Applications of UHPC for non-seismic and seismic ABC Connections and Introduction to Full Structural Columns

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Outline

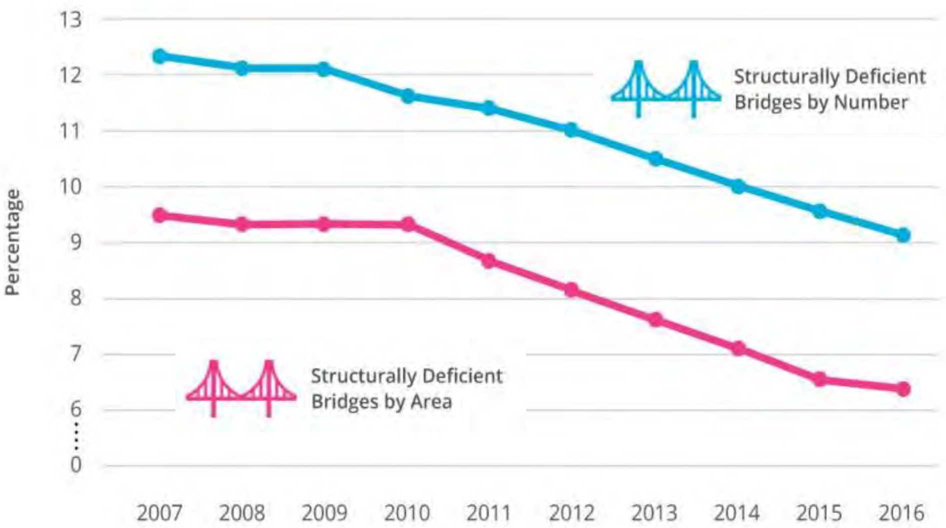
- Introduction
- Application #1: seismic connections
- Application #2: precast deck joints
- Application #3: full seismic columns with Gr 60 & Gr 100 steel

Aging Infrastructure

ASCE 2021 Infrastructure Report Card

Are we making progress?

- 2017→ 2021 Overall grade improved from **D+** in 2017 to **C-** in 2021 (*C = mediocre, D = poor*)



*Source: https://www.infrastructurereportcard.org/americas-grades

Next Generation Infrastructure

ASCE Vision*

- America's infrastructure will be improved and restored through:
  - **Investment**, **leadership**, **planning**, and **preparation for the needs of the future …**
- **Preparation for the needs of the future:** new approaches, materials, and technologies for **resilient**, i.e. quick recovery from extreme events, and **sustainable**, i.e. brings economic, social, and environmental benefits.
  - ✓ Develop active community resilience programs for severe weather and seismic events;
  - ✓ Consider emerging technologies and shifting social and economic trends when building new infrastructure to assure long-term utility;
  - ✓ Improve land use planning to consider the function of existing and new infrastructure, balance between built & natural environments, and population trends in communities;
  - ✓ Support research and development into innovative new materials, technologies, and processes to modernize and extend life of infrastructure, expedite repairs or replacement, and promote cost savings

*Source: https://www.infrastructurereportcard.org/americas-grades/

Next Generation Infrastructure

ASCE Vision*

#GameChangers

e.g. BRIDGE SECTOR

- Bridge-in-a-backpack
- Use of robotics, drones, etc. for inspection

Town in Connecticut Builds Bridge Out of a 'Backpack'

State: Connecticut | **Category:** Bridges
March 07, 2017 | By: ASCE Staff

Accelerated Bridge Construction (ABC)

Traditional bridge construction can be a costly and lengthy process, greatly affecting local traffic. In Weston, Conn., the Department of Transportation used first-of-its-kind "bridge-in-a-backpack" technology to replace a major bridge in just 16 weeks, rather than two years.

The bridge over the Saugatuck River, originally constructed in 1933, experienced about 9,100 crossings each day and was classified as "structurally deficient." Through the use of "bridge-in-a-backpack" capabilities, the project utilized prefabricated, fiber reinforced polymer tubes with concrete instead of steel beams or heavy construction equipment. Precast concrete block retaining walls were used at all four corners of the structure to help speed construction. At the same time as bridge construction, Route 57 was widened and a shoulder/bike lane was added in each direction.

This technique, which dramatically sped up the time period of bridge replacement, saved the state money and greatly reduced the time traffic was affected.

Robotic inspections are more accurate, less costly

State: Georgia | **Category:** Bridges
February 16, 2017 | By: ASCE Staff

The Georgia Department of Transportation partnered with the Georgia Tech Research Institute to create robotic technology that will automatically detect and repair damaged roads. The "Roadbot" is fully automated and requires only a single operator.

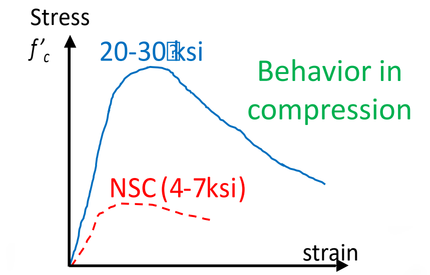
The Roadbot has the potential to save states significant amounts of money by taking a preemptive approach toward road maintenance. By preventing larger damage, the Roadbot could allow states to focus their resources on other projects. Detection accuracy currently sits at 83 percent.

*Source: https://www.infrastructurereportcard.org/americas-grades/

What is UHPC?

- Ultra-High Performance Concrete (UHPC) is a new generation of cementitious materials with superior durability and mechanical properties (e.g. low porosity, high ductility, tensile capacity, etc.)
- UHPC is a mix of Portland cement, sand, silica fume, quartz, water, superplasticizer and usually 2% volumetric high-strength steel fibers.
- FHWA defines UHPC as cementitious composite material whose compressive strength is greater is 21.7 ksi and post-cracking tensile strength of 0.72 ksi.

What is UHPC?



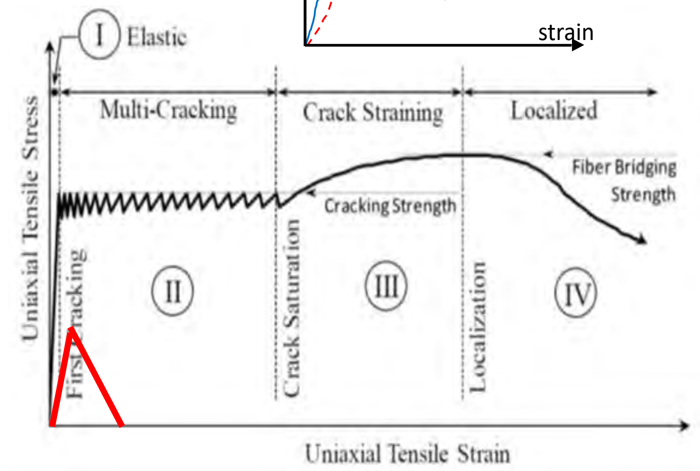
- One of the unique features of UHPC is tensile behavior

- UHPC is attracting larger attention in the bridge industry specially for Accelerated Bridge Construction (ABC) connections

- UHPC is not widely used at larger scales for full structural elements (e.g. columns or girders)

- **Some of Challenges:**

  - Higher cost
  - Lack of trained work force for construction
  - Lack of knowledge on structural performance of full members



Behavior in Tenison (adopted from Graybeal and Russell 2013)

	UHPC	NSC
Compressive Strength (ksi)	20 - 30	4-7
Tensile Cracking Strength (ksi)	0.9 -1.5	0.3
Modulus of Elasticity (ksi)	6000-8000	3000-4000
Poisson's Ratio	0.2	0.2

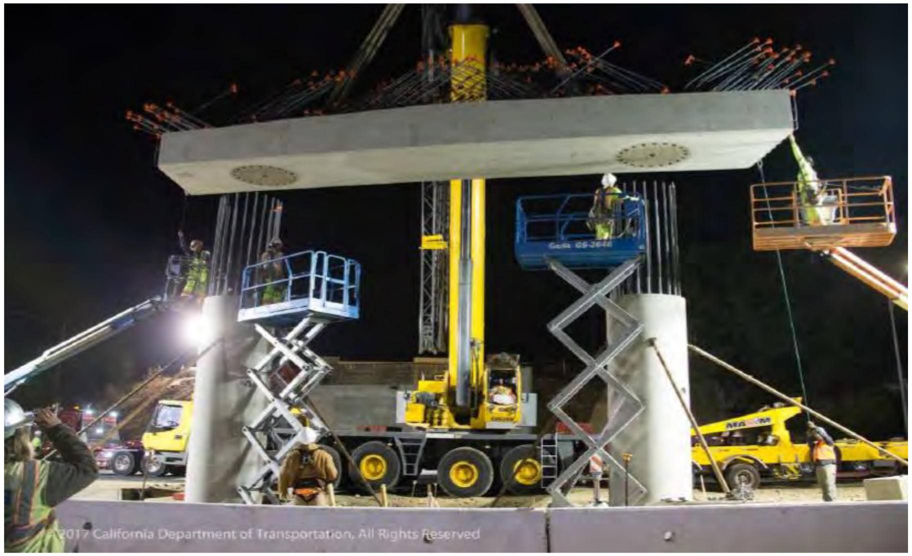
UHPC Connections

Accelerated Bridge Construction

What is ABC?

- Formal use of term “ABC” is relatively new, but ABC has been adopted for decades
- Prefabricating bridge elements and systems (PBES) → major time savings, cost savings, better quality control, safety advantages, convenience for travelers, etc.
- Innovative PBES connections evolved and many of these connections use advanced materials such as **UHPC** → simplify rft. Configuration, lead to smaller joints, provide better interface bond

Precast deck panels with transverse and longitudinal joints, photo credit: Georgia DOT)



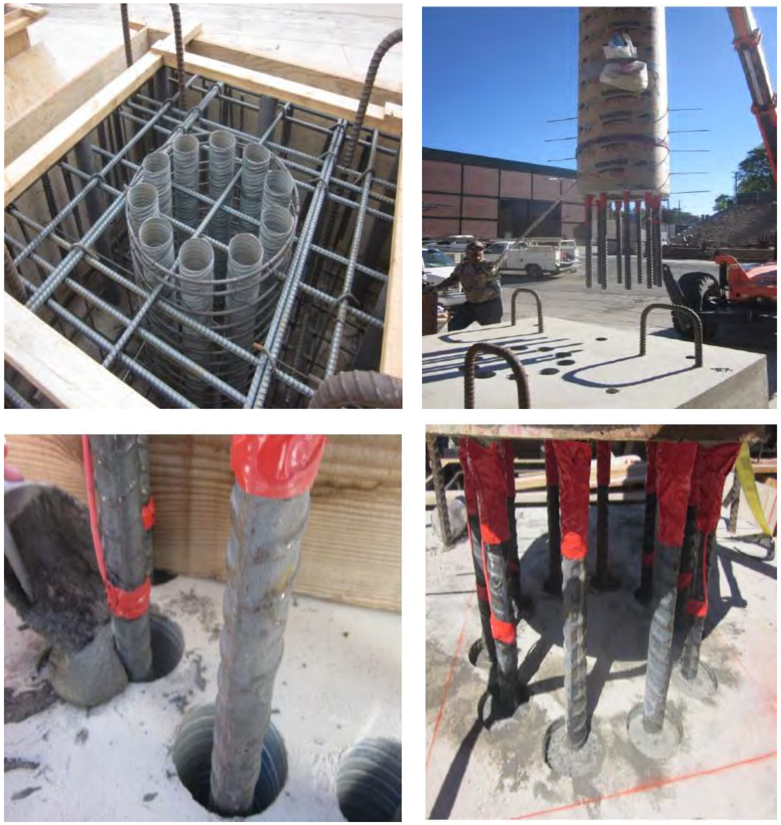
Precast columns and drop bent cap for Laurel Street Overcrossing project in CA (courtesy of Dorie Mellon)

Application #1:

Non-proprietary UHPC for ABC seismic connections

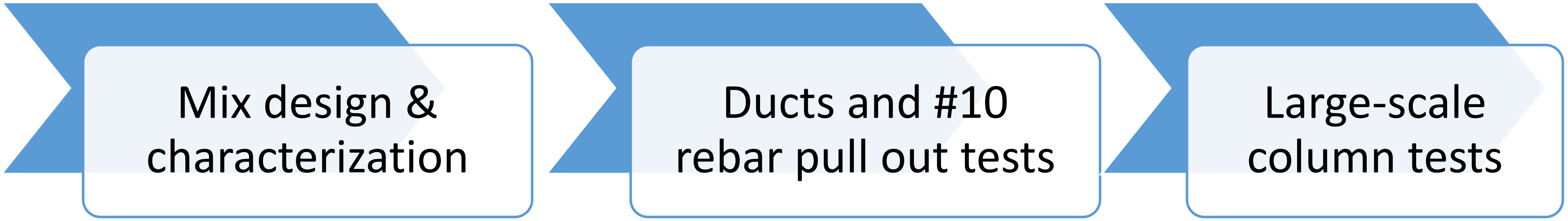
Introduction

- ➢ Column-to-Footing and Column-to-Bent Cap Grouted Duct Connection
- ➢ <u>Challenges with Proprietary UHPC:</u>
  - ▪ 8-10 times more expensive than standard grout and conventional concrete.
  - ▪ Sole-source bidding may be a problem



OBJECTIVE:

Develop non-proprietary UHPC for anchorage for grouted duct connection & demonstrate validity using large/full scale testing



Mix Design & Characterization

Mix Ingredients

Cement, Fine Aggregates, Silica fumes, Superplasticizer (HRWRA), Steel fibers, and Water. Two types of fine aggregates used:

- ✓ Uncrushed natural river sand from Perkins, Sacramento, CA → **UNR-UHPC-A**
- ✓ 100% crushed concrete sand from Spanish Springs, NV → **UNR-UHPC-B**

Mixing Proportions

Mix Ingredients	UNR-UHPC-A	UNR-UHPC-B
	% by weight	% by weight
Cement	37.8	37.8
Fine aggregates	38.6	38.6
Silica fumes	7.3	7.3
Steel fibers	6.6	6.5
Superplascitizer (HRWRA)	0.9	1.1
Water	8.7	8.7

Water/Cement ratio	0.23	0.23
Flow (inches)	>10	>10

Flow test procedure (ASTM C1437/230)

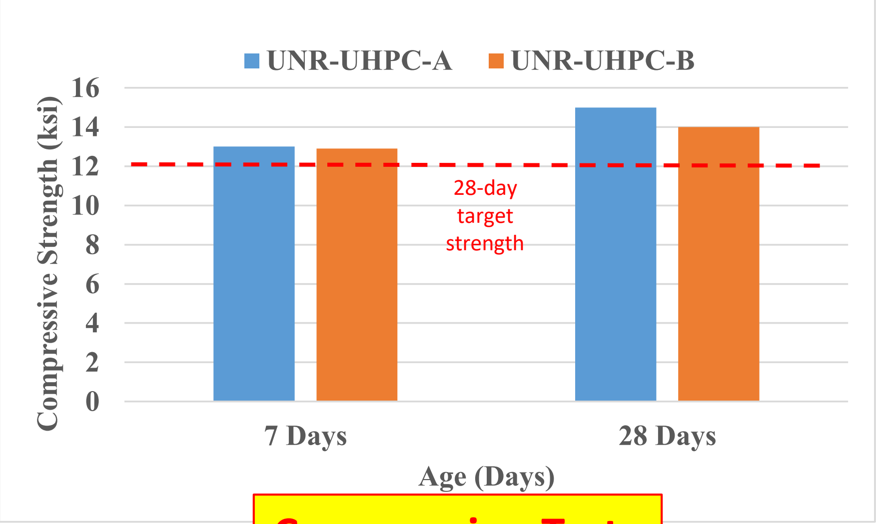
Mix Design & Characterization

Mechanical Tests

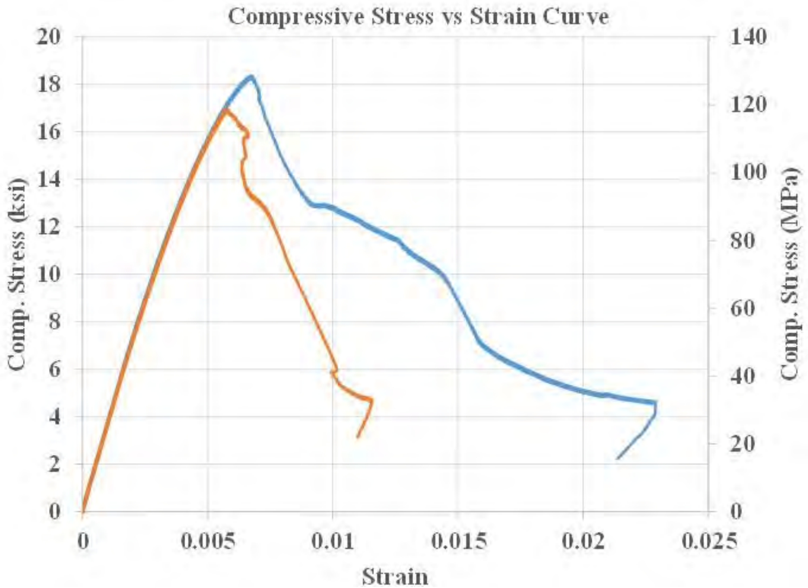
1. <u>Compression Tests</u>
   - Compressive strength (3, 4×8 in cylinders)
   - Stress-strain relationship (2, 3-in by 6-in cylinders)
   - Modulus of Elasticity and Poisson's Ratio (2, 3-in by 6-in cylinders)

2. <u>Flexural Tests</u>
   - Flexural strength (3, 3-in by 3-in c/s beams)
   - Flexural stress vs. strain relationship (3, 3-in by 3-in c/s beams)

3. <u>Direct Tension Tests</u>
   - Tensile strength (3, 1-in by ½ in cross section dog bone specimen)
   - Tensile stress vs. strain relationship (3,1-in by ½ in cross section dog bone specimen)



