Use of UHPC for Longitudinal Joints in Deck Bulb Tee Bridge Girders

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Overview

Based on research program conducted at the University of Washington, in collaboration with Washington State University, sponsored by WSDOT.

Project components:

- Material development (Mix developed by *Qiao* at Washington State University, Pullman).
- Structural testing done at University of Washington, Seattle.

Focus of presentation:

Structural testing of deck joints between precast girders.

Introduction

- UHPC is a relatively new structural material that has properties that are useful for both ***seismic*** and ***non-seismic ABC***. It has good properties:
  - In tension: high strength, excellent ductility.
  - In bond: very high bond strength, excellent ductility.
  - In shear: good (but less is known yet).
  - In compression: typically much stronger than the demand requires.
  - Durability: good for reducing maintenance and life cycle costs.
- Particularly effective when used in joints.
- New material. Not yet codified in AASHTO specifications (LRFD, seismic Guide Spec or ABC Guide Spec).
- Quite extensive research, particularly by Graybeal at FHWA. Also NCHRP 18-18.
- Now moving into the implementation phase.
- Quite a number of applications in practice, e.g. for deck joints.

Materials for UHPC joints

UHPC MATERIALS:

- Cement
- Fine Aggregate
- Water (0.14 < w/c < 0.22)
- Coarse aggregate (not always)
- High-Range Water-Reducing Admixture (HRWRA)
- Fly ash/slag (optional)
- Silica Fume

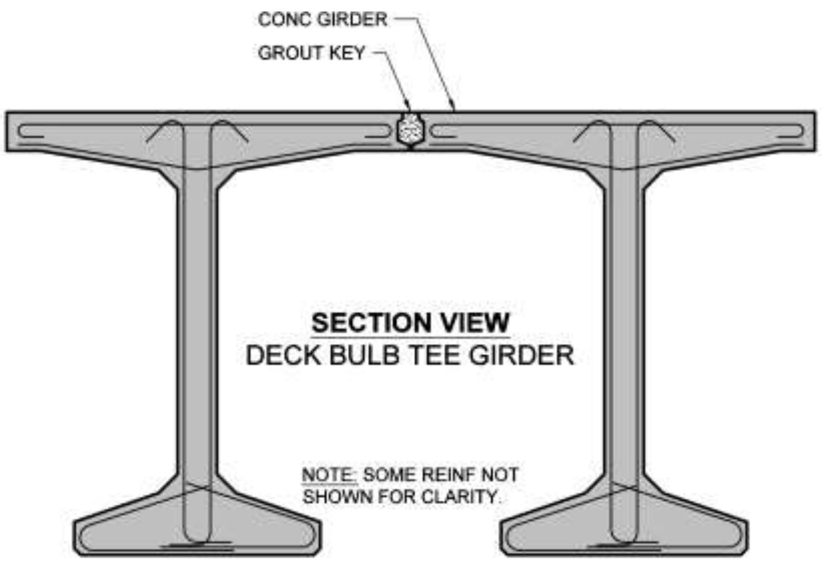
To create a dense, impermeable, paste.

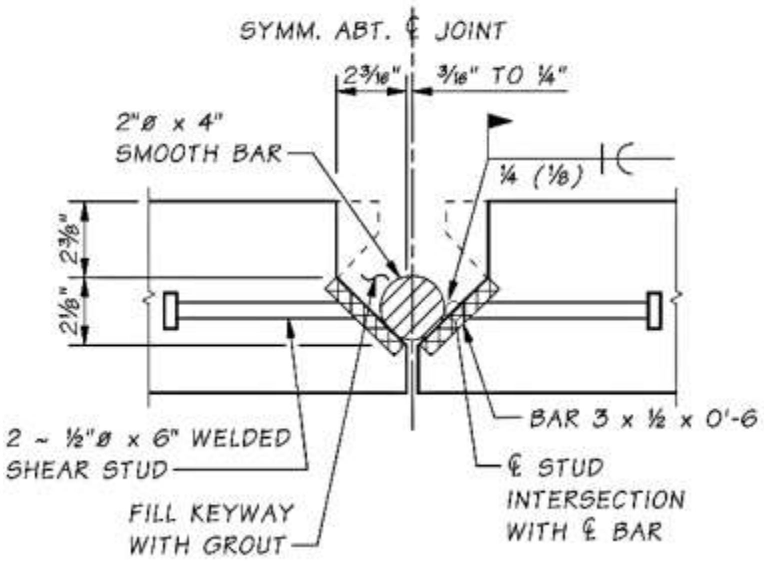
- Steel fibers
  - *Fibers: very high strength (400 ksi).*
  - *L/d ≈ 65 designed to ensure bond failure, rather than fracture, of individual fibers.*
  - *Gives some "pseudo-ductility" in tension.*

Note: The fibers and HRWA are the most expensive items.

Introduction

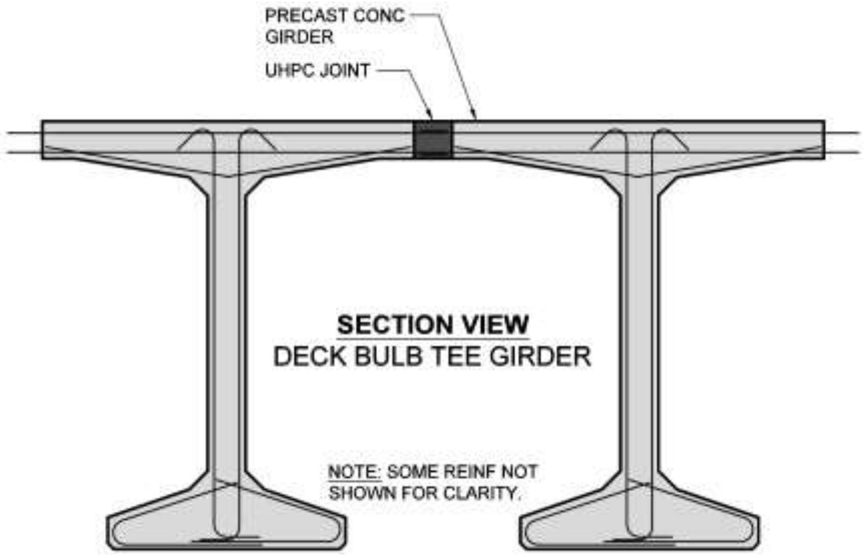
- Fully pc girders (e.g. deck bulb tees) save construction time by avoiding the need for casting a deck. They are a major contributor to ABC.
- The girders must be connected between flanges, for wheel loads.
- Previous connections: steel inserts in the girder flanges, welded together on-site and supplemented by a grout key.
- Connection not durable: damage under heavy truck loading.

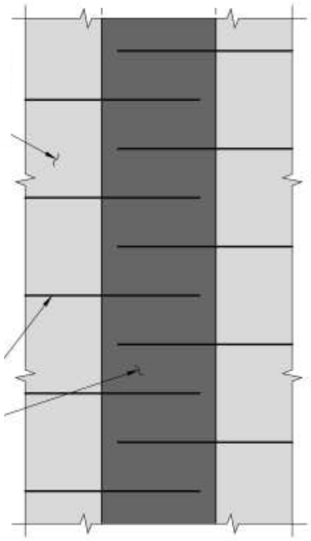




Introduction

- UHPC connection stronger and more durable. Allows deck bulb tees to be used on major highways.
- Bars project from girder flanges, connect by lap-splices using UHPC





Plan View

Introduction

Benefits specific to joints

UHPC has excellent bond strength. This allows

- Narrow joints, thus simple formwork
- Strength gain: quite fast. Depends on mix and curing procedures.
- Excellent durability in service, which leads to:
- Lower life-cycle costs.

Economics of UHPC

- UHPC is very expensive per cubic yard. But…….
- You do not need much of it:
  - Joints are narrow.
  - Connections are small.
- Cost of a UHPC joint about 10% - 30% of the cost of a girder.
- Extra $ cost outweighed by the value of the time savings (ABC).

Proprietary vs Generic UHPC

Proprietary

- Most UHPC used today in the US is proprietary.
- Supplier may come to site to supervise or do the mixing and casting.
- The supplier owns the risk. Material priced accordingly.

Non-proprietary

- Contractors could design, mix and cast their own generic UHPC.
- Generic → cheaper, but the contractor would own the risk.
- Most prefer to avoid the risk and pay the price of proprietary UHPC.
- Non-proprietary UHPCs are now being developed, e.g. at FIU-ABC Center. These will likely change the market-place. Need to:
  - Select target properties (bond strength, tension strength?)
  - Develop QA/QC tests and procedures for those properties.

