EXPLORING FIBER-REINFORCED POLYMER CONCRETE FOR ACCELERATED BRIDGE CONSTRUCTION APPLICATIONS

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PRECAST SUPERSTRUCTURE ELEMENTS

ADVANTAGES:

- Reduced traffic impacts
- Reduced field labor
- Reduced total project costs
- Improved worker safety
- Improved quality

Image: Graybeal, B. (2014) "Design and Construction of Field-Cast UHPC Connections." FHWA Publication No: FHWA-HRT-14-084, USDOT FHWA, Washington, DC

CLOSURE JOINTS IN PRECAST SUPERSTRUCTURE ELEMENTS

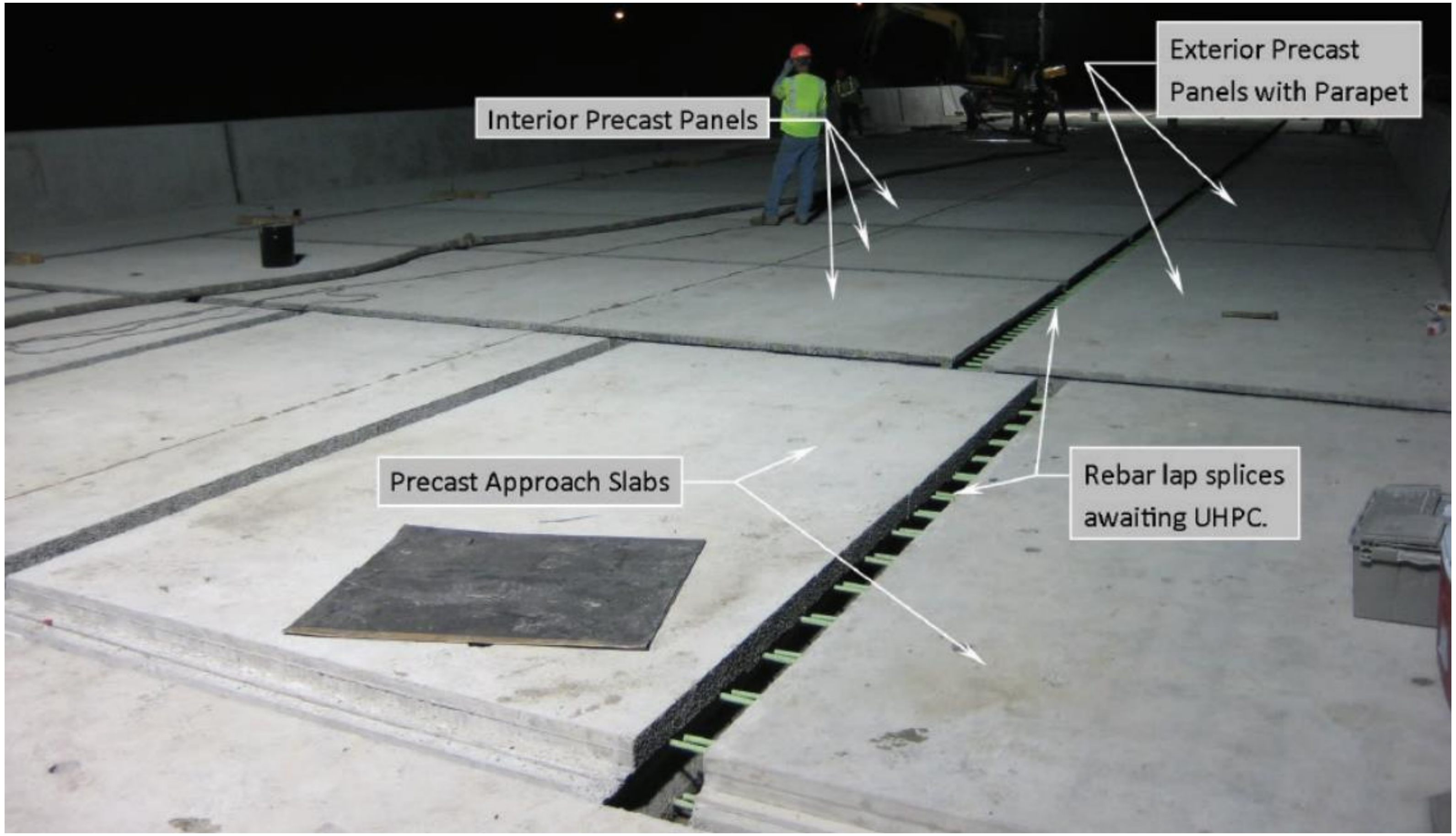


Image: Graybeal, B. (2014) "Design and Construction of Field-Cast UHPC Connections." FHWA Publication No: FHWA-HRT-14-084, USDOT FHWA, Washington, DC

CLOSURE JOINTS IN PRECAST SUPERSTRUCTURE ELEMENTS

> Required joint width largely determined by tension and bond strengths of closure joint material

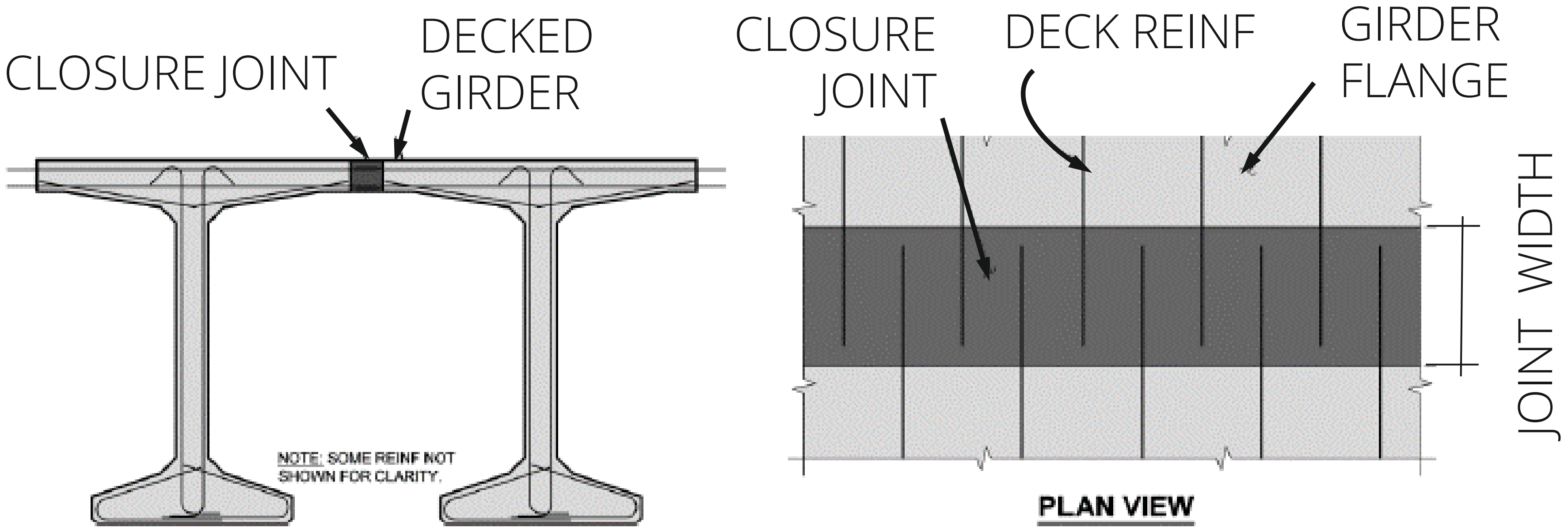


Image: Peruchini, T.J. (2017) "Investigation of Ultra-High Performance Concrete for Longitudinal Joints in Deck Bulb Tee Bridge Girders." Masters Thesis, University of Washington, Seattle, WA.

UHPC CLOSURE JOINT GEOMETRY

> Joint width $10d_b$ minimum

For:

- $f_y \leq 75$ ksi
- Bar size $\leq$ #8
- $f'_c \geq 14$ ksi
- Fiber content $\geq 2\%$

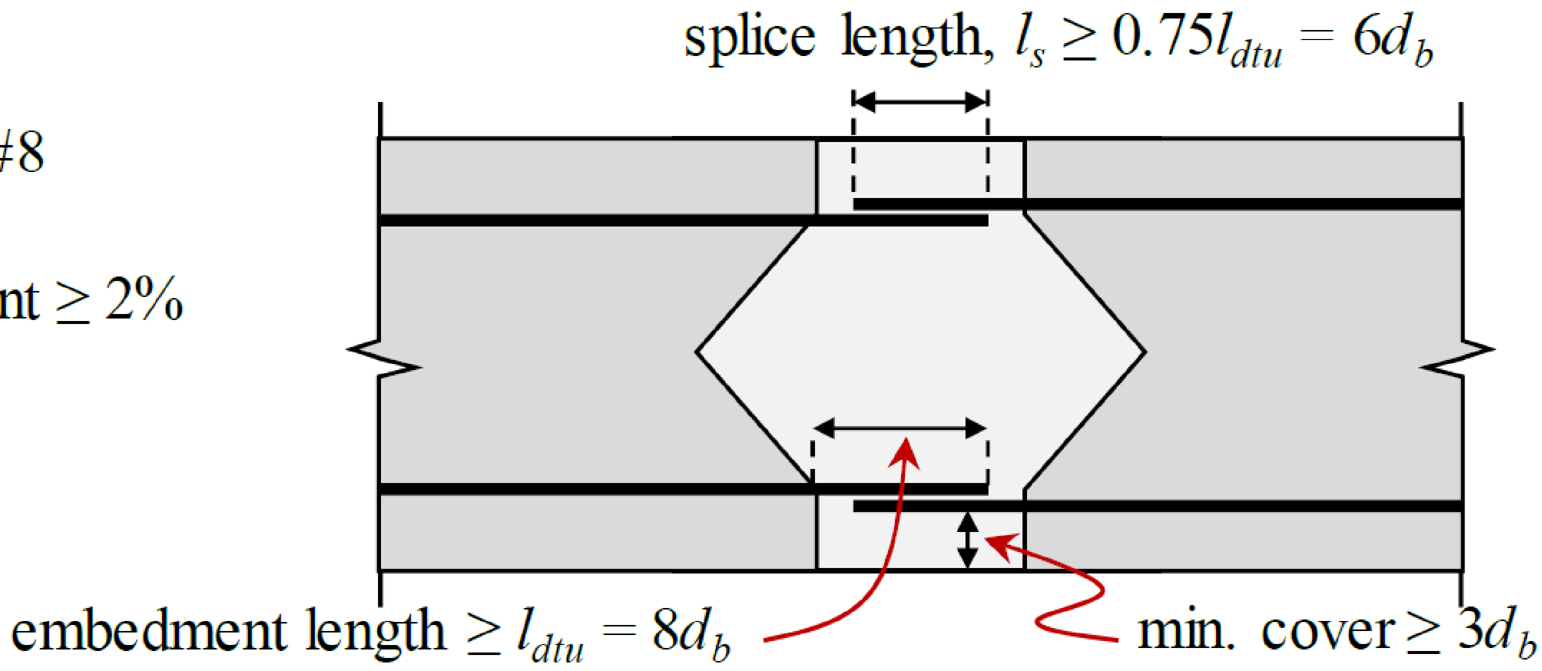


Image: Garber, D., and E. Shahrokhinasab. (2019). "ABC-UTC Guide for: Full-Depth Precast Concrete (FDPC) Deck Panels."

POLYMER CONCRETE (PC)

ADVANTAGES:

- Rapid gain in strength (~4 hour traffic return)
- High tensile strength (up to ~2 ksi)
- Excellent bond to concrete and reinforcement

CHALLENGES:

- Temperature dependent properties
- Lack of design guidance
- Creep

POLYMER CONCRETE OVERLAYS

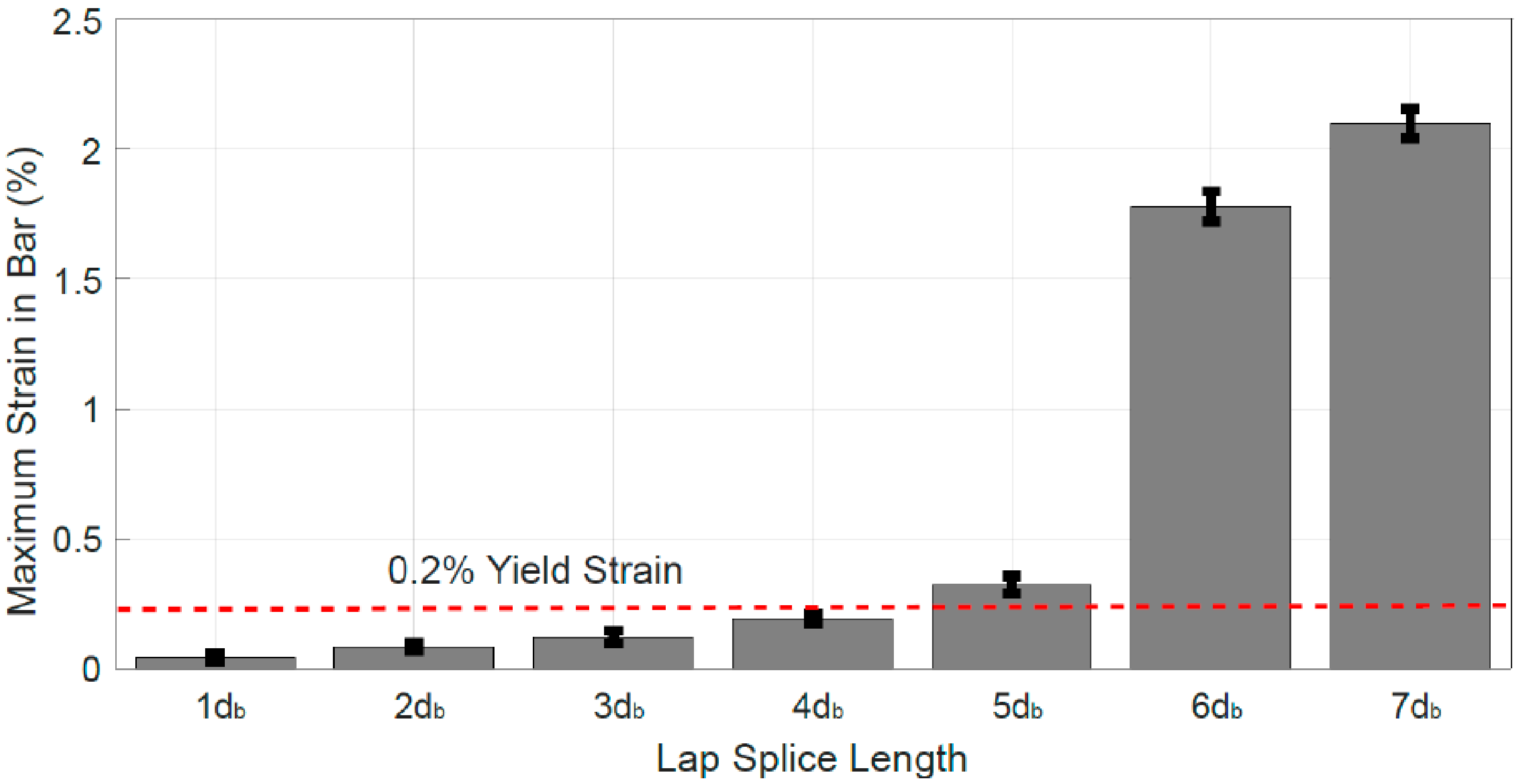
- PC overlays have an established history of use
- Have performed well overall

Polyester PC Overlay
Spokane, WA after 6 years

Image: Anderson et al. (2019) “Polyester Polymer Concrete Overlay Final Report.” Washington State Department of Transportation Report: WA-RD 797.2, WSDOT, Olympia, WA.