Compression Tests



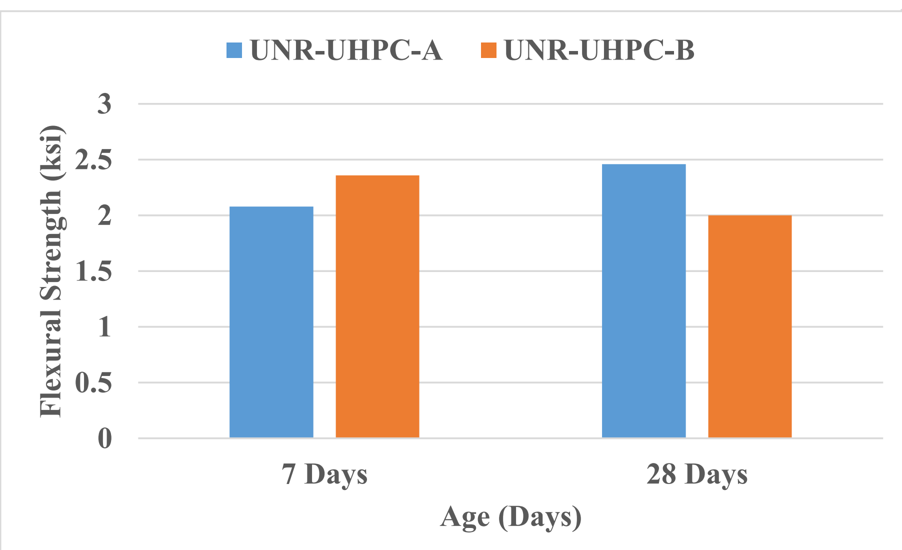
Mix Design & Characterization

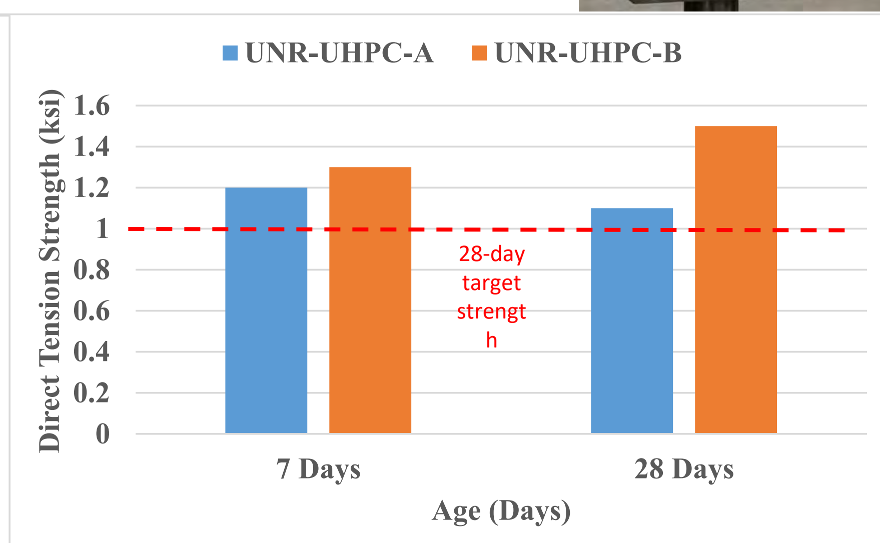
Flexure Tests

- ✓ ASTM C78 Test Method
- ✓ 3-in by 3-in by 12-in beam

Direct Tension Tests

- ✓ Tested using ½ × ½ in cross-section dog bone specimen





Grouted Ducts Tests

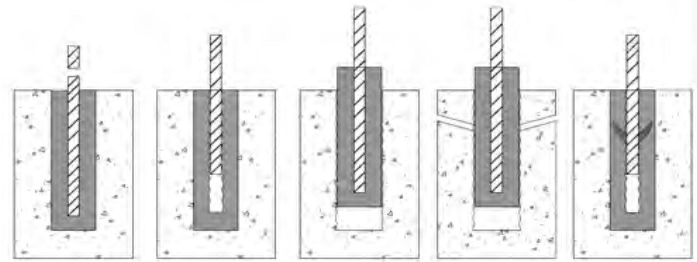
Test Specimens

#10 Rebars embedded in UHPC-filled corrugated ducts

Test Parameters

For a total of 22 tests, the following test parameters were varied:

1. Embedment Length
2. Bundling of Bars
3. Duct Diameter
4. Duct Thickness
5. Duct Material
6. Grout Mix



Possible modes of failures in grouted duct connections

Group	ID	Rebar size	Embedment Length		Duct Properties			Grout material	Test parameter
			multiples of d_b	inch	nominal size	thickness	material *		
A	A1	#10	$4d_b$	5.1	4	26	GS	UNR-UHPC-A	Embedment length
	A2	#10	$8d_b$	10.2	4	26	GS		
	A3	#10	$12d_b$	15.2	4	26	GS		
	A4	#10	$16d_b$	20.3	4	26	GS		
	A5	2-#10	$4d_b$	7.2	5	26	GS		Bundling of bars
	A6	2-#10	$8d_b$	14.4	5	26	GS		
	A7	2-#10	$12d_b$	21.6	5	26	GS		
	A8	2-#10	$16d_b$	28.7	5	26	GS		
B	B1	#10	$4d_b$	5.1	4	26	GS	UNR-UHPC-B	Embedment length
	B2	#10	$8d_b$	10.2	4	26	GS		
	B3	#10	$12d_b$	15.2	4	26	GS		
	B4	#10	$16d_b$	20.3	4	26	GS		
	B5	2-#10	$4d_b$	7.2	5	26	GS		Bundling of bars
	B6	2-#10	$8d_b$	14.4	5	26	GS		
	B7	2-#10	$12d_b$	21.6	5	26	GS		
	B8	2-#10	$16d_b$	28.7	5	26	GS		
C	C1	#10	$8d_b$	10.2	4	24	GS	UNR-UHPC-A	Duct thickness
	C2	#10	$8d_b$	10.2	4	26	PD1		Duct material
	C3	#10	$8d_b$	10.2	4	26	PD2		
	C4	#10	$8d_b$	10.2	5	26	GS		Duct size
D	D1	#10	$12d_b$	15.2	4	26	GS	Ductal	Mix
E	E1	#10	$12d_b$	15.2	4	26	GS	Grout	

* GS: galvanized steel; PD1: polymer duct type 1; PD2: polymer duct type 2

Grouted Ducts Tests

Construction of Specimens

- 4 concrete blocks
- 22 ducts with varying embedment length & different materials

Grouted Ducts Tests

Test Setup

Grouted Ducts Tests

Test Results

Group	ID	Rebar	Embedment length	Maximum Load (kips)	Displacement (in)	Mode of failure
A	A1	#10	4db	73.2	1.32	Duct-bond failure
	A2	#10	8db	81.7	2.38	Duct-bond failure
	A3	#10	12db	124.3	8.99	Rebar rupture
	A4	#10	16db	122	9.67	Rebar rupture
	A5	2-#10	4db	74.6	1.75	Duct-bond failure
	A6	2-#10	8db	133.6	2.62	Duct-bond failure
	A7	2-#10	12db	217.6	4.09	Duct-bond failure
	A8	2-#10	16db	228.3	4.55	Duct-bond failure
B	B1	#10	4db	57.4	2.22	Duct-bond failure
	B2	#10	8db	107.6	3.1	Duct-bond failure
	B3	#10	12db	121.5	7.66	Rebar rupture
	B4	#10	16db	123.1	7.7	Rebar rupture
	B5	2-#10	4db	88.7	1.7	Duct-bond failure
	B6	2-#10	8db	156.3	1.64	Duct-bond failure
	B7	2-#10	12db	184	2.89	Duct-bond failure
	B8	2-#10	16db	242.9	8.77	Rebar rupture
C	C1	#10	8db	105	3.33	Duct-bond failure
	C2	#10	8db	4.3	2.32	Duct-bond failure
	C3	#10	8db	79.5	1.6	Duct-bond failure
	C4	#10	8db	88.9	1.99	Duct-bond failure
D	D1	#10	12db	123.8	8.33	Duct-bond failure
E	E1	#10	12db	93.3	3.61	Duct-bond failure

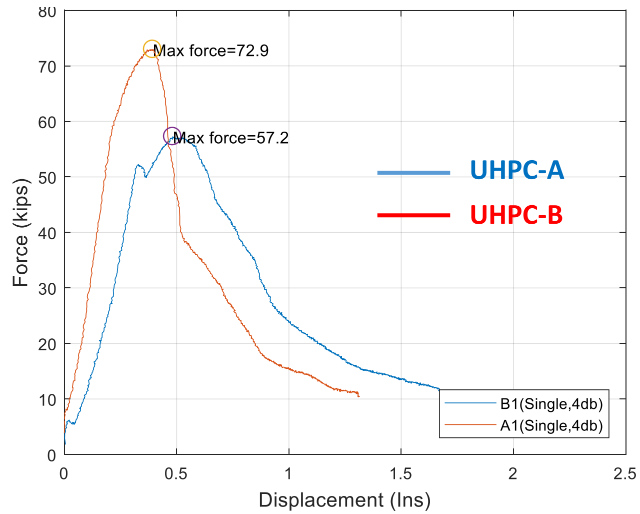
Typical failure modes

Grouted Ducts Tests

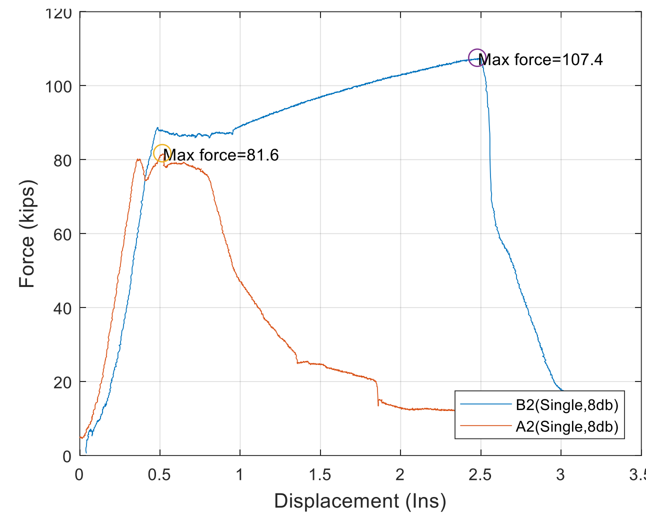
Force vs. Displacement Relationships

1. Effect of UNR-UHPC mixes (Single Bars)

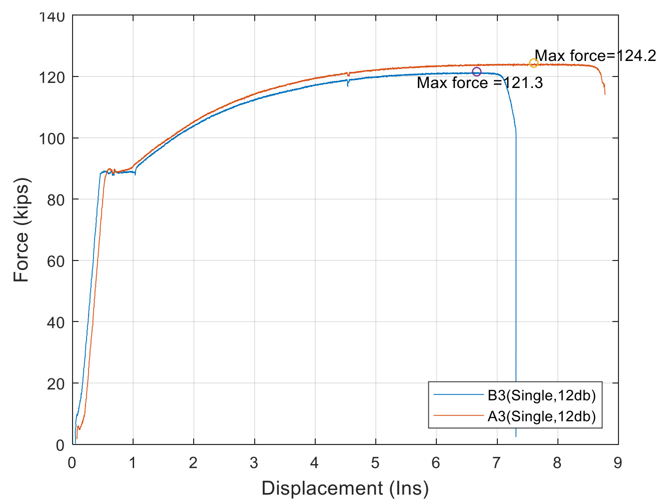
- Rebar fracture in both mixes at embedment length of 12 db and 16 db.
- Mix B performed better in specimen with 8db embedment length.



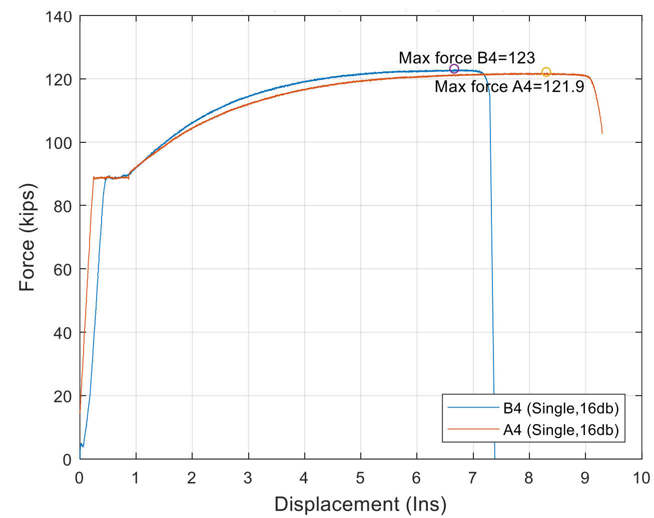
(a) 4db



(b) 8db



(c) 12db



(d) 16db

Grouted Ducts Tests

Bond Strengths

- Bar bond strength: Peak tensile force/ surface area of the bar embedded.
- L_{ab} = anchorage length based on bar bond strength

$$L_{ab} = \frac{d_b * f_s}{4 * \tau_{b,n} * \sqrt{f_g'}}$$

- Duct bond strength: Peak tensile force/surface area of the duct embedded
- L_{ad} = anchorage length based on duct bond strength

$$L_{ad} = \frac{d_b^2 * f_s}{4 * d_d * \tau_{d,n} * \sqrt{f_c}}$$

$$L_{ab} = \frac{d_b * f_s}{4 * \tau_{b,n} * \sqrt{f_g}}$$

$$L_{ad} = \frac{d_b^2 * f_s}{4 * d_d * \tau_{d,n} * \sqrt{f_c'}}$$

Group	ID	d_b (in)	d_d (in)	l_{ag} (in)	Bundled	f'_c (ksi)	f'_g (ksi)	P max (kips)	$\tau_{b,n}$	$\tau_{,d,n}$
A	A1	1.27	4	5.1	1	4.9	16.1	73.2	0.9	0.52
	A2	1.27	4	10.2	1	4.9	16.1	81.7	0.5	0.29
	A3	1.27	4	15.2	1	4.9	16.1	124.3	0.51	0.29
	A4	1.27	4	20.3	1	4.9	16.1	122	0.38	0.22
	A5	1.8	5.26	7.2	2	4.9	16.1	74.6	0.46	0.28
	A6	1.8	5.26	14.4	2	4.9	16.1	133.6	0.41	0.25
	A7	1.8	5.26	21	2	4.9	16.1	217.6	0.46	0.28
	A8	1.8	5.26	28.7	2	4.9	16.1	228.3	0.35	0.22
B	B1	1.27	4	5.1	4.3 1	4.9	15.35	57.4	0.72	0.4
	B2	1.27	4	10.2	1	4.9	15.35	107.6	0.67	0.38
	B3	1.27	4	15.2	1	4.9	15.35	121.5	0.51	0.29
	B4	1.27	4	19	1	4.9	15.35	123.1	0.41	0.23
	B5	1.8	5.26	7.2	4.4 2	4.9	15.35	88.7	0.56	0.34
	B6	1.8	5.26	14.2	2	4.9	15.35	156.3	0.5	0.3
	B7	1.8	5.26	21	2	4.9	15.35	184	0.4	0.24
	B8	1.8	5.26	28.7	2 4.3	4.9	15.35	242.9	0.38	0.23
C	C1	1.27	4	10.2	1	4.9	16.1	105	0.64	0.37
	C2	1.27	4	10.2	1	4.9	16.1	4.3	0.03	0.02
	C3	1.27	4	10	1	4.9	16.1	79.5	0.5	0.29
	C4	1.27	5.26	10.2	1 4.4	4.9	16.1	88.9	0.54	0.24
D	D1	1.27	4	15.2	1	4.9	17	123.8	0.5	0.29
E	E1	1.27	4	14.3	1	4.9	9.9	93.3	0.52	0.24

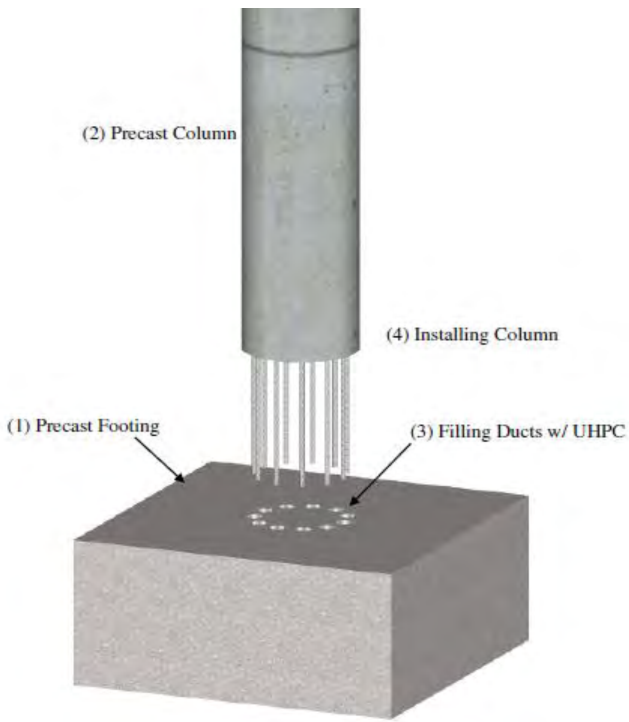
Proposed Design Equation

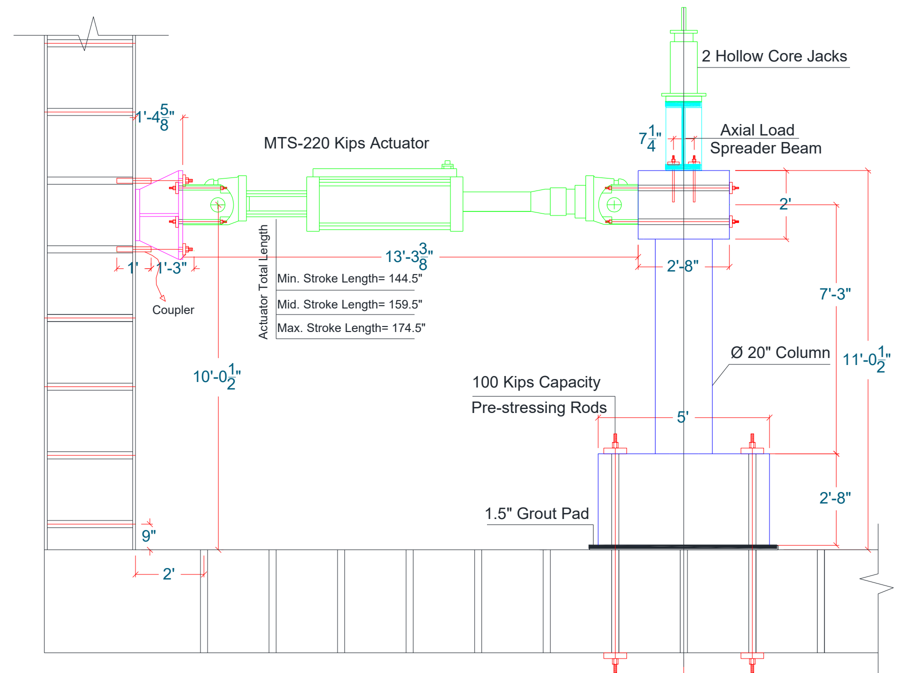
Anchorage length(L_{ag}) ≥ max (L_{ab} and L_{ad})

$$L_{ab} = \frac{d_b * f_s}{1.63 * \sqrt{f'_{grout}}} \qquad L_{ad} = \frac{1.0 * d_b^2 * f_s}{d_d \sqrt{f'_c}}$$

Large-Scale Column Tests

Two 0.4 scaled columns tested under axial and cyclic loading





Strong Floor
with 3 Ksi Bearing Strength

	Longitudinal Reinforcement			Transverse Reinforcement			
Specimen	% of Ag	RFT.	Grade	% of Ag	RFT.	Grade	Description
S1	2.01%	8 # 8	Gr 60	0.998%	# 3@ 2.5 in spirals	Gr 60	Un-debonded Rebars
S2	2.01%	8 # 8	Gr 60	0.998%	# 3@ 2.5 in spirals	Gr 60	Debonded Rebars