Behavior of UHPC joints

Forces to be carried:

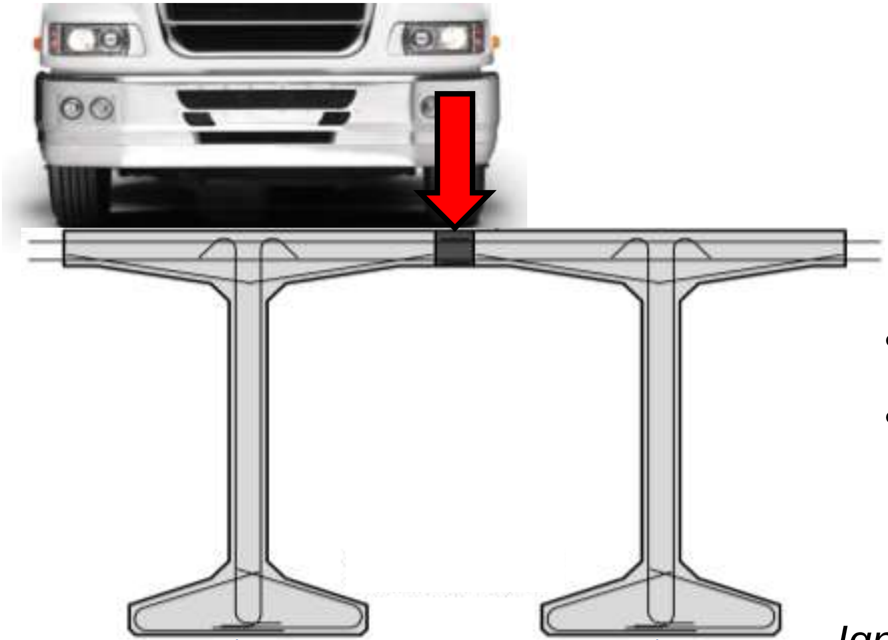
- Transverse moments due to wheel loads,
- Transverse moments due to correcting differential camber,
- Shear due to wheel loads or differential camber.

Other (prescriptive) criteria:

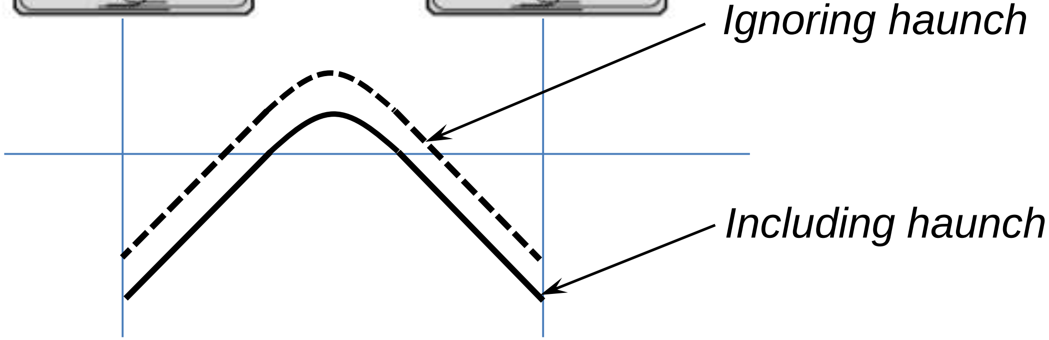
- To take full advantage of the AASHTO wheel load distribution factors, the girders must be ***"sufficiently connected to act as a unit"***. This is interpreted here to mean that the UHPC joint has flexural strength equal to that of the pc deck member.

Behavior of UHPC joints

Transverse moments due to wheel loads



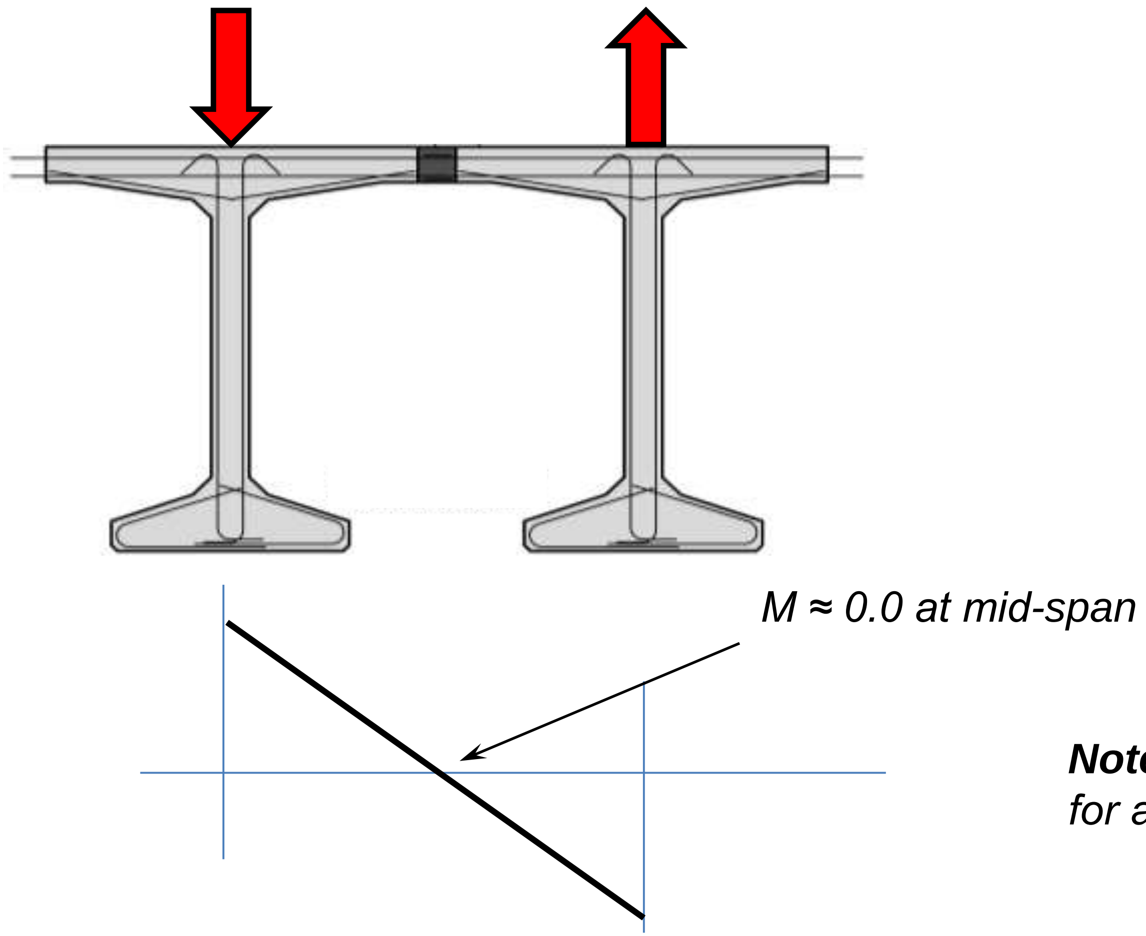
- Haunch helps.
- Moves moment from M+ (at joint) to M- (over web).



Moments due to wheel loading

Behavior of UHPC joints

Transverse moments due to correction of differential camber.



***Note**: shear stress ≈ 5 psi for a 1” difference in camber.*

Moments due to camber correction

Behavior of UHPC joints

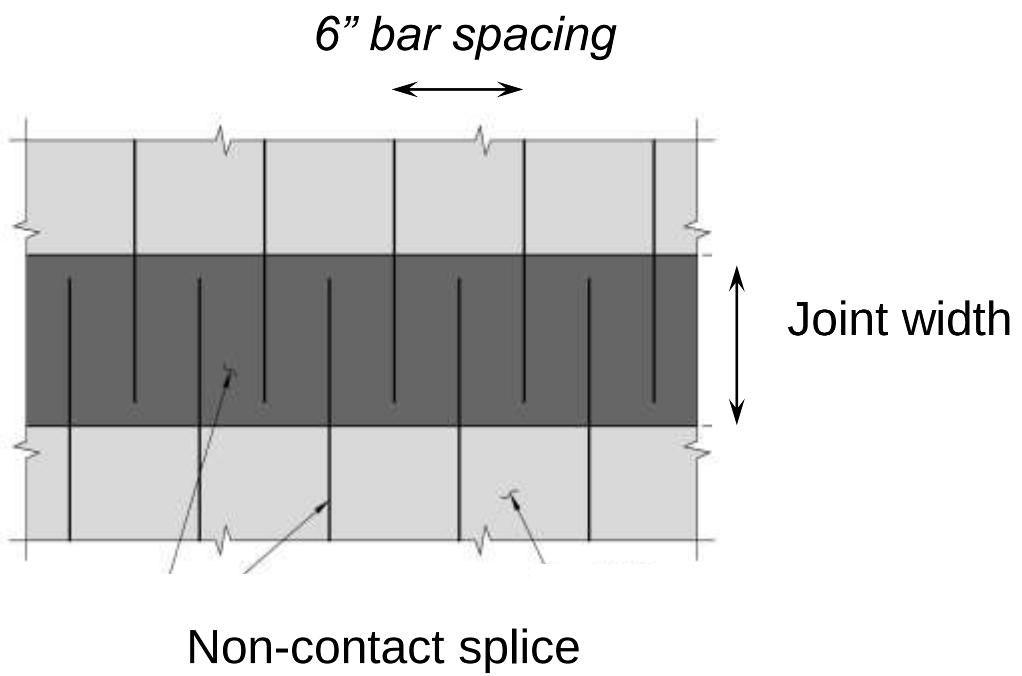
FEA of deck showed:

- M_{max} due to wheel loads only about 15% of capacity.
- ***"Equal strength criterion"*** is much more stringent criterion than moments due to applied loads.
- Design to achieve "***Equal Strength***" implies VERY conservative design for real wheel loads.

