws1t/how_important_is_geometry_in_aerospace_engineering/

Haber, Saiidi, and Sanders (2013)

- This report for Caltrans focused on three areas:
  - Uniaxial testing of up-set headed coupler (HC), and grouted coupler (GC).
  - Laboratory testing of five half-scale precast reinforced concrete columns.
  - Finite element modeling using OpenSees software.



Location of rupture   Location of rupture

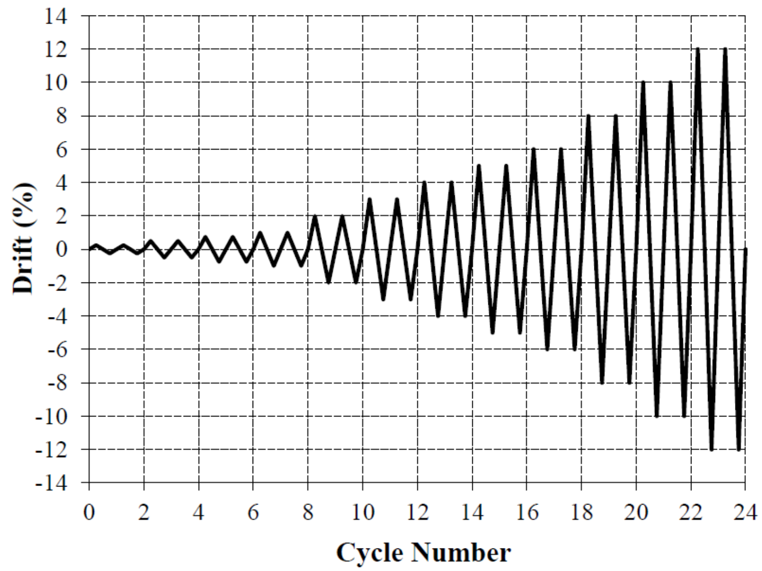
Uniaxial Tests at the University of Nevada, Reno*

* Figures without references are from the corresponding sources being summarized.

Haber, et al. (2013), cont.

- Laboratory column tests
  - 9 ft in height by 2 ft in diameter, 11 No. 8 bars with steel ratio of 1.92%

(a)

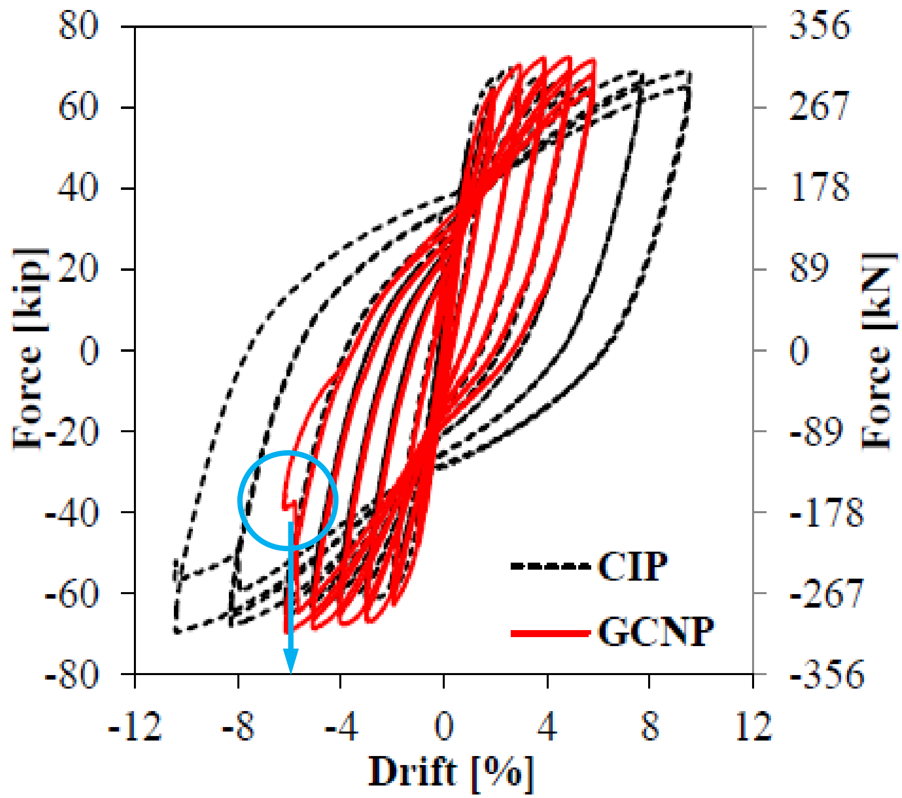


(b)

(a) Photo of Test Set-up and (b) Loading Protocol (Quasi-Static Cyclic Loading with Increasing Drift)

Haber, et al. (2013), cont.

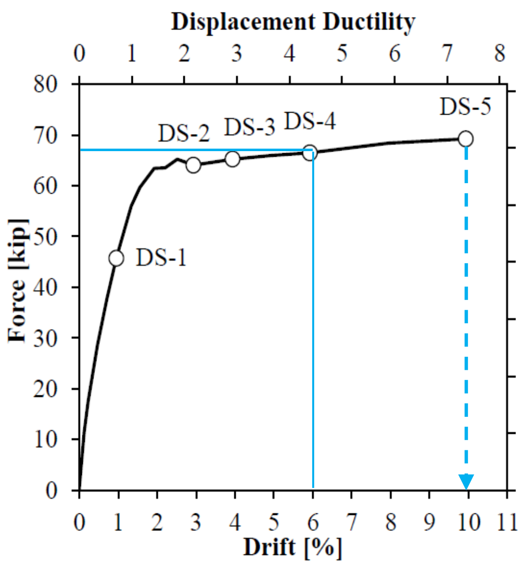
- Typical column test results



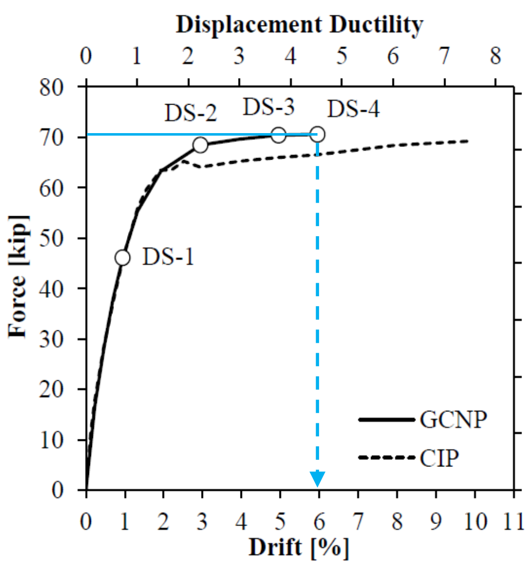
Hysteretic Force-displacement of GCNP vs. CIP Columns

Haber, et al. (2013), cont.

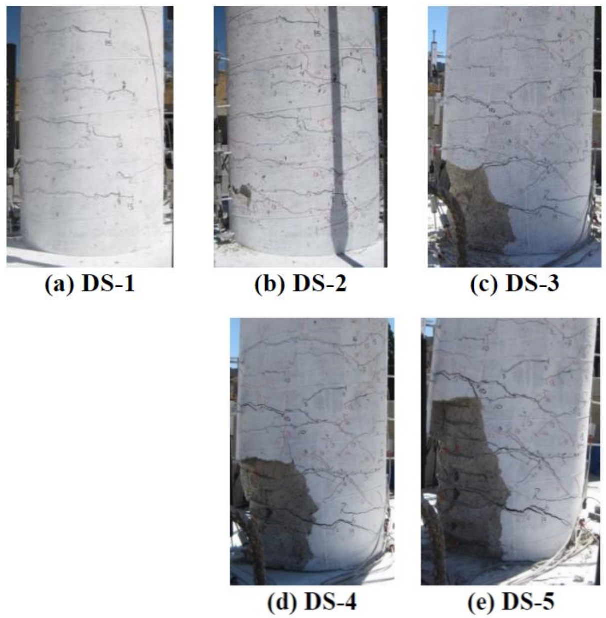
- Force-displacement envelops



CIP Column Force-displ.



GCNP Column Force-displ.

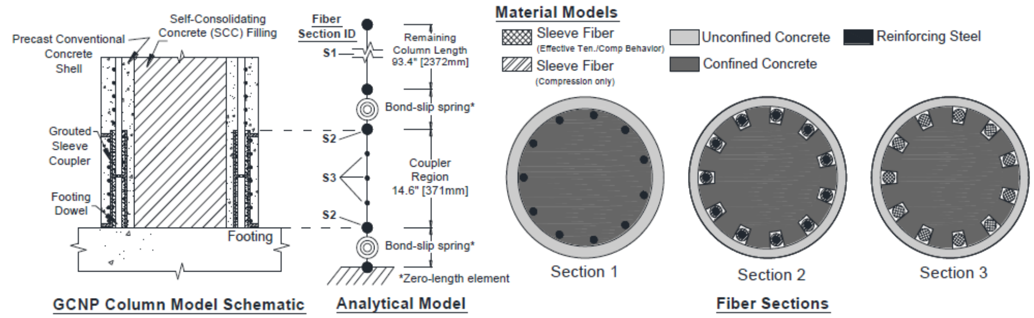


Damage States Defined by Vosooghi & Saiidi (2010)

- Damage states:
  - **DS-1**: presence of flexural cracks, **DS-2**: first spall and development of shear cracks, **DS-3**: extensive cracking and spalling of concrete, **DS-4**: visible longitudinal and/or transverse reinforcement, and **DS-5**: on-set of confined concrete core damage (imminent failure).

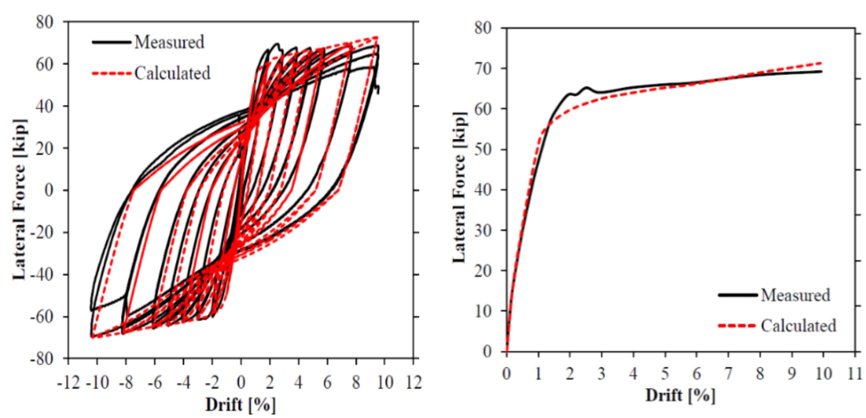
Haber, et al. (2013), cont.