Large-Scale Column Tests

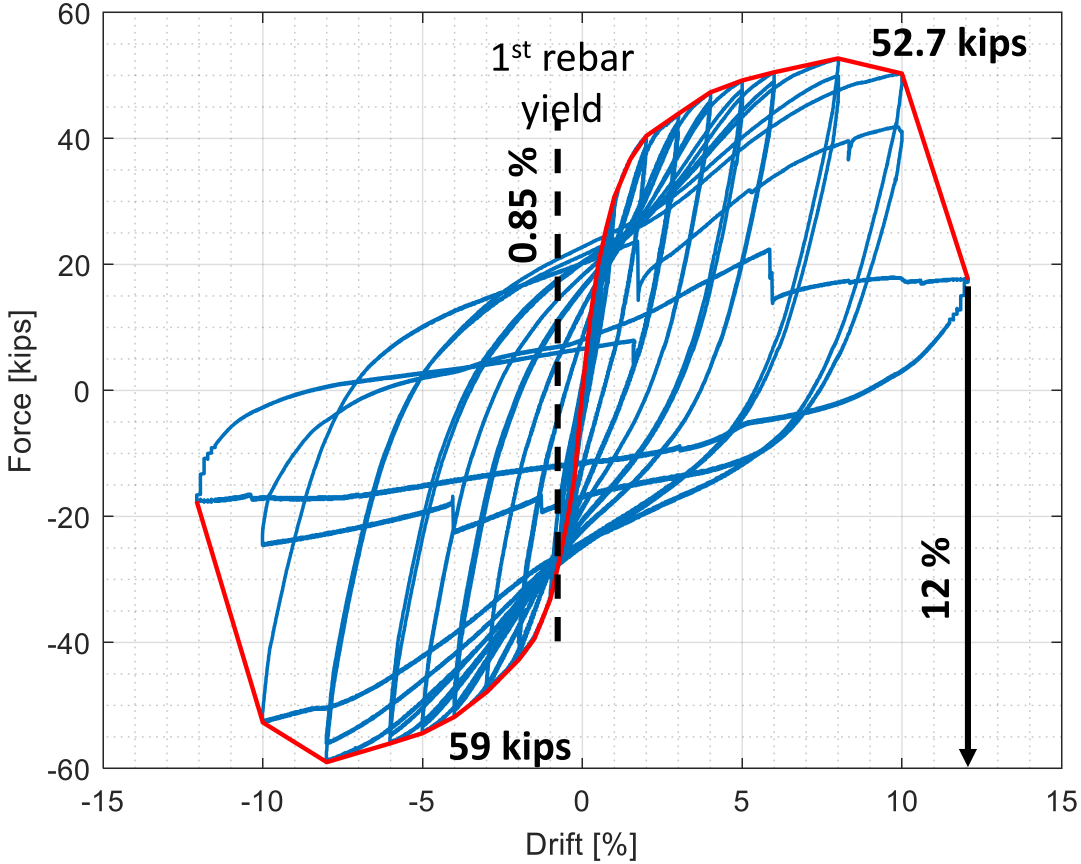
Construction

Large-Scale Column Tests

Damage Progression and Test Pictures

Large-Scale Column Tests

Force-Drift (Hysteretic) Behavior



P_{max} = 52.7 kips & 59 kips

Drift $_{yield}$ = 0.85 %

Drift $_{capacity}$ = 10.42 %

μ_{Δ} = 7.02

Compare to Tazarv and Saiidi (2015)

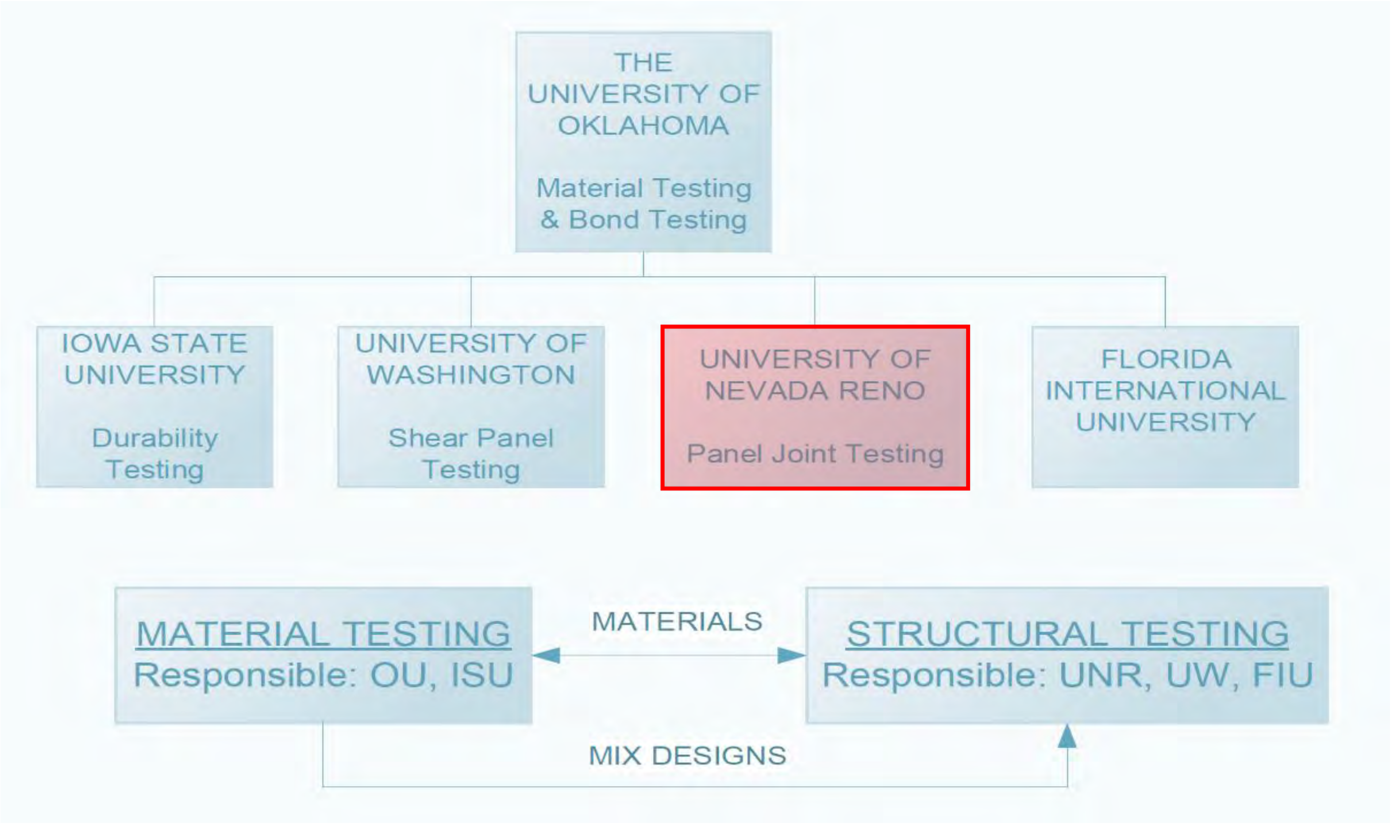
	NSC	Prop. UHPC	Non-Prop. UHPC
Column Scale	0.5	0.5	0.42
f'c (ksi)	4.45	3.4	6.2
f'UHPC (ksi)	N/A	23	17.1
Fy [Fu] (ksi)	68.8 [111]	65.8 [92]	64 [106]
Drift $_{yield}$	0.79 %	0.89 %	0.85 %
Drift $_{max}$	9.93 %	8.96 %	10.42 %
μ_{Δ}	7.36	6.3	7.02

Application #2:

Non-proprietary UHPC for ABC Deck Connections

ABC-UTC Non-Proprietary UHPC

ABC-UTC multi-institutional Collaboration

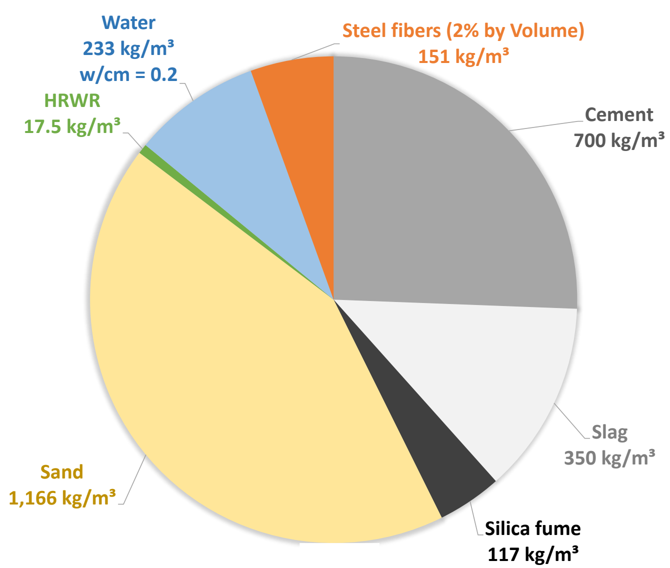


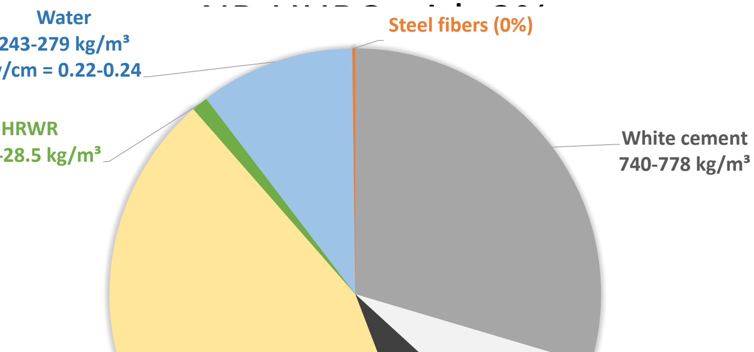
UNR Specific Objectives

1. Collaborate with OU on acquiring local materials for reproducing reference non-proprietary UHPC mix design & Investigate the effect of material sourcing and variability, such as fine aggregate types and particle gradation, on the main material mechanical properties

2. Investigate the global and local structural behavior of the full-depth deck panels with transverse and longitudinal NP-UHPC field joints to validate the use of the material for real applications

NP-UHPC Mix Design



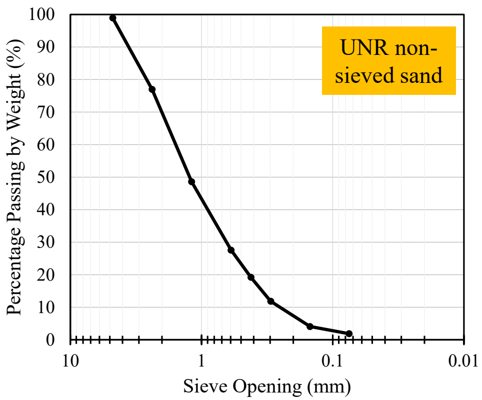


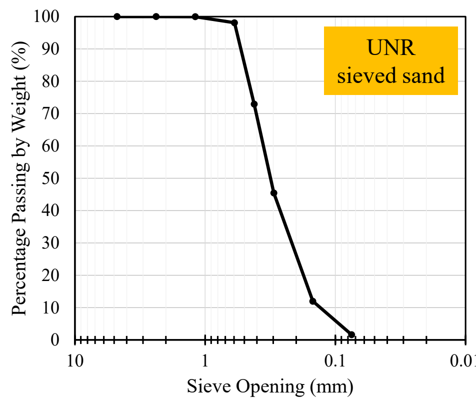
Material Variability

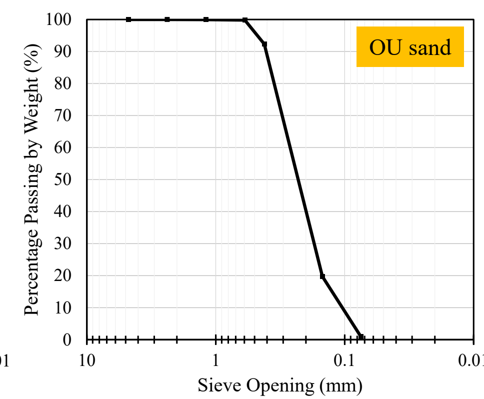
Material sources for reference and UNR mixes

Material	Acquired by UNR		Provided by OU	
	Type/Name	Supplier	Type/Name	Supplier
Cement	Type I/II	Nevada Cement, Reno-NV	Type I	Ash Grove, Chanute-KS
Silica Fume	MasterLife® SF100	BASF	Norchem	Norchem, Marietta-OH
Slag	Slag Cement	Lehigh Hanson, Sacramento-CA	Lafarge Slag	LafargeHolcim, South Chicago-IL
Steel Fibers	Dramix® OL 13/0.2	Bekaert	Dramix® OL 13/0.2	Bekaert
HRWR	MasterGlenium®7920	BASF	MasterGlenium®7920	BASF
Aggregate	Crushed Aggregate Sand	Martin Marietta, Sparks-NV	Fine Masonry Sand	Metro Materials, Norman-OK
Water	Potable Water	N/A	Potable Water	N/A

Varying aggregate type & particle grading?







(a) (b) (c)

Material Variability

To test the material source variability, aggregate grading, and variation in steel fiber ratio → Five NP-UHPC mixes used in this study

Notion	Prescriptive Batch ID*	Local materials acquired by	Steel fiber content (% by volume)	Sand type (as per Figure 3)
B1	B1 – UNR – 2% – NS	UNR	2 %	Type A
B2	B2 – UNR – 2% – S	UNR	2 %	Type B
B3	B3 – UNR – 1% – NS	UNR	1 %	Type A
B4	B4 – UNR – 1% – S	UNR	1 %	Type B
B5	B5 – OU – 2% – NS	OU	2 %	Type C

**"NS" denotes non-sieved sand or raw sand, and "S" denotes sieved sand*

1

Material Characterization Testing of NP-UHPC

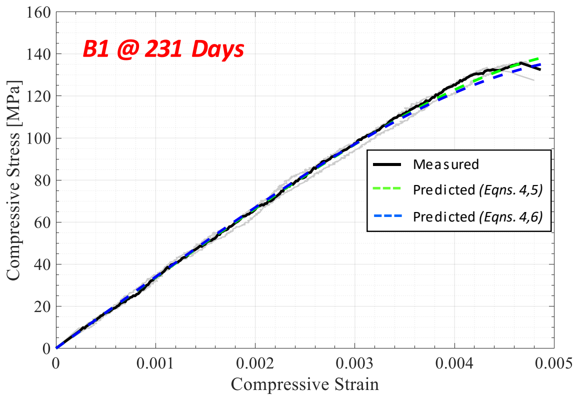
Compression samples

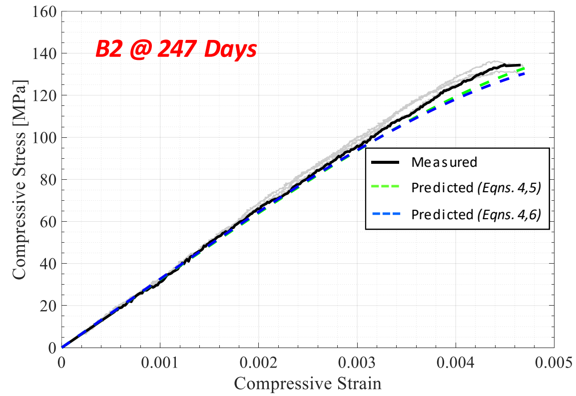
Flexure samples

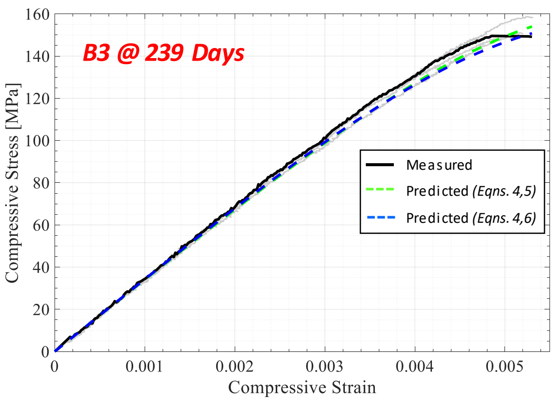
Tensile dog-bone samples

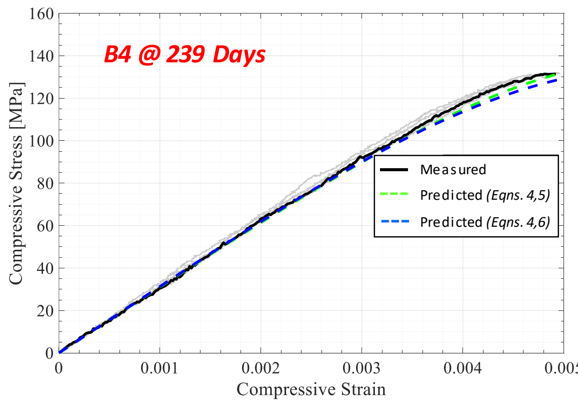
Material Characterization Testing of NP-UHPC

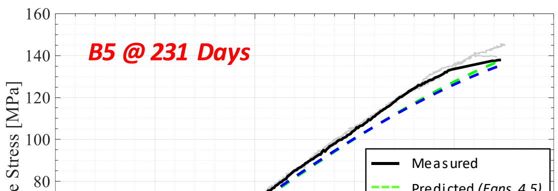
Compression Test Results – Stress-strain relationships











$$f_c = \varepsilon_c E(1-\alpha) \quad \ldots\ldots(1)$$

$$\alpha = a\, e^{\frac{\varepsilon_c E}{b f_c'}} - a \quad \ldots\ldots\ldots(2)$$

$$\alpha = a\left(\frac{\varepsilon_c E}{f_c'}\right)^b \quad \ldots\ldots\ldots(3)$$

where,

- f_c is compressive stress
- ε_c is compressive strain
- E is the actual measured modulus of elasticity based on the experimental results
- α is linearity deviation parameter that is determined based on Equations 2 & 3 (*Graybeal 2007 [a=0.011, b=0.44] & Haber et al., 2018 [a=0.106, b=2.754]*)

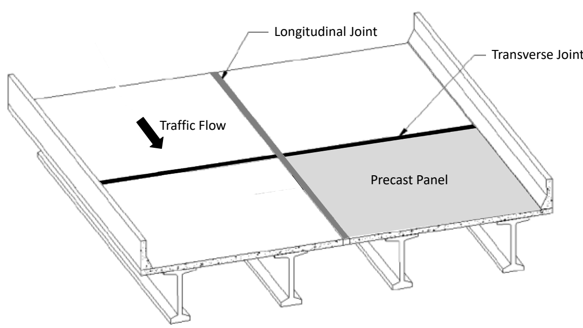
Full-Depth Deck Panels Field Joints Testing

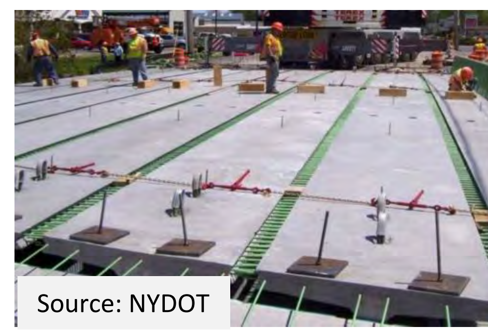
Experimental Program and Test Matrix

Total of 4 NP-UHPC specimens + 2 more reference specimens that used commercial/proprietary UHPC

Specimen Name	Joint Orientation	Specimen Dimensions (L × W × thickness)	Closure material	Lap splice type	Joint width	Lap splice length
S1-T-NP-UHPC	Transverse	9′× 8′ × 8′′	NP-UHPC (2%)	Straight	6′′	5′′
S2-T-NP-UHPC-Loop	Transverse	9′ × 8′ × 8′′	NP-UHPC (2%)	Loop	6′′	4.5′′
S3-T-NP-UHPC-1%	Transverse	9′ × 8′ × 8′′	NP-UHPC (1%)	Straight	8′′	7′′
S4-L-NP-UHPC	Longitudinal	8′ × 7′ × 6′′	NP-UHPC (2%)	Straight	6′′	5′′