Behavior of UHPC joints

To give the joint the same flexural strength as the pc deck slab:

- Splice length must be great enough to ensure bar yield, not bond failure.
- Note: splice is non-contact (individual bars at about 3” centers).



Materials for UHPC joints

UHPC MIXES – A SAMPLE:

Units: lb/yd^3

	Water	Cement	Silica Fume	BF Slag	Gypsum	Sand	Coarse Aggregate	HRWRA	Steel Fiber	w/cm Ratio
Lee & Lee	253	966	179	297	46	962	1461	-	212	0.22
Graybeal	219	1200	390	0	0	1720	0	50	263	0.14
Collepardi	362	1574	394	0	0	1736	0	21	315	0.18
Allena & Newtson	376	1500	374	0	0	1347	0	51	201	0.20
Karmout	303	1011	157	0	0	530	1670	30	0	0.26
WSU Mix C3	**325**	**1500**	**260**	**0**	**0**	**1574**	**0**	**101**	**236**	**0.18**

w/cm Ratio: 0.185 **Volume of Steel Fibers:** 1.80%

Lee, Jun Ki, and Seung Hoon Lee. "Flexural Behavior of Ultra-High-Performance Fiber-Reinforced Concrete Moment Connection for Precast Concrete Decks." ACI Structural Journal112.4 (2015): 451.

Graybeal, B. A., "Material Property Characterization of Ultra-High Performance Concrete, Federal Highway Administration, Pub. No: FHWAHRT-06-103, Turner-Fairbank Highway Res. Center, McLean, VA, USA, 2006.

Collepardi, S., Coppola, L., Troli, R., and Collepardi M., "Mechanical properties of modified Reactive powder Concrete", ACI international Conference on "Superplasticizers and Other Chemical Admixtures in Concrete", SP 173, October 1997

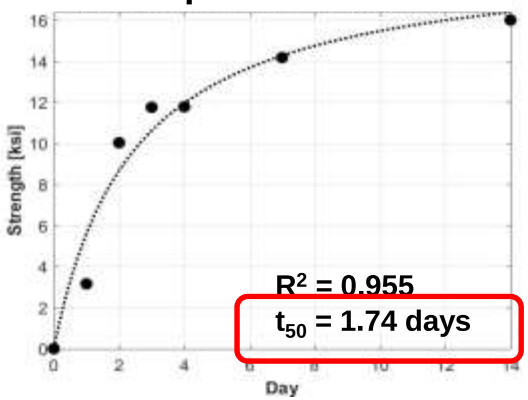
Allena, S., and Newtson, C. M., "Ultra High Strength Concrete Mixtures Using Local Materials," J. Civ. Eng. Arch., Vol. 5, No. 4 (Serial No. 41), 2011, pp. 322-330.

Qiao, P., and Zhou, Zhidong., "Developing Connections for Longitudinal Joints between Deck Bulb Tees," June 2016.

Materials for UHPC joints

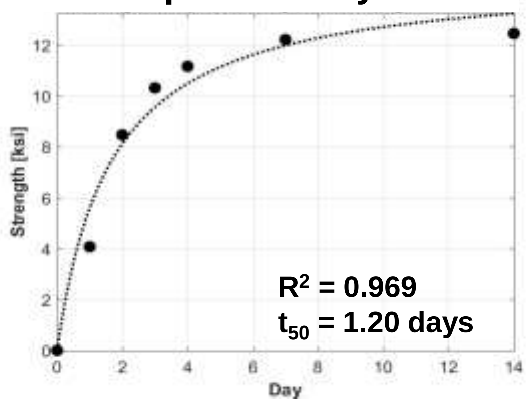
Tension and bond develop faster than compression.

Compression Cube



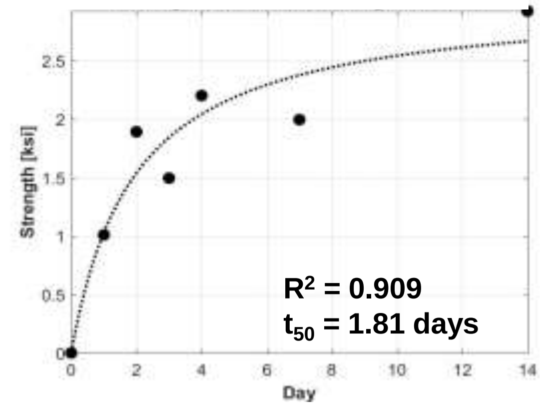
Avg Strength = 16.0 ksi

Compression Cylinder



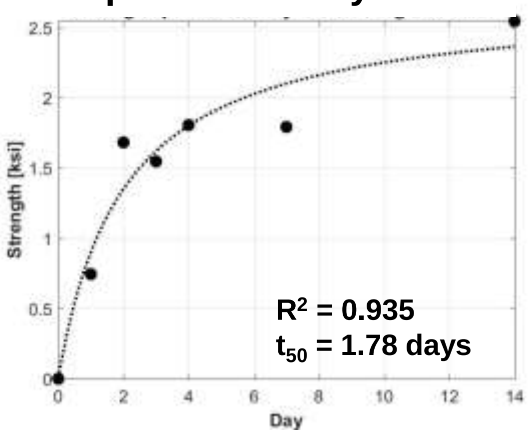
Avg Strength = 13.1 ksi

Flexural Beam



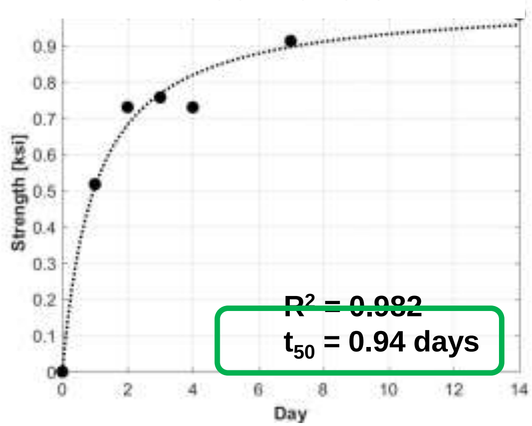
Avg Strength = 2.7 ksi

Split-Tension Cylinder



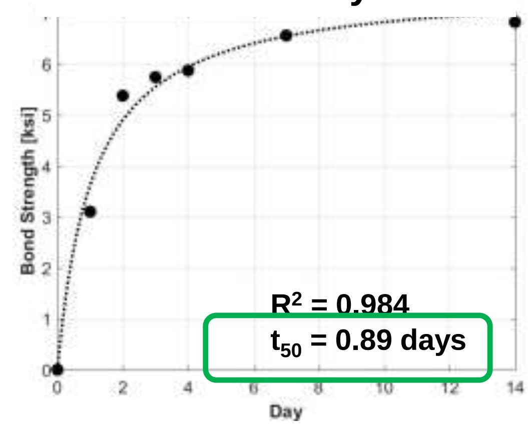
Avg Strength = 2.2 ksi

Direct Tension



Avg Strength = 1.0 ksi

Pullout Bond Cylinder



Avg Strength = 7.1 ksi

Design of UHPC joints

REQUIREMENTS

- Lap-splice bars for full tension strength.
- ***M*⁺** most important – bottom bar splice.

Photo: *Azizinamini*

SOLUTIONS:

Bar details:

- Hooked bars or U-bars? *Greater probability of mis-placement during fabrication or bar conflicts during erection.*
- Headed bars? *Difficulties with getting double-headed bars made to exact required length.*
- Straight bars? *May need longer splice, wider joint, more UHPC.*

Straight bars chosen. Joint can still be made narrow (minimum about 7”).

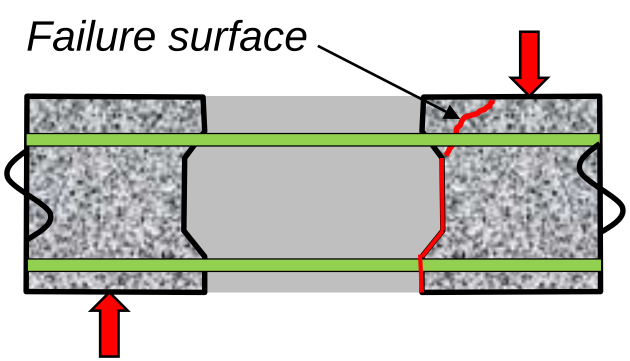
Graybeal also finds straight bars (even epoxy coated) are best.