- Analytical studies
  - OpenSees FEM software used for analysis

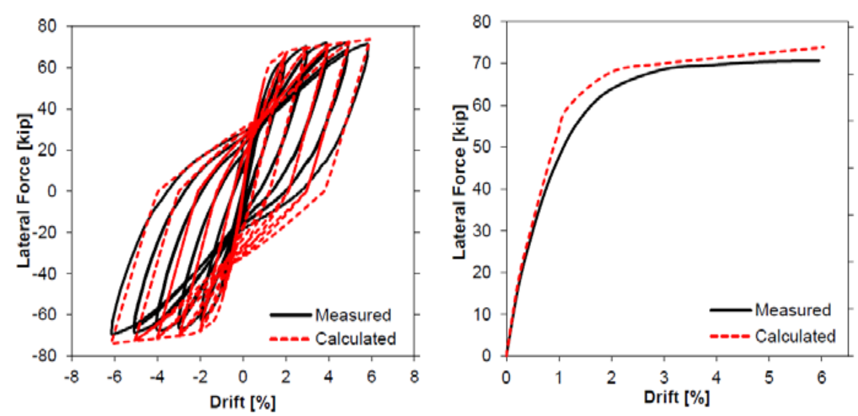


Details of the Analytical Model for the GCNP Column

  - Sample results for CIP and GCNP:



Measured versus Calculated Responses for CIP



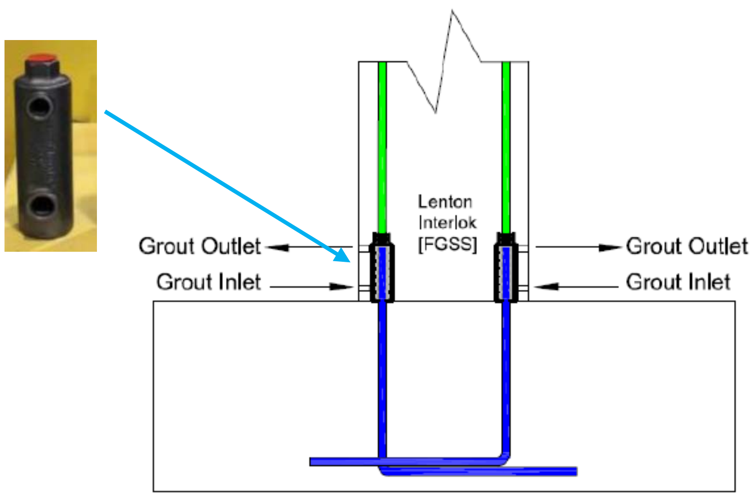
Measured versus Calculated Responses for GCNP

Haber, et al. (2013), cont.

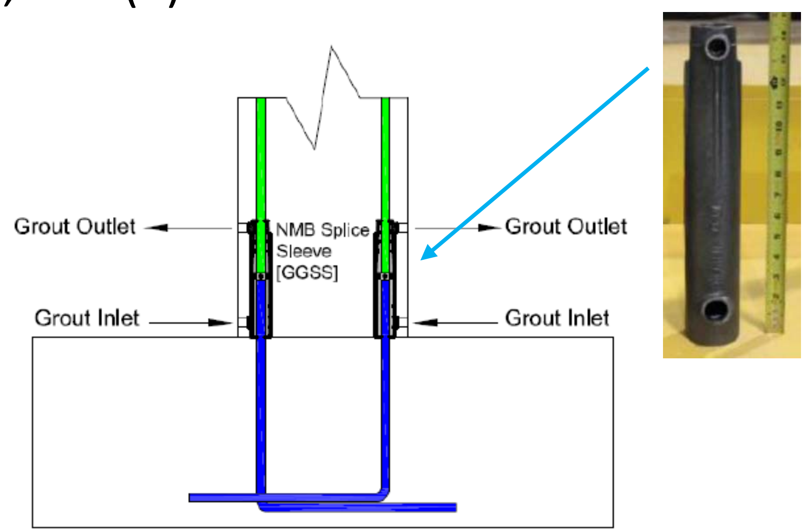
- Summary:
  - In individual grouted coupler tests, all samples had bar fracture failure away from the coupler.
  - When grouted couplers were placed in columns, the primary mode of failure was fracture of longitudinal bars.
  - Finite element models gave similar force-displacements compared to laboratory test results.
- Conclusions:
  - With demands of less than 6% drift, the use of grouted couplers in columns is acceptable.

Pantelides, et al. (2014)

- In this University of Utah project, (8) half scale connections were tested in laboratory under cyclic quasi-static loading:
  - Column-to-cap beam: (3) with FGSS and (1) CIP
  - Column-to-footing: (3) with GGSS, and (1) CIP



Fastened-Grouted Splice Sleeve (FGSS)
Column-to-cap Beam Connection



Grouted-Grouted Splice Sleeve (GGSS)
Column-to-footing Connection

- Experimental set-up: Similar to UNR (cyclic loading with increasing drift).

Pantelides, et al. (2014), cont.

- Conclusions:
  - CIP specimens had the best ductile performance.
  - Specimens that had grouted connectors in the footing or column cap performed better than the ones with couplers in the column.
- Recommendation:
  - Grouted coupler connections are acceptable for use in ABC applications.

Grouted Couplers in Western U.S.

- Use of grouted couplers in bridge column plastic hinge zones.

State	Grouted Couplers in Column Plastic Hinge Zones	Comments
Alaska	No	AKDOT prefers the use of grouted pockets or ducts when connecting precast caps to columns/piles.
California	No	The findings from UNR were presented, but it was voted not to allow grouted couplers in the plastic hinge zones columns.
Hawaii	No	State of Hawaii is not currently using any ABC methodologies.
Nevada	No	Although research on ABC column connections at the University of Nevada Reno (UNR) had been considered, no ABC column connections are currently used in the State of Nevada.
Oregon	No	ODOT does not have any special specs for splices for ABC.
Utah	**Yes**	UDOT Structures Design and Detailing Manual has a section on grouted couplers in ABC applications. This section is based on the report by the University of Utah research reported by Pantelides, et al.
Washington	No	WSDOT does not approve the use of mechanical couplers for connections of precast bridge members. The WSDOT prefers the use of grouted ducts similar to the ones used by AKDOT.

Utah Bridge Manual Section

- Utah Structures Design and Detailing Manual, Feb. 2015 Section 20.4.6.3, Commercial Grouted Splice Couplers:

  "… The use of grouted splice couplers is permissible in plastic hinging zones. The standard requirements for column confinement apply around the couplers. Adjust the cover to the reinforcing and spiral or ties to accommodate the larger grouted splice coupler section. Refer to the SD drawings for examples of how grouted splice couplers are used. …

  …

  Use a grouted splice coupler sleeve size one reinforcing size larger than the reinforcing size used. Detail the minimum gap between the grouted splice couplers to be the greatest of the following:

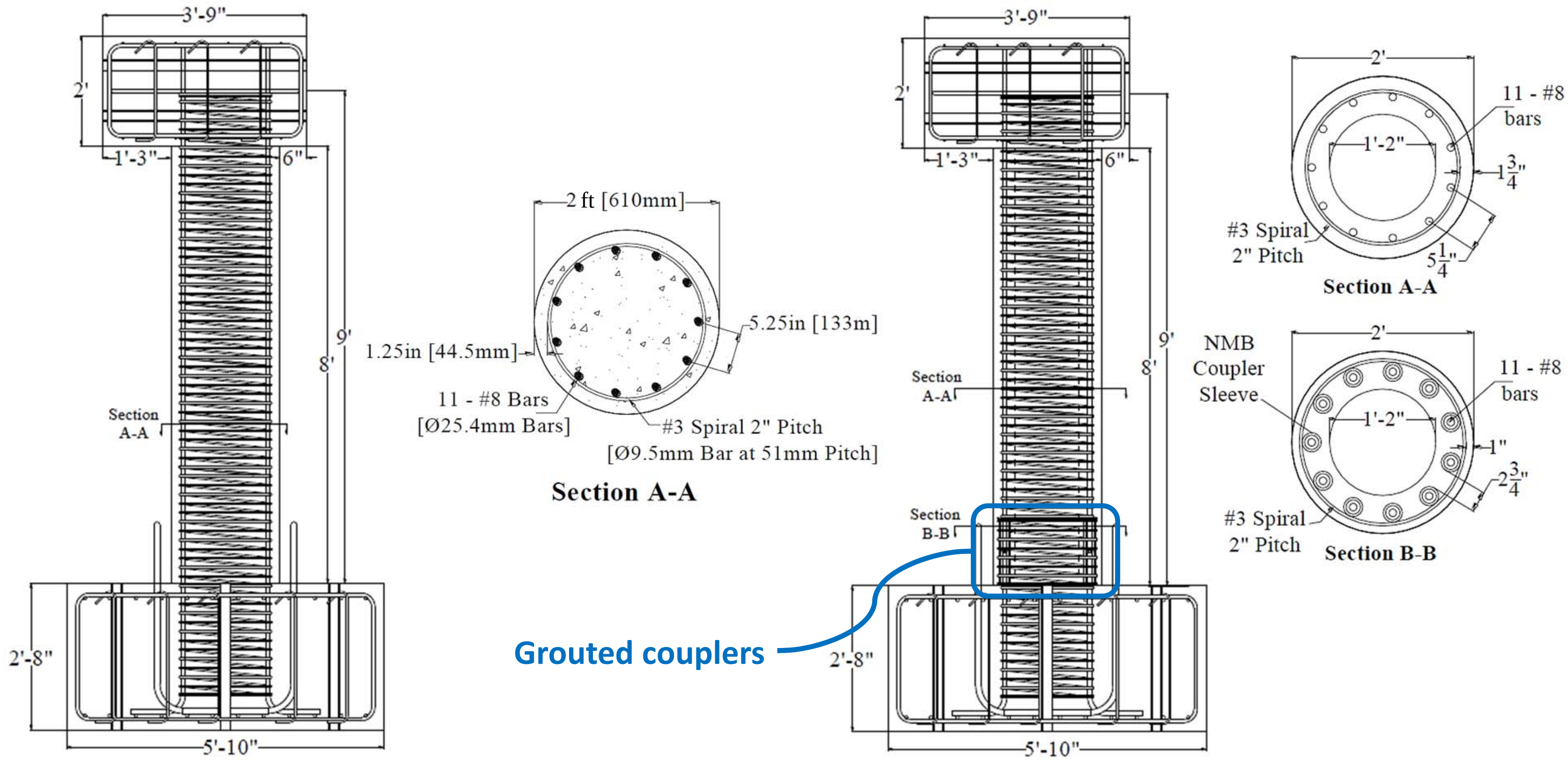
  - *1 in.*
  - *1.33 × (maximum aggregate size of the coarse aggregate)*
  - *Nominal diameter of the connected reinforcing."*

Presentation Outline

- Literature Review
- Computer Models of the Univ. of Nevada, Reno (UNR) Columns
- Analysis of Representative Bridges in Idaho
- Recommendations for Idaho Bridge Manual

Computer Models of UNR Columns

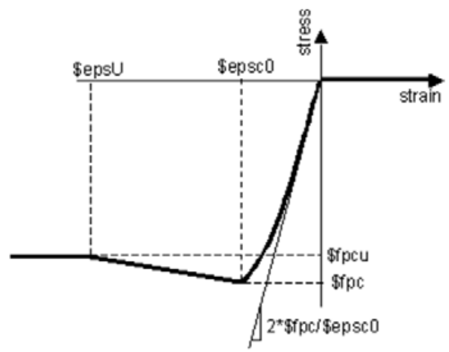
- Modeled cast-in-place (CIP) column and the column with grouted couplers and no pedestal (GCNP).