Full-depth deck panels (Trans)

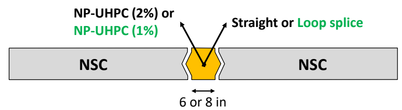




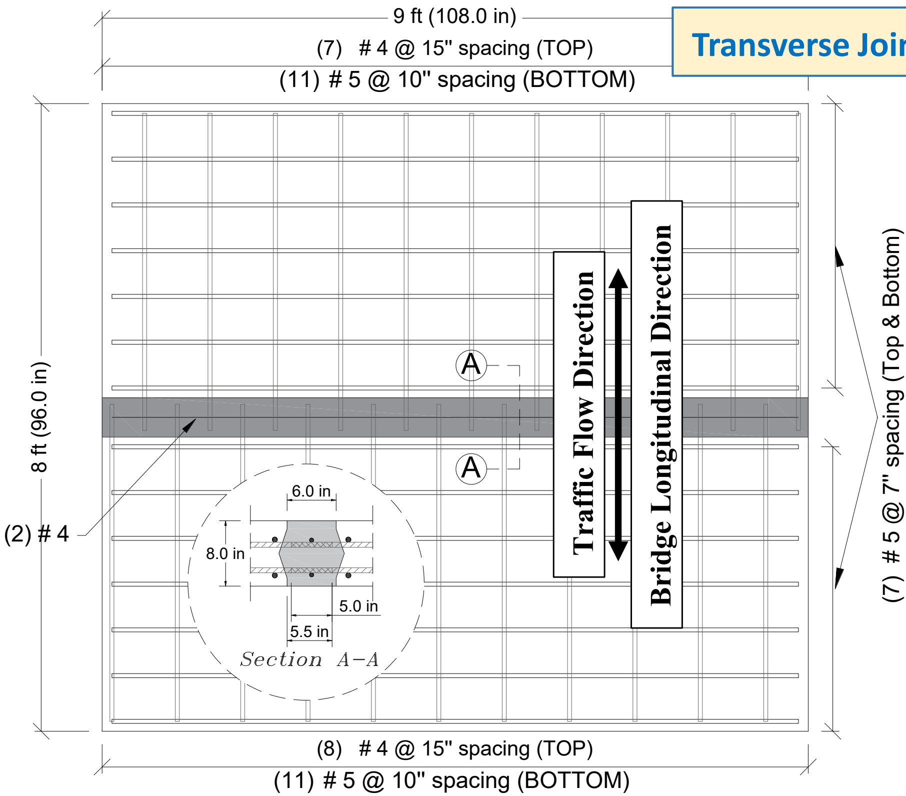
Deck-bulb-tee girders (long)

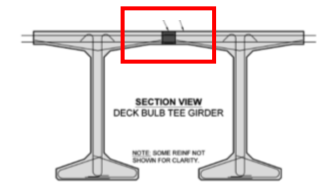
Full-Depth Deck Panels Field Joints Testing

Specimens Design

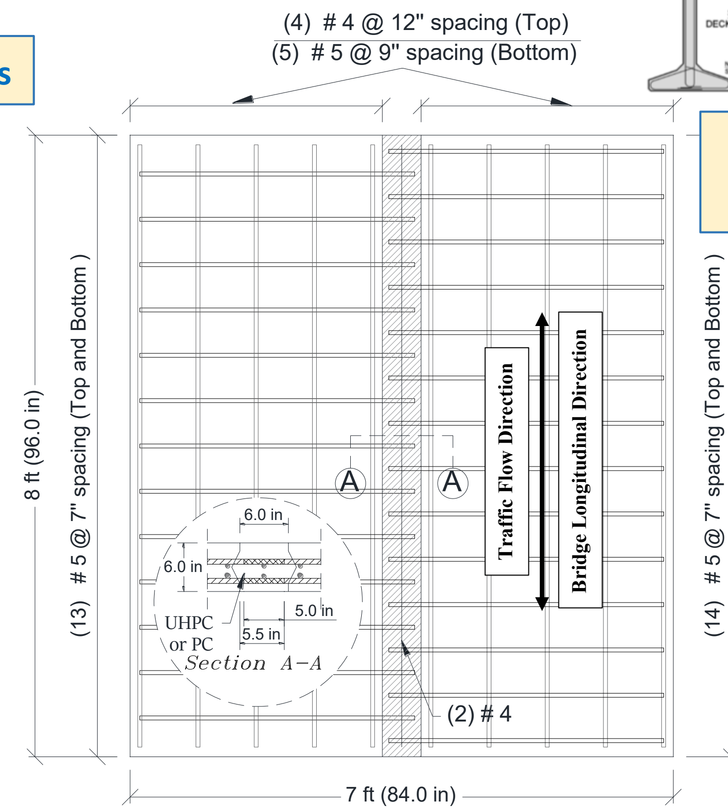


Transverse Joints





Longitudinal Joints

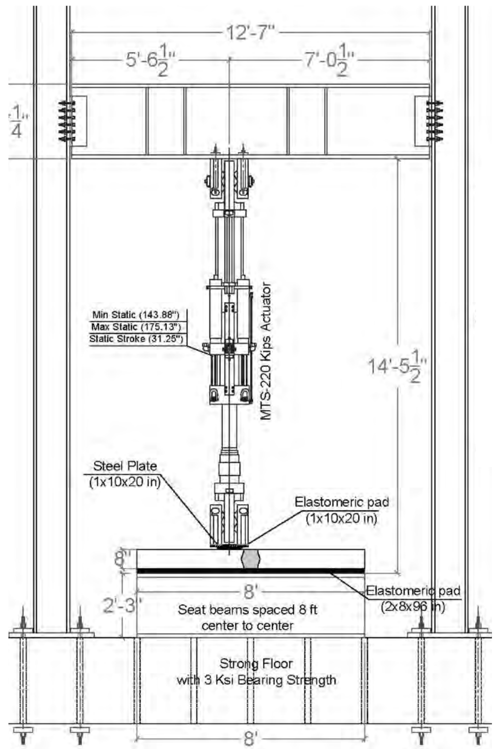


Full-Depth Deck Panels Field Joints Testing

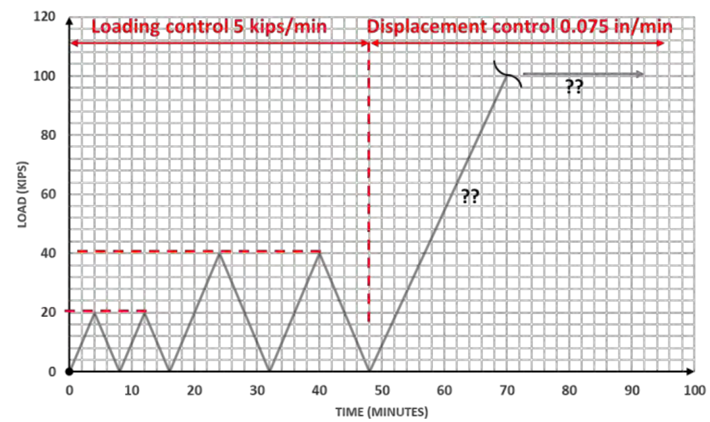
Specimens Construction

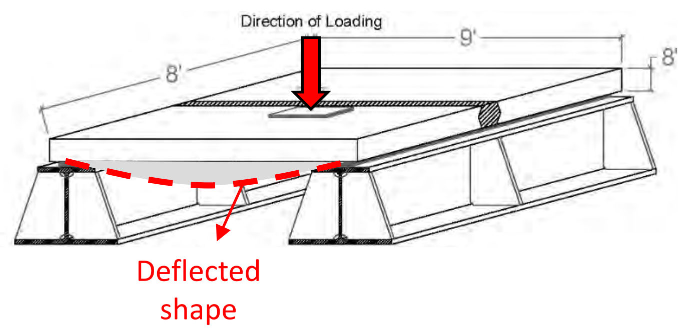
Full-Depth Deck Panels Field Joints Testing

Test Setup and Loading Protocol



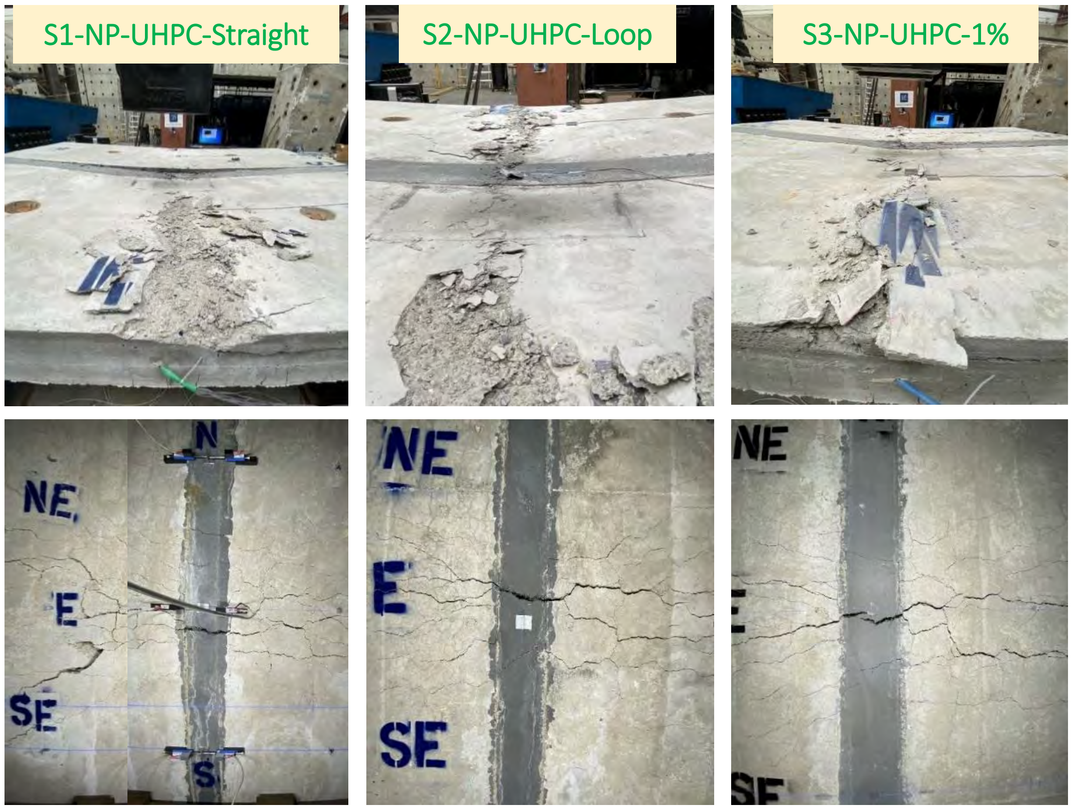
Sample from Transverse joints specimens





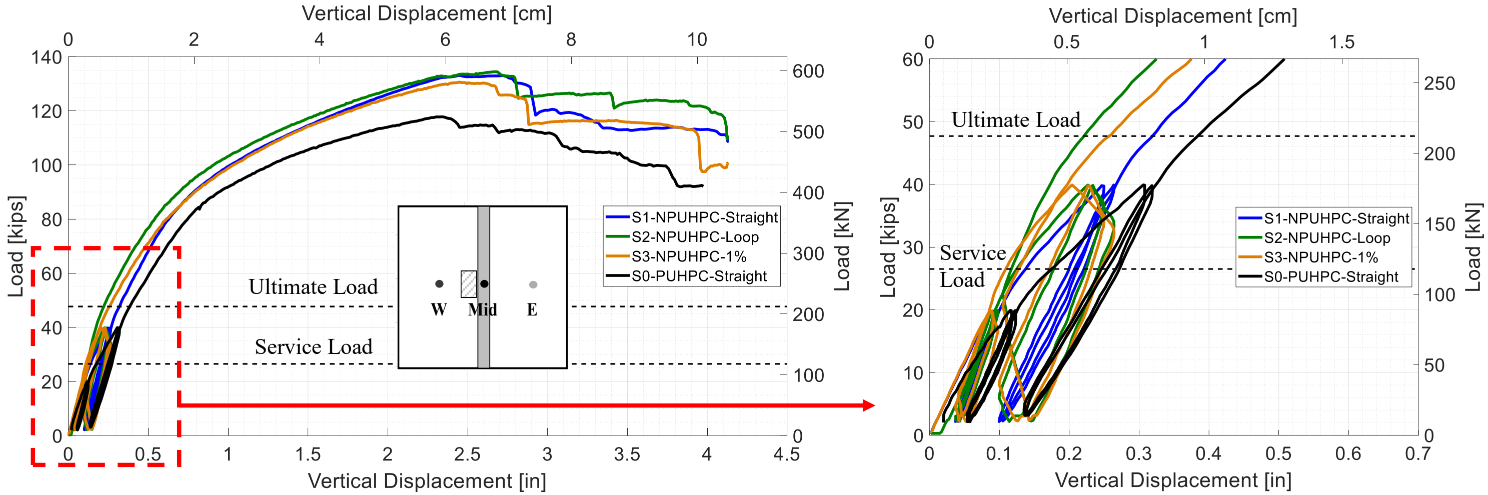
Full-Depth Deck Panels Field Joints Testing

Transverse Joints: Damage Progression and Mode of Failure



Full-Depth Deck Panels Field Joints Testing

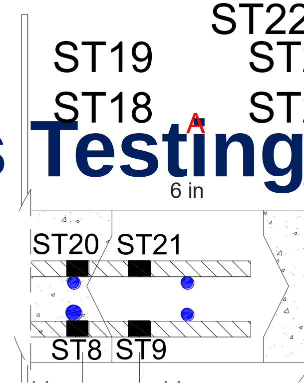
Transverse Joints: Global Behavior: Load-deflection Relationships



Specimen Name	Peak Load (kips)	Load @ 1st Interface Crack (kips)	Mid-span Deflection (in)			Initial Stiffness, (kips/in)
			@ Peak Load	@ Service Load	@ Ultimate Load	
S0-**P-UHPC**-Straight	117.9	**116.9**	2.33	0.175	0.384	240
S1-NP-UHPC-Straight	133.1	75.3	2.45	0.137	0.319	290
S2-NP-UHPC-Loop	**134.5**	100.0	**2.64**	0.136	0.317	**310**
S3-NP-UHPC-1%	130.6	89.9	2.43	0.172	0.390	265

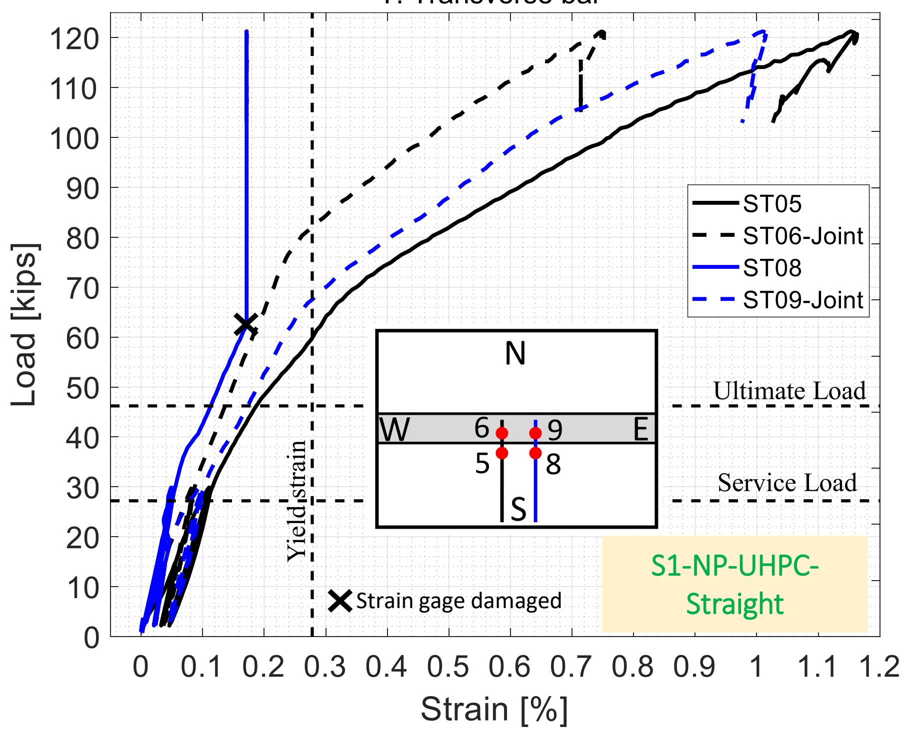
Full-Depth Deck Panels Field Joints Testing

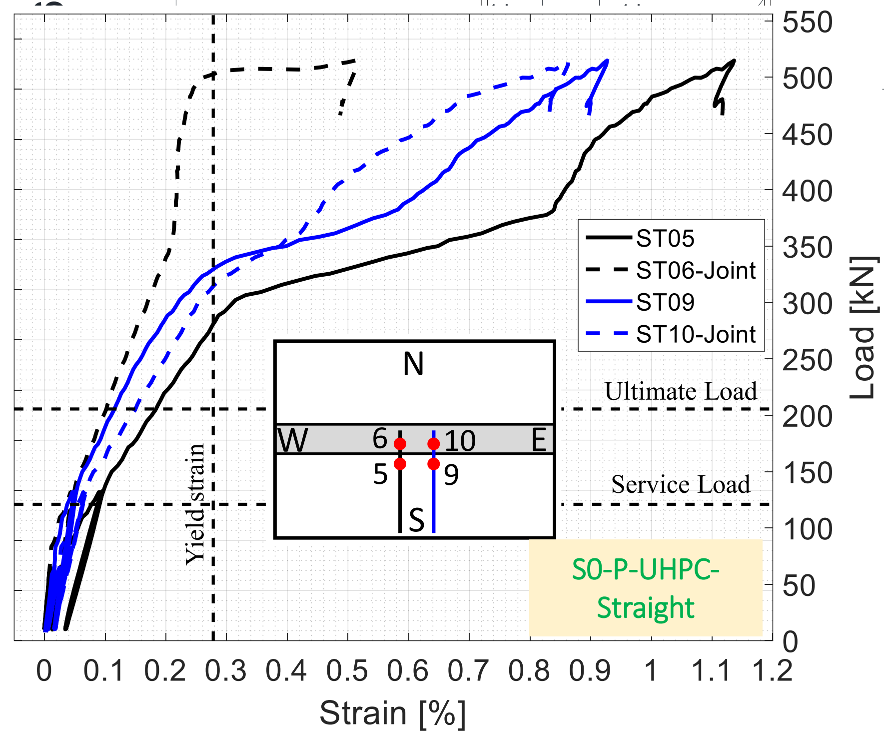
Transverse Joints: Local Behavior: Load-strain Relationships