Design of UHPC joints

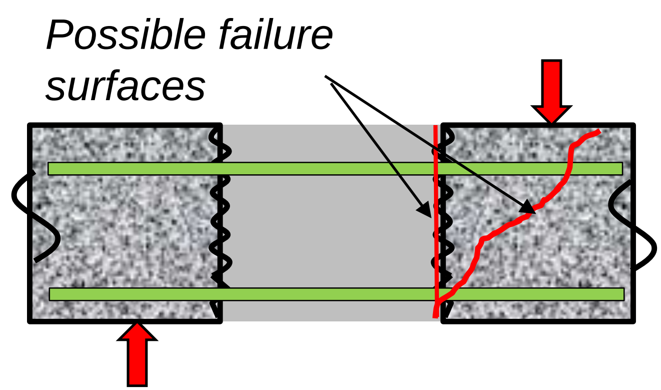
JOINT PROFILE: TO KEY OR NOT TO KEY?

Design options:

1. ***Joint key*** to provide shear strength. Potential for stress concentration and crack at re-entrant corner of key.
2. ***Roughened vertical surface,*** *no key*. Sliding shear force is resisted by shear friction. Diagonal cracking at higher load. Roughening method and surface preparation both affect the outcome.
3. ***No preparation***. Shear force is carried by shear friction on smooth surface.



1. Joint key

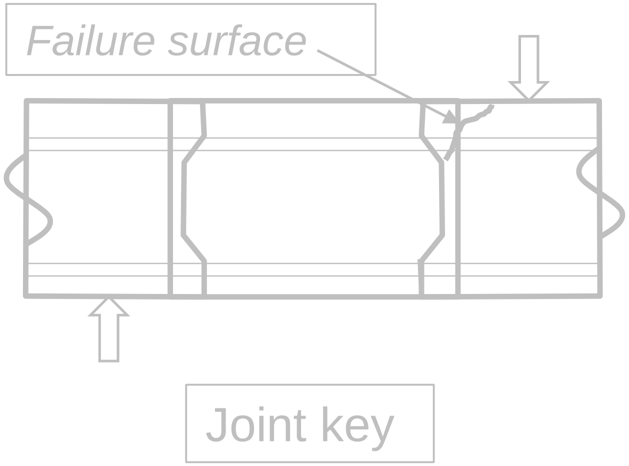


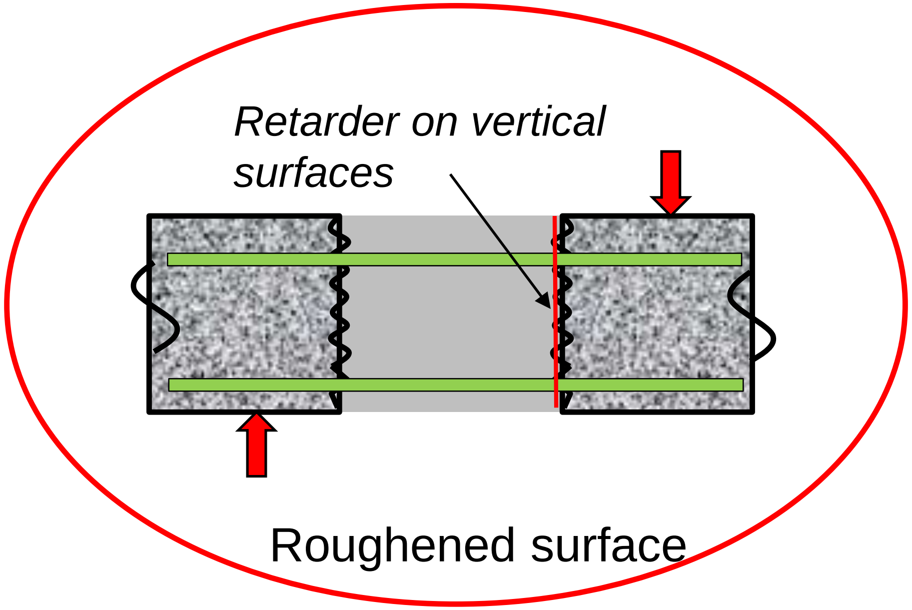
2. Roughened surface

Design of UHPC joints

JOINT PROFILE

- UW tests on deck panels used ***no preparation.***
- No sign of shear slip.
- Recommendation:
  - – Form roughened vertical face of girder flange using retarder.
  - – Pre-wet prior to placing UHPC.





Design of UHPC joints

DESIGN OF NON-CONTACT SPLICE

For conventional concrete, AASHTO requires a splice length

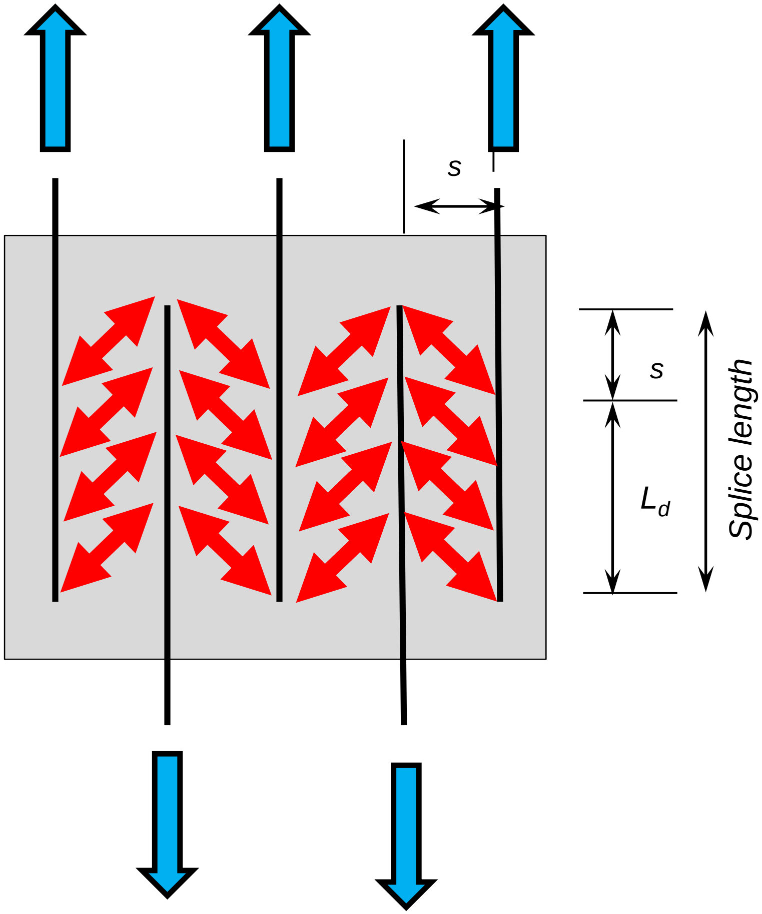
$$L_{splice} > L_d + s$$

L_d = development length
s = bar spacing.

UHPC:

A non-contact splice is (slightly) stronger than a contact splice.

[See Yuan and Graybeal (2015), Peruchini et al. (2017)].



Design of UHPC joints

SPLICE LENGTH OBTAINED BY TESTING

At UW, tested:

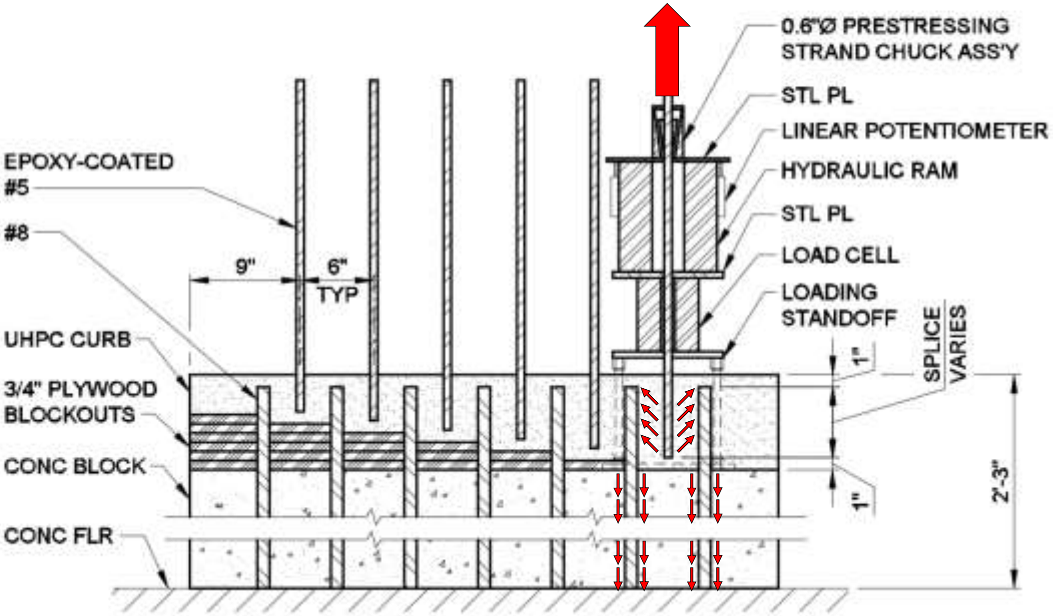
"Pullout bond" – pull the bar, react against the surrounding concrete.
"Splice bond" – pull the bar, resistance from non-contact splice bars.