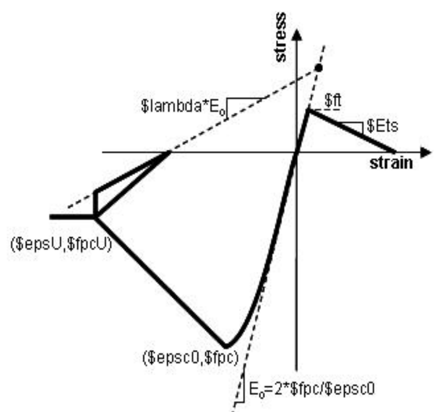
CIP Column | **GCNP Column**

Computer Models of UNR Columns

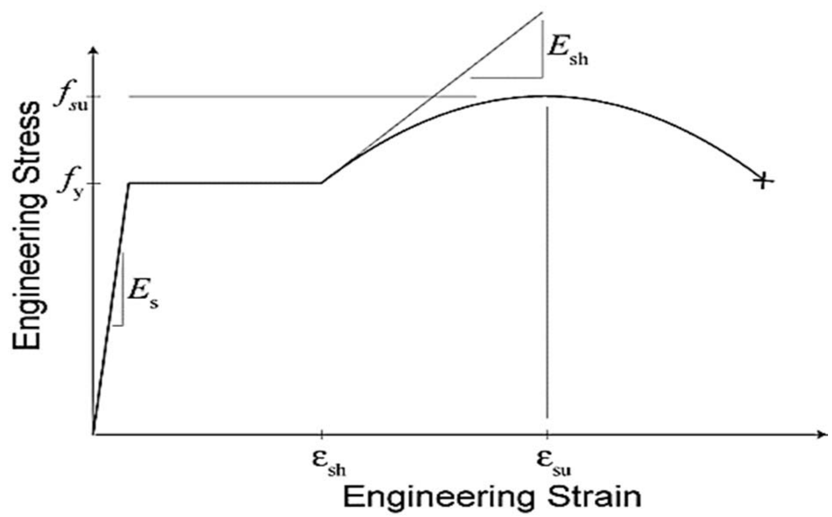
- OpenSees typical material models



"*Concrete01*" Model



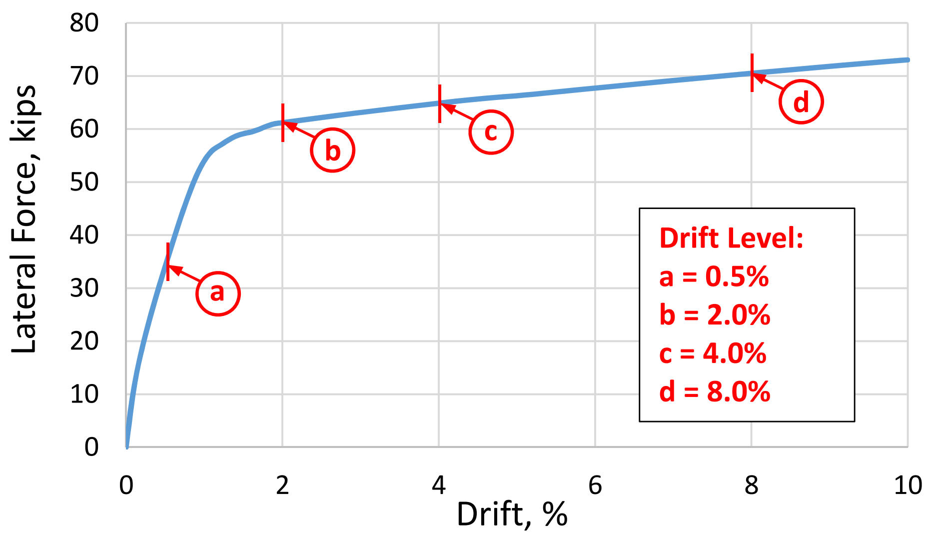
"*Concrete02*" Model

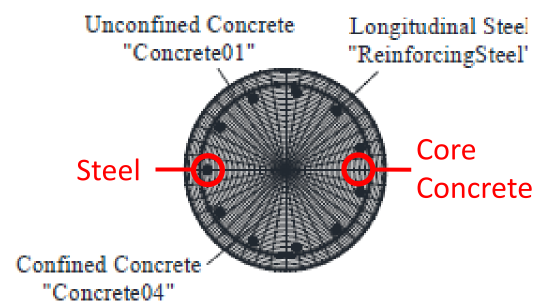


"*Reinforcingsteel*" Model used for Steel Reinforcing Bars and Grouted Couplers

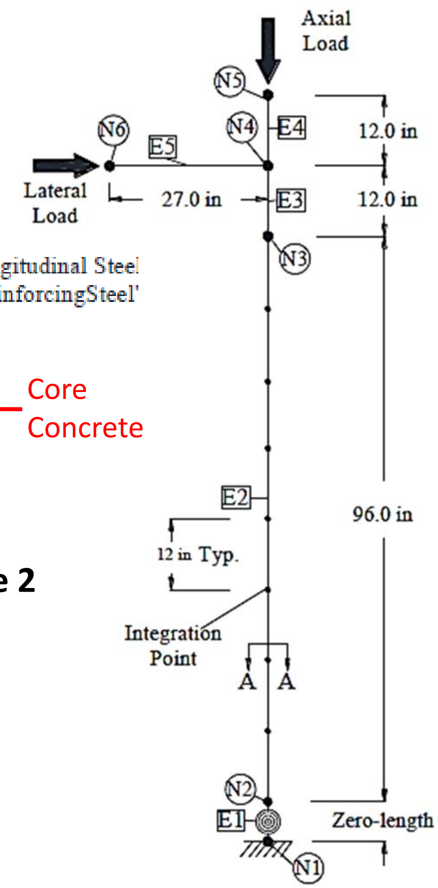
ISU Results for UNR CIP Column

- Stress-strain at different drift levels

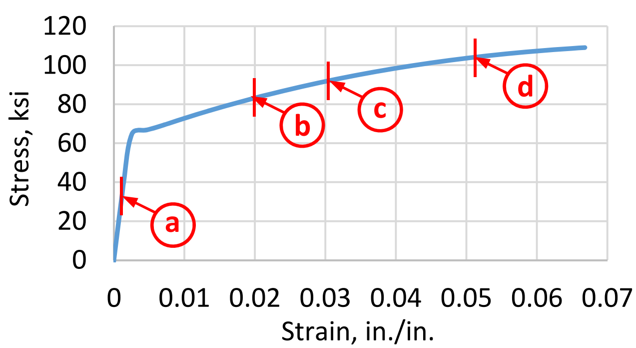




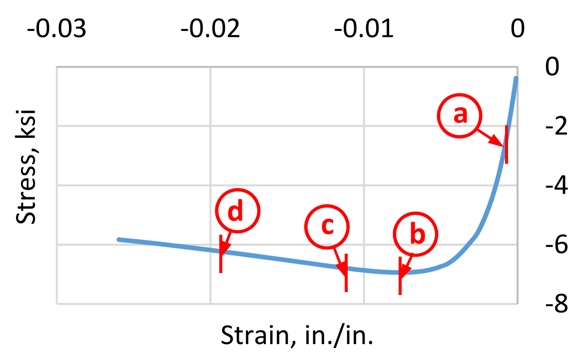
Section at Node 2



OpenSees Model



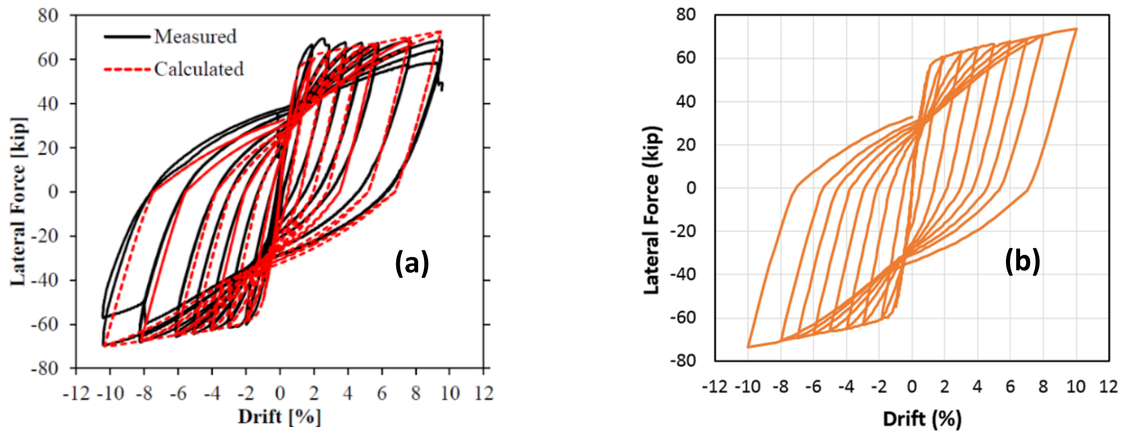
Tension Steel Stress-Strain



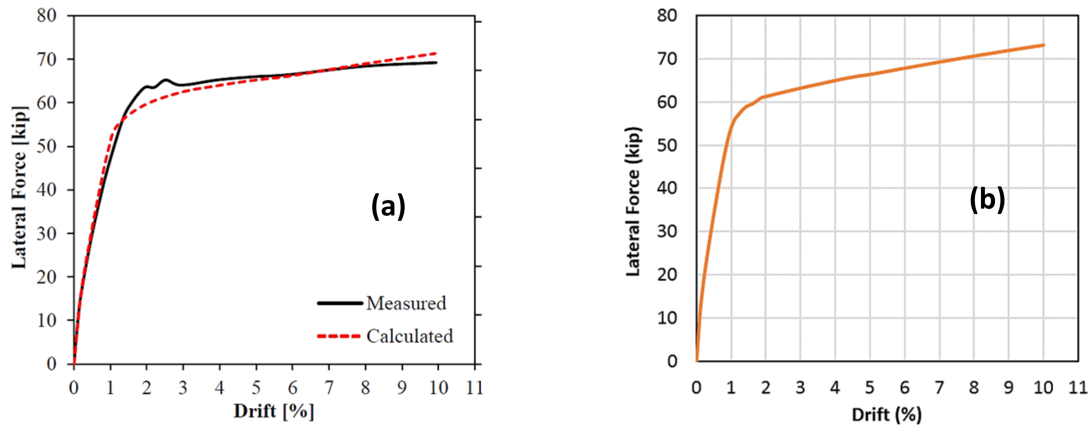
Core Concrete Stress-Strain

UNR vs. ISU Results, CIP Column

- Force-displacements, top of the column



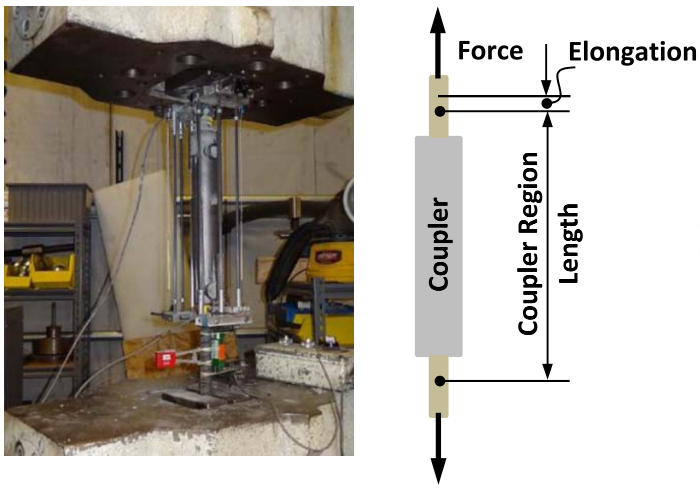
(a) UNR Measured and Calculated and (b) ISU Calculated Hysteretic Force-displacement Curves



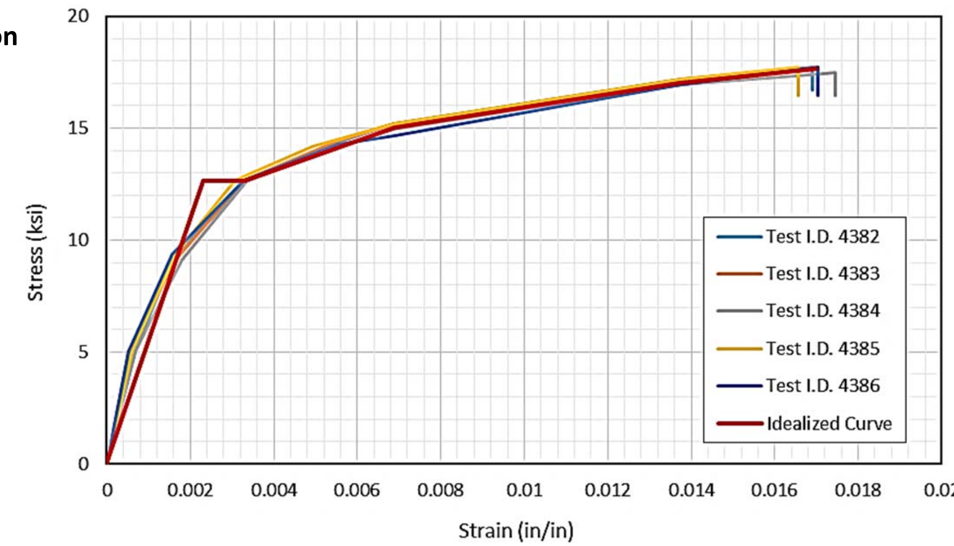
(a) UNR Measured and Calculated Average Envelope and (b) ISU Calculated Curves

Splice Sleeve North America Data

- Experimental data in SSNA report (ER-5645, 2013)



Experimental Tests Performed for Splice Sleeve North America by Wiss, Janney, Elstner Associates, Inc. (SSNA Report ER-5645, 2013)

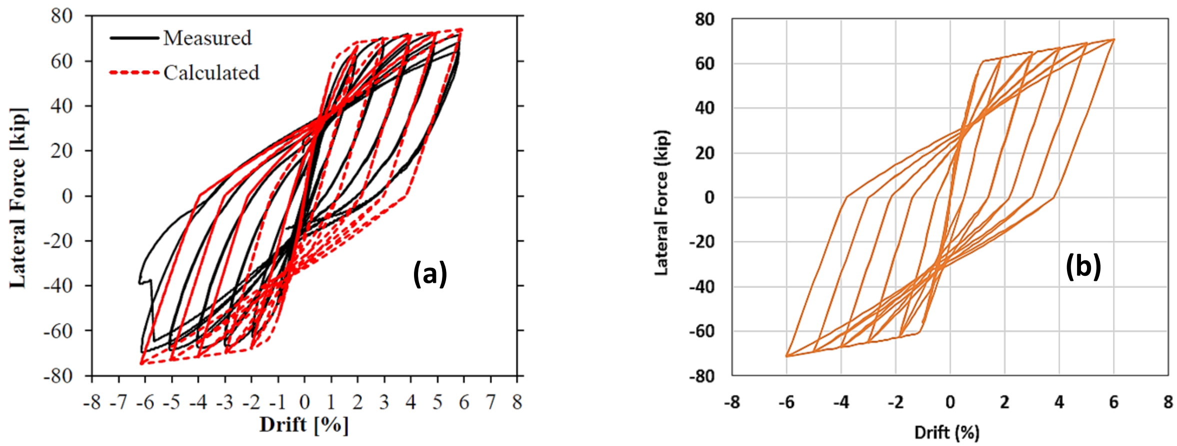


Stress-Strain Relationship for SSNA 8U-X (used for UNR's No. 8 Bars)

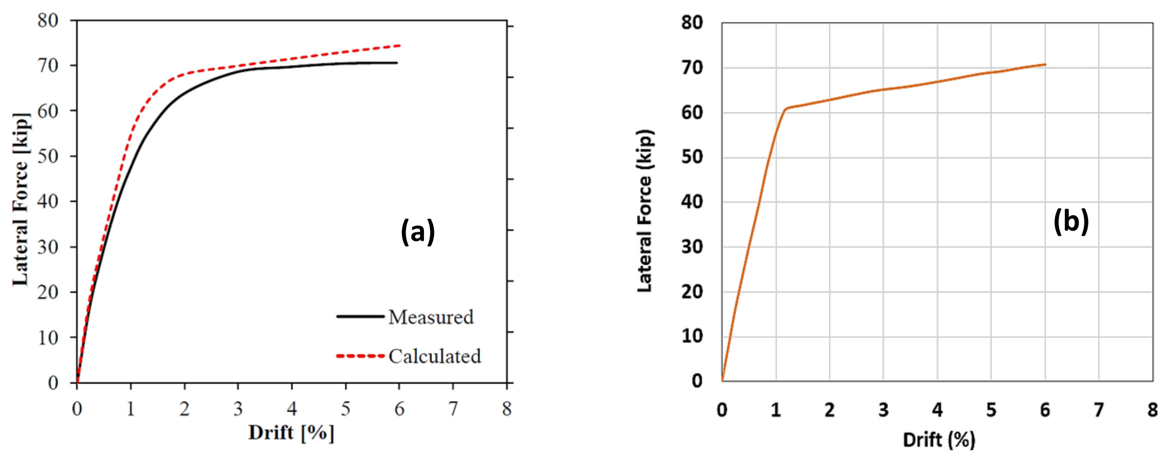