SPLICE TESTS OF POLYMER CONCRETE

> Able to achieve significant yielding of bars with $6d_b$ lap splice



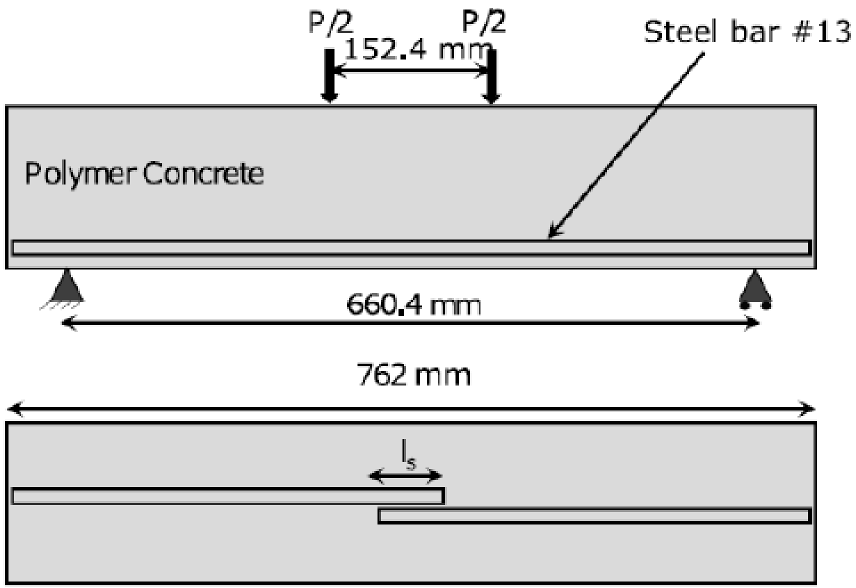


Image: Mantawy, I, Chennareddy, R, Genedy, M. and Taha, M.R. (2019) "Polymer Concrete for Bridge Deck Closure Joints in Accelerated Bridge Construction" Infrastructures, 4(31).

TEST OF PMMA CONCRETE CLOSURE JOINT

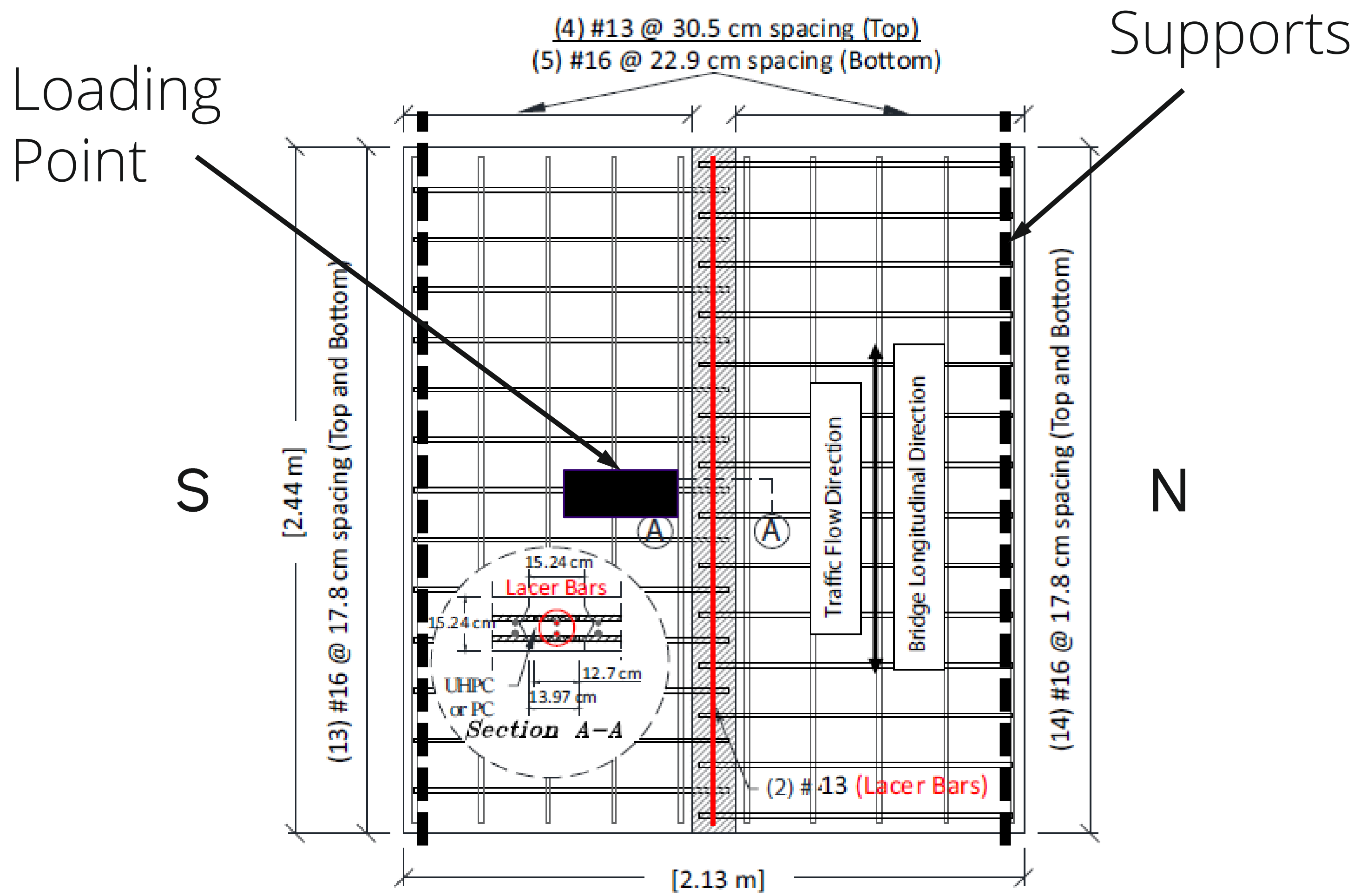


Image: Abokifa, M. and Moustafa, M.A.(2021) "Experimental behavior of poly methyl methacrylate polymer concrete for bridge deck bulb tee girders longitudinal field joints" *Construction and Building Materials*, 270, 121840.

TEST OF PMMA CONCRETE CLOSURE JOINT (UNR)

> PC and UHPC closure joint specimen behaved similarly

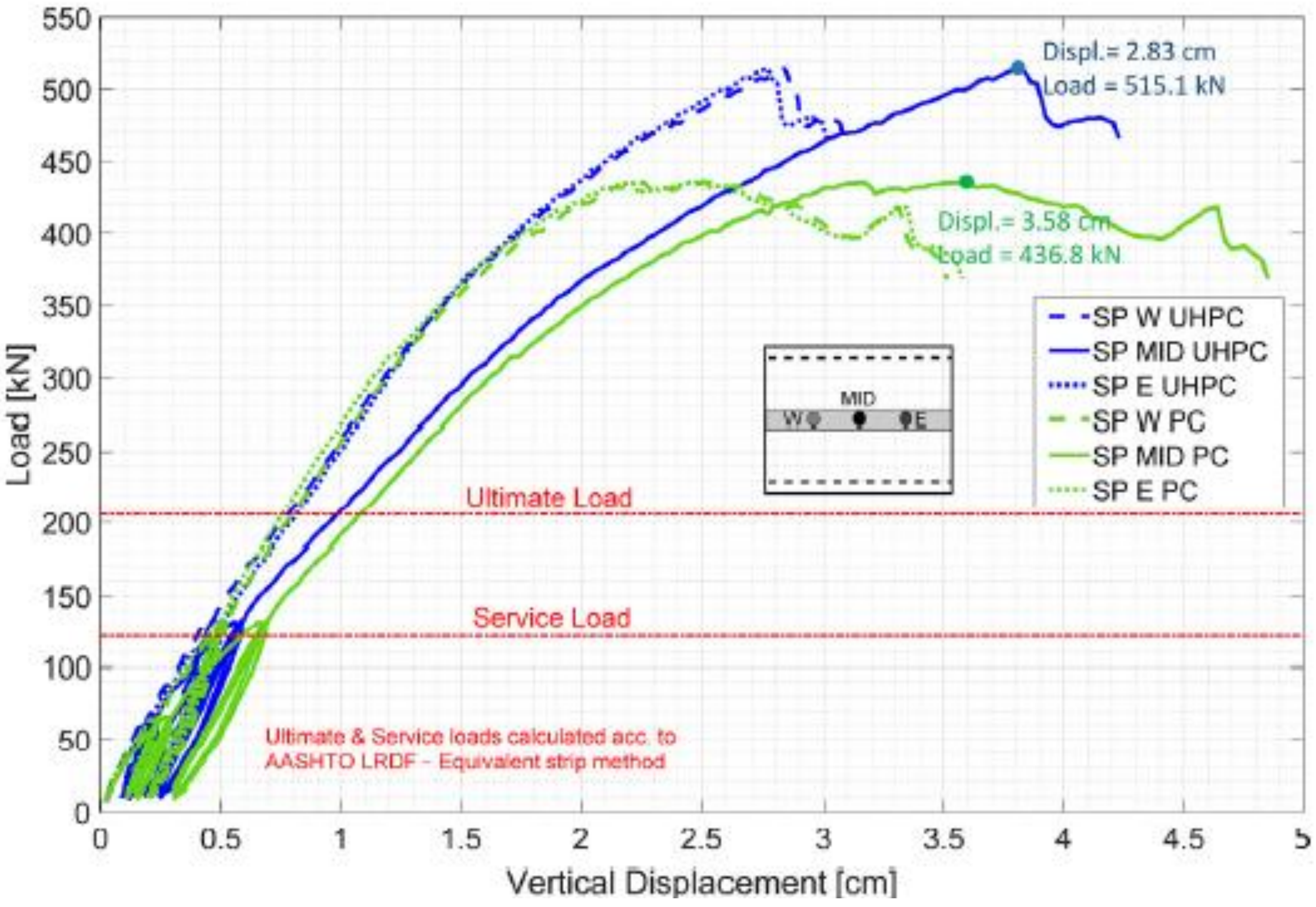
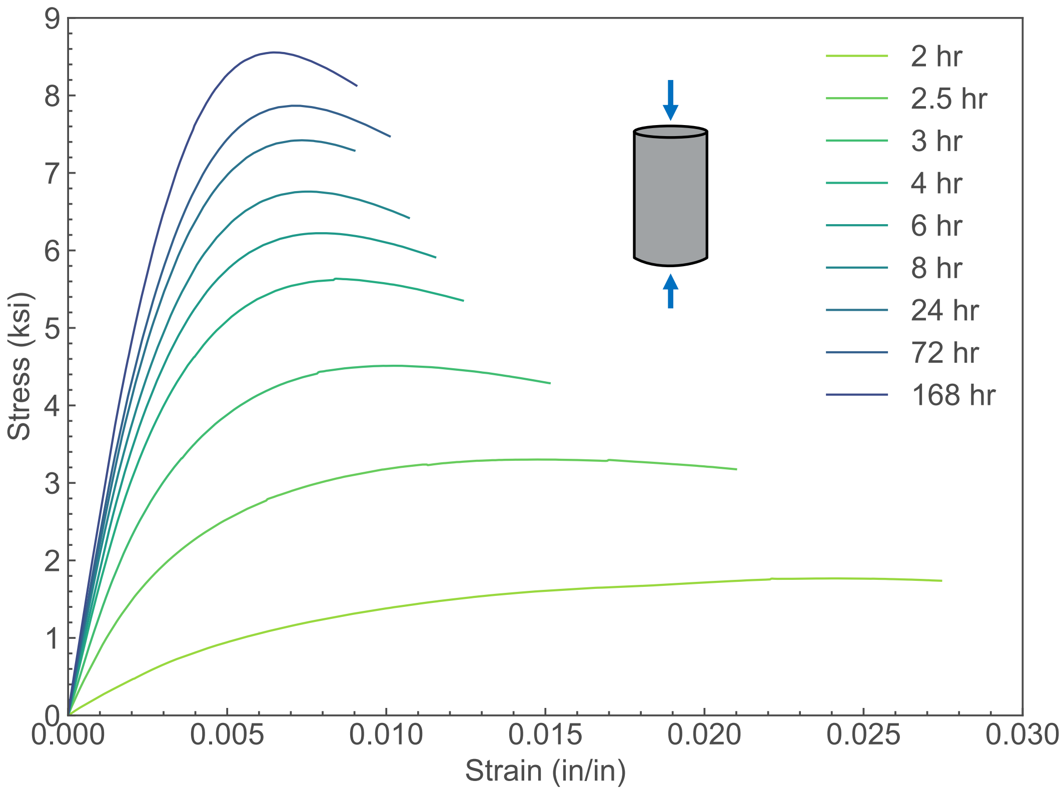
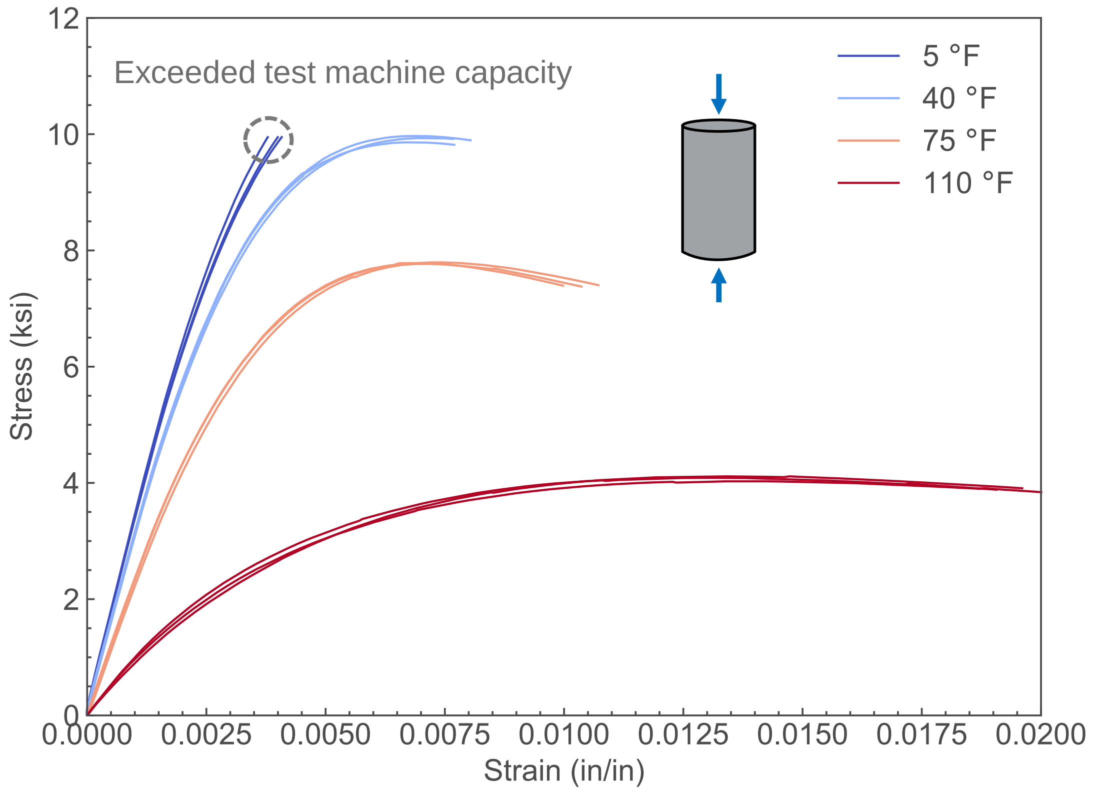