All tests with…

- #5 at 6" top and bottom (gr. 60 epoxy-coated bars).
- 1.8% fibers by volume.

Design of UHPC joints

SPLICE BOND TESTS

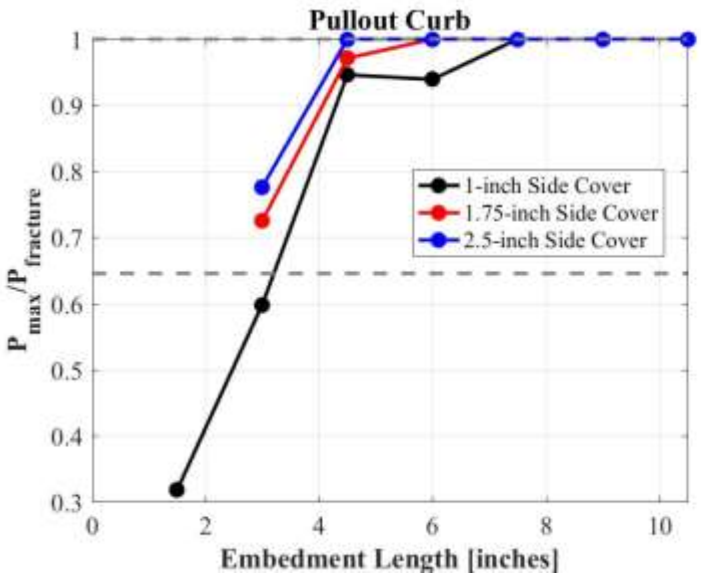


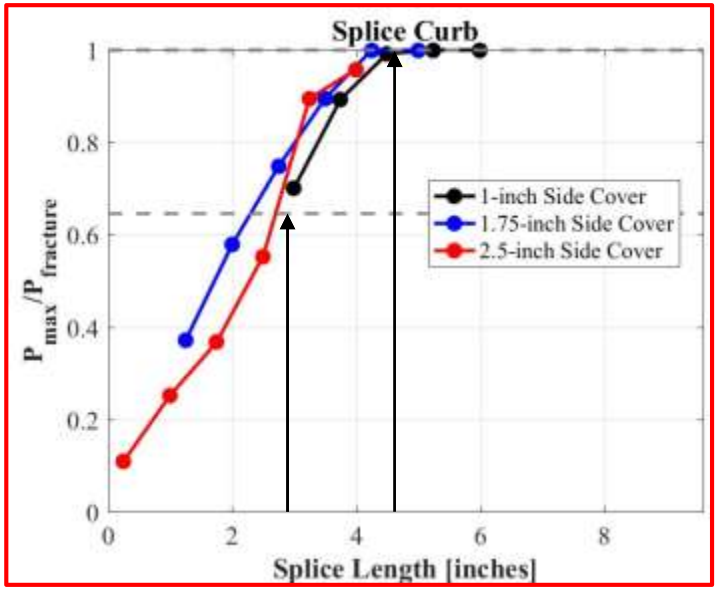
Base conc block

UHPC splice “curb”

Design of UHPC joints

PULLOUT & SPLICE TEST RESULTS





Fracture ~ 31 kips (100 ksi)

Yield ~ 20 kips (65 ksi)

- Strength proportional to splice length.
- Not very sensitive to side cover.
  - Yuan and Graybeal (2015) found some sensitivity.

These tests show (with 1” side cover):

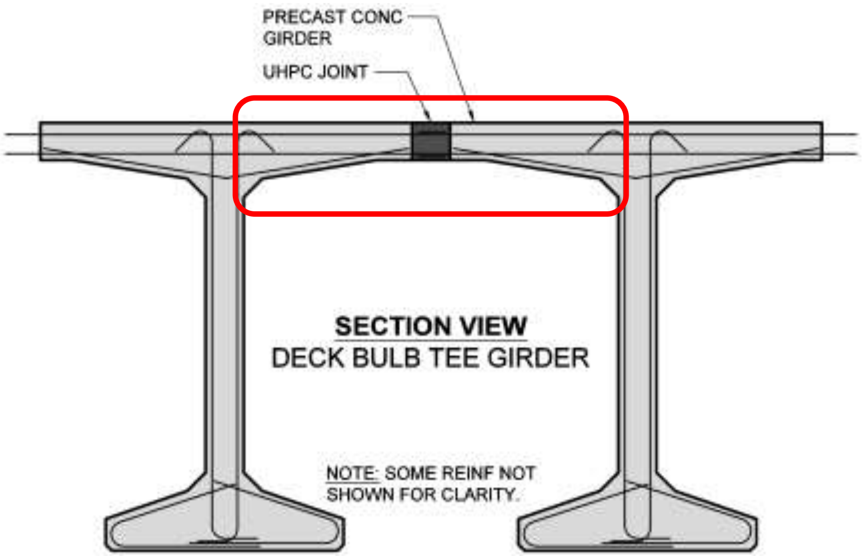
- Yield – 3” ($4.8d_b$)
- Fracture – 4.5” ($7.2\ d_b$)

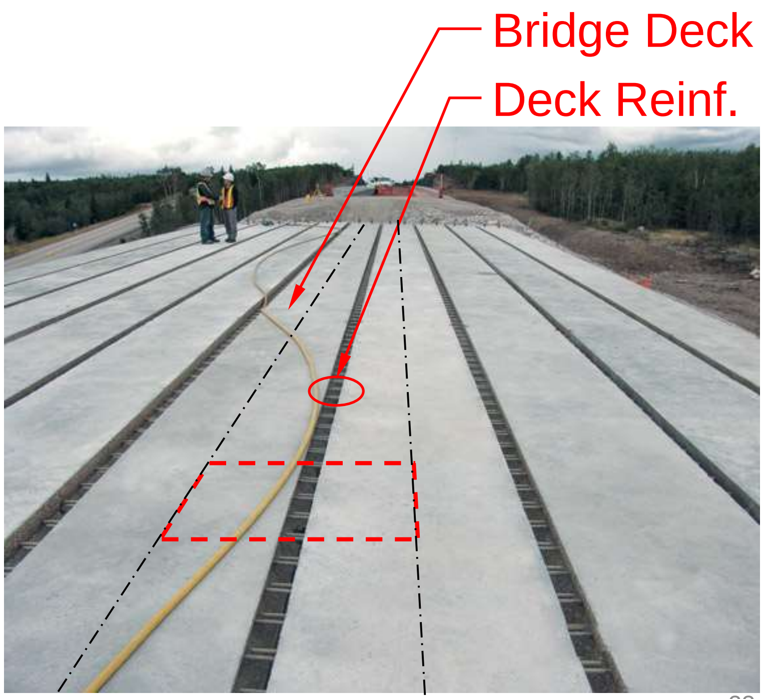
Fiber content expected to influence splice strength.

Design of UHPC joints

DATA FROM SIMULATED DECK TESTS.

Test panels simulate a transverse strip of deck with a UHPC joint.