- Data were also obtained for No. 11 and No. 14 bar couplers (needed for the ITD bridge columns).

UNR vs. ISU Results, GCNP Col.

- Force-displacements, top of the column



(a) UNR Measured and Calculated and (b) ISU Calculated Hysteretic Force-displacement Curves



(a) UNR Measured and Calculated Average Envelope and (b) ISU Calculated Curves

Presentation Outline

- Literature Review
- Computer Models of the Univ. of Nevada, Reno (UNR) Columns
- Analysis of Representative Bridges in Idaho
  - Assumptions and methodology
  - Analysis of three bridges
  - Analysis of single columns with grouted couplers under large drift
- Recommendations for Idaho Bridge Manual

Analysis of Bridges in Idaho

- Assumptions and Methodology
  - TAC's request: Consider the most seismically active location in Idaho.
    - Montpelier, Idaho, and soil classification D.
    - $S_{DS} = 0.907$, $S_{D1} = 0.486$. $\Rightarrow$ SDC C (based on new AASHTO Seismic Guide).
  - For each bridge, three models were used:
    - Cracked linear-elastic columns.
      - Effective section properties as per LRFD Seismic Guide Sec. 5.6.
    - Nonlinear CIP columns.
      - Nonlinear materials for unconfined concrete, confined concrete, and longitudinal steel bar (properties as per Sec. 8.4 of LRFD Seismic Guide).
    - Nonlinear columns with grouted couplers at the top and bottom of columns.
      - Steel and concrete same as CIP model.
      - Nonlinear coupler model based on experimental data.
  - For simplicity, we used the "single-mode spectral" method.