Image: Abokifa, M. and Moustafa, M.A.(2021) "Experimental behavior of poly methyl methacrylate polymer concrete for bridge deck bulb tee girders longitudinal field joints" *Construction and Building Materials*, 270, 121840.

TIME/TEMPERATURE INFLUENCE

> Mechanical properties depend on both time and temperature





TIME/TEMPERATURE INFLUENCE

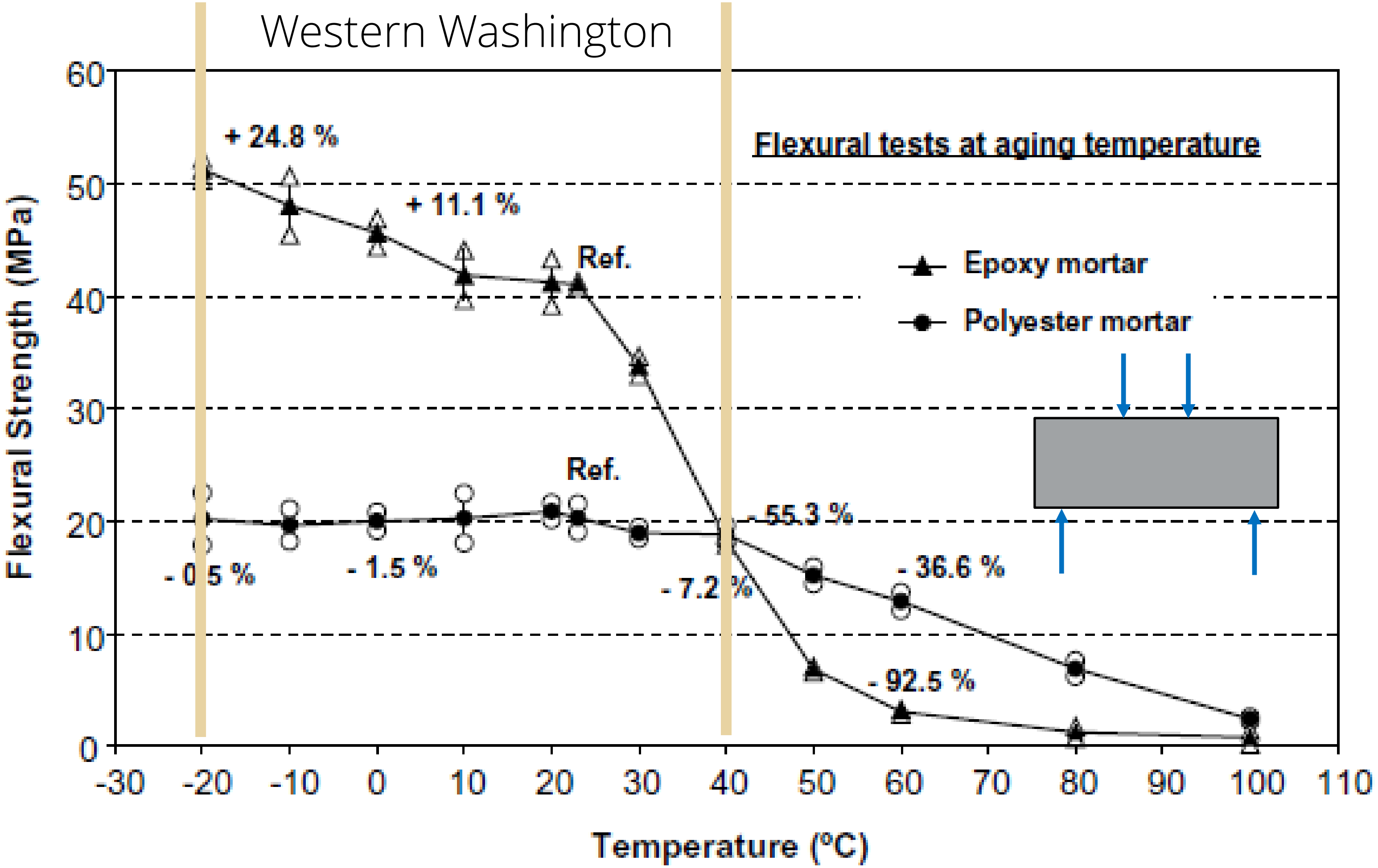
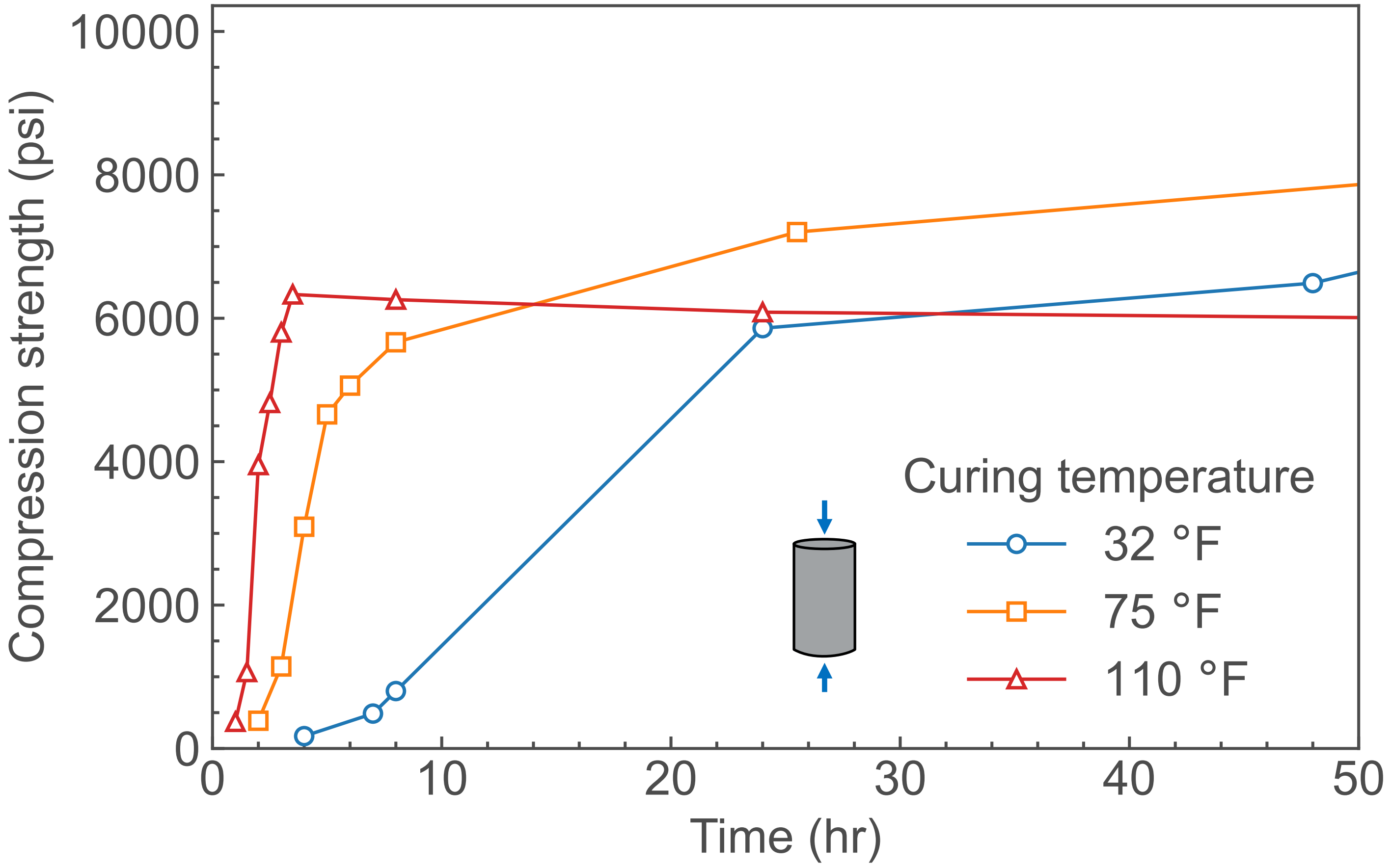


Image: Ribeiro et al. (2002) Flexural performance of polyester and epoxy polymer mortars under severe thermal conditions." *Cement & Concrete Composites*, 26: 803-809

TIME/TEMPERATURE INFLUENCE

- Similar to cementitious concrete, rate of strength development affected by curing temperature
- Can be tailored for various service conditions through binder chemistry



POLYMER CONCRETE COMPARISON

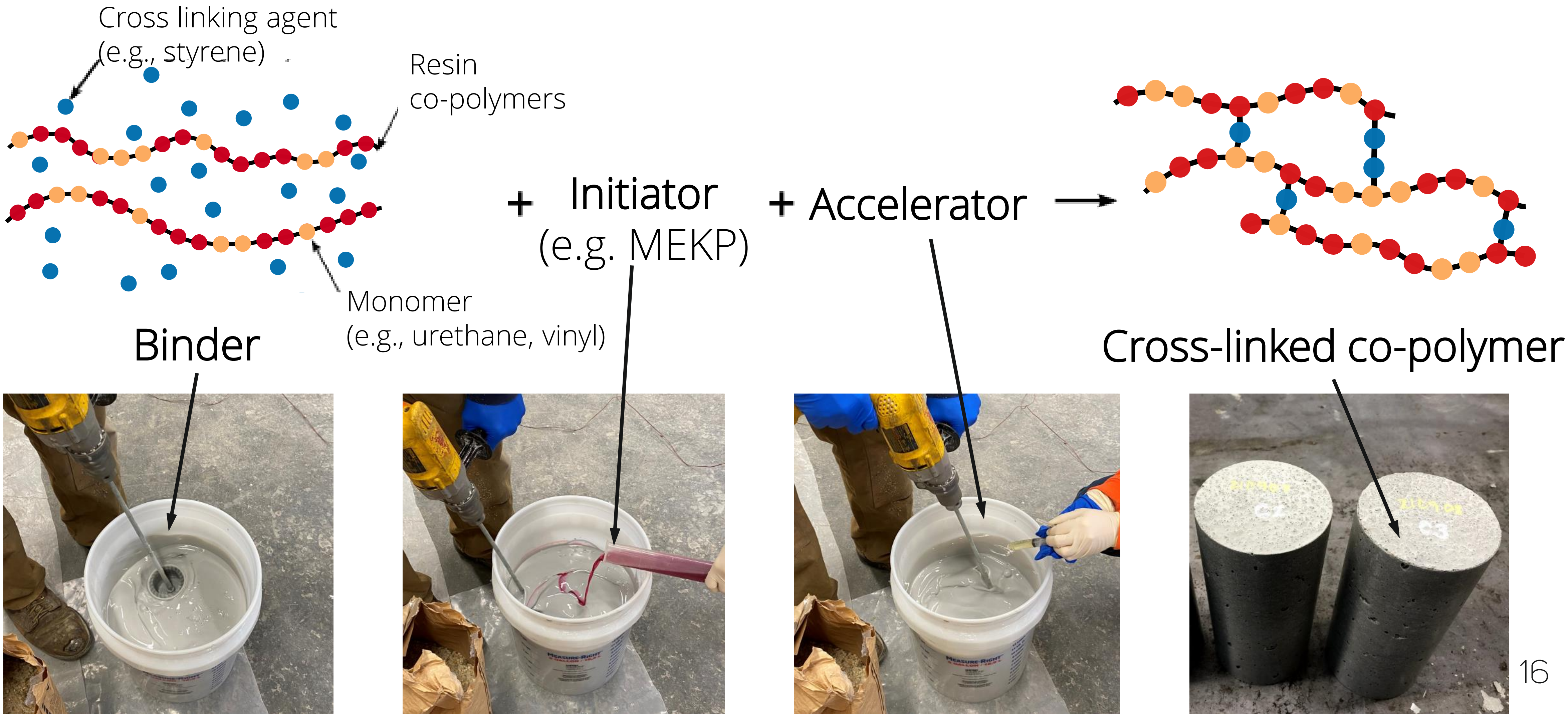
Material	UHPC	PMMA (Transpo)	Polyester (Kwik Bond)	HCSC (Kwik Bond)
Compression Strength (ksi)	24	9	6	10
Direct Tension Strength (ksi)	1.2	1.2	0.8	1.5
Compression Modulus (ksi)	7000	1200	1500	2500
Coefficient of thermal expansion (in/in/°F)	$6\text{-}8 \times 10^{-6}$		$\sim 10 \times 10^{-6}$	$\sim 11 \times 10^{-6}$
Development length (d_b)	~8	~4+*	~6*-10**	~6**

* At room temperature
** At elevated temperature

WHAT IS HCSC?