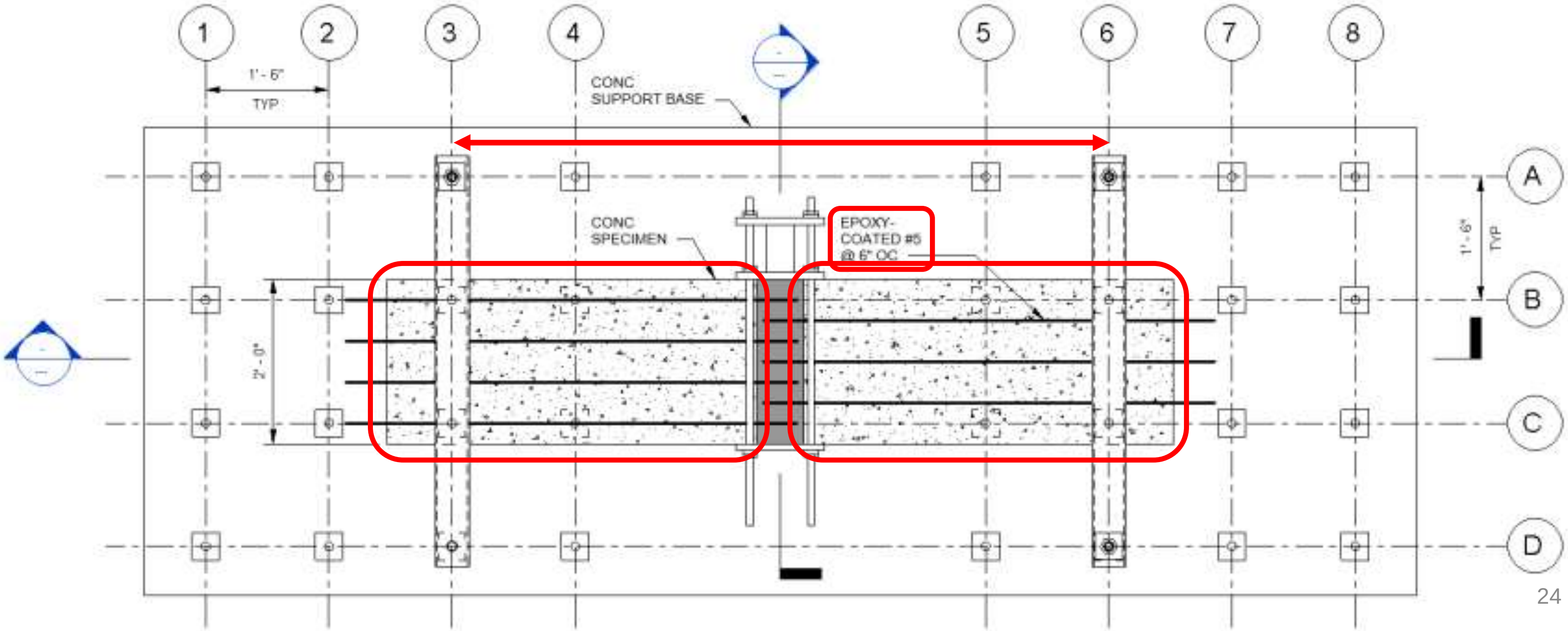




Design of UHPC joints

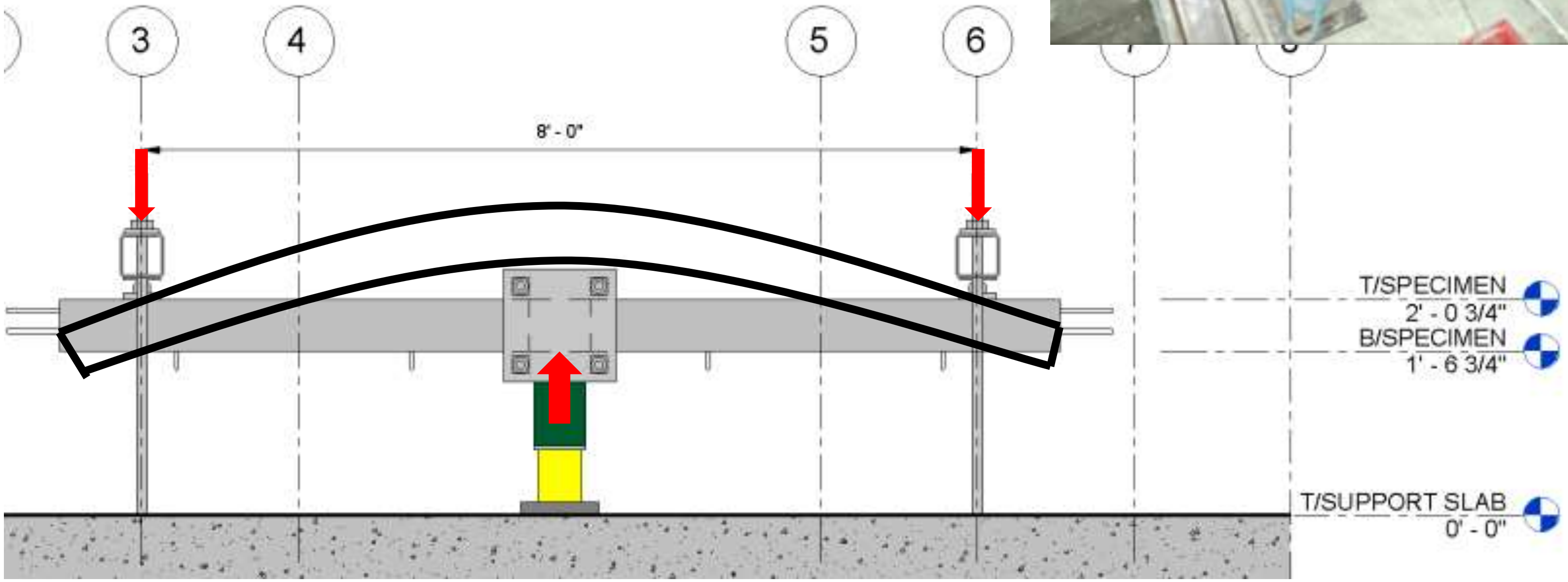
SIMULATED DECK TEST SETUP

- 2'-0" x 4'-5" x 6" panels.
- Joint width 3" – 7"
- #5 at 6" top and bot. (gr 60 epoxy-coated).
- 8'-0" maximum span.
- Simple span (statically determinate).
- Test upside down (to observe cracking).



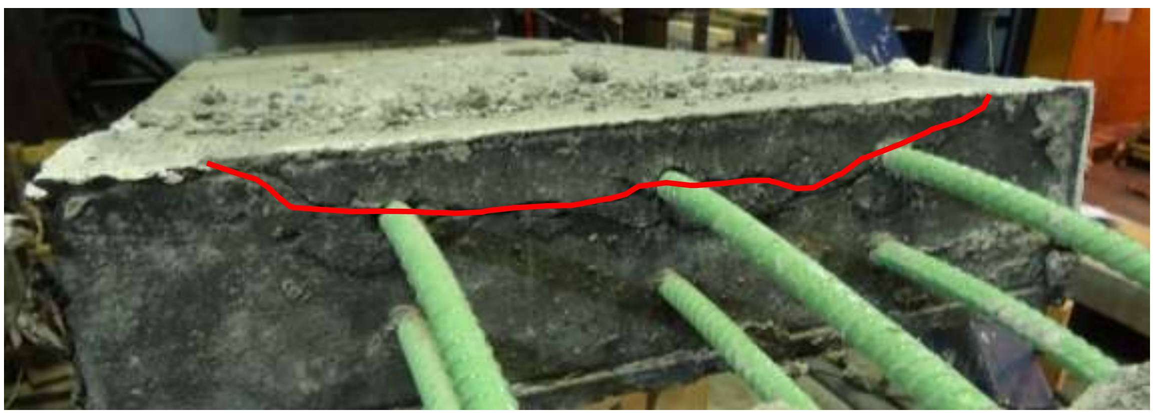
Design of UHPC joints

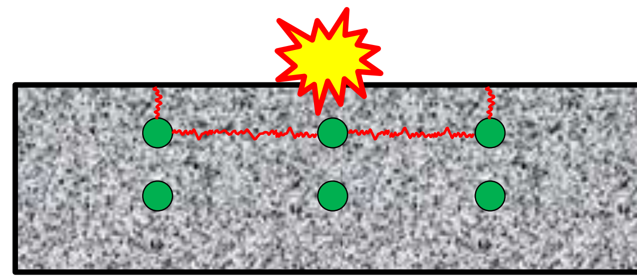
SIMULATED DECK TEST SETUP



TEST FAILURE MODES

As bars elongate inelastically & slip, crack opens at interface



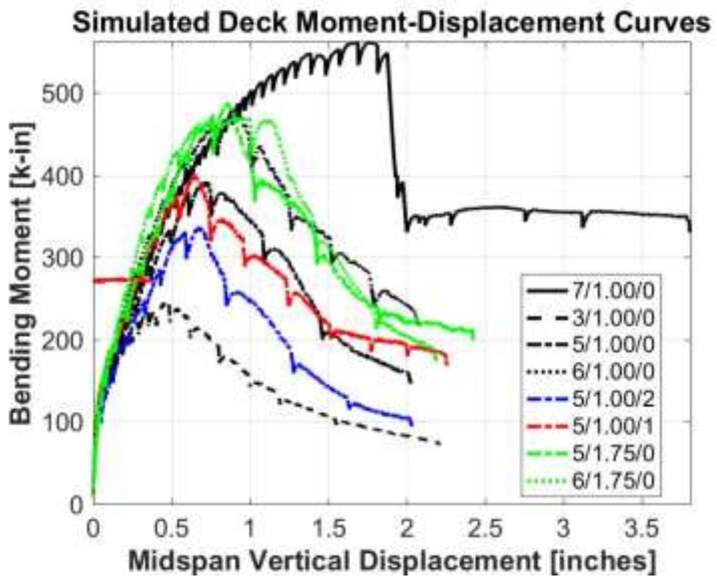


For short splice lengths, splice fails by UHPC splitting (joint = 3").

For long splice lengths, (joint = 7", splice = 5" = $8d_b$)
→ failure by bar fracture.