Site Conditions for Montpelier

USGS Design Maps Summary Report

User–Specified Input

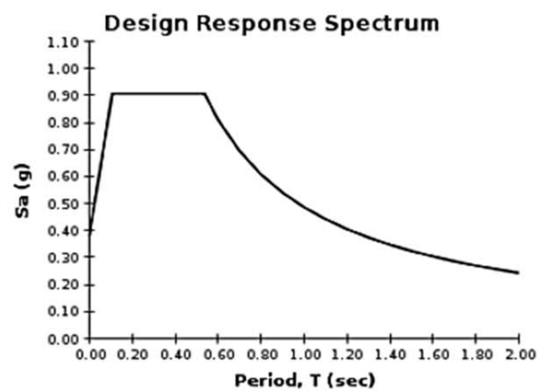
Building Code Reference Document 2009 AASHTO Guide Specifications for LRFD Seismic Bridge Design
(which utilizes USGS hazard data available in 2002)

Site Coordinates 42.32204°N, 111.29481°W

Site Soil Classification Site Class D – "Stiff Soil"

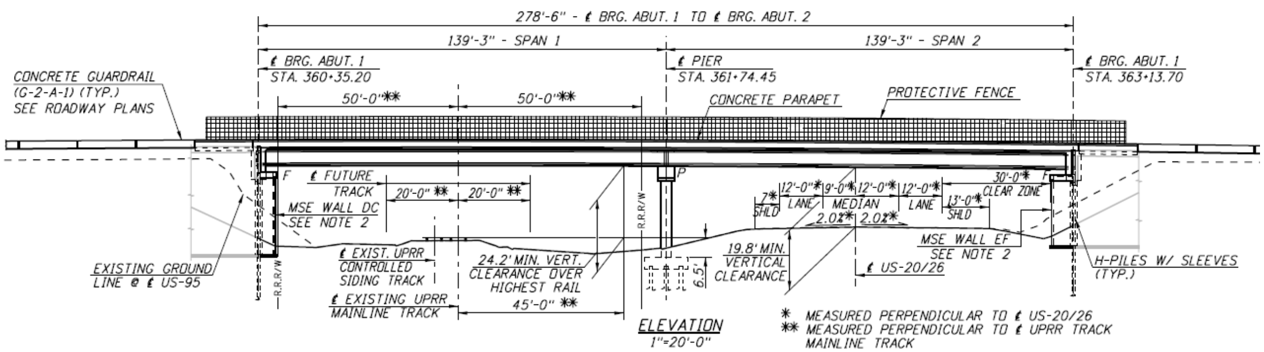
USGS–Provided Output

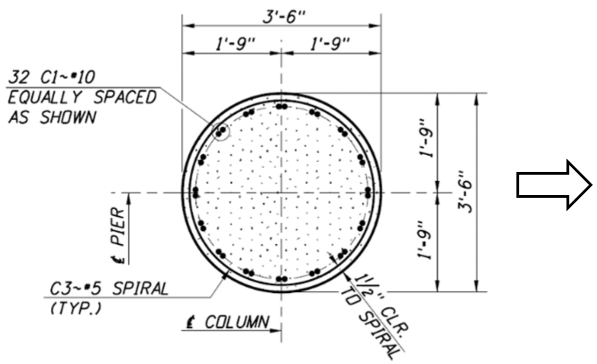
PGA =	0.322 g	A_s =	0.379 g
S_S =	0.758 g	S_{DS} =	0.907 g
S_1 =	0.258 g	S_{D1} =	0.486 g

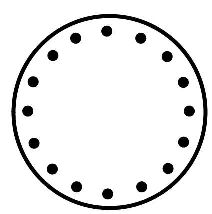


Bridge on US-95 at Parma

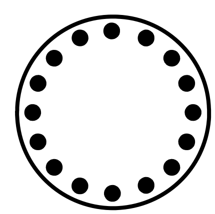
- Two spans, three circular columns in the pier
  - 3.5-ft diameter columns with height of 25.6 ft.
  - No. 10 bars replaced with No. 14 bars.
  - SSNA No. 14 U-X used in columns with grouted couplers. (Diam. = 3.47 in. , Area = 9.45 in.^{2}).







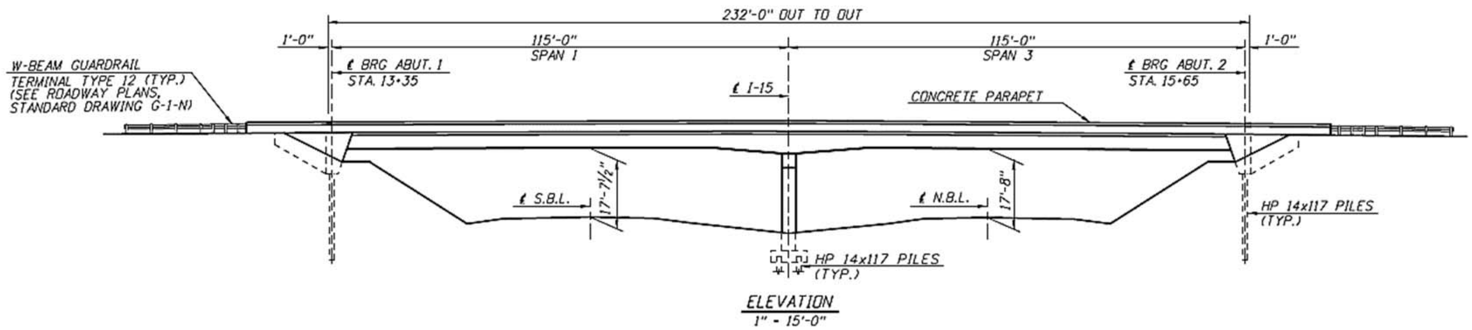
Steel Section with (16) No. 14 Bars

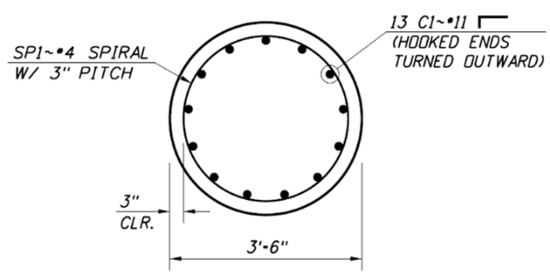


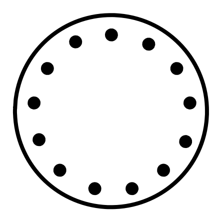
Grouted Coupler Section with (16) SSNA No. 14 U-X

Bridge on SH-22 over I-15 at Dubois

- Two spans, four circular columns per pier
  - 3.5-ft diameter columns with height of approx. 14.1 ft.
  - SSNA SNX 11 used in columns with grouted couplers. (Diam. = 3.05 in., Area = 7.31 in.^{2}).



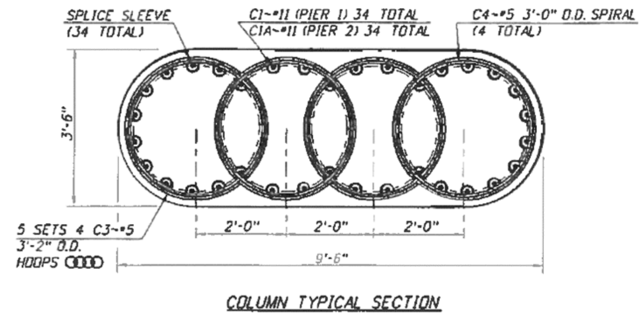


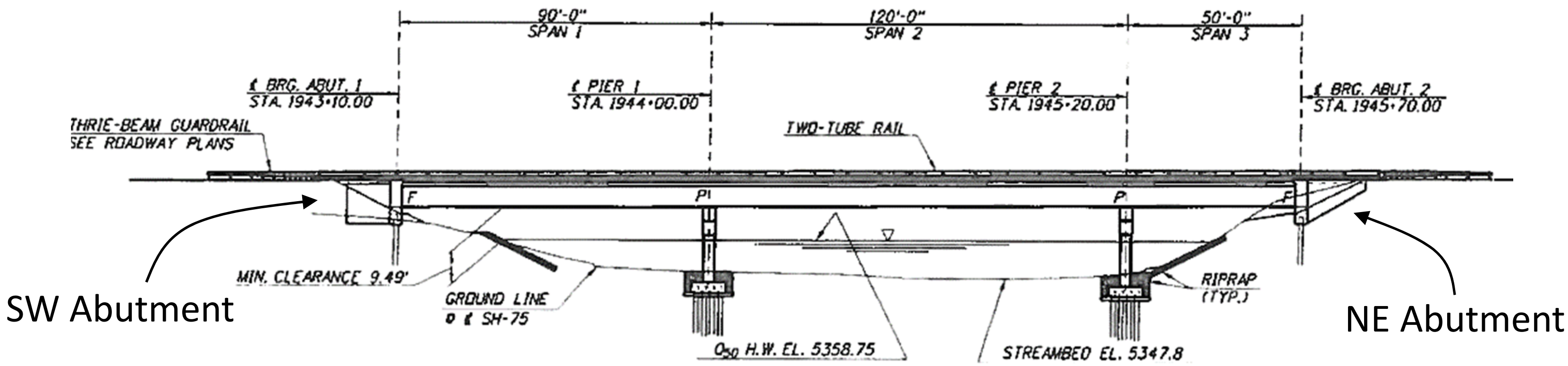


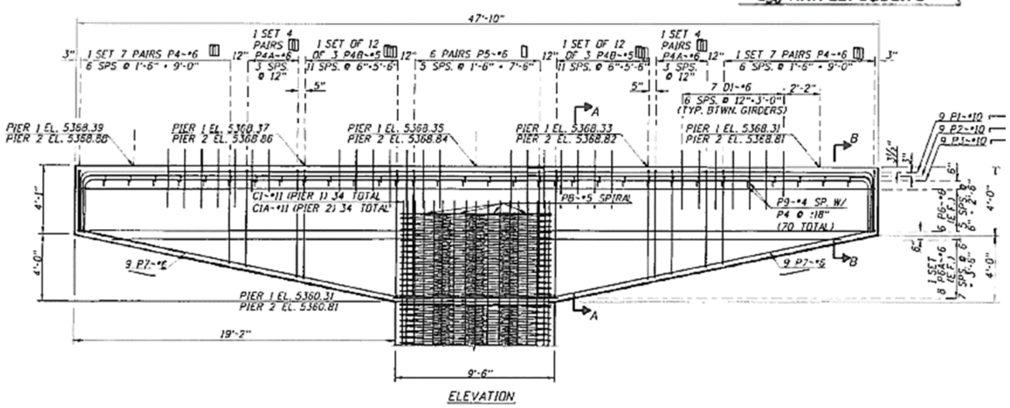
Grouted Coupler Section
with (13) SSNA No. SNX 11

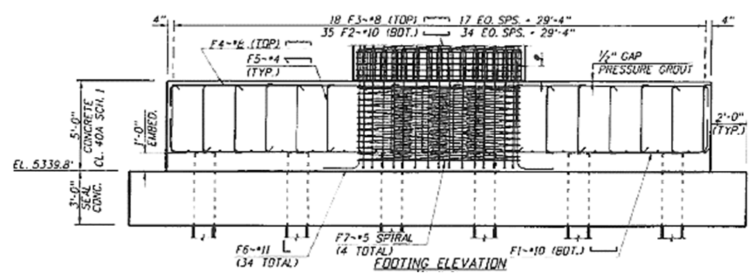
Bridge on SH-75 over Salmon River

- Three spans, one oblong col. in each pier.
  - Columns approx. 15.5 ft and 16.0 ft in height.
  - Grouted couplers used to connect to footing.
  - Couplers modeled with SSNA SNX 11.