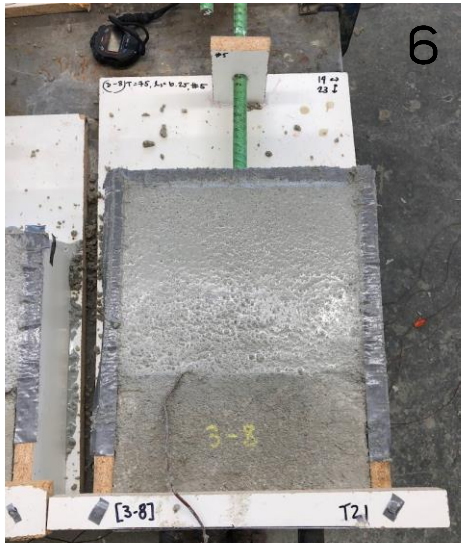
- Hybrid Composite Synthetic Concrete
- Graded silica aggregates
- Basalt chopped fibers
- Urethane vinyl ester hybrid co-polymer binder
- HMWM (High molecular weight methacrylate) primer
  - Aids in bonding with concrete and steel substrates

HCSC – COMPONENTS



HCSC – MIXING PROCESS

1. Add initiator and accelerator to binder, mix with drill ~30 sec
2. Add initiated binder
3. Add aggregate
4. Mix (~1-2 min)
5. Cast specimens
6. Hand-finish



HCSC – MIXING PROCESS

> Larger volumes can be produced using volumetric mix trucks

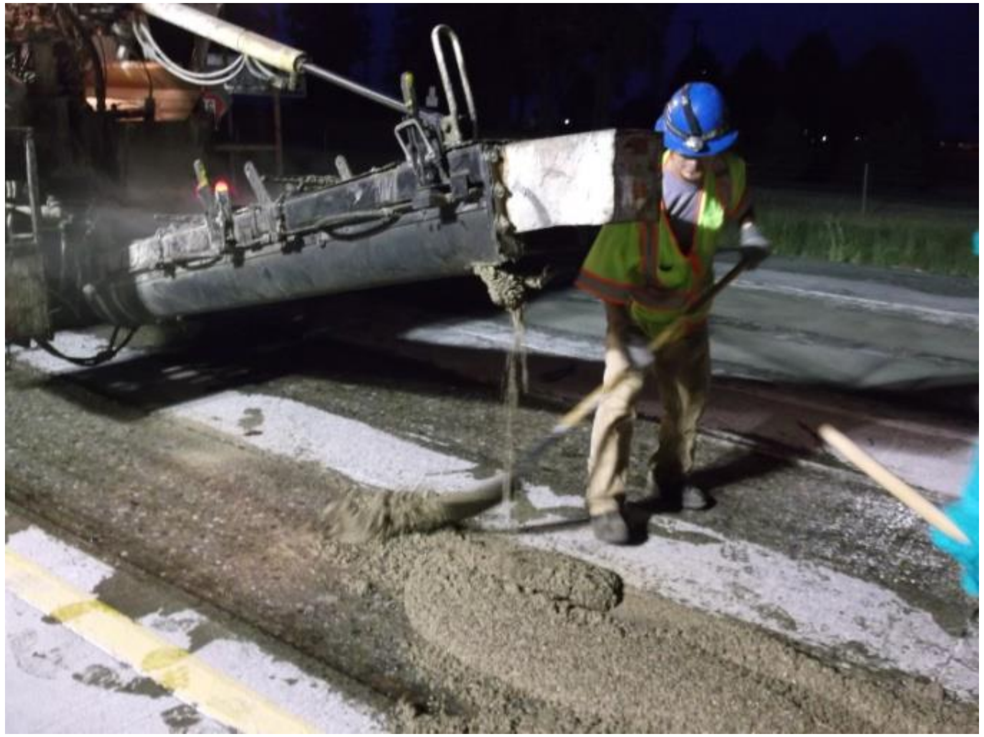


Image: Anderson et al. (2019) "Polyester Polymer Concrete Overlay Final Report." Washington State Department of Transportation Report: WA-RD 797.2, WSDOT, Olympia, WA.

RESEARCH OBJECTIVES

1. Characterize the mechanical properties of FRPC at multiple temperatures and ages
2. Characterize the splice performance of deformed bars embedded in FRPC materials at multiple temperatures
3. Develop preliminary design recommendations for the use of FRPC in closure joints for ABC applications

MECHANICAL PROPERTIES

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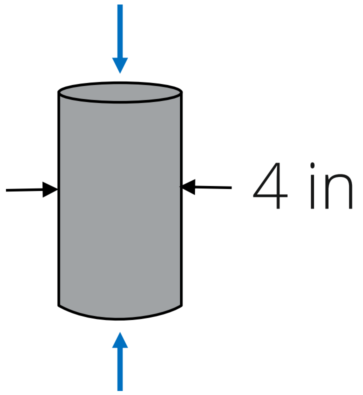
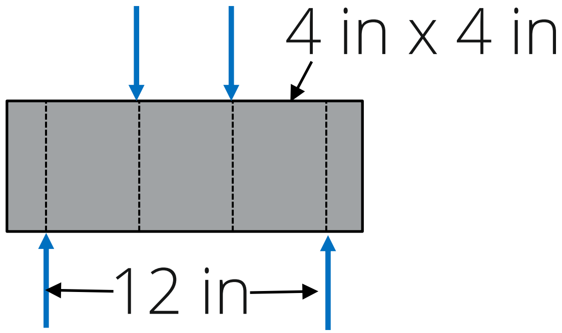
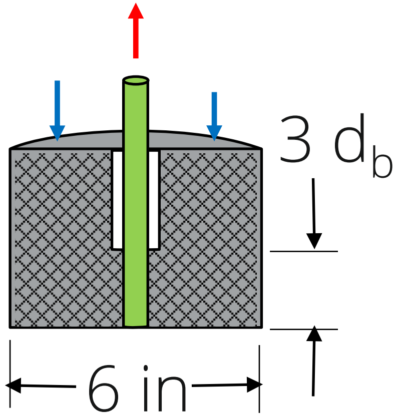
Compression
(ASTM C39)



Flexure
(ASTM C78)

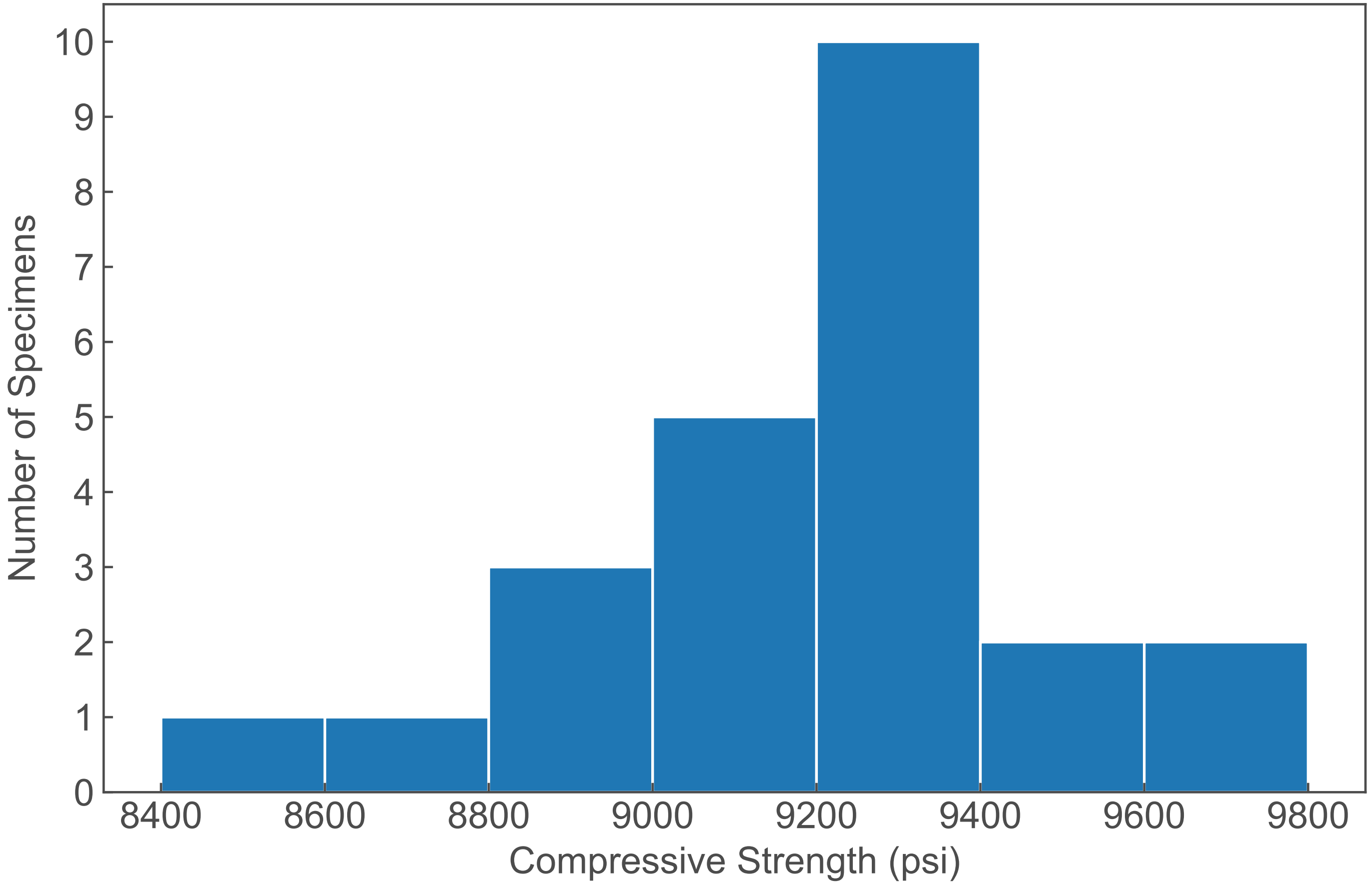


Bond
(~ASTM D7913)



7-DAY COMPRESSIVE STRENGTH

> Consistent 7-day strengths batch to batch (approx. 75 °F testing temp)



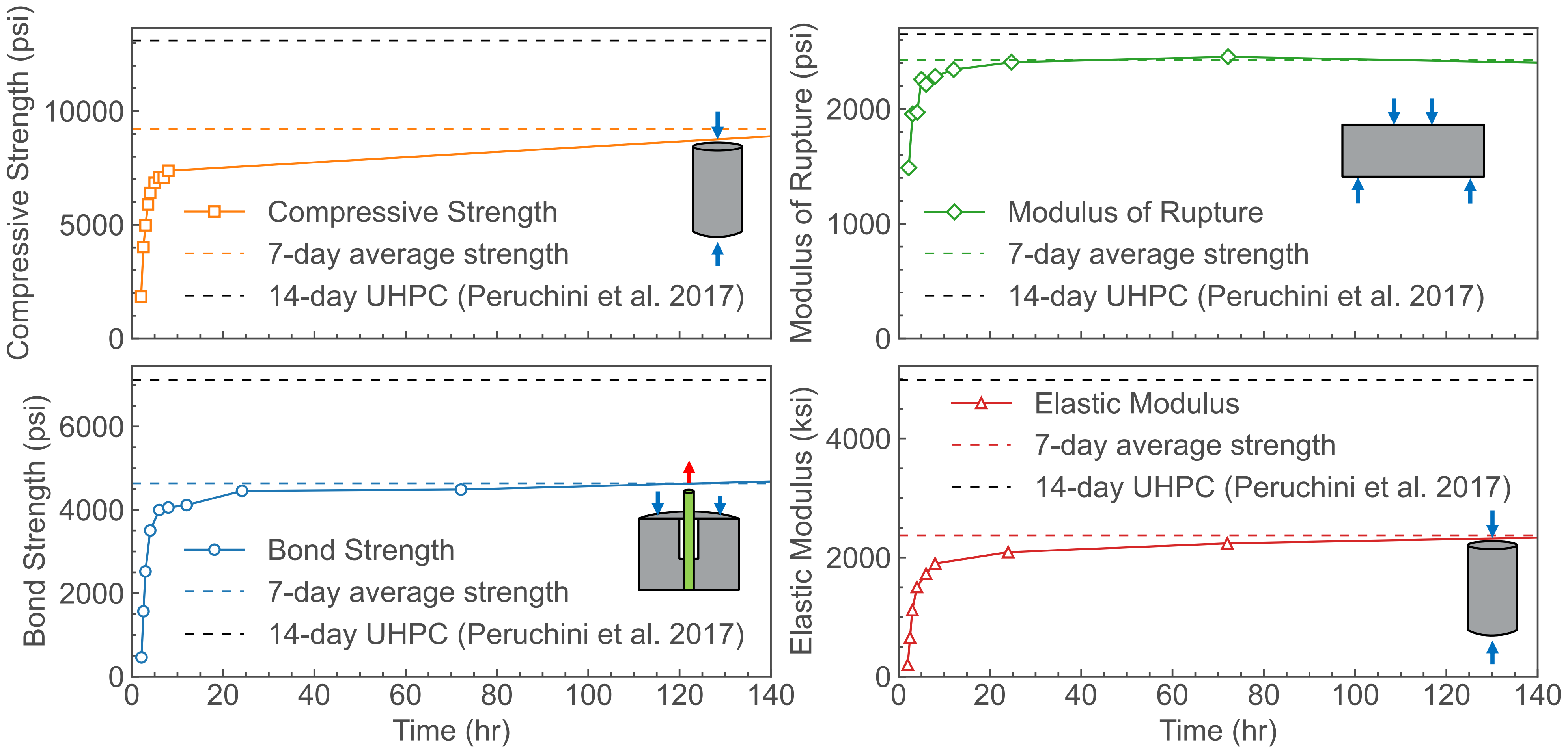
INFLUENCE OF ACCELERATOR ON STRENGTH GAIN OVER TIME

- Strength gain over time can be tailored to specific need
- Tradeoff between working time and rapid strength gain