Strain Gage #

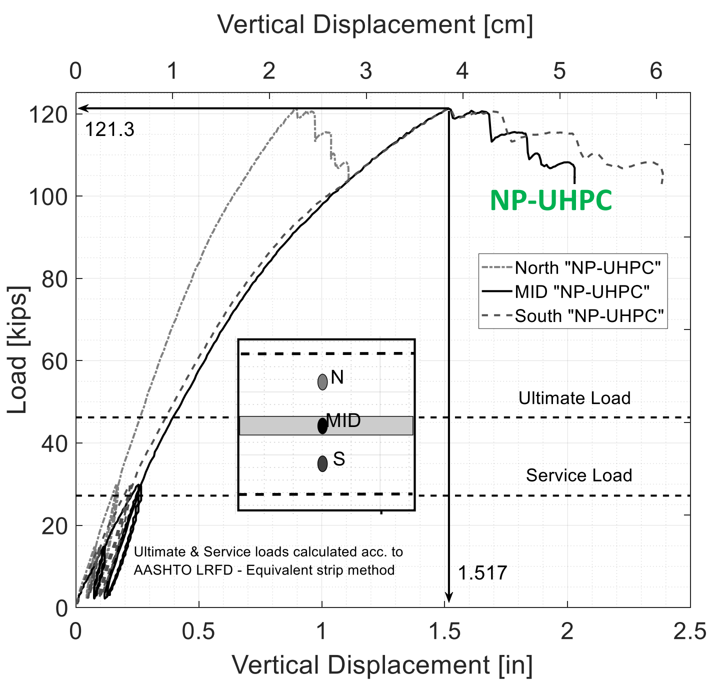
T: Transverse bar

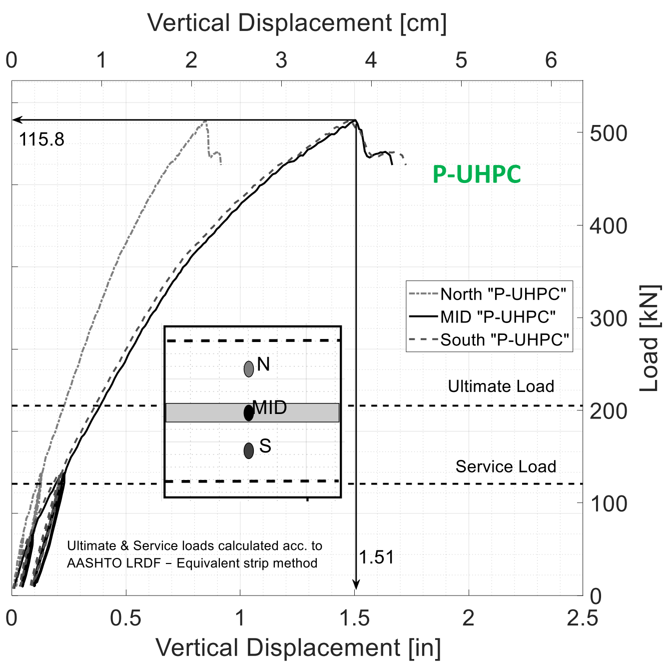


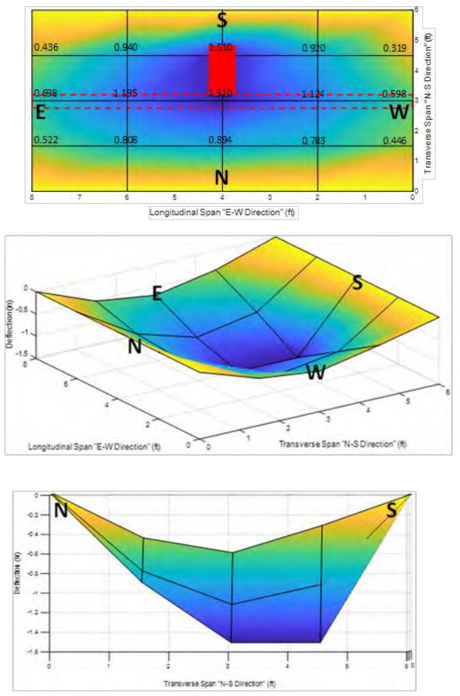


Full-Depth Deck Panels Field Joints Testing

Longitudinal Joints: Global Behavior: Load-deflection Relationships







Sample load-deflection relationship for non-proprietary vs. commercial UHPC for longitudinal joint specimens

Application #3:

UHPC columns with Grade 60 & Grade 100 steel

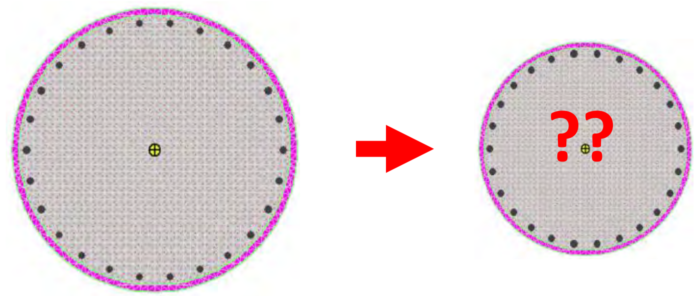
Introduction

Focusing on bridge columns…

If UHPC to replace normal strength concrete

- Higher strength → more compact cross-sections & efficient structures
- High durability → longer service life and minimal maintenance costs
- Suitable for harsh environments (e.g. coastal bridges)

Why Seismic? e.g. UHPC Column Jackets



NSC Column **UHPC Column**

Mission Bridge Seismic Retrofit, British Columbia, Canada (LAFARGE)

Goals

Overall goal:

Conduct fundamental research to understand the basic structural and seismic response of UHPC columns with high-strength steel

How this benefits ABC:

- Enhanced understanding of structural behavior of columns for future/subsequent use in prefabricated/precast columns
- Compact cross-sections leads to lighter structures (easier transportation and handling, faster construction time)
- High durability is crucial for bridges in harsh environments (e.g. marine structures) where precast construction is commonly used

Objectives

1. Investigate the seismic performance of four large-scale UHPC columns under combined axial and lateral loading.
2. Determine the damage progression and the mode of failure of the UHPC columns.
3. Investigate the effect of longitudinal reinforcement detailing on the design capacity of UHPC columns
4. Conduct a comparison between UHPC and NSC columns.

Experimental Program

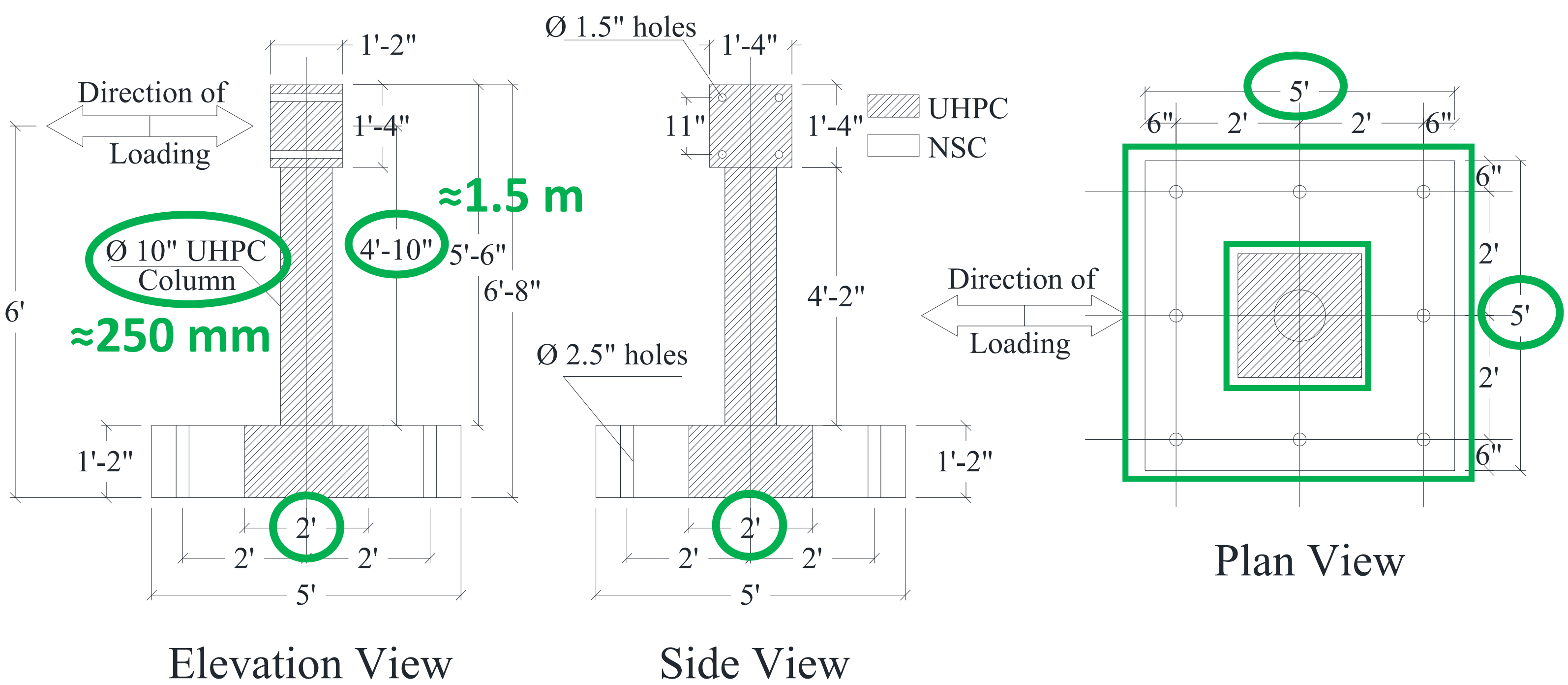
The experimental program consists of four large-scale UHPC columns tested under combined axial and cyclic lateral loading at UNR

Specimen		Longitudinal Reinforcement		Transverse Reinforcement		Tested Variable	Type of Testing
		#	$\%A_g$	#	$\%A_g$		
Group I (Gr. 60)	S0	6#5	2.37%	#3@2in	1.1%	NSC	Analytical
	S1	6#5	2.37%	#3@2in	1.1%	UHPC vs NSC	Experimental
Group II (Gr. 100)*	S2	6#5	2.37%	#3@2in	1.1%	Gr 100 vs Gr 60	Experimental
	S3	6#5	2.37%	#3@4in	0.55%	Low confinement	Experimental
	S4	6#4	1.53%	#3@2in	1.1%	Low long. steel ratio	Experimental

* Gr. 100 is for the longitudinal reinforcement only in Group II specimens.

Experimental Program

- The specimens approx. 1/6 scale of typical California bridge column.
- Footing is capacity protected and consists of 2 parts (UHPC and NSC).



Stages of Construction

Specimen Construction Stages: (a) Casting of NSC Footing; (b) Casting of UHPC Footing; (c) Casting of UHPC Column; (d) Casting of UHPC Column Head.

Material Properties

- A commercial proprietary UHPC mix used → Ductal® JS1000
- UHPC cylinders 3X6 tested in compression after surface preparation/grinding

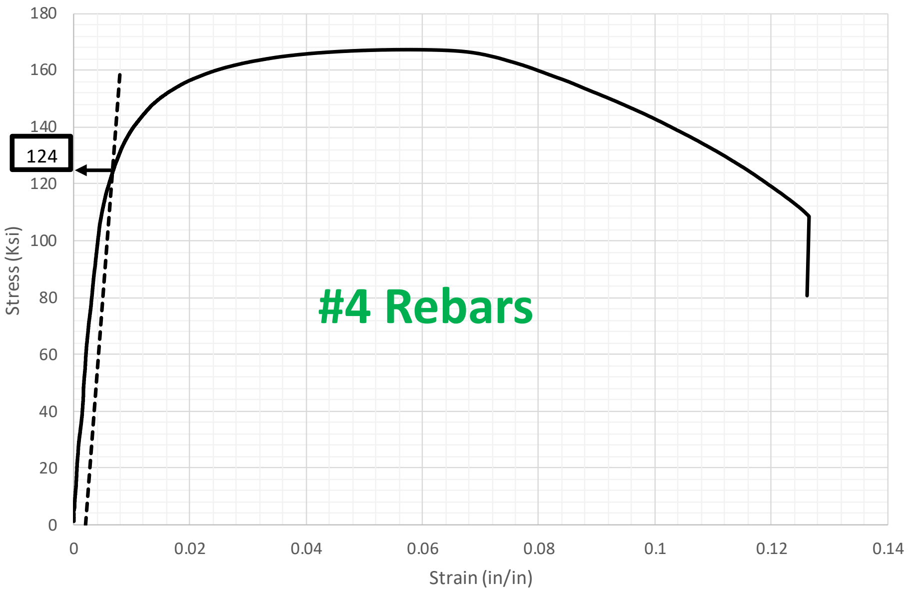
Specimen	S1	S2	S3	S4
Column Test day Strength (ksi)	29.64	31.17	33.28	30.95

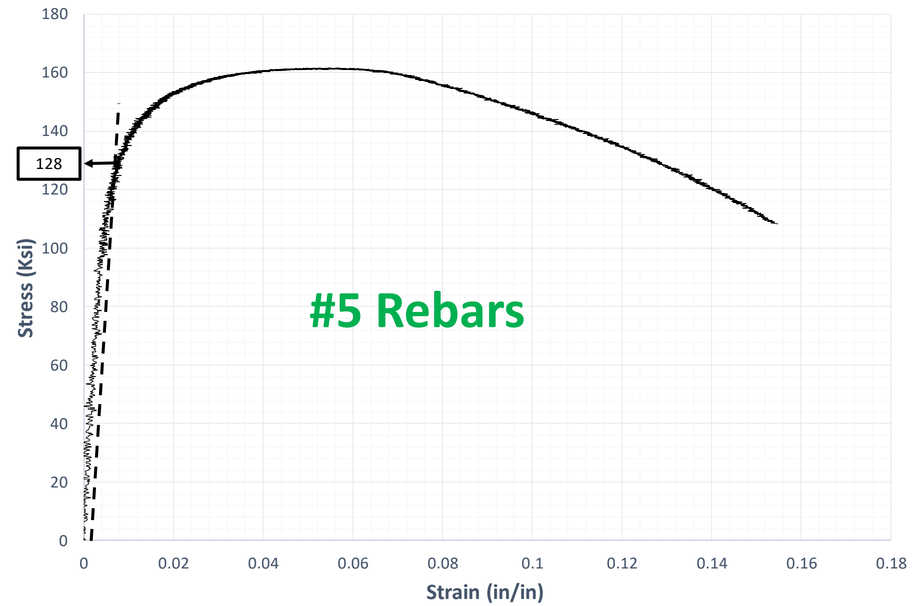
Material Properties

- #5 Grade 60 rebars (ASTM A706) used
- #4 and #5 MMFX Grade 100 CHX9100 rebars (ASTM A1035) used



Material Properties

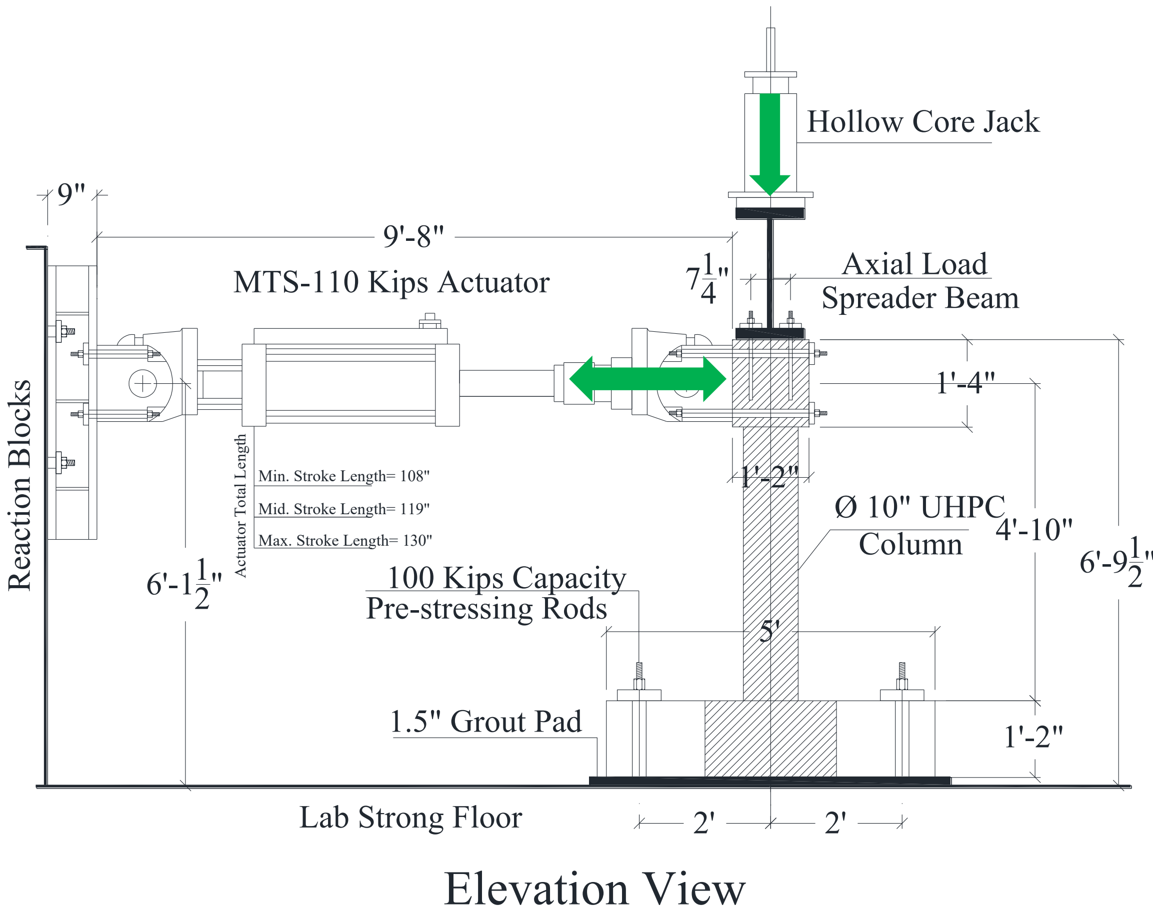


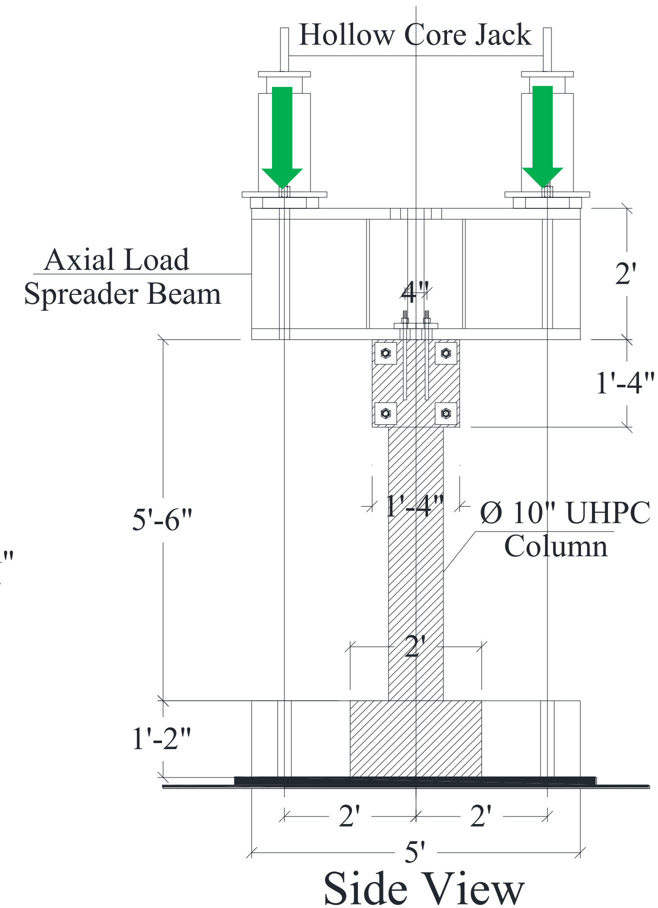


Diameter bar	Yield Strength (ksi)	Ultimate Strength (ksi)	Ultimate Strain (%)
#4	124	167	12.6
#5	128	162	15.4