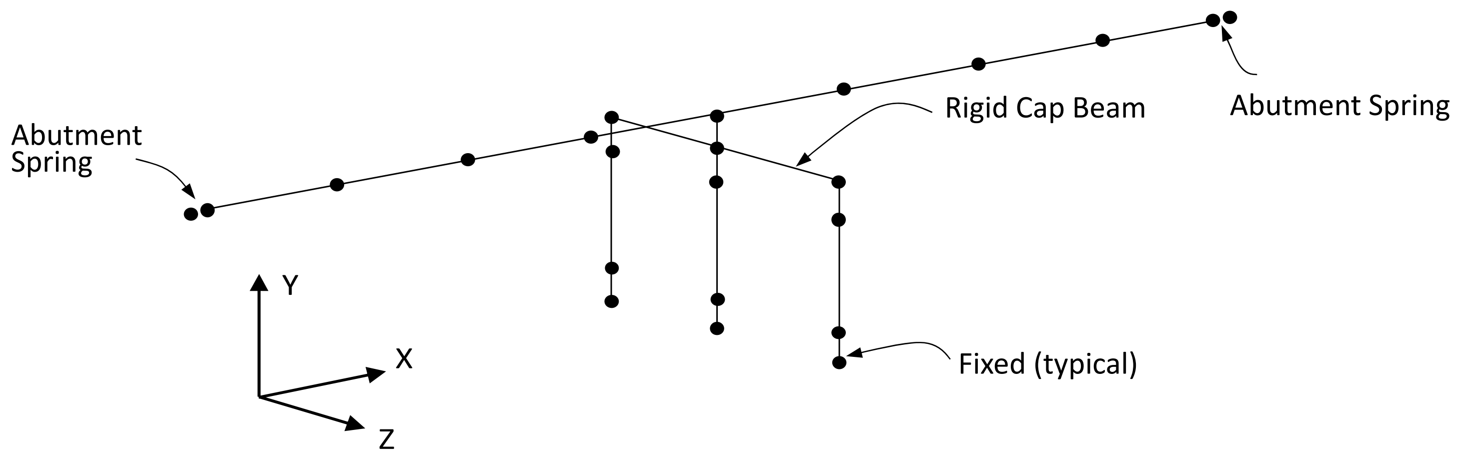






Detailed Analysis of Parma Bridge

- Spine (Stick) Model:
  - Linear-elastic model is shown below.
  - Model with CIP columns and the model with grouted couplers are similar in geometry, but column elements have nonlinear materials with fiber section.
  - In the nonlinear models more elements are used in the columns to represent bond-slip, segments with couplers, or for recording stress-strain.



Detailed Results for Parma Bridge

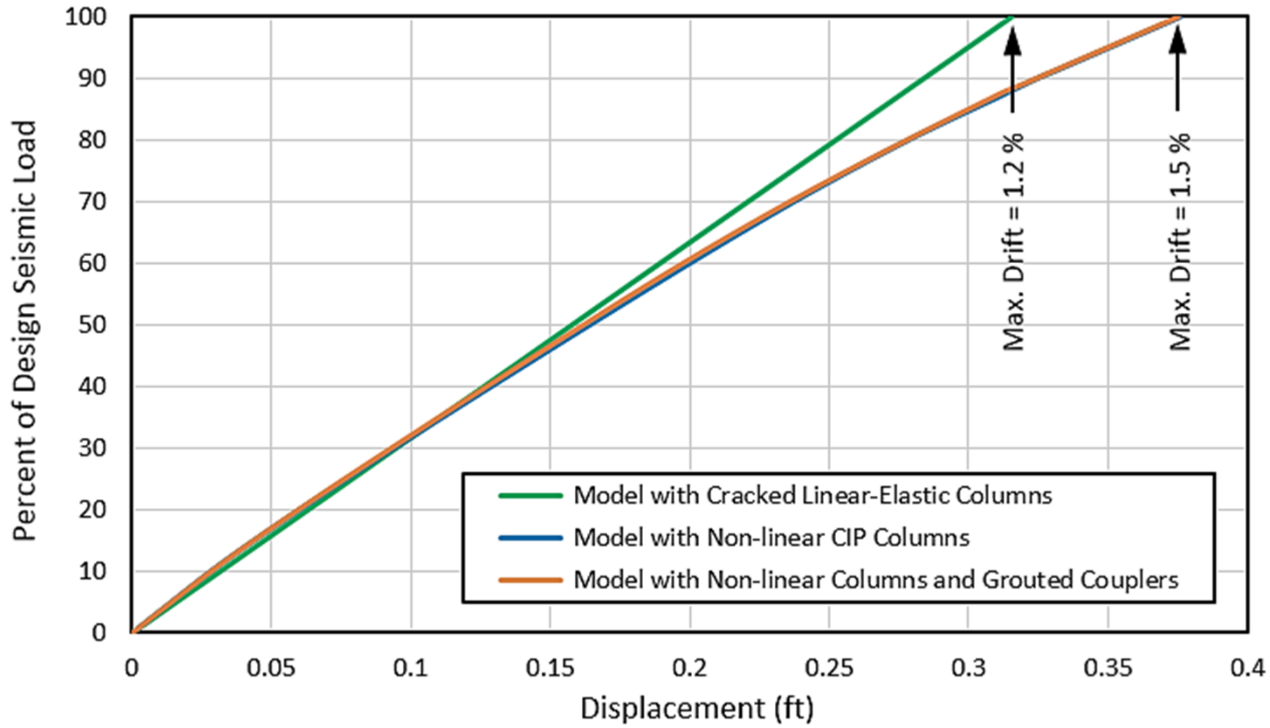
- Column displacements, drifts, and base reactions

	Column Model		
	Cracked Linear-elastic	**Nonlinear CIP**	**Nonlinear w/ coupler**
Transverse			
Top of Column Displ., ft	0.315	0.376	0.375
Column Drift, %	1.23	1.46	1.46
Col. Base Shear, k	385	271.6	272.4
Col. Base Moment, k-ft	5,440	3,624	3,634
Longitudinal			
Top of Column Displ., ft	0.082	0.081	0.080
Column Drift, %	0.32	0.31	0.31
Col. Base Shear, k	87	97	98
Col. Base Moment, k-ft	1,298	1,347	1,366

- Results for the other two bridges are given in the project report.

Detailed Results for Parma Bridge

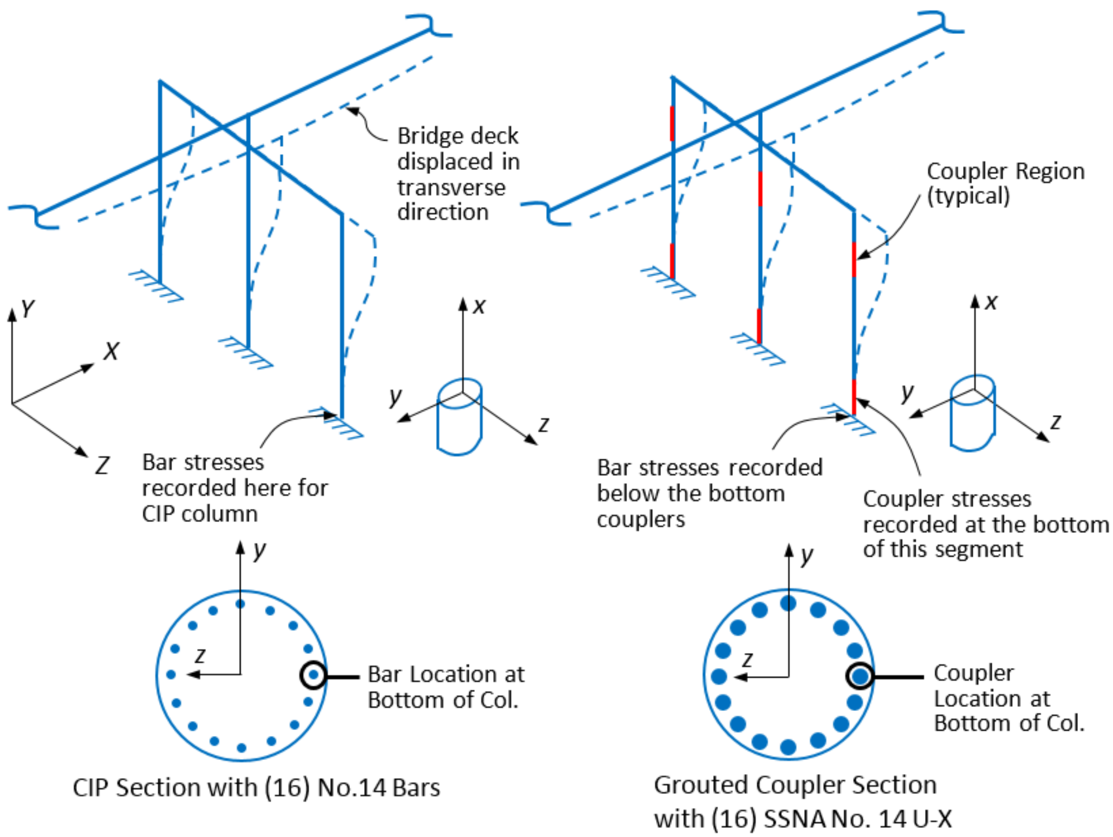
- Column displacements vs. percentage of design transverse load



- For the other two bridges, no significant differences between the two nonlinear responses are observed.
- Parma has the largest drift values.