Accelerator by Volume Initiator	Approximate Working Time	Time to 70% of 7-day Compressive Strength
1%	20 min	4 hrs
3%	16 min	4 hrs
8.3%	7 min	2 hrs

STRENGTH GAIN OVER TIME

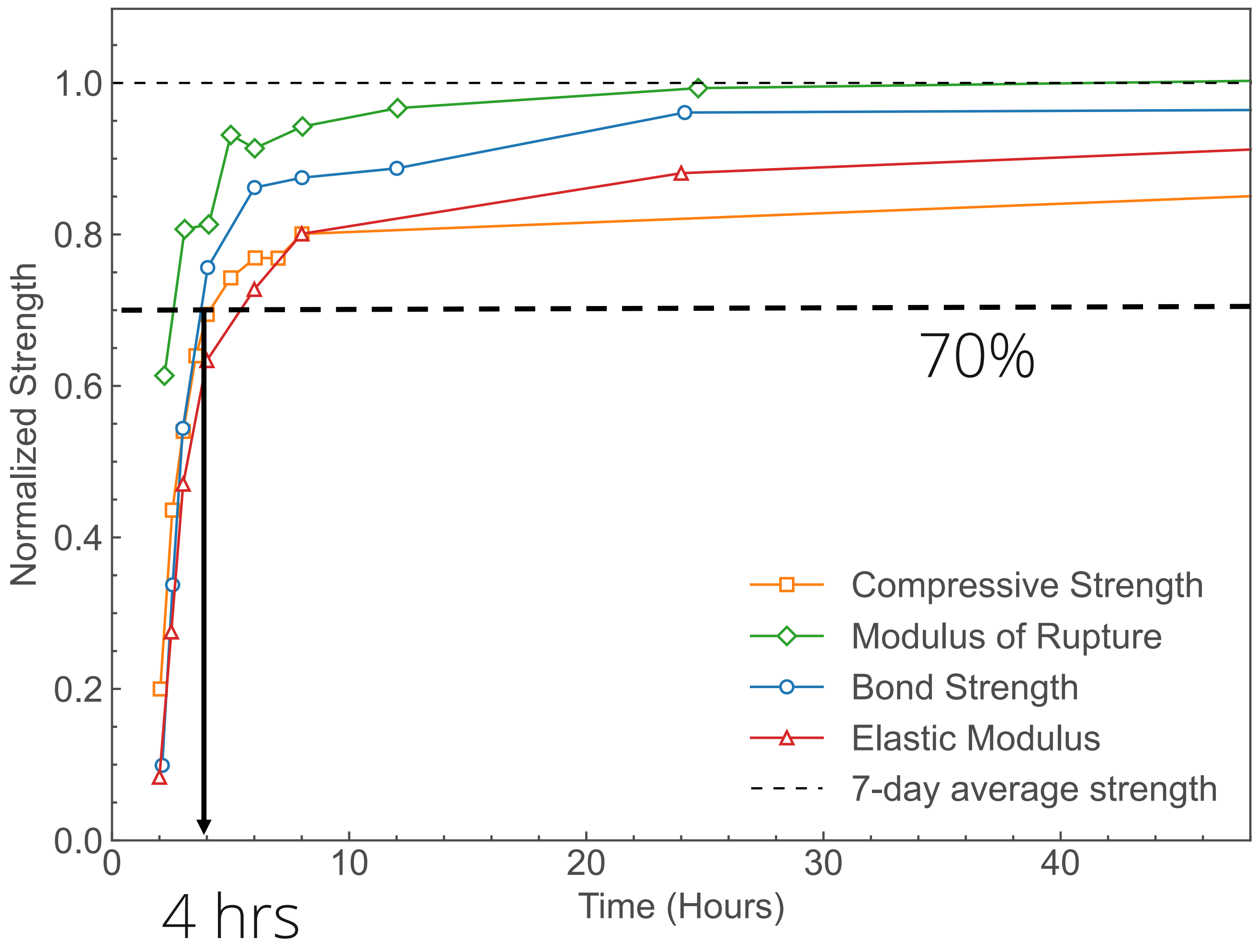
> Cured and tested at room temperature (approx. 75 °F)