Test Setup

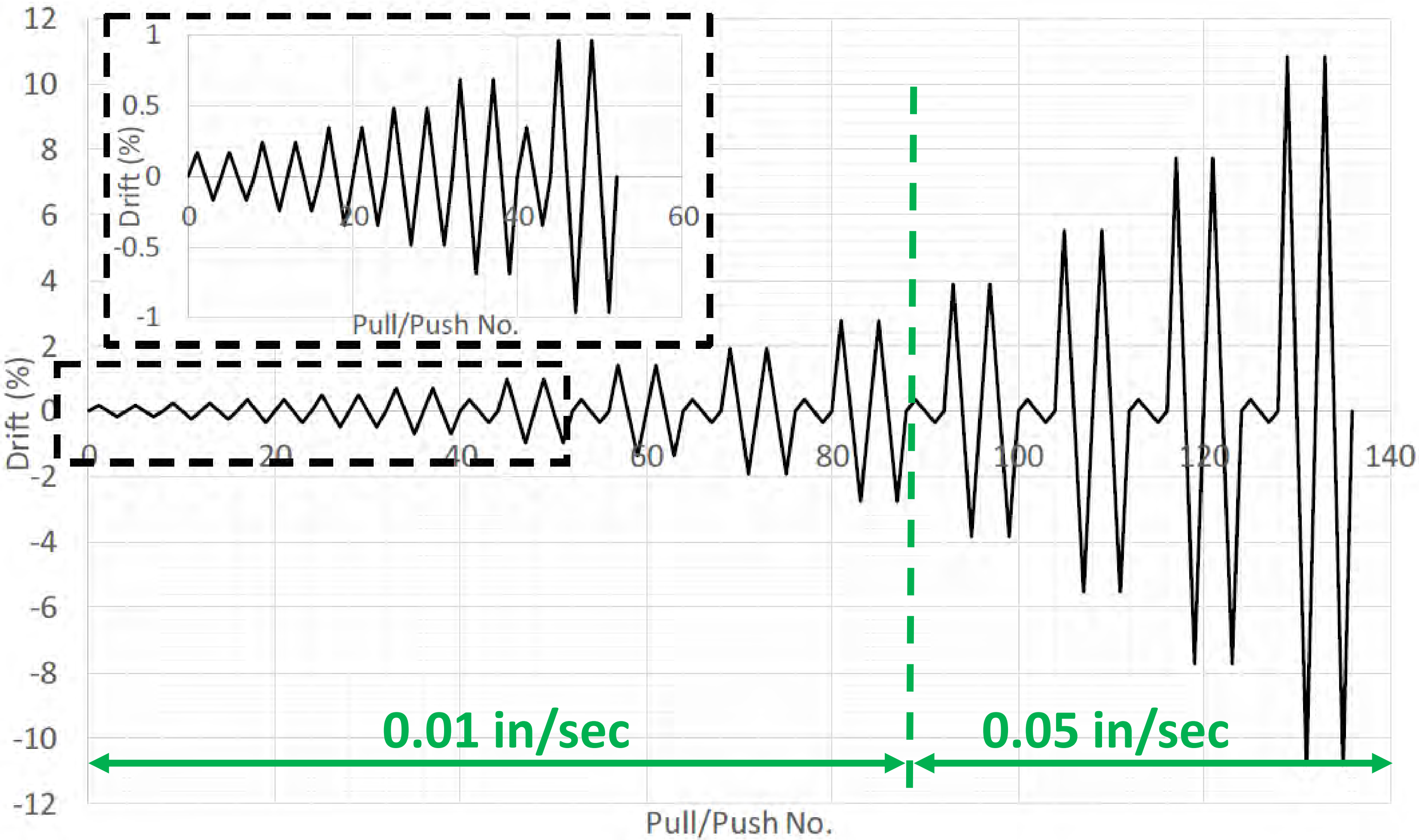
- Axial load 120 kips equivalent to 5% axial load index



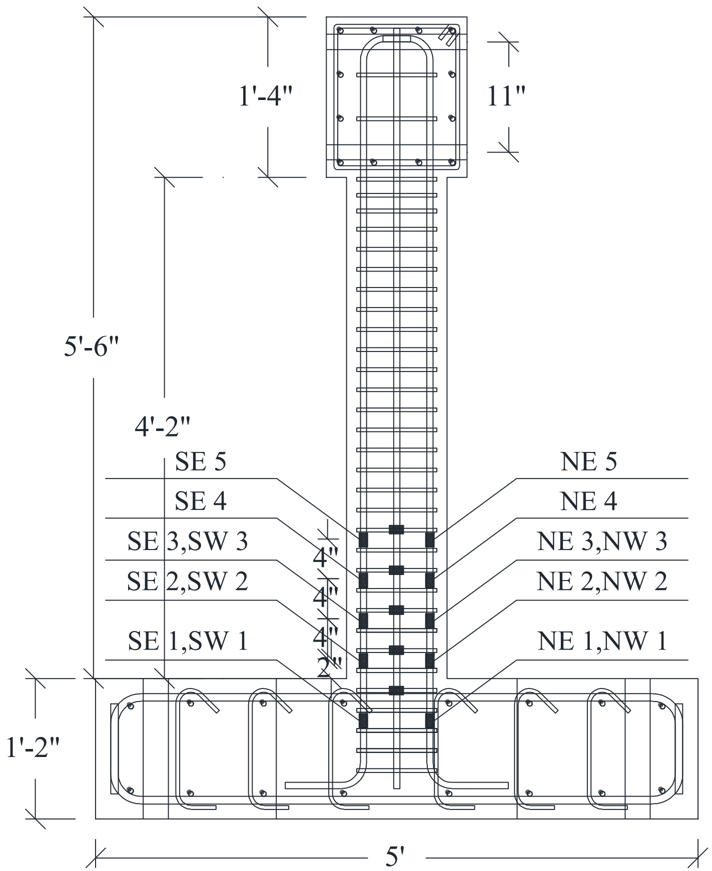


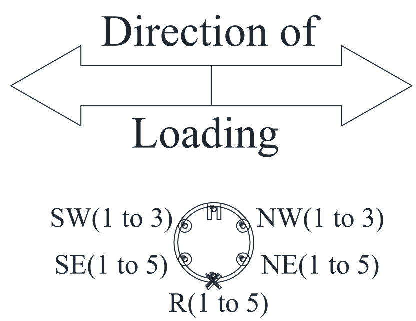
Loading Protocol

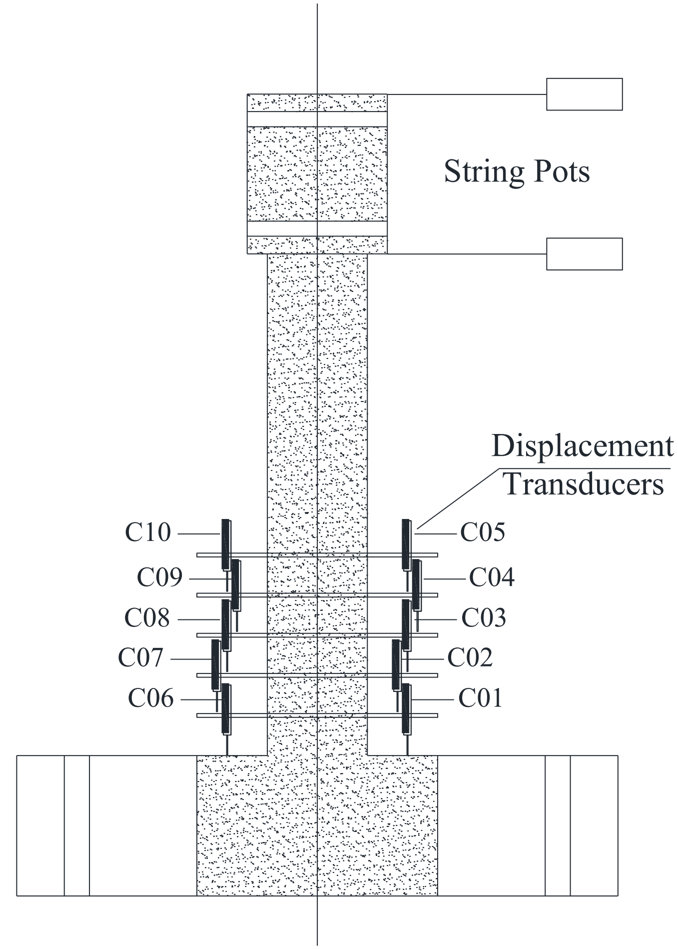
- Cyclic loading groups



Instrumentation Plan







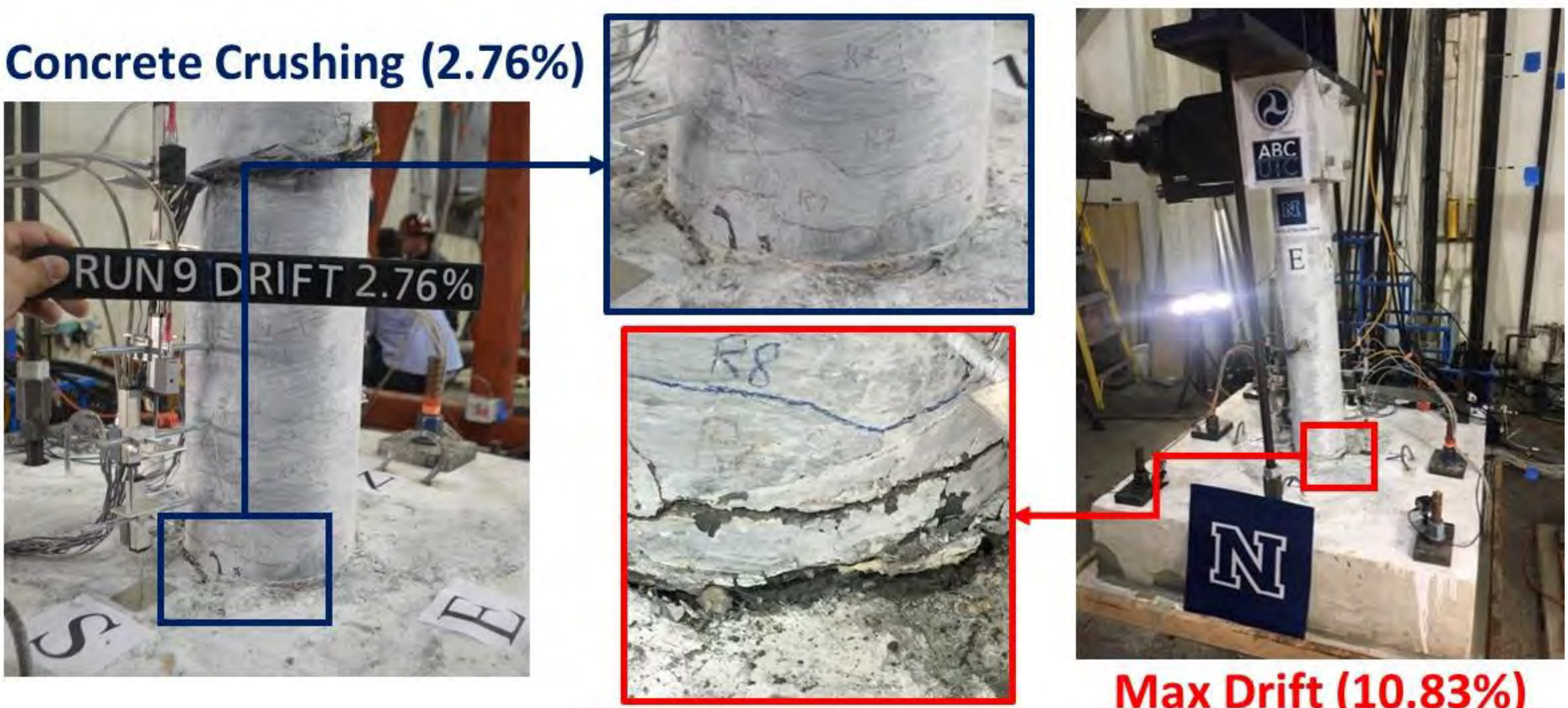
Strain gages (5 Levels)

Wire potentiometer → disp
LVDTs → curvature

Results-Damage Progression

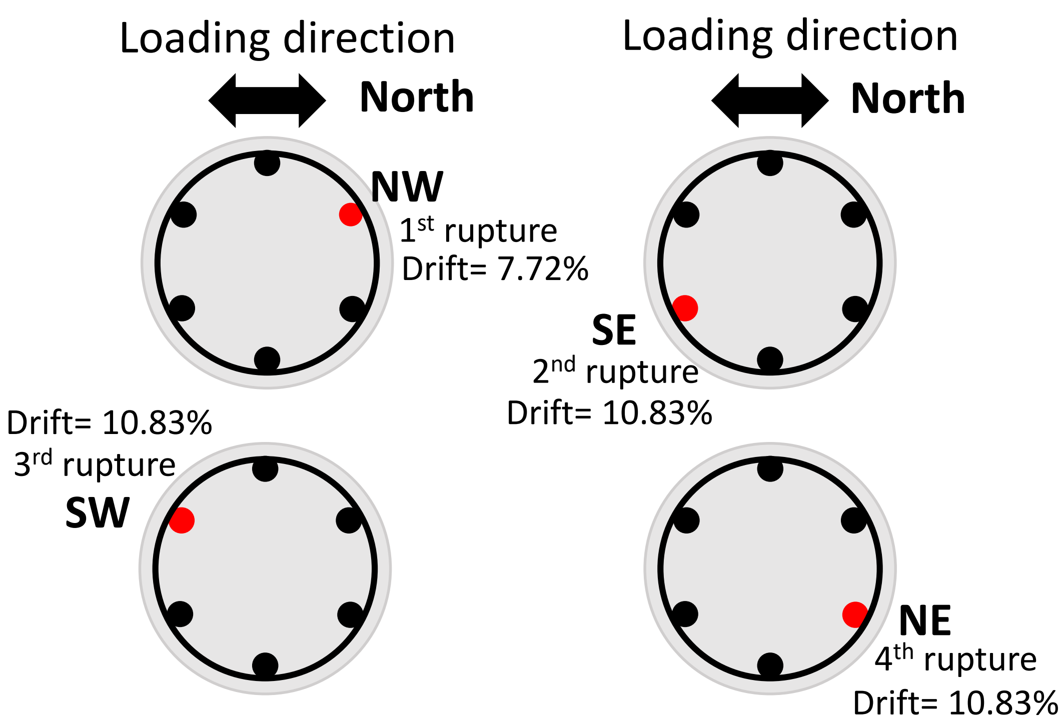
Typical mode of failure (S1 shown here)

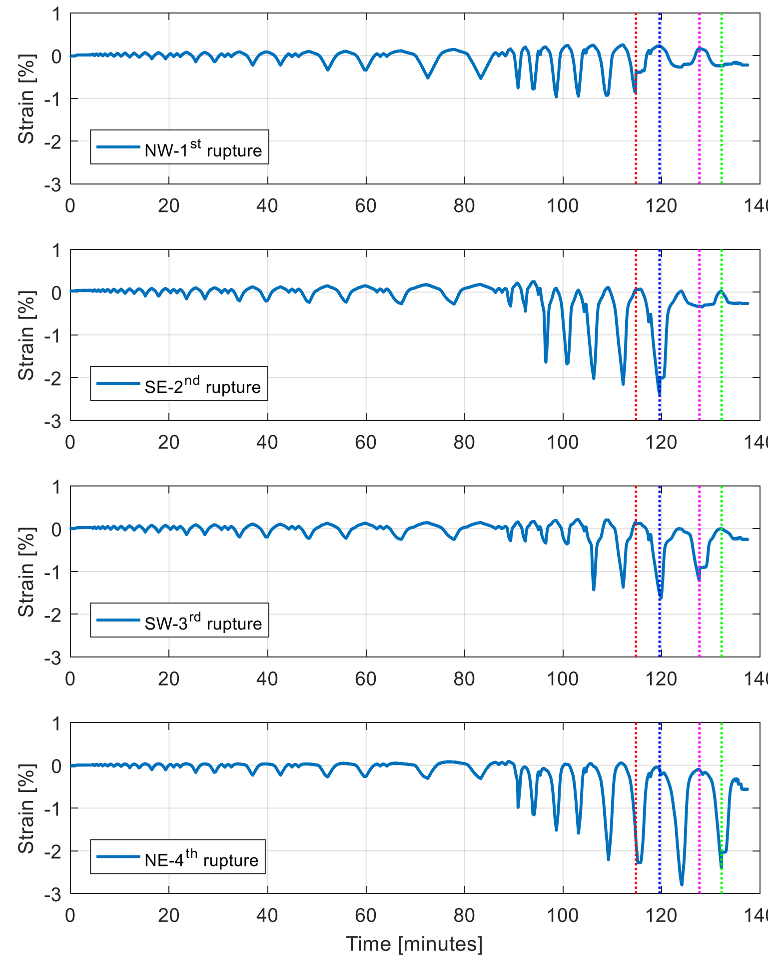
- Mode of Failure was bar fracture (No cover spalling or bar buckling).