Detailed Results for Parma Bridge

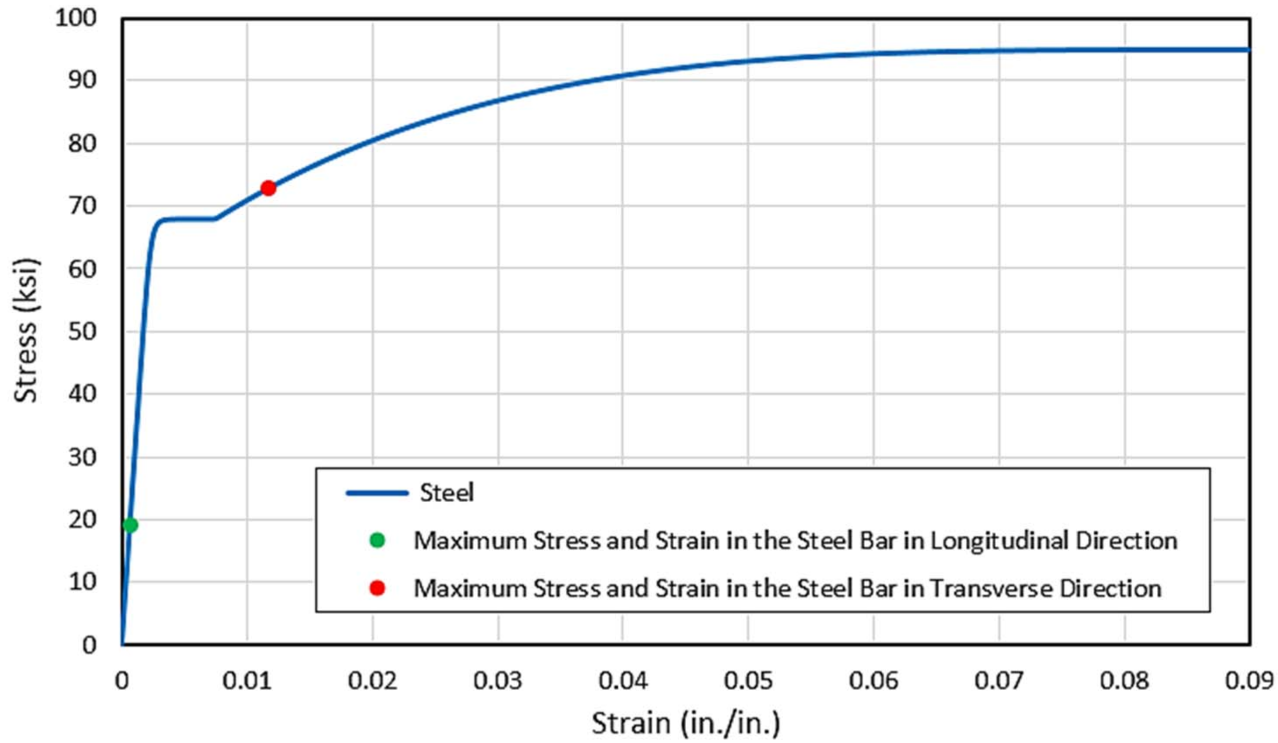
- Stress-strain analysis



Stress-strain Locations: Left CIP Column, Right Column with Couplers

Detailed Results for Parma Bridge

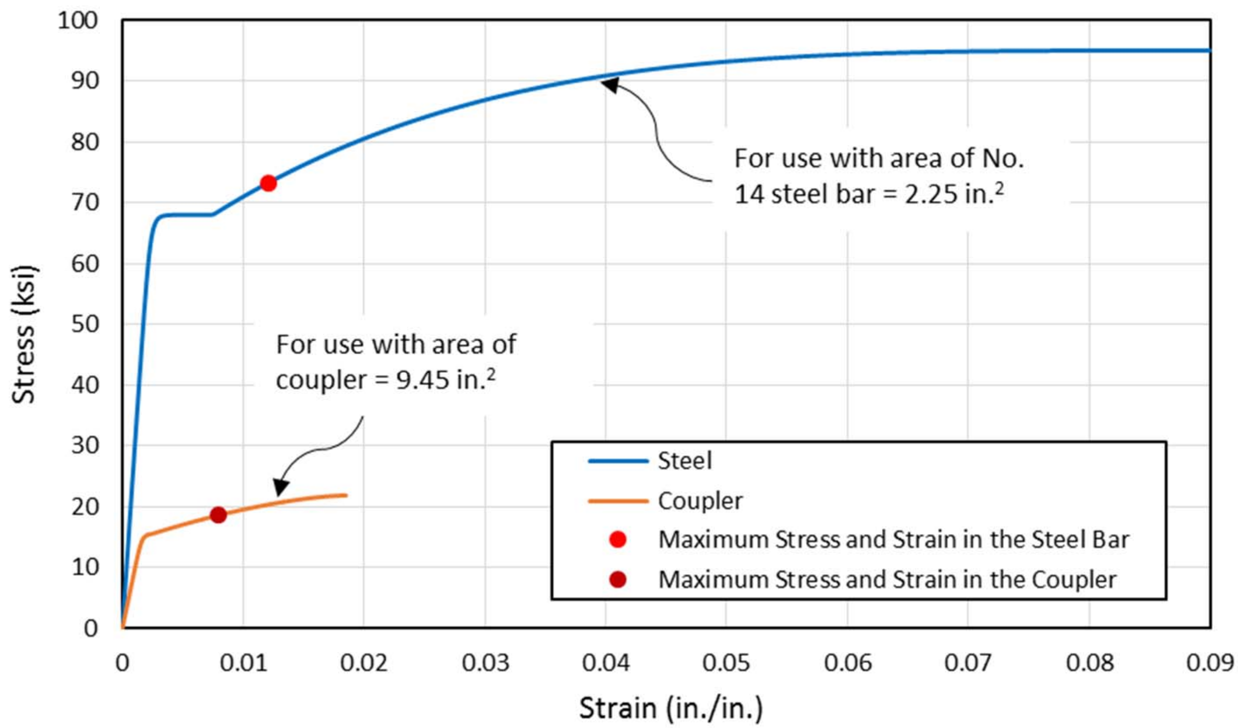
- Stress-strain values in the most stressed steel bar in the CIP col.



- Similar results are observed in the other two bridges.
- Parma's steel bars are stressed the most.

Detailed Results for Parma Bridge

- Stress-strain values in the most stressed steel bar and grouted coupler column with grouted coupler



- Compared to the other two bridges, Parma's couplers are stressed the most.

Comparison with Seismic Guide

- Approximate equations in Seismic Guide for displacement capacity Δ_C and displacement demand Δ_D
  - For SDC C, and Type 1 structure (ductile substructure, elastic superstructure), the displacement capacity is approximated by (Sec. 4.8.1):

$$\Delta_C = 0.12\, H_o\{-2.32\ln(x) - 1.22\} \geq 0.12\, H_o$$

Where, $x = {}^{\Lambda B_o}/_{H_o}$, H_o = column height in ft, B_o = column diam. in ft, Λ = end restraint factor.

  - The displacement demand using elastic analysis and orthogonal combination:

$$\Delta_{D,Linear\ Magnified} = \left(R_d\, \Delta_{D,Linear}\right)_T + 0.3\left(R_d\, \Delta_{D,Linear}\right)_L$$

Where, R_d is obtained as per Seismic Guide, Sec. 4.3.3.

  - Alternatively, using nonlinear analysis, the nonlinear demand becomes:

$$\Delta_{D,Nonlinear} = \left(\Delta_{D,Nonlinear}\right)_T + 0.3\left(\Delta_{D,Nonlinear}\right)_L$$

How close are these?

Comparison with Seismic Guide, cont.

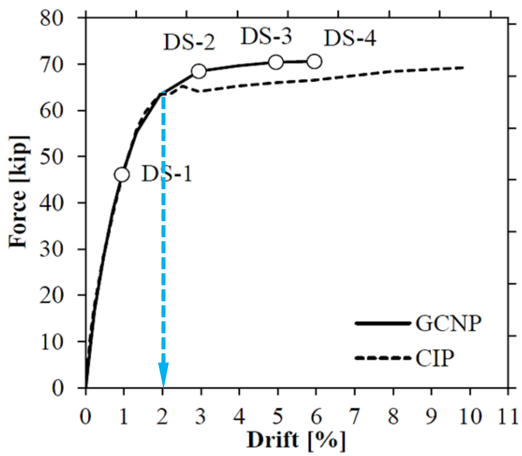
- Displacement/drift capacity versus demand for all bridge columns

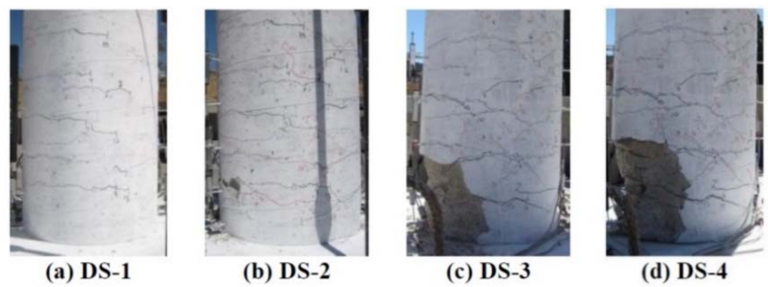
	Parma	**Dubois**	**Salmon River**
Capacity			
H_o, ft	25.60	14.05	15.47
B_o, ft	3.5	3.5	9.5[b]
Δ_C, ft	0.458	- [a]	0.155
Drift = Δ_C/H_o, %	1.79	- [a]	1.00
Demand, Magnified Linear-elastic Analysis			
Transverse R_d	1.149	1.711	1.420
Longitudinal R_d	1.632	2.077	2.051
$\Delta_{D,Linear\ Magnified}$, ft	0.402	0.159	0.112
Drift = $(\Delta_{D,Linear\ Magnified})/H_o$, %	1.57	1.13	0.72
Demand, Nonlinear Analysis			
$\Delta_{D,Nonlinear}$, ft	0.400	0.128	0.082
Drift = $(\Delta_{D,Nonlinear})/H_o$, %	1.56	0.91	0.53

[a] LRFD Bridge Seismic Guide Article 4.8.1 equations may only be used for clear heights greater than or equal to 15 ft.
[b] Using the transverse direction, thus the major dimension of the oblong cross-section is used.

Analysis of Idaho Bridges

- Observations:
  - Bridge column drifts are low in the most seismic location in Idaho. Using the orthogonal combination, the largest drift is about 1.6%.
  - Recall the UNR experimental results show that there is no significant difference between CIP and GCNP columns up to 2% drift. We found the same to be true.