STRENGTH GAIN OVER TIME

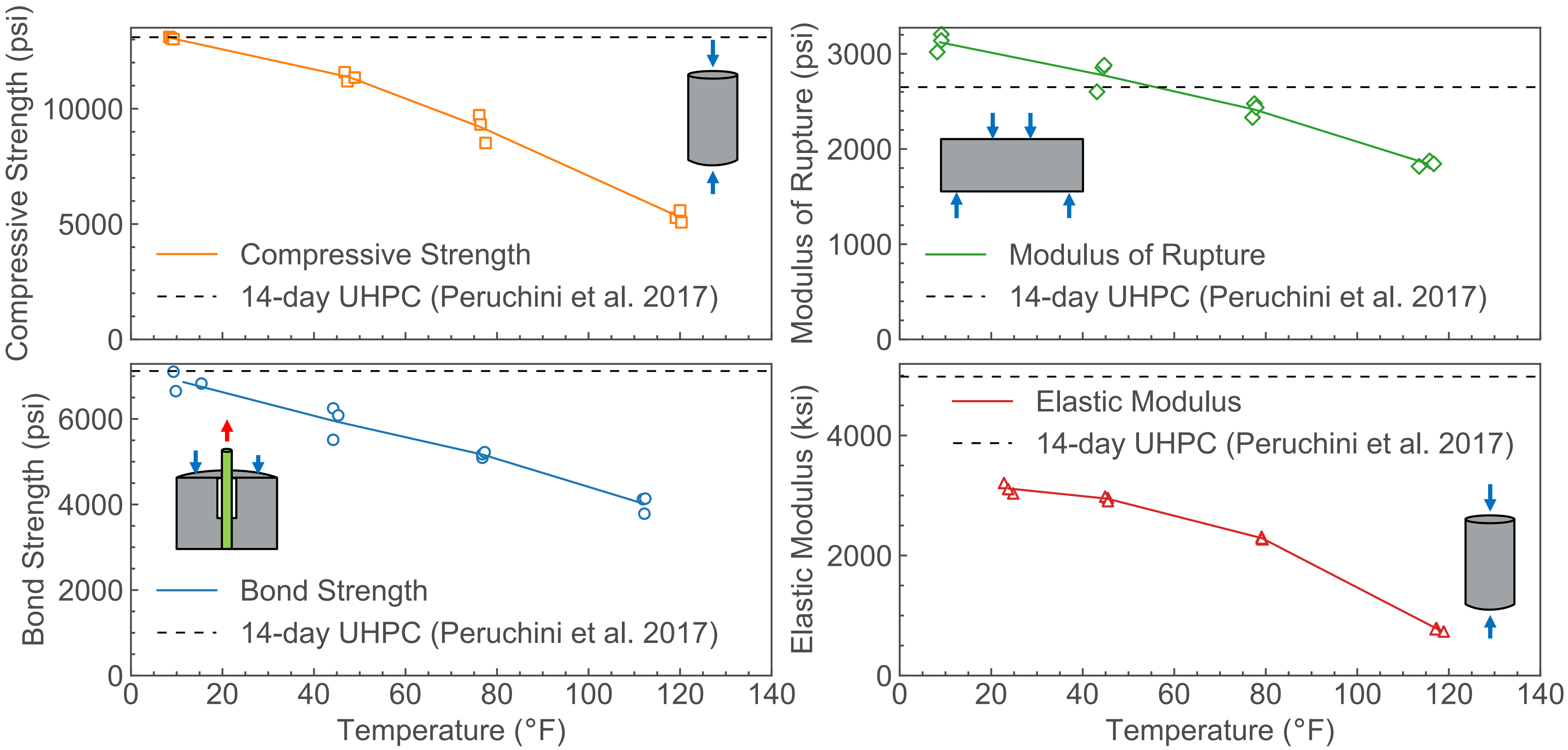
> Over 70% of final strength in 4 hours

> 3% accelerator by volume initiator



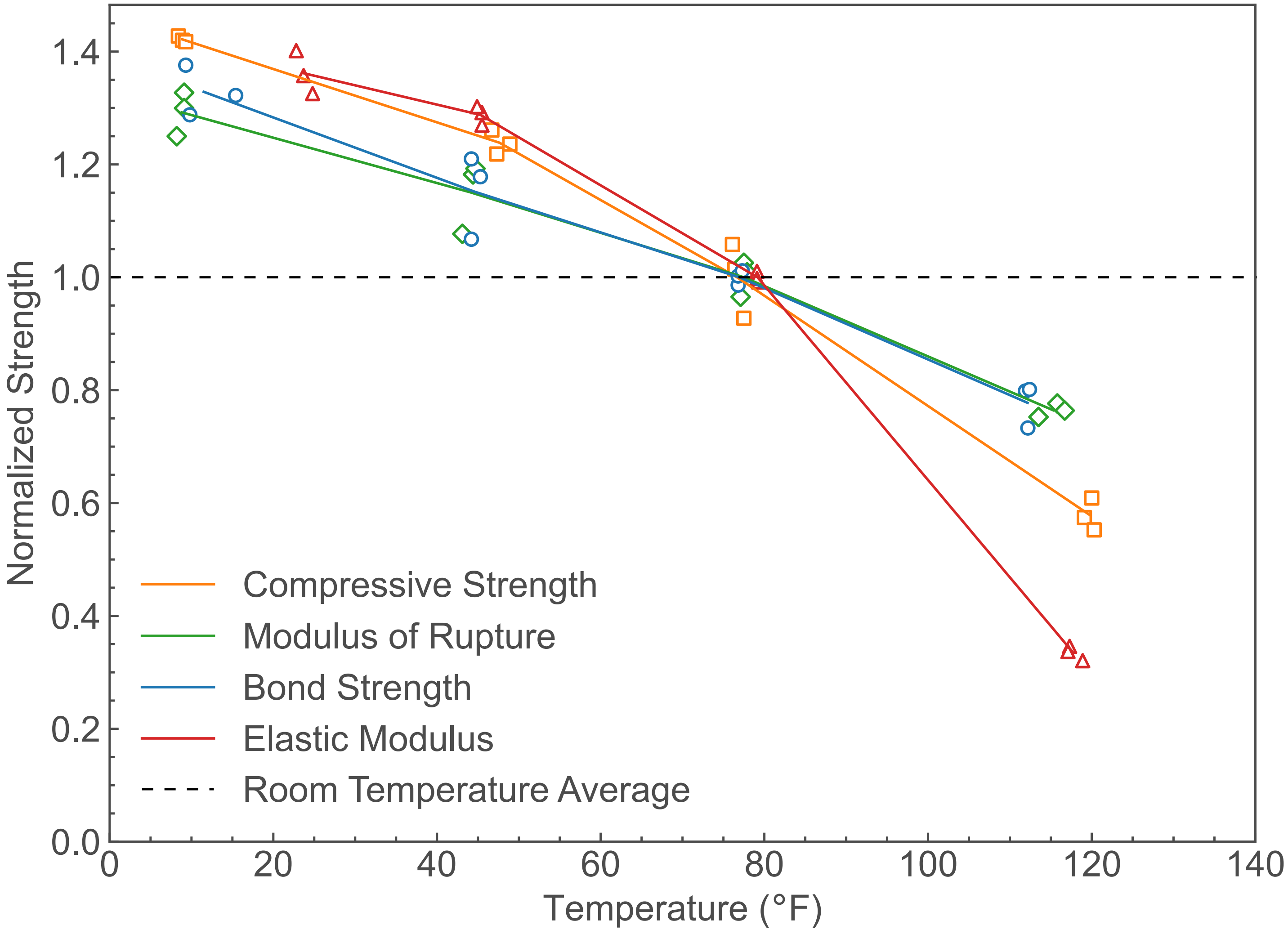
INFLUENCE OF TESTING TEMPERATURE

> 7 day cure at room temp, 16 hour conditioning at test temp



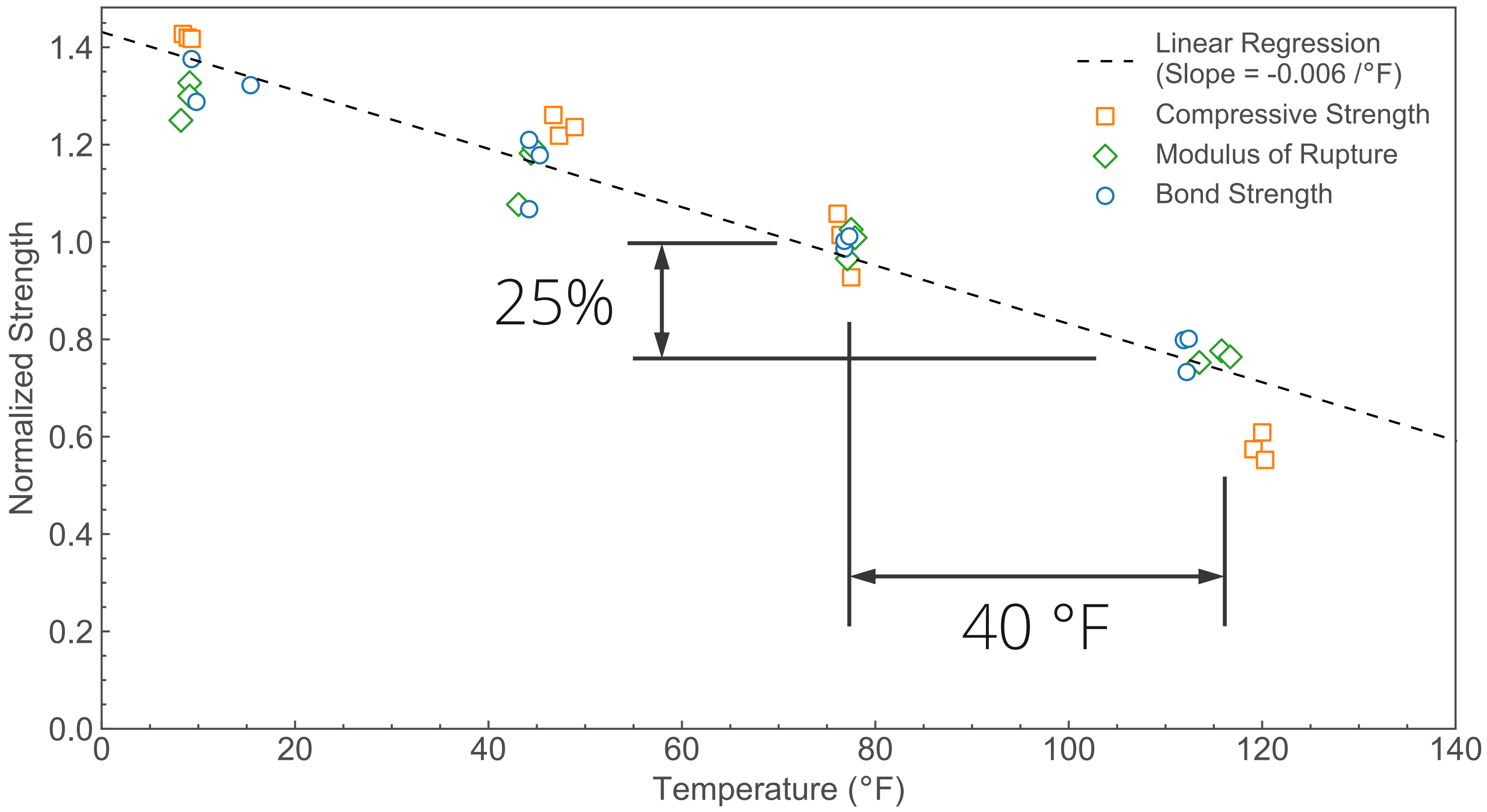
INFLUENCE OF TESTING TEMPERATURE

> Similar trends between test series



INFLUENCE OF TESTING TEMPERATURE

> Strengths were inversely proportional to temperature over selected range



RESEARCH OBJECTIVES

1. Characterize the mechanical properties of FRPC at multiple temperatures and ages
2. Characterize the splice performance of deformed bars embedded in FRPC materials at multiple temperatures
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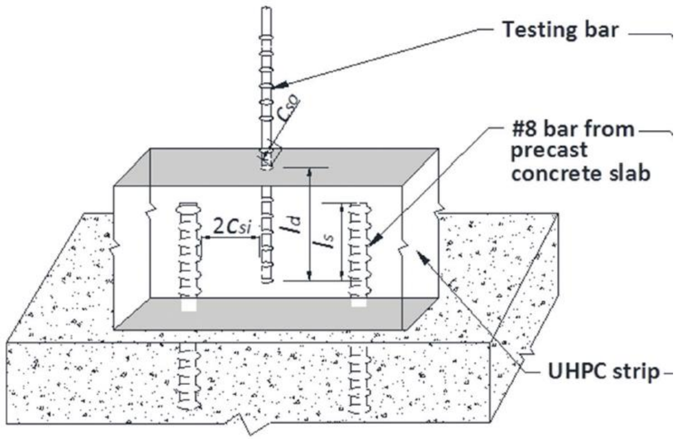
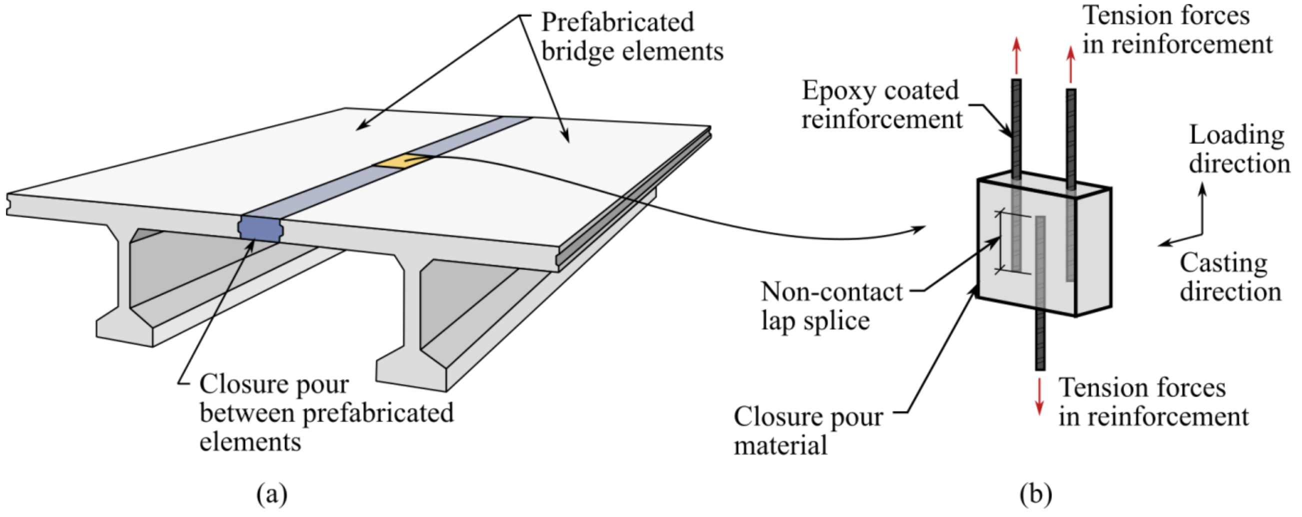
NON-CONTACT SPLICE TESTS

- Specimen based on FHWA "curb" test for UHPC
- Adapted for temperature conditioning and testing in universal testing machine

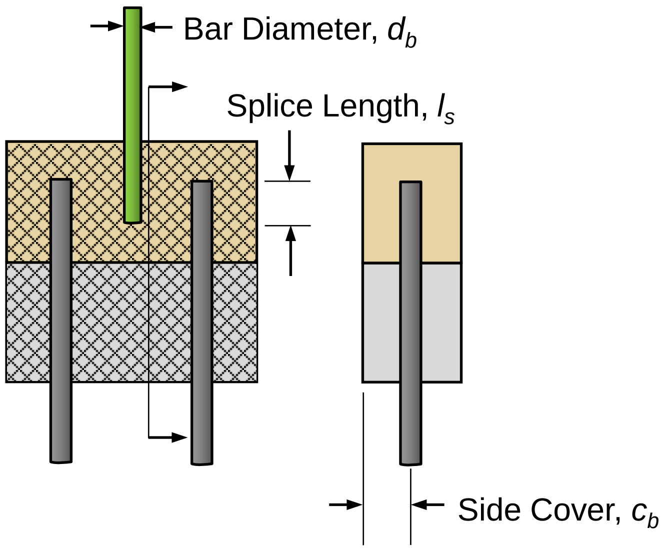




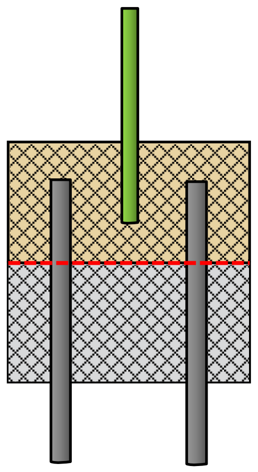
From: Graybeal, B. (2014). "Bond Behavior of Reinforcing Steel in Ultra-High Performance Concrete." FHWA Report HRT-14-089, Federal Highway Administration, Washington, DC

INFLUENCE OF PRIMER

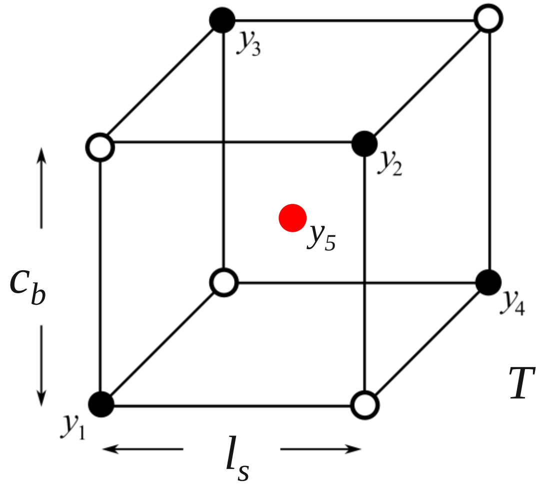
- > Scoping study to investigate influence of HMWM primer
- > Fractional factorial design (2^{3-1} - Resolution III)



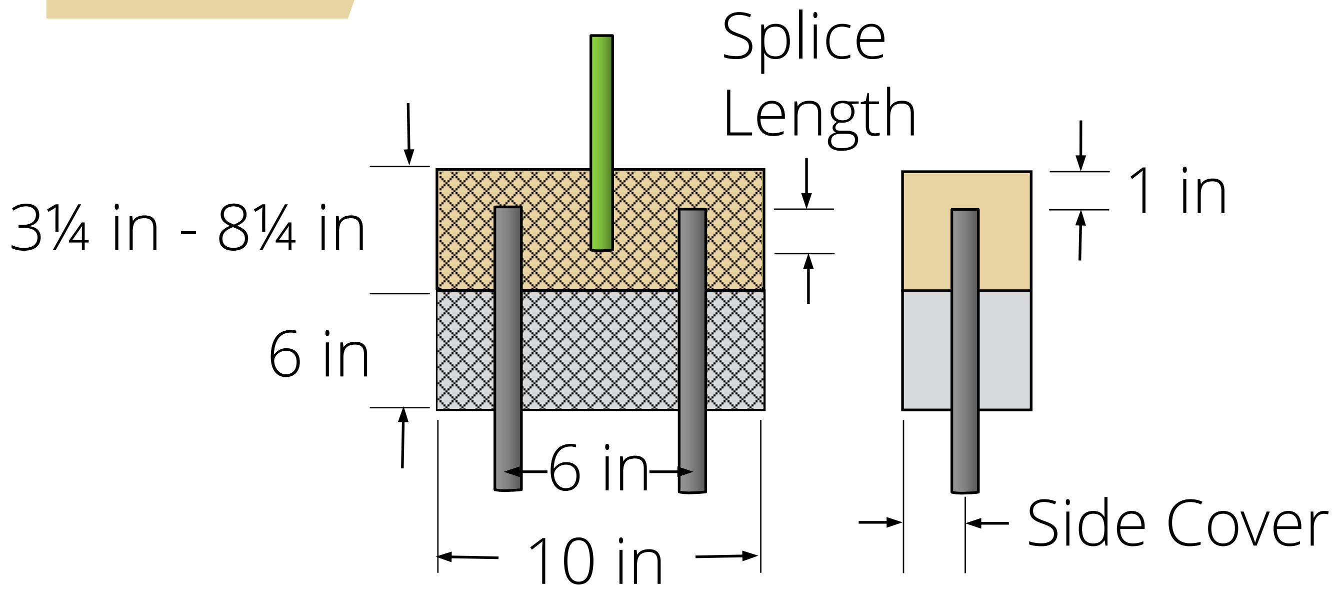
With HMWM Primer
(5 specimens)

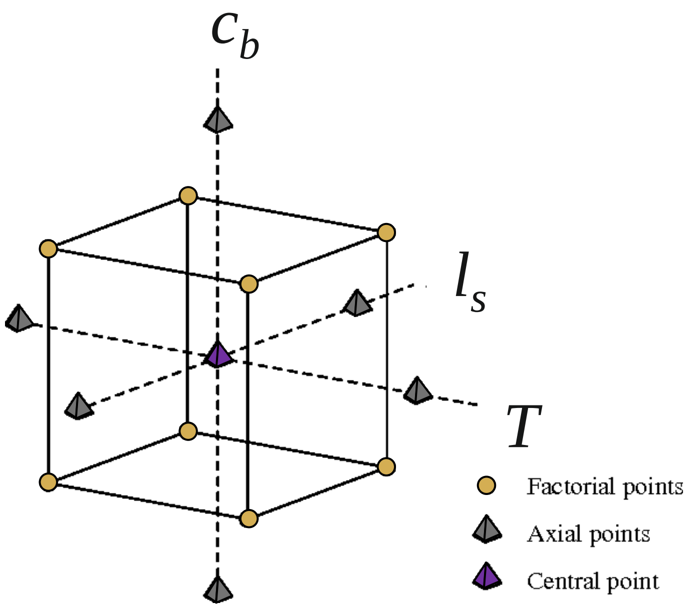


Without HMWM Primer
(5 specimens)