Results-Damage Progression

Specimen S1 (L=2.4%-Gr.60, T=1.1%-Gr.60)

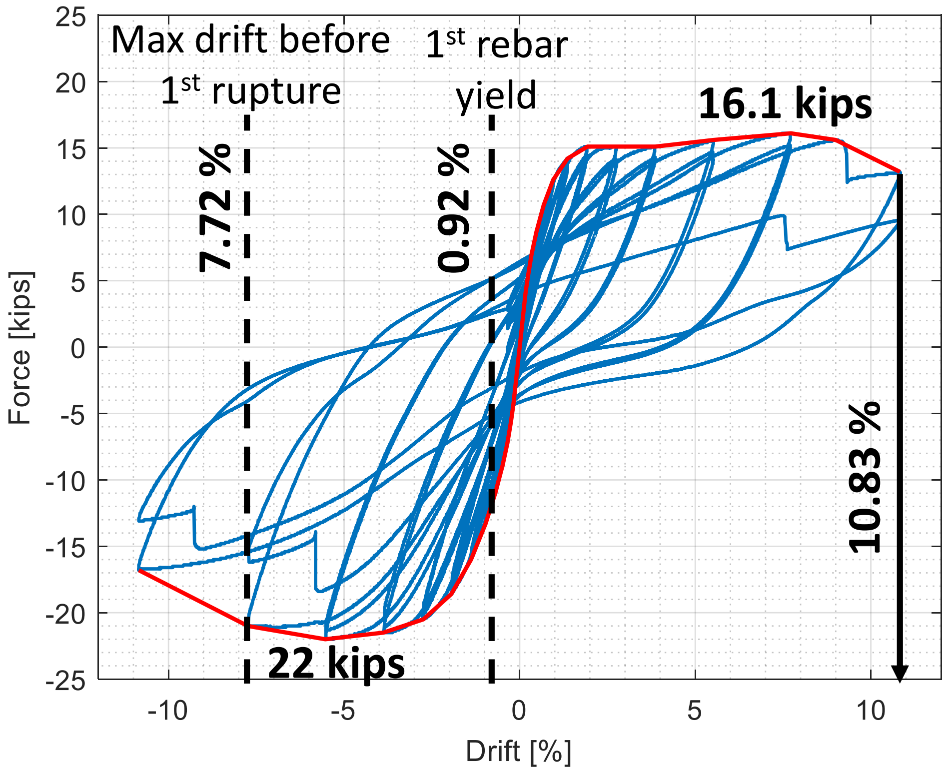




Strain history at 4” above column-footing face

Hysteretic Response

Specimen S1 (L=2.4%-Gr.60, T=1.1%-Gr.60)



P_{max} = **16.1 kips**

& 22 kips

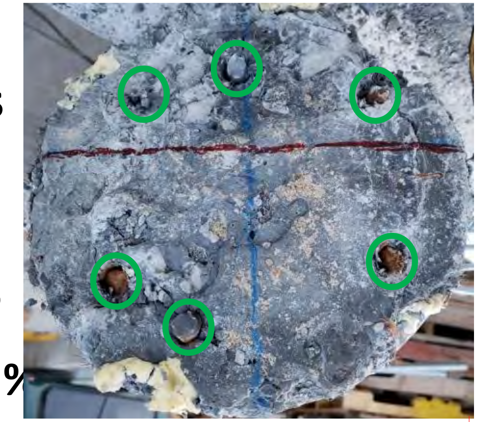
Drift $_{yield}$ = **0.92 %**

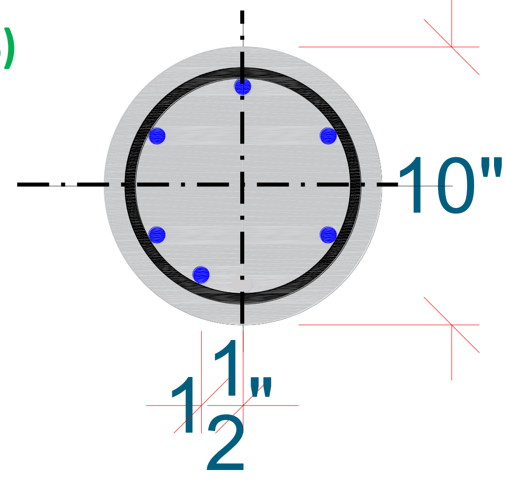
Drift $_{rupture}$ = **7.72 %**

μ_{Δ} = **8.4** (65 %)

Loading direction

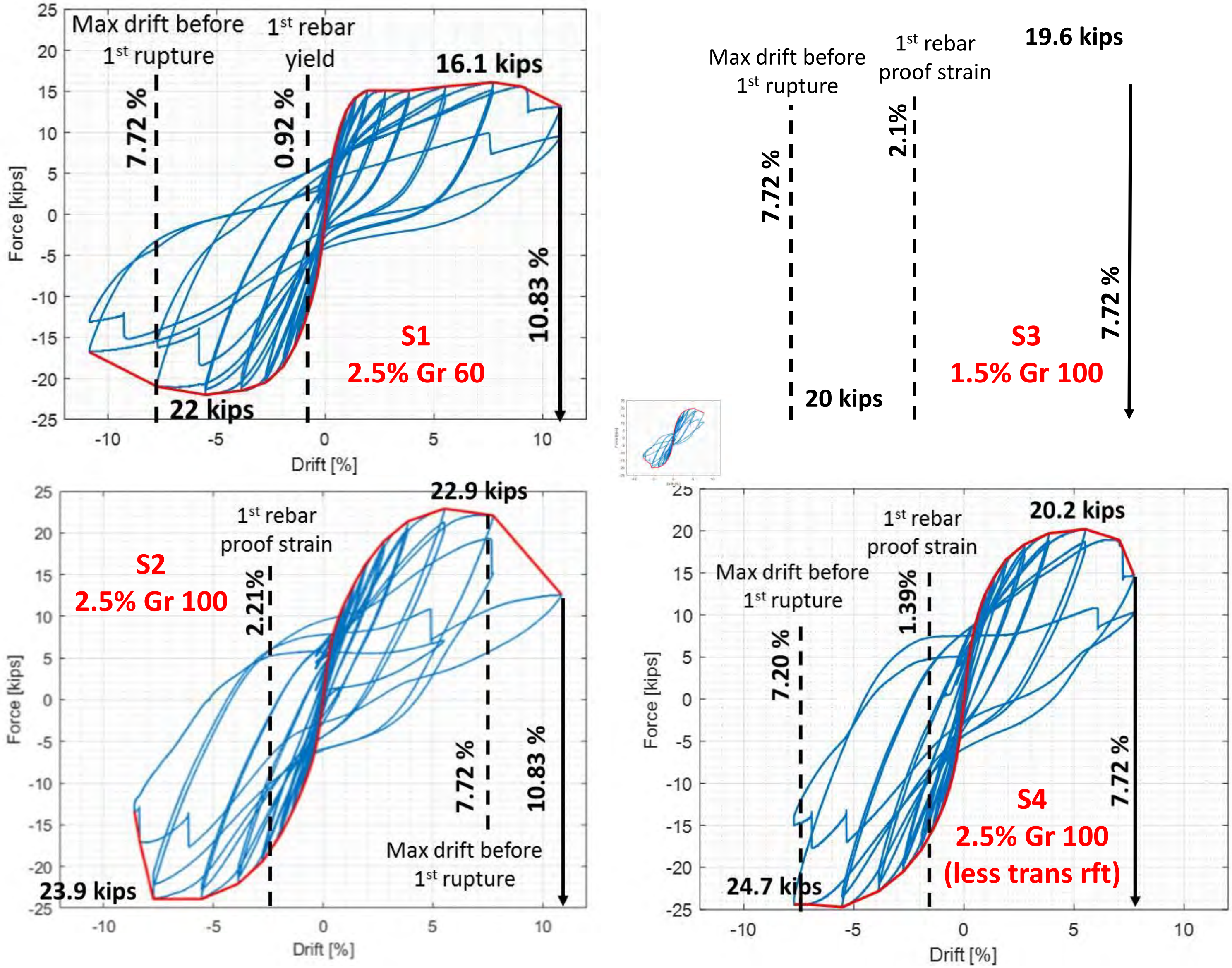
North (push) ⟷ **South (pull)**



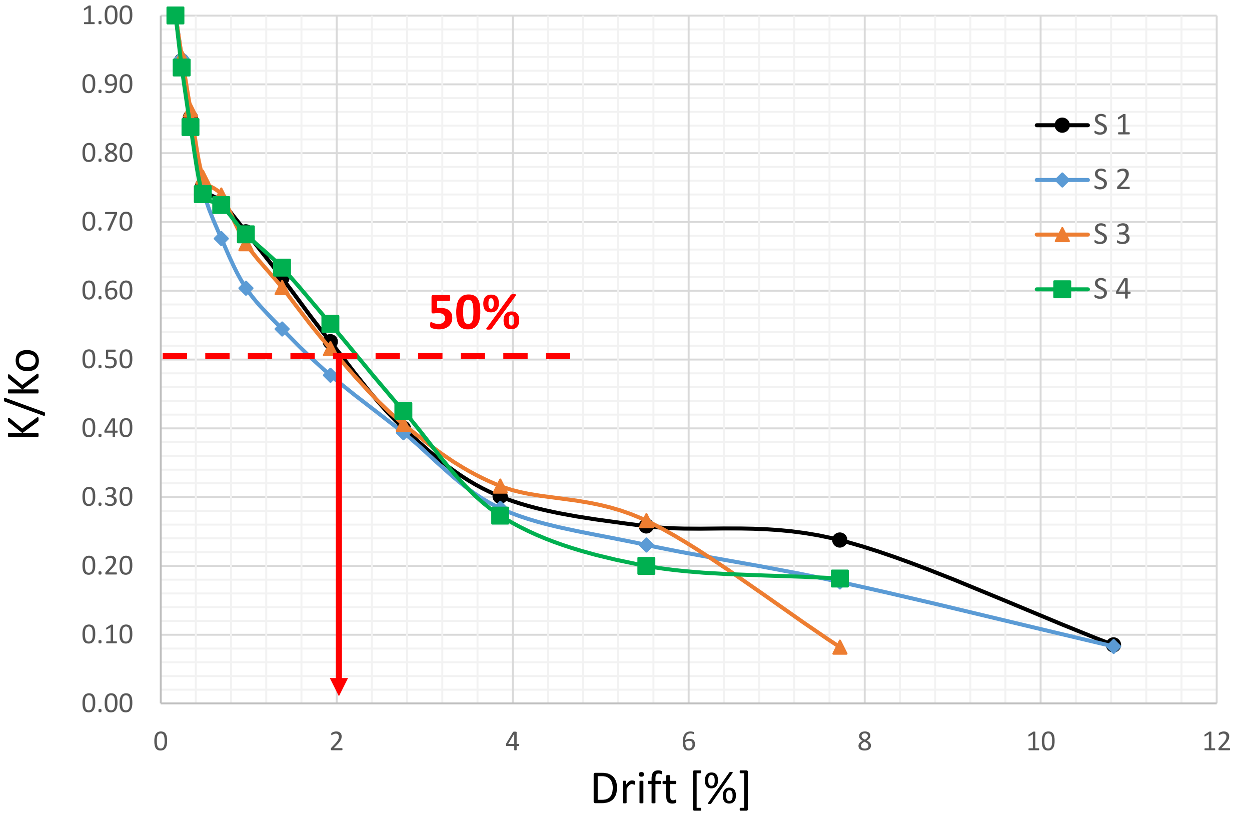


- Exceeds AASHTO Seismic Guide Specs displacement ductility requirement of 5

Hysteretic Response



Stiffness Degradation



For S1 Spec.

$$K_o = 42\, kips/in.$$

$$K_o = \frac{3 * E_c I_{eff}}{L^3}$$

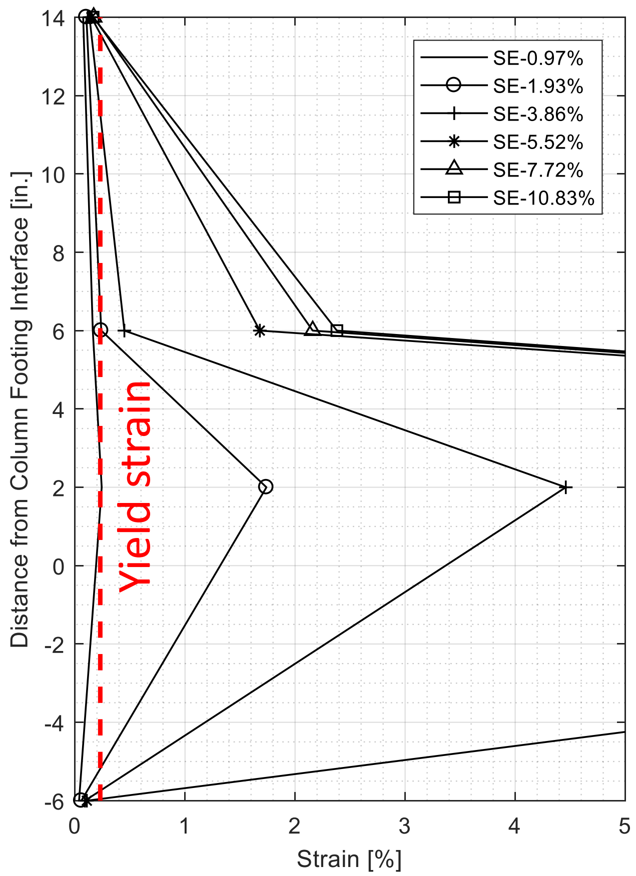
$$E_c I_{eff} = 0.7 * E_c I_g$$

$$E_c = 46{,}200\sqrt{f_c'}$$

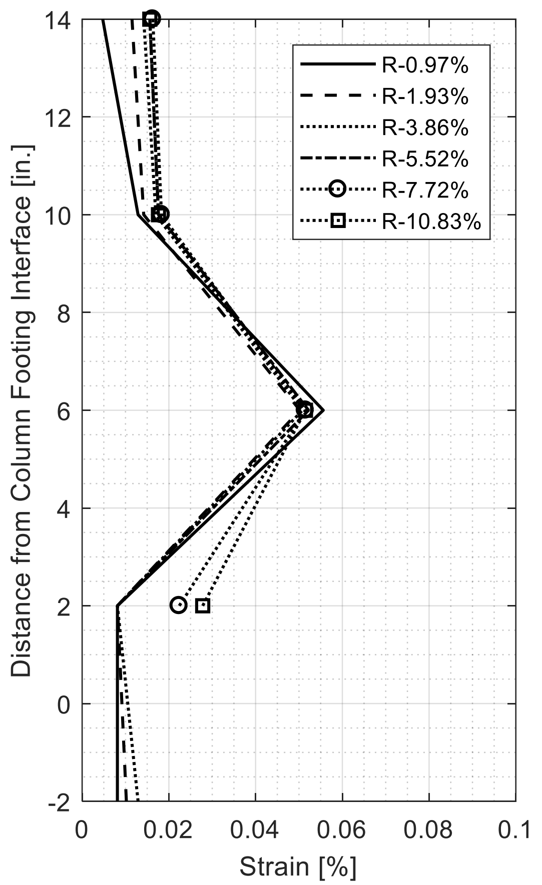
Graybeal (2007)

Strains

Specimen S1 (L=2.4%-Gr.60, T=1.1%-Gr.60)



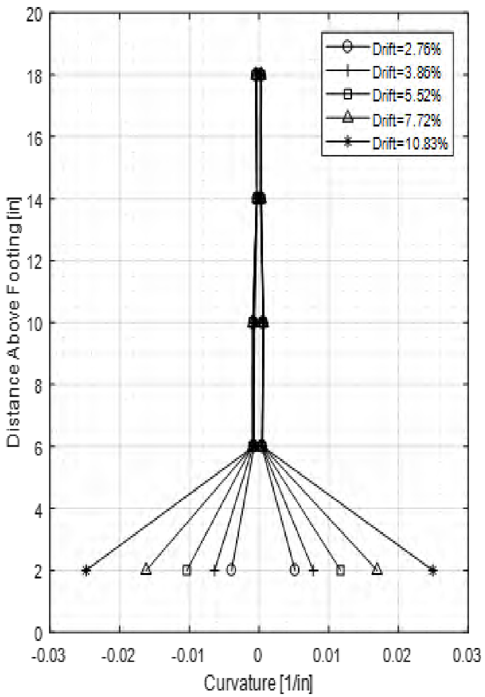
Longitudinal reinforcement strains



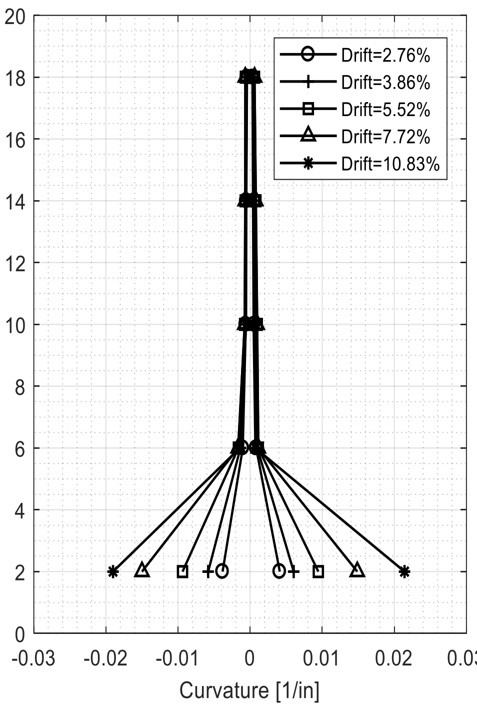
Transverse reinforcement strains

Curvature Profiles

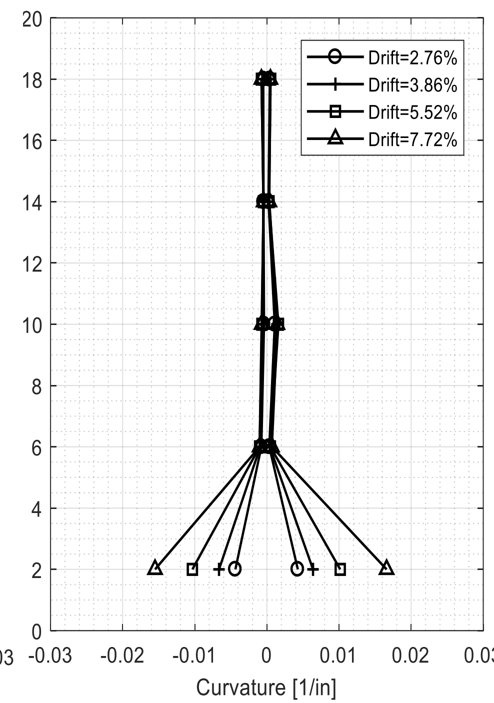
Specimen S1



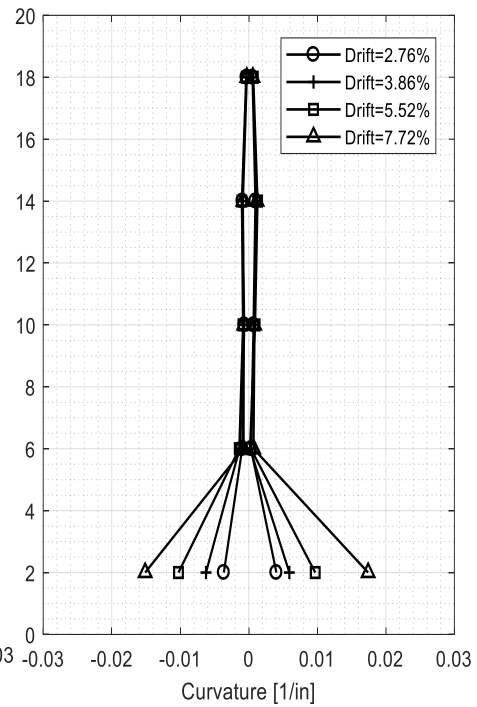
Specimen S2



Specimen S3



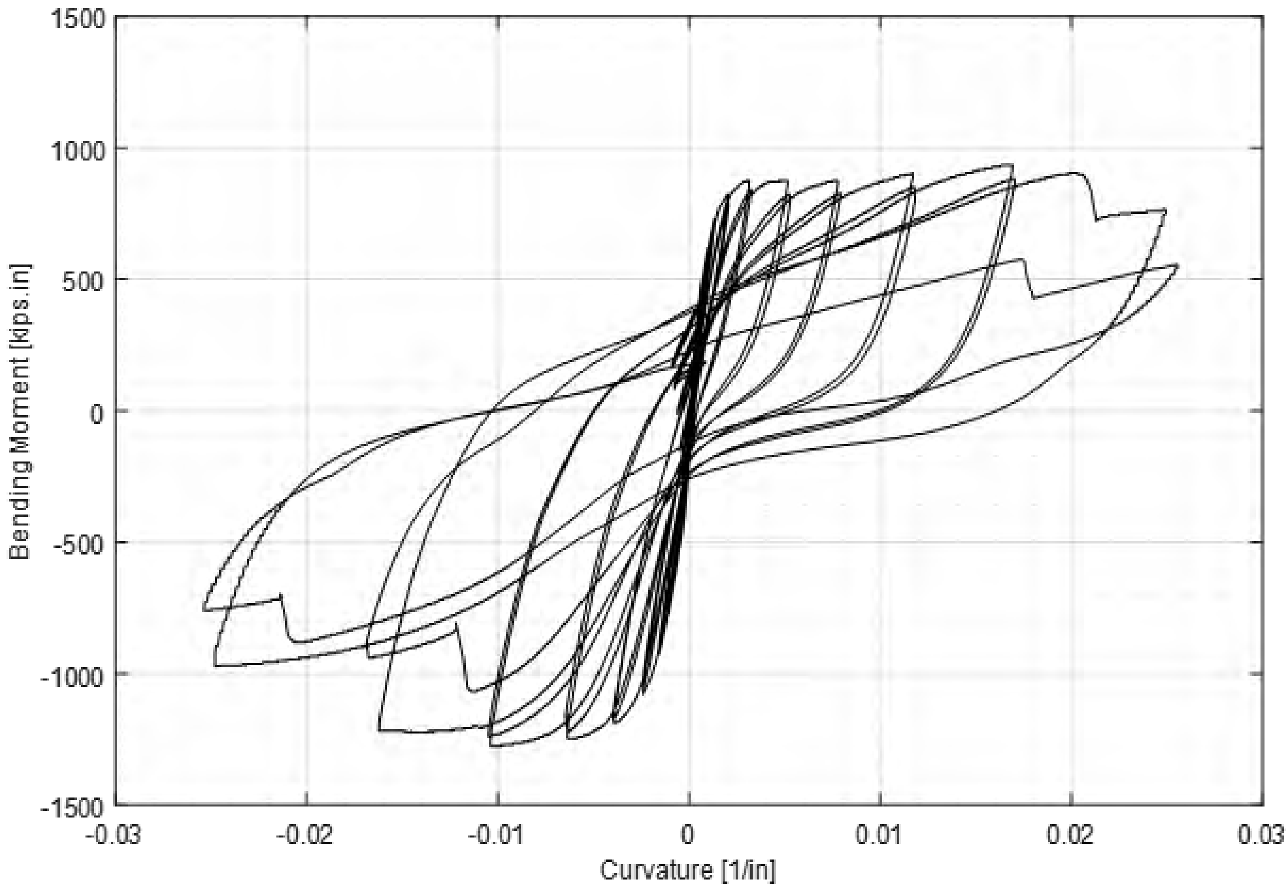
Specimen S4



UHPC column curvatures within plastic hinge region

Moment-Curvature Response

Specimen S1 (L=2.4%-Gr.60, T=1.1%-Gr.60)