Experimental Results

Specimen	Joint Width/Cover/Offset [in]	Interfacial Bending Moment [k-in]
Specimen 1	7/1.00/0	562.2
Specimen 2	3/1.00/0	245.8
Specimen 3	5/1.00/0	391.7
Specimen 4	5/1.00/2	336.9
Specimen 5	5/1.00/1	400.6
Specimen 6	6/1.00/0	474.1
Specimen 7	5/1.75/0	487.4
Specimen 8	6/1.75/0	471.5



Conclusions

In general:

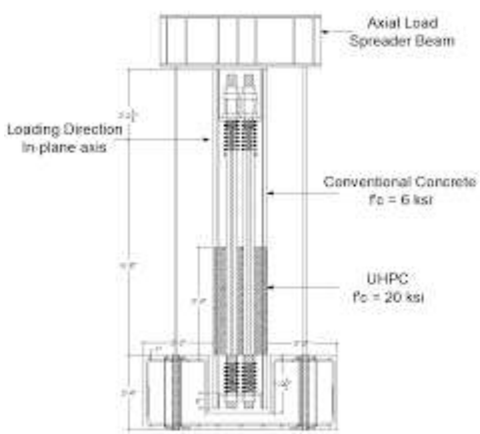
- UHPC is valuable for connecting precast elements for ABC.
- Bond and tension strength are the characteristics of UHPC most important for joints. Compressive strength higher than that of the surrounding concrete is unnecessary. Consider ***SHPC*** (***S***ufficiently ***H***igh ***P***erformance ***C***oncrete) and focus on the properties that are really needed.
- UHPC is expensive per cubic yard, but quantities needed are small, durability is high, life cycle costs expected to be competitive.

For deck joints:

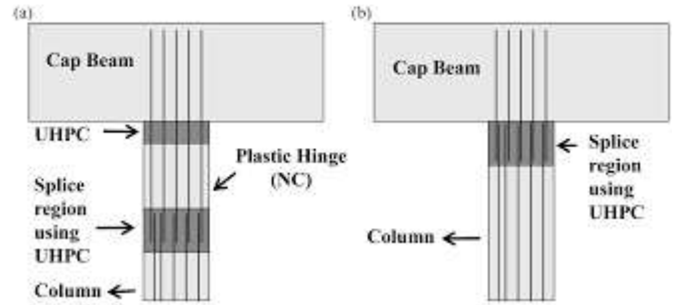
- Design of longitudinal joints is dominated by the prescriptive "Equal Strength Criterion", rather than by actual loads.
- With straight #5 bars in a 6" deck,
  Can achieve fracture with splice length = 5" ($8d_b$), joint width = 7".
- Use 9" or 10" joint width to allow for tolerances.

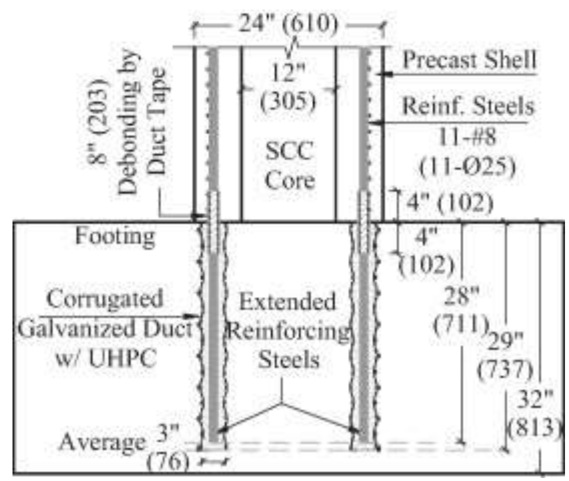
Questions?