NON-CONTACT SPLICE TESTS





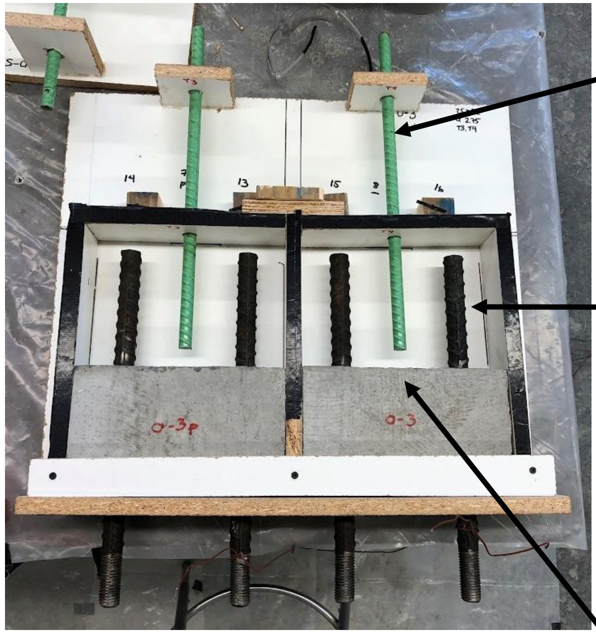
Level	Temperature (°F)	Splice length (in)	Side Cover (in.)	Bar size
-2	5 °F	1.25	0.75	No. 3
-1	40°F	2.5	1.375	No. 4
0	75 °F	3.75	2.0	No. 5
+1	110 °F	5	2.625	No. 6
+2	145 °F	6.25	3.25	No. 7

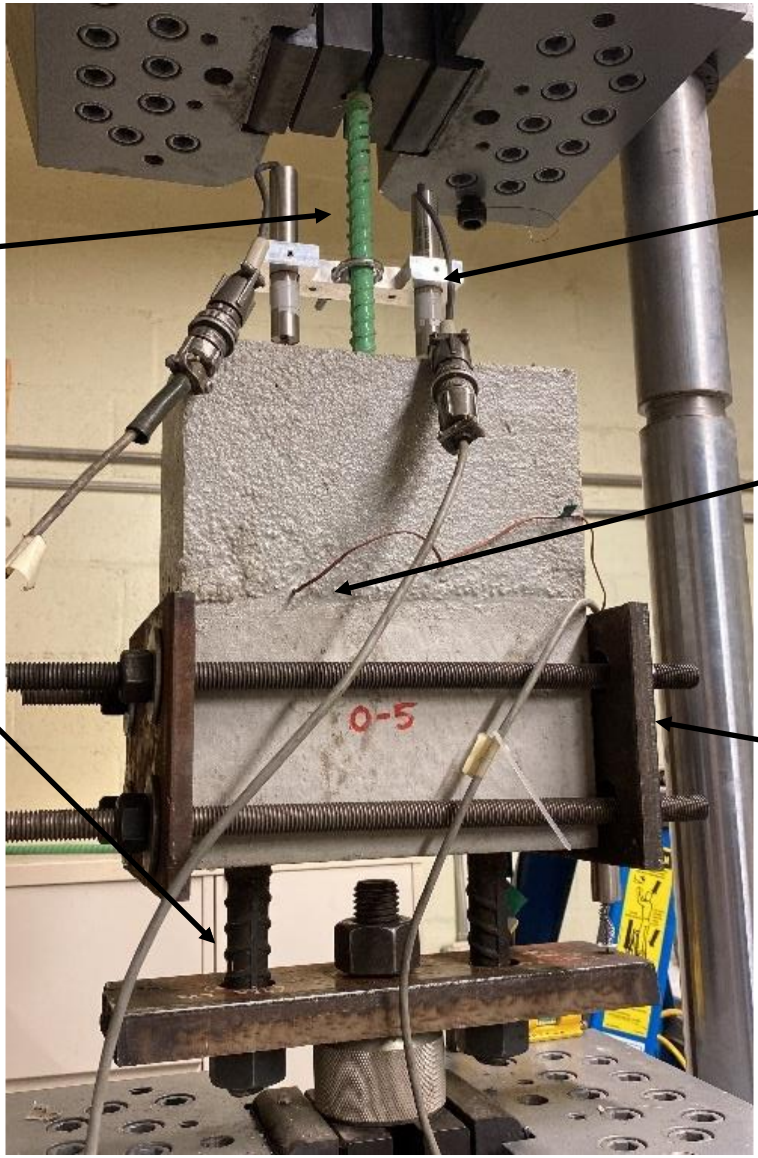
NON-CONTACT SPLICE TESTS

	Run	T|ℓs|cb|db	Observed Failure	Bar Stress (ksi)
Block/Batch 0 Scoping Study	0-01p	+1|-1|-1| 0	Splitting	40.06
	0-01	+1|-1|-1| 0 *	Splitting	35.92
	0-02p	-1|-1|+1| 0	Splitting	80.92
	0-02	-1|-1|+1| 0 *	Splitting	73.42
	0-03p	-1|+1|-1| 0	Splitting	74.42
	0-03	-1|+1|-1| 0 *	Splitting	64.01
	0-04p	+1|+1|+1| 0	Splitting	84.38
	0-04	+1|+1|+1| 0 *	Splitting	82.97
	0-05p	***0 | 0 | 0 | 0***	***Splitting***	***79.11***
	0-05	0 | 0 | 0 | 0 *	Splitting	71.98
Block / Batch 1	1-01	-1|+1|-1|-1	Bar Fracture	87.17
	1-02	-1|-1|+1|-1	Bar Fracture	87.47
	1-03	+1|-1|-1|-1	Splitting	60.52
	1-04	+1|+1|+1|-1	Bar Fracture	85.41
	1-05	-1|-1|-1|+1	Splitting	39.15
	1-06	-1|+1|+1|+1	Splitting	96.05
	1-07	+1|+1|-1|+1	Splitting	48.69
	1-08	+1|-1|+1|+1	Splitting	43.69
	1-09	**0 | 0 | 0 | 0**	***Splitting***	***85.68***
	1-10	**0 | 0 | 0 | 0**	***Splitting***	***82.66***

	Run	T|ℓs|cb|db	Observed Failure	Bar Stress (ksi)
Block / Batch 2	2-01	-1|-1|-1|-1	Splitting	73.28
	2-02	-1|+1|+1|-1	Bar Fracture	87.13
	2-03	+1|+1|-1|-1	Splitting	76.01
	2-04	+1|-1|+1|-1	Pullout	70.80
	2-05	-1|+1|-1|+1	Splitting	54.92
	2-06	-1|-1|+1|+1	Splitting	67.65
	2-07	+1|-1|-1|+1	Splitting	31.28
	2-08	+1|+1|+1|+1	Splitting	69.41
	2-09	**0 | 0 | 0 | 0**	***Splitting***	***78.97***
	2-10	**0 | 0 | 0 | 0**	***Splitting***	***81.44***
Block / Batch 3	3-01	0 | 0 | 0 |-2	Bar Fracture	104.03
	3-02	0 | 0 | 0 |+2	Splitting	50.73
	3-03	-2 | 0 | 0 | 0	Splitting	95.27
	3-04	+2 | 0 | 0 | 0	Pullout	22.78
	3-05	0 | 0 |-2 | 0	Splitting	46.26
	3-06	0 | 0 |+2 | 0	Bar Fracture	95.63
	3-07	0 |-2 | 0 | 0	Splitting	49.57
	3-08	0 |+2 | 0 | 0	Bar Fracture	95.17
	3-09	**0 | 0 | 0 | 0**	***Splitting***	***81.99***
	3-10	**0 | 0 | 0 | 0**	***Splitting***	***81.07***