M_u = **933 k-in**

& **1276 k-in**

Φ_y = 0.00116 1/in

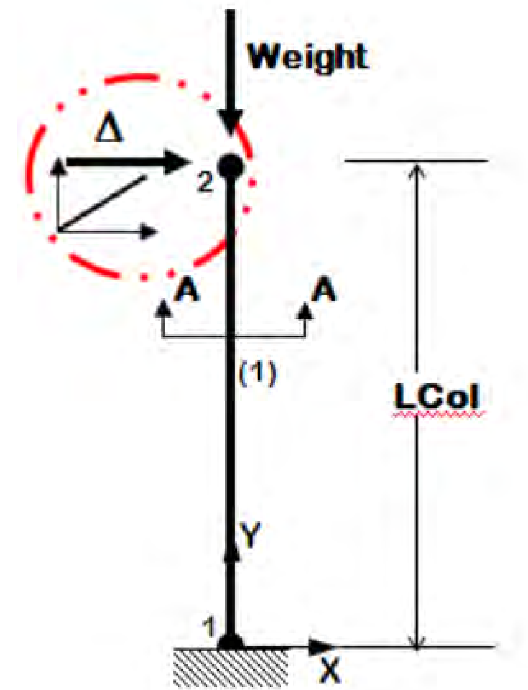
Φ_u = 0.025 1/in

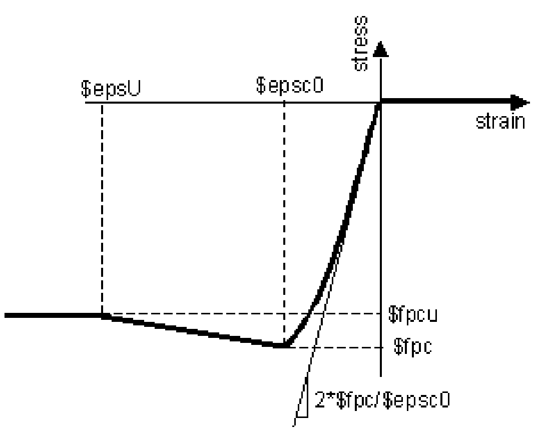
μ_Φ = 15.4

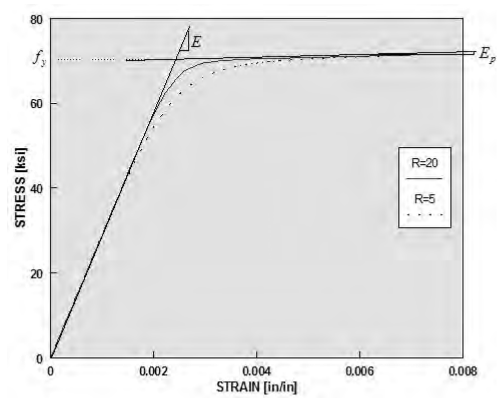
Moment-Curvature relationship

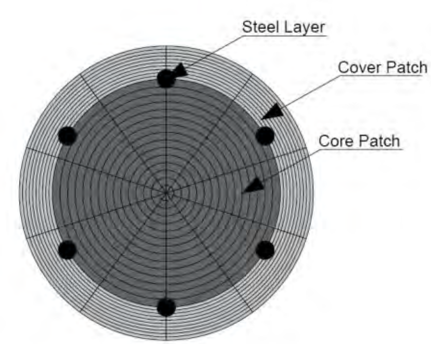
NSC Column Model

- Similar column analytically investigated using OpenSEES FEA model and Section Analysis (S0)
- 3-D two node fiber-section model.
- Nonlinear force-based element, *forceBeamColumn, with PDelta* geometric stiffness matrix.
- *Concrete01* and *Steel02* material models.



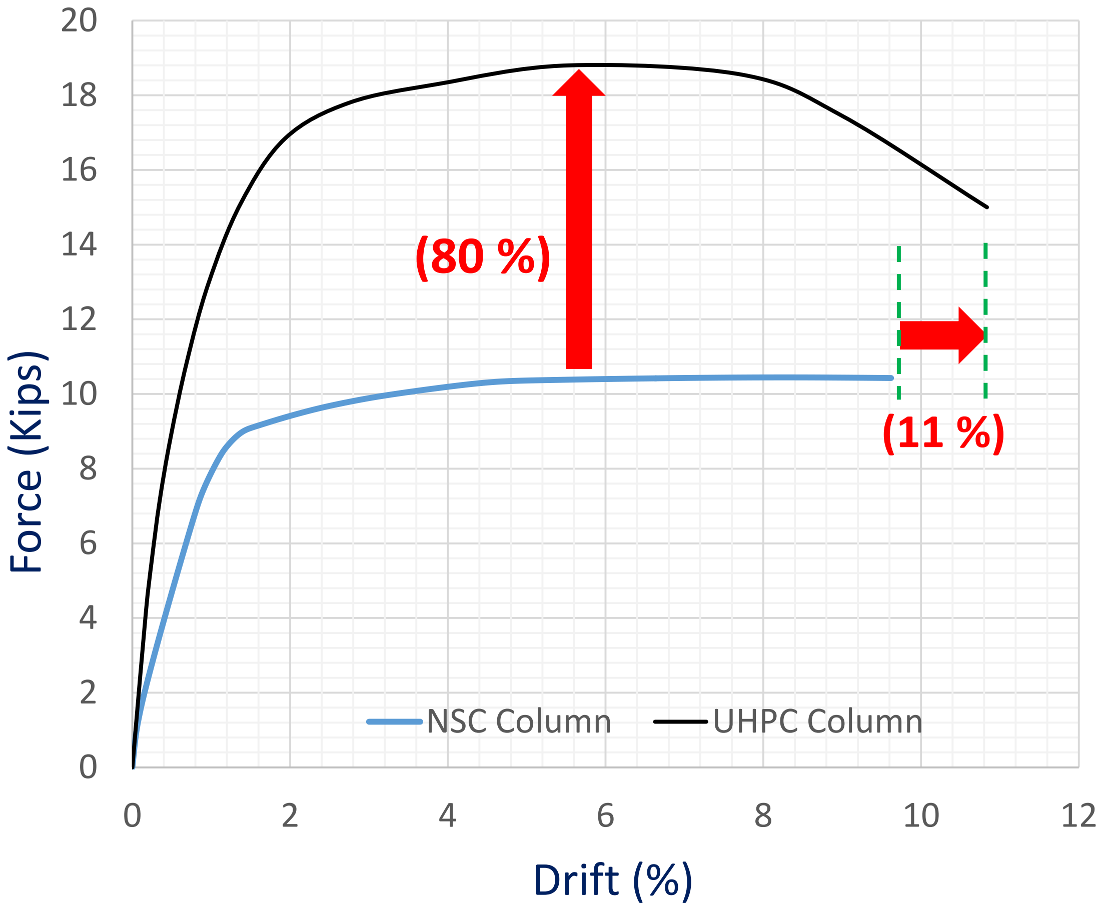






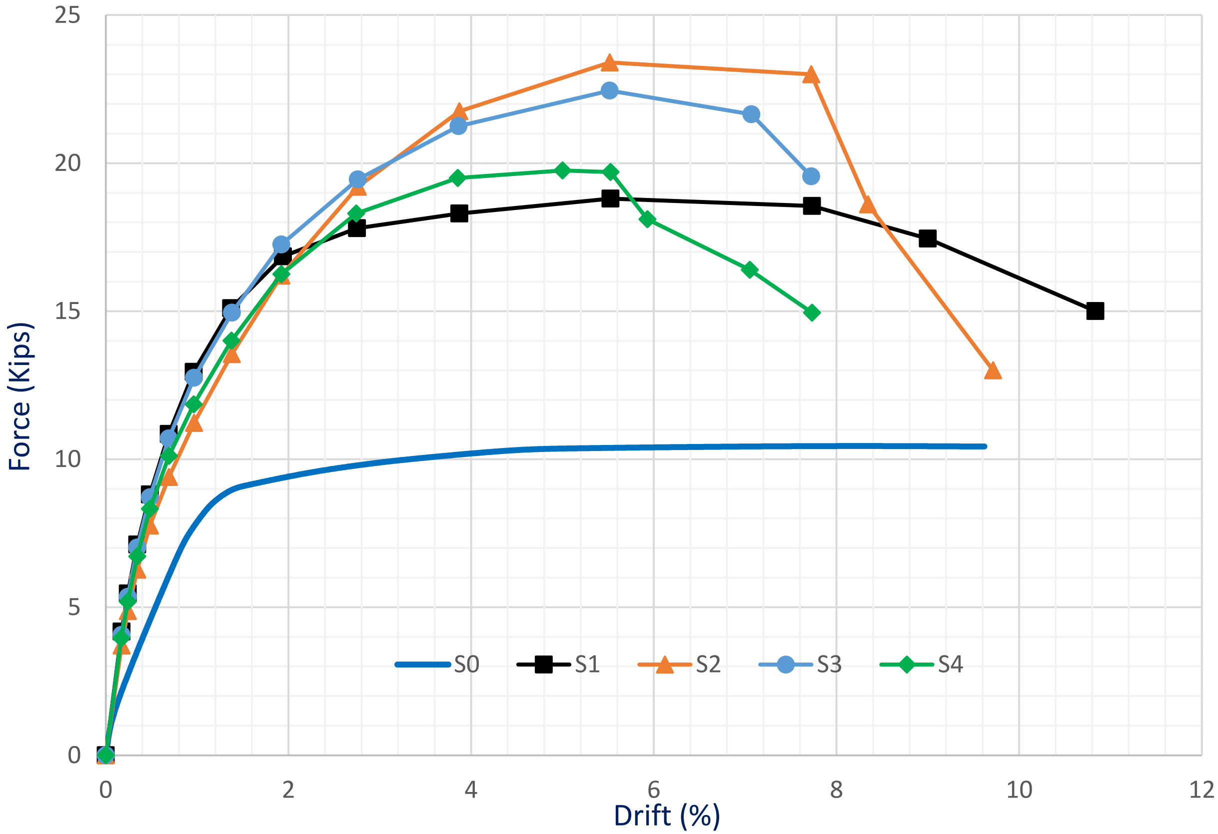
UHPC (S1) vs. NSC (S0) Columns

- Average backbone curves used for comparison.



	NSC	UHPC
	10-in, 6#5-Gr.60, 5% axial load ratio	
f_c	**5 ksi**	**30 ksi**
P_{max} (kips)	**10.44**	**18.8**
Drift $_{yield\text{-}ideal}$	**1.20 %**	**1.29 %**
Drift $_{max}$	**9.62 %**	**10.84 %**
μ_{Δ}	**8.0**	**8.4**

Lateral Load Capacity



	P_{max} (kips)	Ratio to S1 specimen
S0	10.44	55.5 %
S1	18.80	100 %
S2	23.40	125 %
S3	22.45	120 %
S4	19.75	105 %

S1 vs S2 → Gr. 100 vs Gr.60

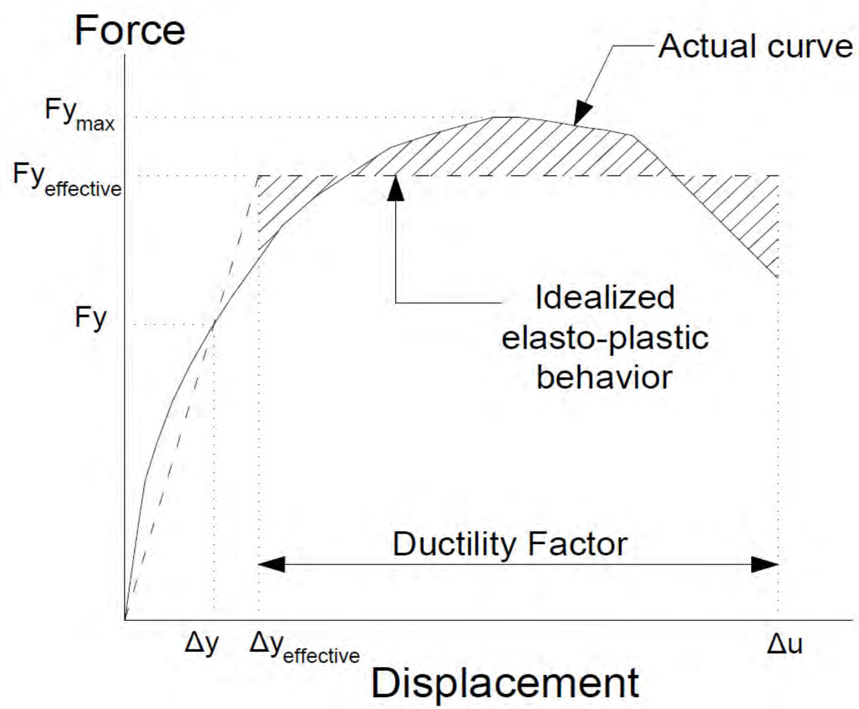
S2 vs S3 → 50% less confinement

S2 vs S4 → 35% reduction in long. steel

Drift Capacity

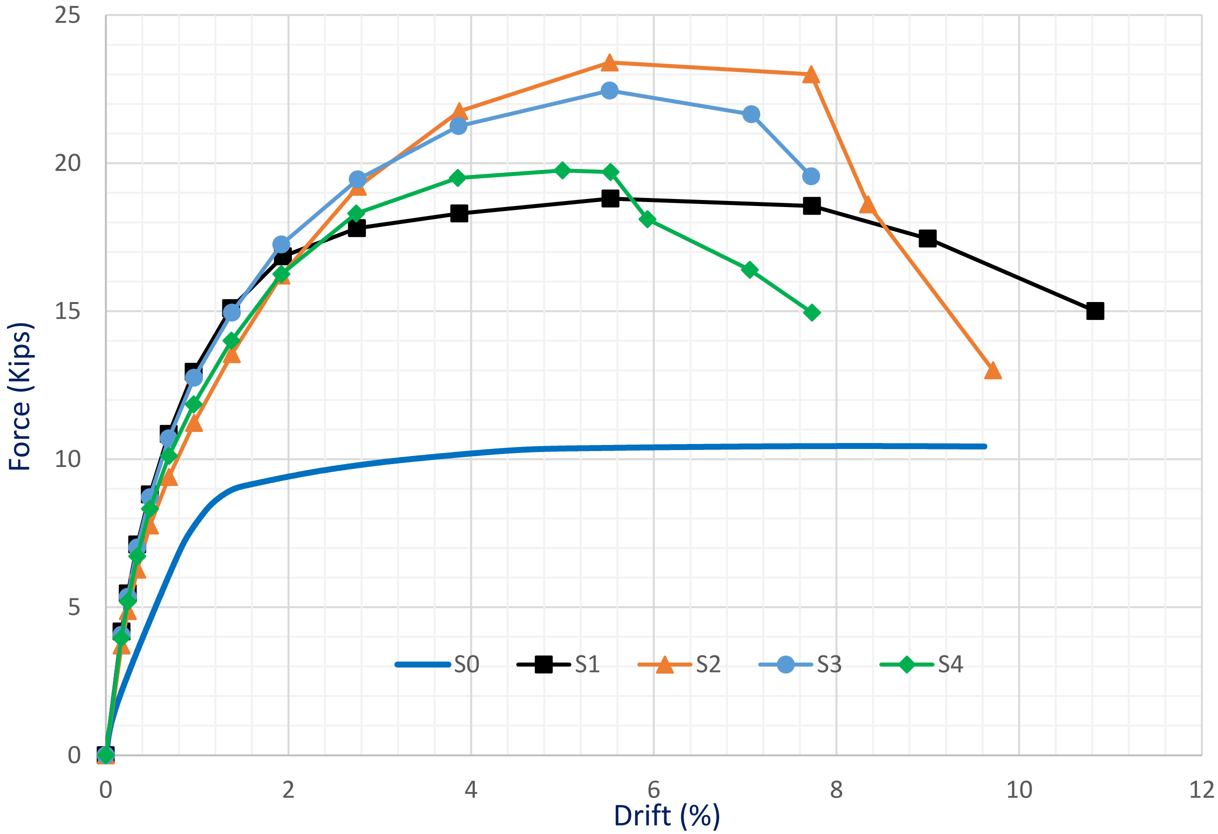
- The bilinear elasto-plastic curve method.

  (*Valid only for columns reinforced with Gr. 60 rebars*).



- Group II is compared to Group I with respect to their drift capacity.
- The drift capacity is lesser of ultimate drift and measured drift at 80% of maximum lateral load capacity.

Drift Capacity



	$Drift_{max}$ (%)	Ratio to S1 specimen
S0	9.62	**88.75%**
S1	10.84	**100%**
S2	8.34	**77%**
S3	7.72	**71.2%**
S4	7.43	**68.5%**

S1 vs S2 → Gr. 100 vs Gr.60

S2 vs S3 → 50% less confinement

S2 vs S4 → 35% reduction in long. steel

Thank You! Questions?