Vadot

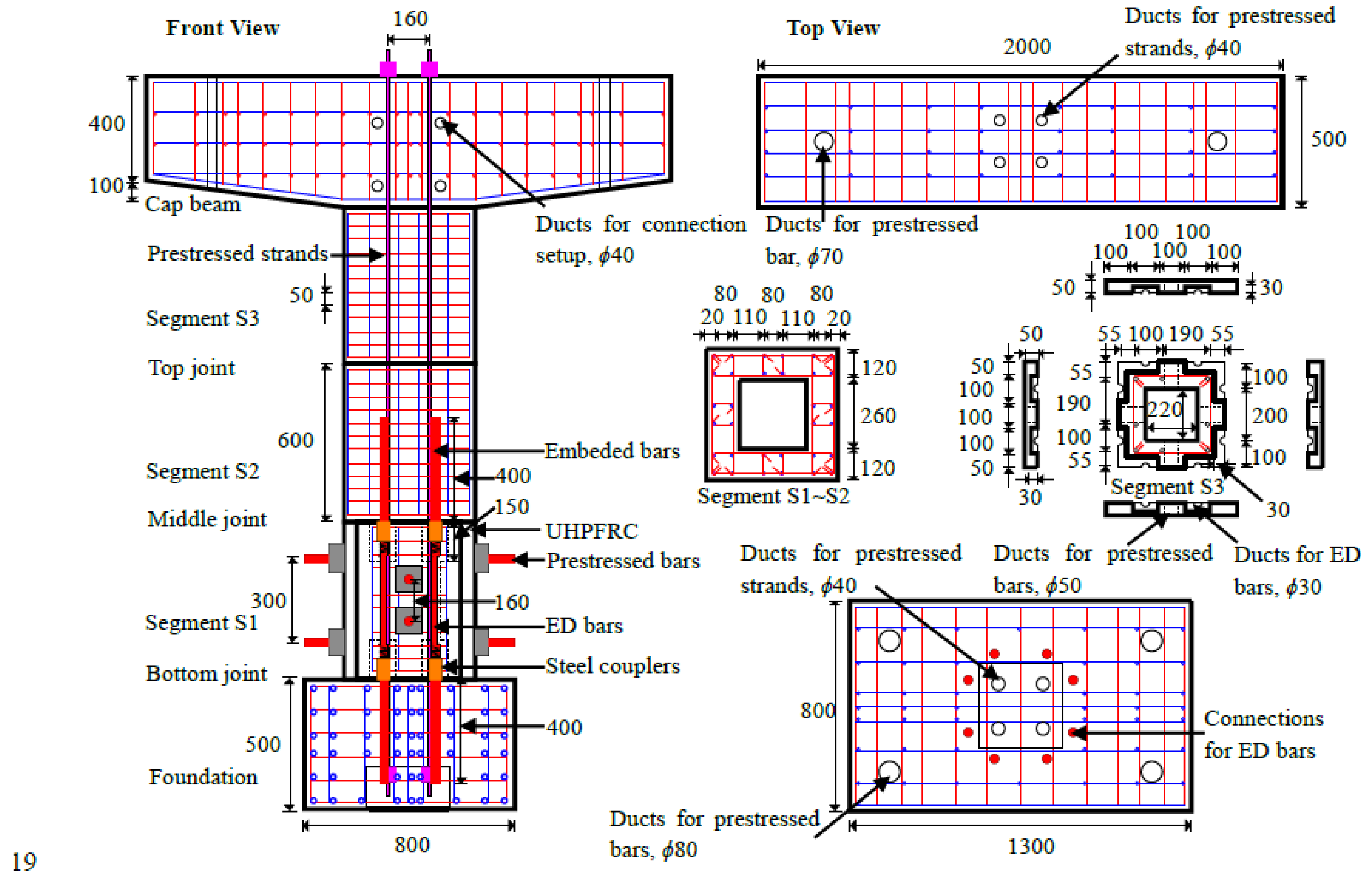


Aziz Tazarv/saiidi



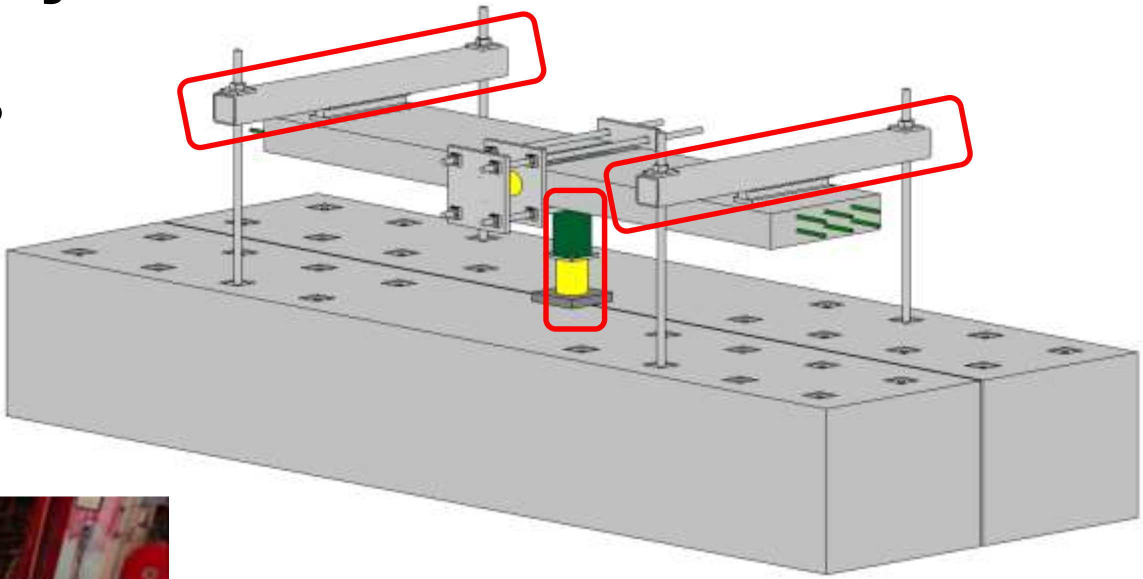


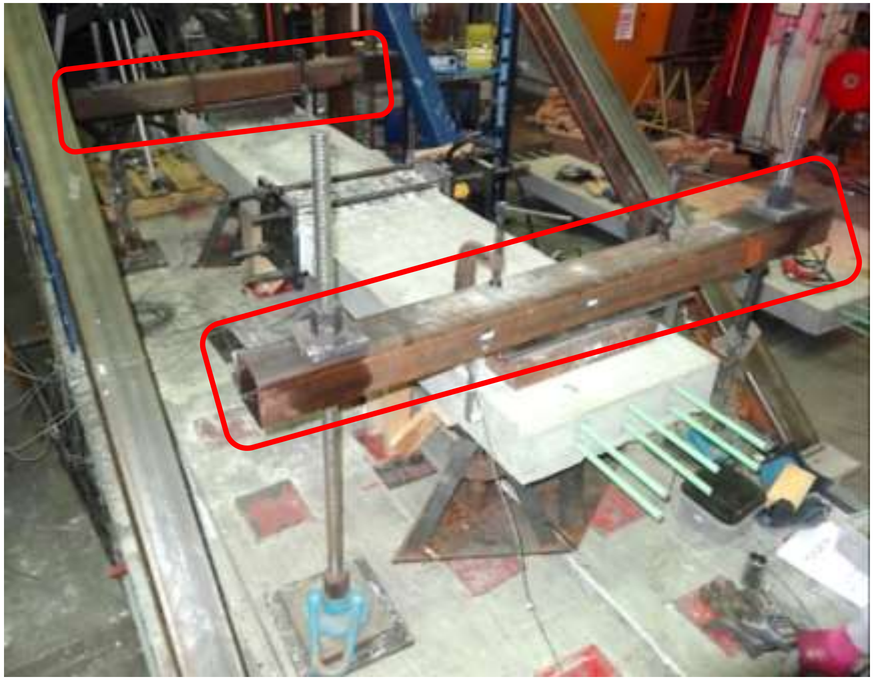
Wang and Wang (Eng Str dec 2018) SEU Nanjing.



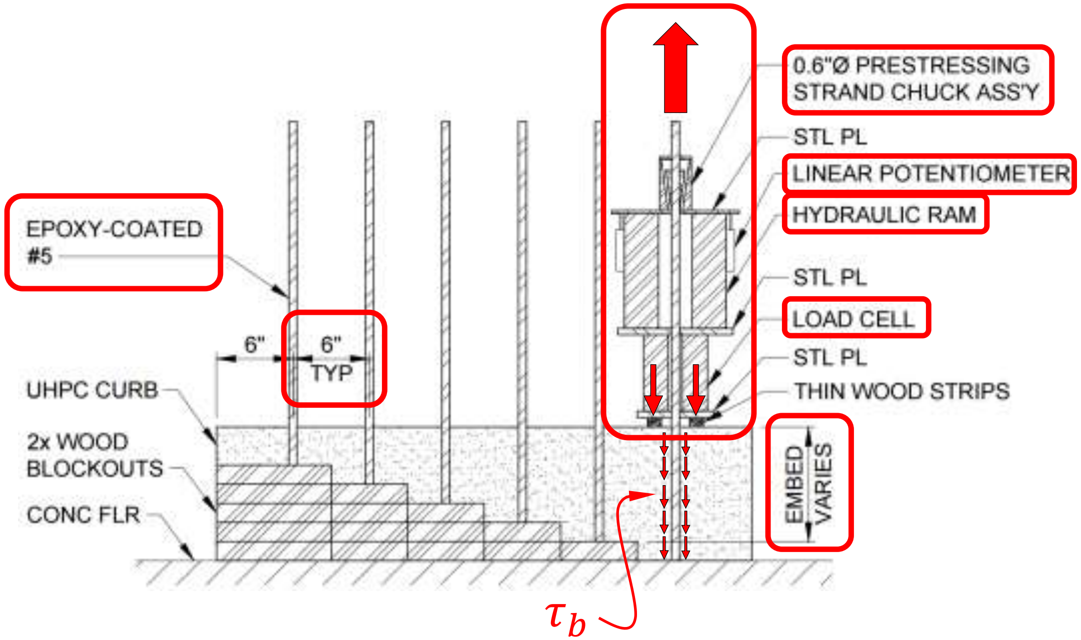
Design of UHPC joints

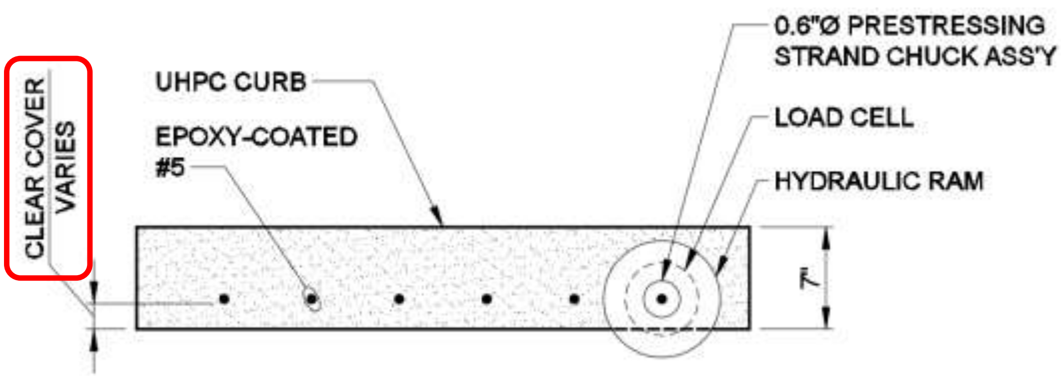
SIMULATED DECK TEST SETUP

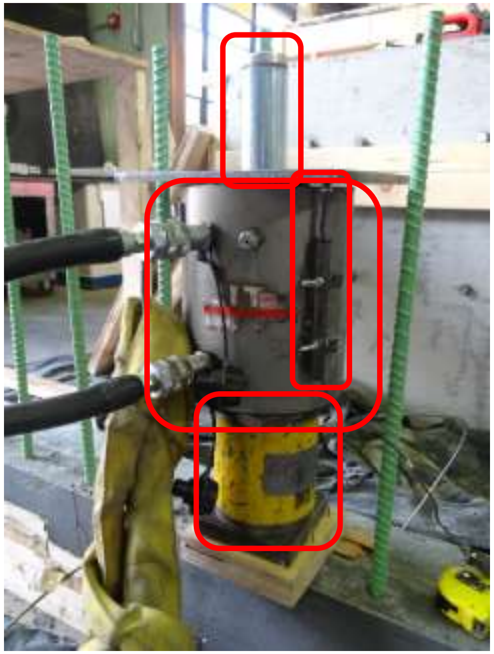




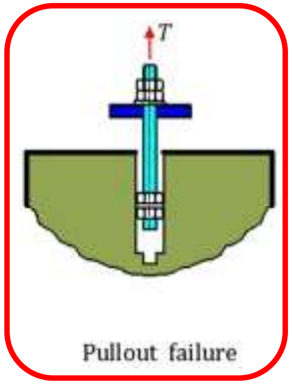
Design of UHPC joints







PULLOUT TESTS



Design of UHPC joints

Bar conflicts

Photo: Azizinamini

Material Test Specimen Name	Dimensions	Reference
Compression Cube	2” x 2” x 2”	ASTM C109 (ASTM International 2016)
Compression Cylinder	4”Ø x 8” (UHPC) 6”Ø x 12” (Conventional Concrete)	ASTM C39 (ASTM International 2017)
Split-Tension Cylinder	4”Ø x 8”	ASTM C496 (ASTM International 2011)
Flexural Beam	3” x 4” x 16”	ASTM C78 (ASTM International 2016)
Pullout Bond Cylinders	#5 epoxy-coated rebar embedded in 6”Ø x 4” cylinder and bonded over 1 inch	N/A (Custom Test)
Direct Tension	Reduced Section (3”x2” at ends, 2”x2” at middle)	N/A (Custom Test)
Modulus of Elasticity Cylinder	4”Ø x 8”	ASTM C469 (ASTM International 2014)