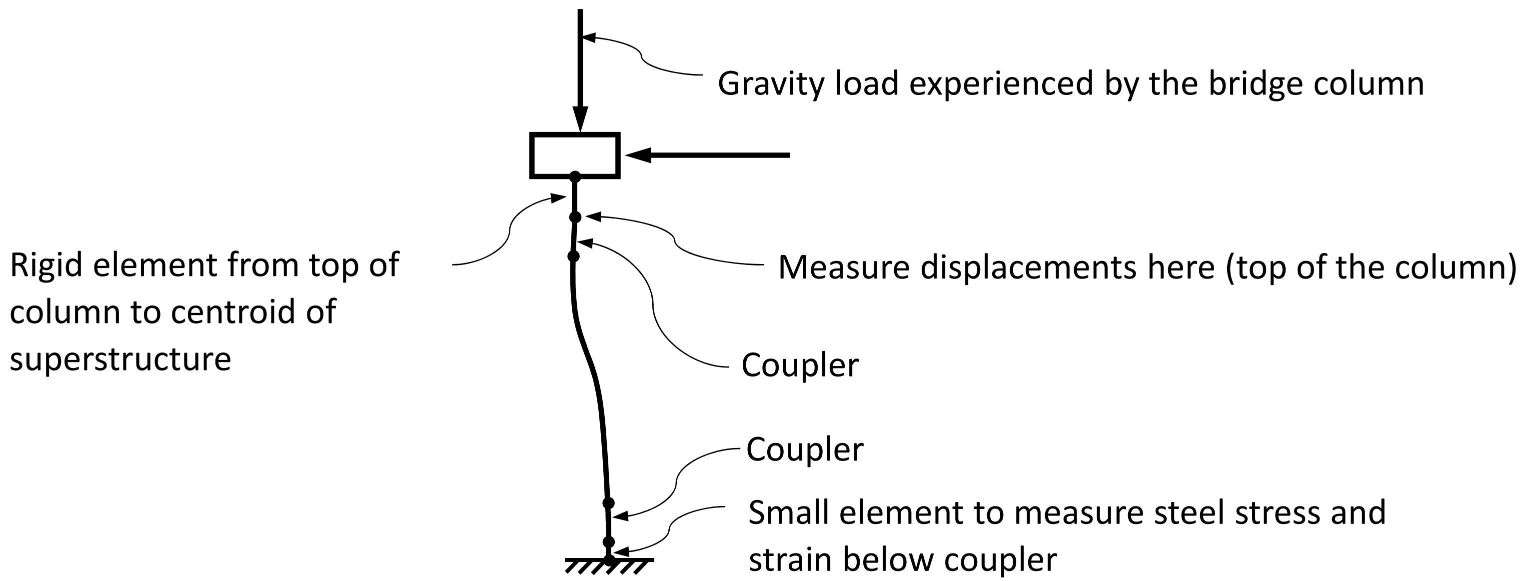


Measured force-displacement envelopes with damage progression indicators from UNR Report (Haber, et al., 2013).

  - The most stressed steel bars and couplers have stresses greater than yield stresses, but much less than the ultimate stresses.
  - Seismic Guide's approximate relations for the magnified linear-elastic displacement/drift demand result in either the same or larger values (i.e., more conservative) than the nonlinear results.

Single Columns under Large Drifts

- Considered single columns from two of the bridges.
  - Pushed horizontally until failure of grouted coupler was observed.



Single Column with Fixed-fixed Boundary Conditions

Single Columns under Large Drifts

- Results for Parma Bridge

Column Nonlinear Drift, %	Coupler Region	
	Stress, ksi	Strain, in./in.
0.25	4.50	0.0005
0.5	11.25	0.0012
0.75	15.40	0.0021
1	16.65	0.0044
1.5	18.59	0.0080
2	19.21	0.0094
2.5	19.88	0.0110
3	20.50	0.0126
3.5	21.08	0.0144
4	21.56	0.0165
4.4	21.80[a]	0.0185[a]

[a] Ultimate stress and strain values for SSNA No. 14 U-X grouted coupler

- Observation: Bridge columns are able to withstand at least 4 percent of nonlinear drift before failure of grouted couplers.

Presentation Outline

- Literature Review
- Computer Models of the Univ. of Nevada, Reno (UNR) Columns
- Analysis of Representative Bridges in Idaho
- Recommendations for Idaho Bridge Manual

Recommendations for Idaho Bridge Manual

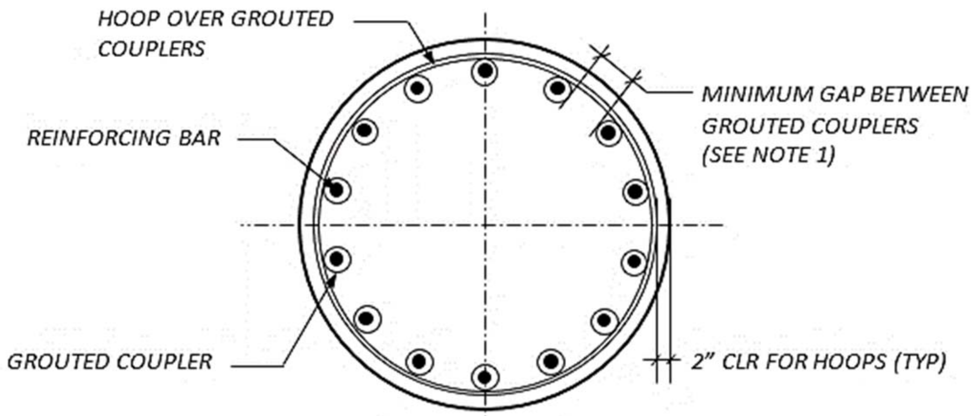
- Grouted splice couplers may be used to connect precast columns to footings or cap beams for columns with less than **4 percent drift**.
  - Displacements may be obtained through nonlinear analysis.
  - Alternatively, the displacements may be obtained by linear-elastic analysis (i.e., using cracked column section) and magnification factors as per AASHTO Seismic Guide's Article 4.3.3.
  - In both cases, combination of orthogonal seismic displacements are to be used as per Seismic Guide's Article 4.4.

Recommendations, cont.

- The total length of grouted splice couplers shall not exceed $15d_b$, where d_b is the longitudinal reinforcing bar diameter. See the list of approved grouted couplers.
- Grouted couplers in plastic hinge zones must develop 150% of the specified yield strength of the connected reinforcing bar.
- Minimum clear distance between grouted splice couplers is recommended to be the same as those specified for reinforcing bars. See the typical detail drawings. The clear cover for the shear reinforcement over grouted couplers in the precast column shall be 2”.
- Grout for grouted couplers shall be provided by the manufacturer.

Recommendations, cont.

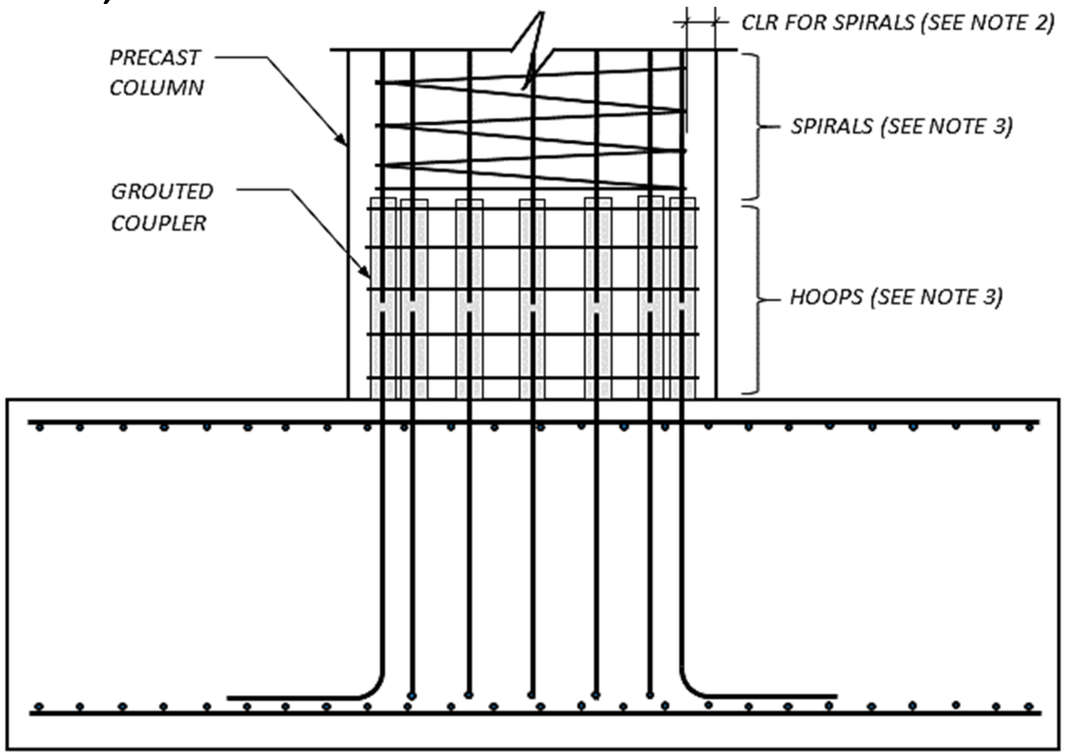
- Typical connection details



COLUMN SECTION
NTS

Recommendations, cont.

- Typical details, cont.



COLUMN/FOOTING ELEVATION
NTS

NOTES:

1. LARGER OF (1) 1 IN., (2) 1.33 TIMES MAX. COARSE AGGREGATE SIZE, AND (3) NOMINAL DIAMETER OF CONNECTED REINFORCING.
2. CLEAR COVER FOR SPIRALS = 2” + (DIAM. OF COUPLER – DIAMETER OF BAR)/2
3. FOLLOW THE REQUIREMENTS OF AASHTO LRFD BRIDGE DESIGN SPECIFICATIONS SECTION 5.10.6.

Acknowledgements

- Thanks to ITD and FHWA for supporting this project
  - **Project Sponsor –** Matt Farrar, P.E.
  - **Project Manager –** Dan Gorley, P.E.
  - **TAC Members**
    - Leonard Ruminski, P.E.
    - Ned Parrish
  - **FHWA-Idaho Advisor –** Ed Miltner
- Peer Reviewer
  - Dr. Saiidi, University of Nevada, Reno
- Students
  - Barbara Earles, Supreme Maskey, Maria Tangarife, and Kyle Gagnon

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