TEST SPECIMENS





Test bar

Anchor bars

Exposed aggregate surface

LVDTs

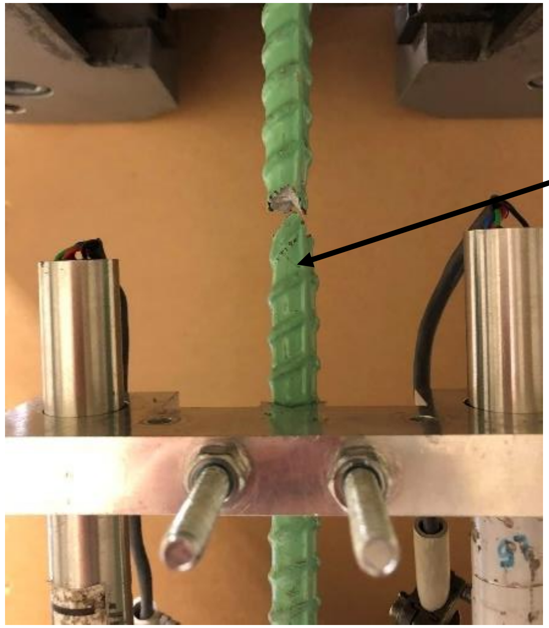
Thermocouple

Safety restraint

EXPERIMENTAL RESULTS

OBSERVED FAILURE MODES

Splitting

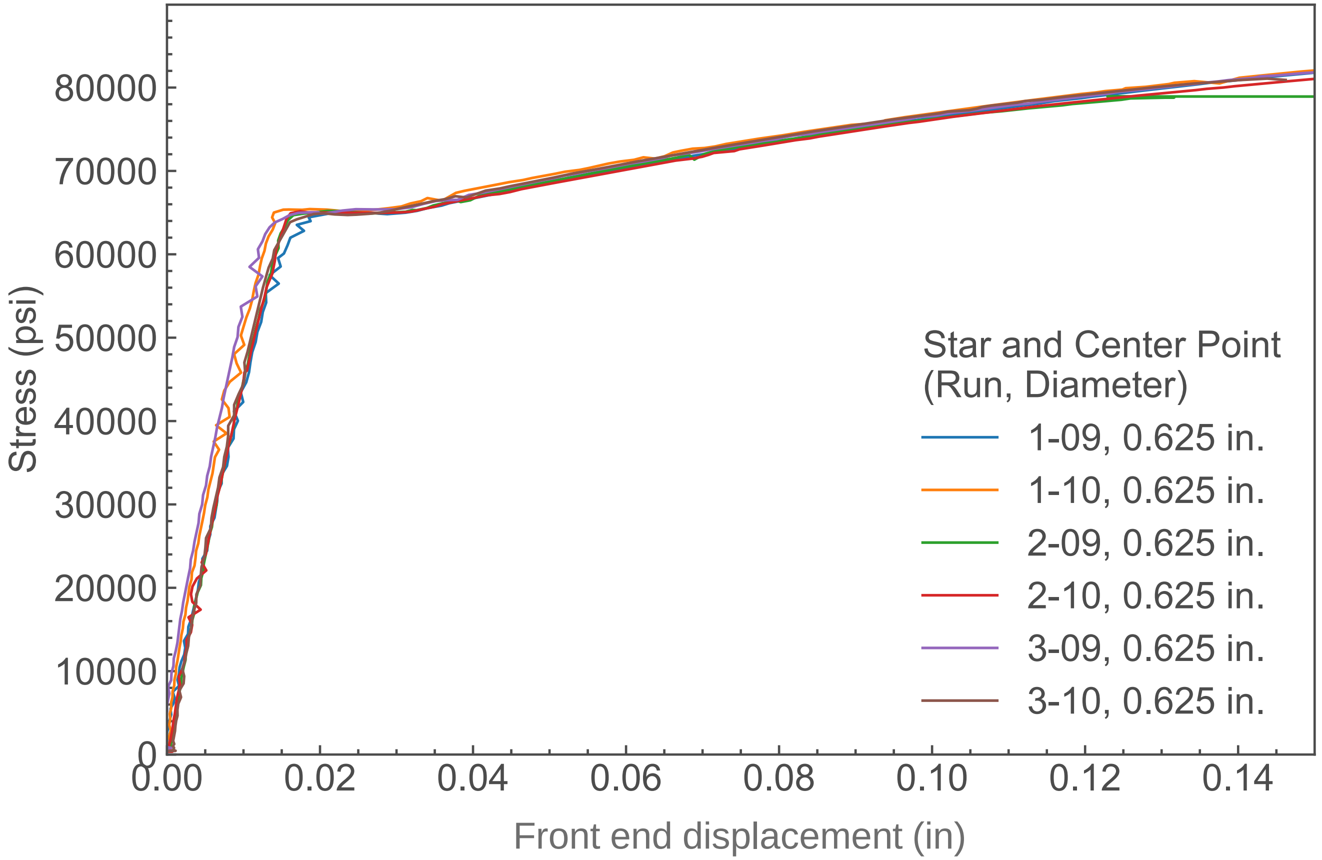


Bar Fracture

Pullout

BATCH VARIABILITY

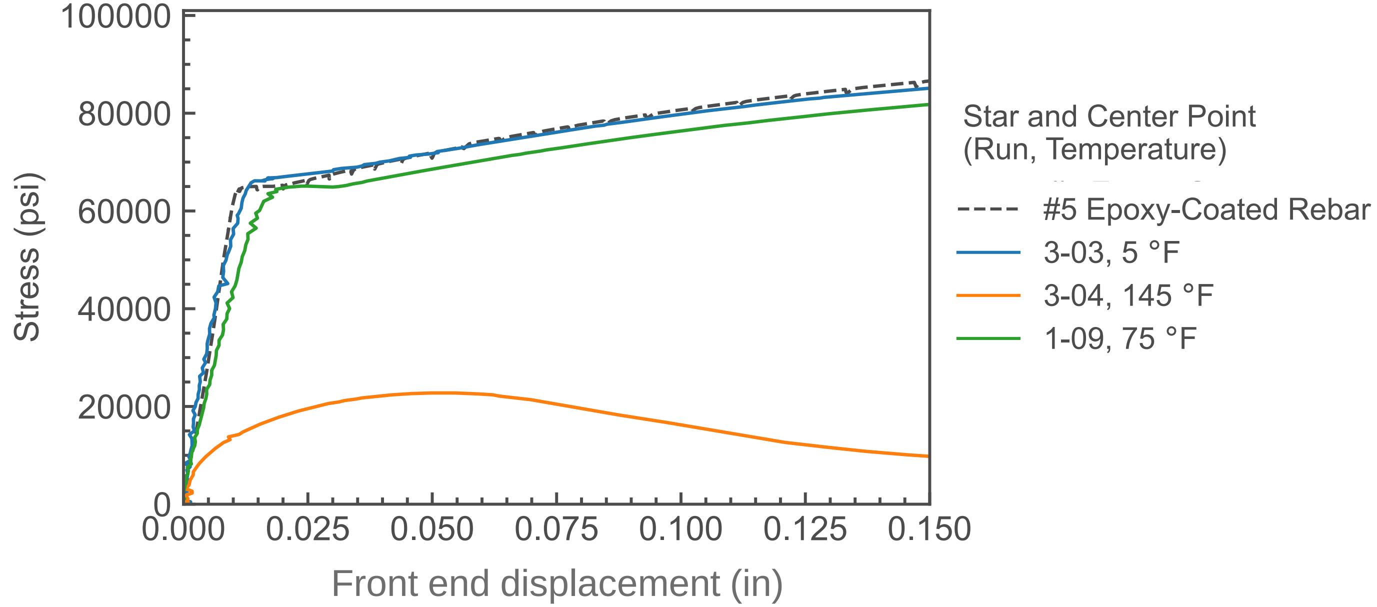
> Consistent center-point results

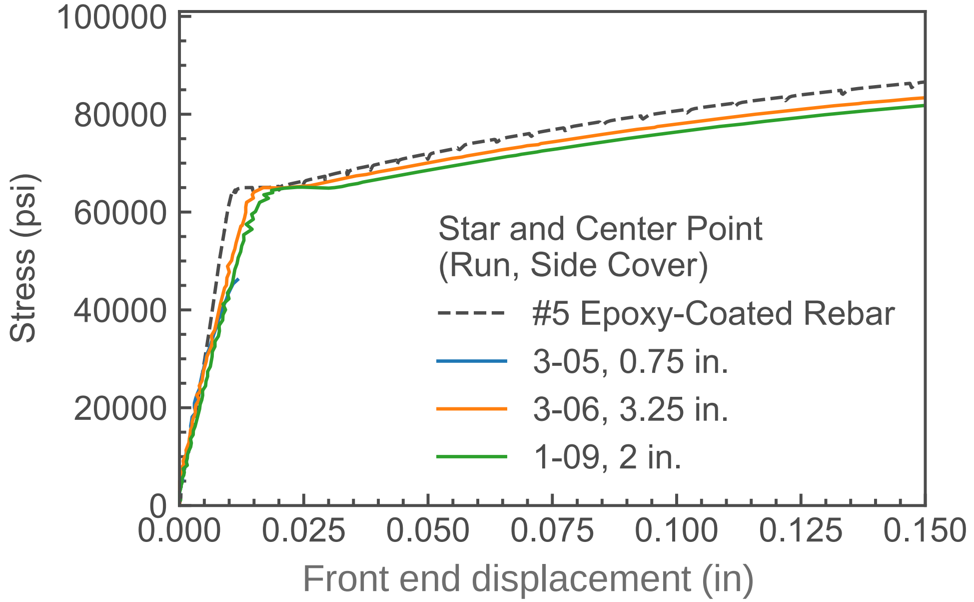


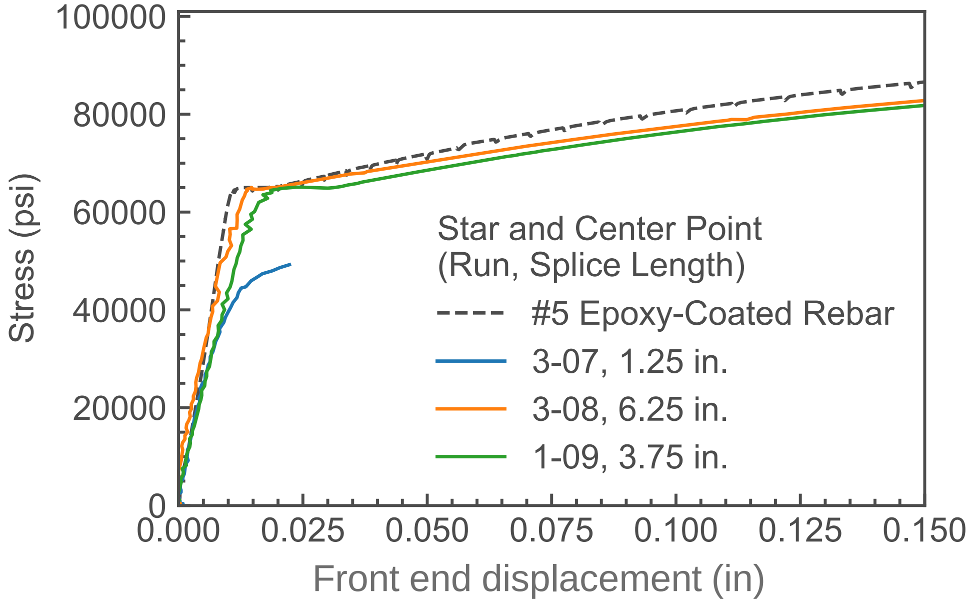
Run	Bar Stress (ksi)
1-09	85.7
1-10	82.7
2-09	79.0
2-10	81.4
3-09	82.0
3-10	81.1
Mean	82.0
Standard Deviation	2.2
Coeff. Of Variation	2.7 %

INFLUENCE OF PARAMETERS

- Splice strength increases with larger splice lengths and larger cover, decreases with higher temperatures

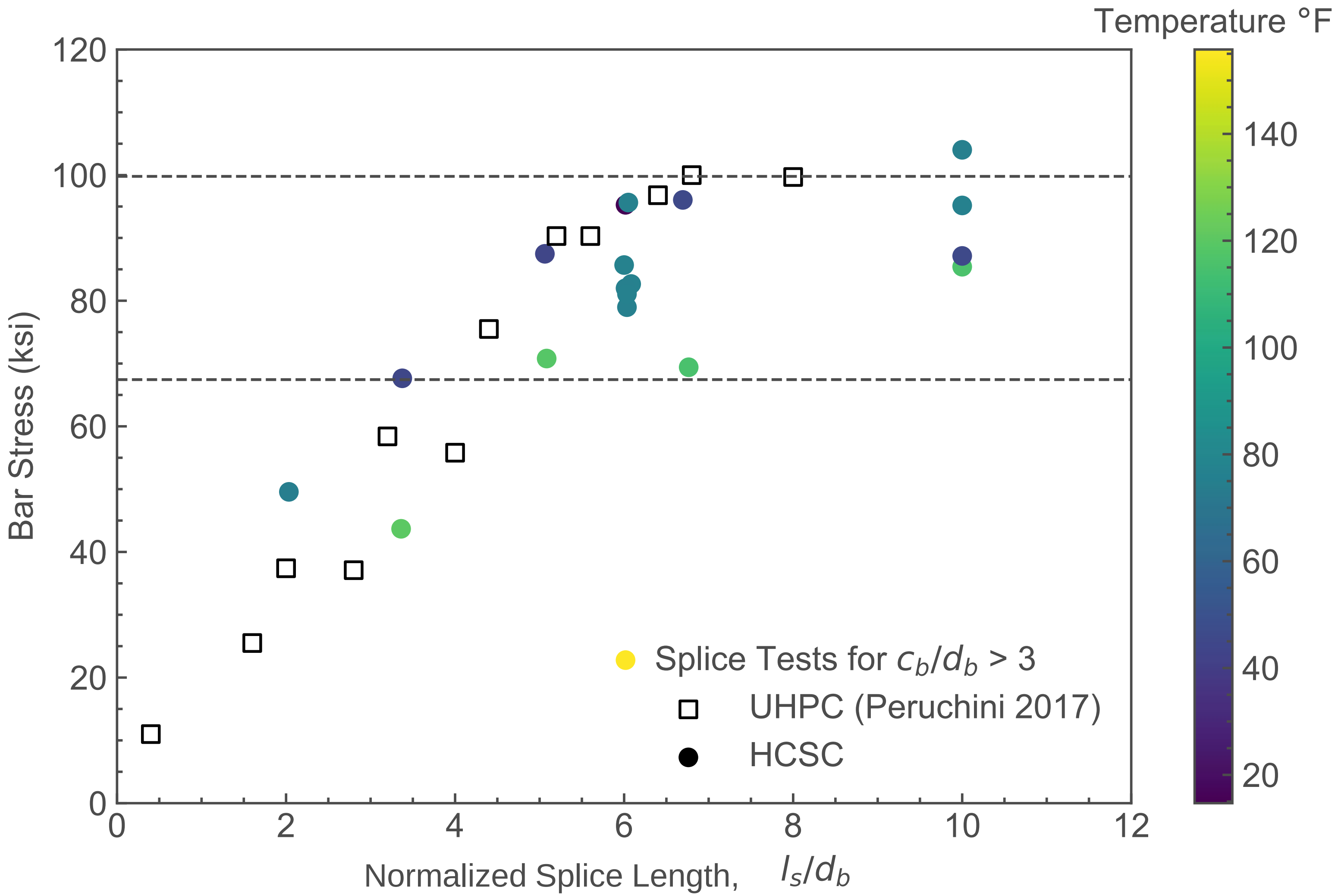






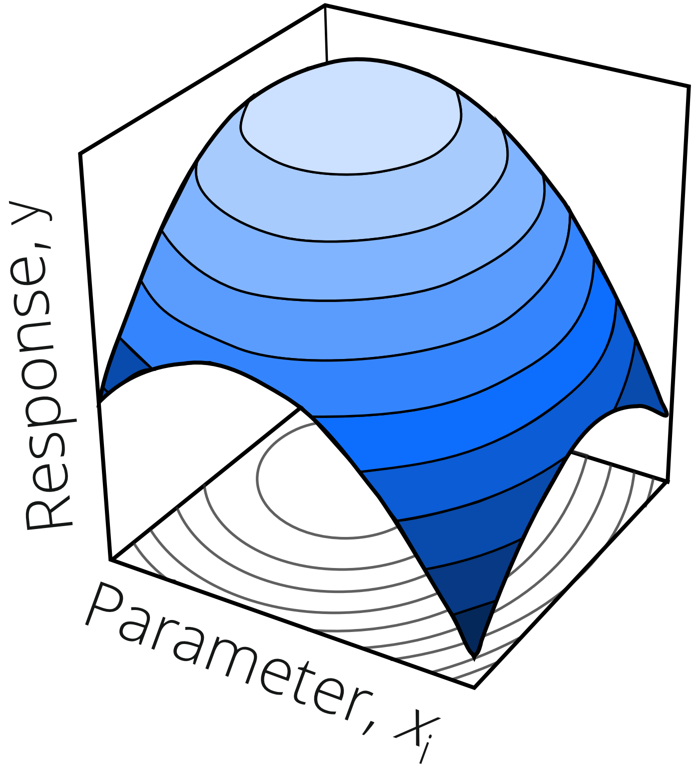
COMPARISON TO UHPC

- Comparable bar stress to non-proprietary UHPC
- Influence of splice length and temperature, as expected



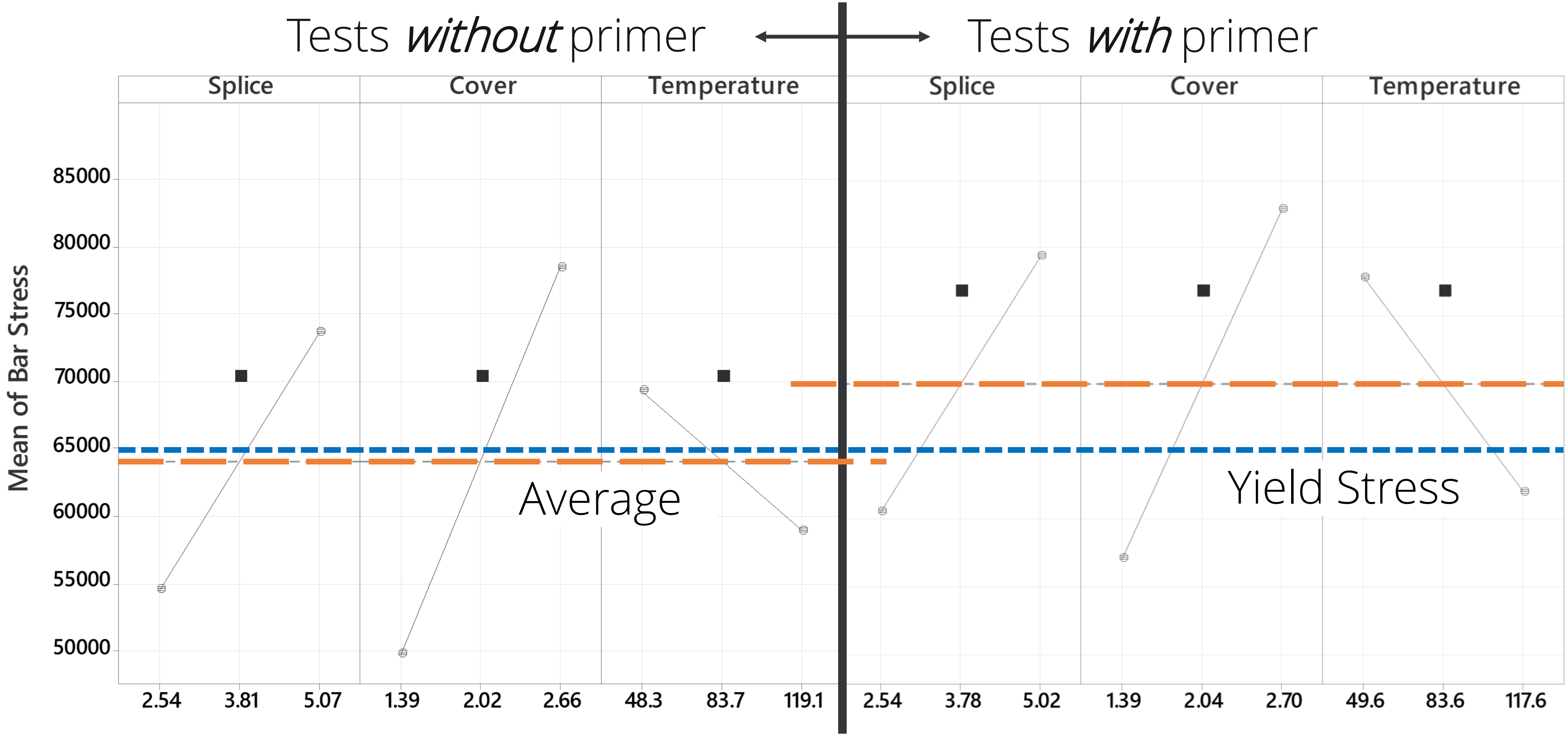
STATISTICAL ANALYSIS

- Response surface regression
- Quadratic terms and one way interactions included
- Removed non-statistically significant terms one at a time



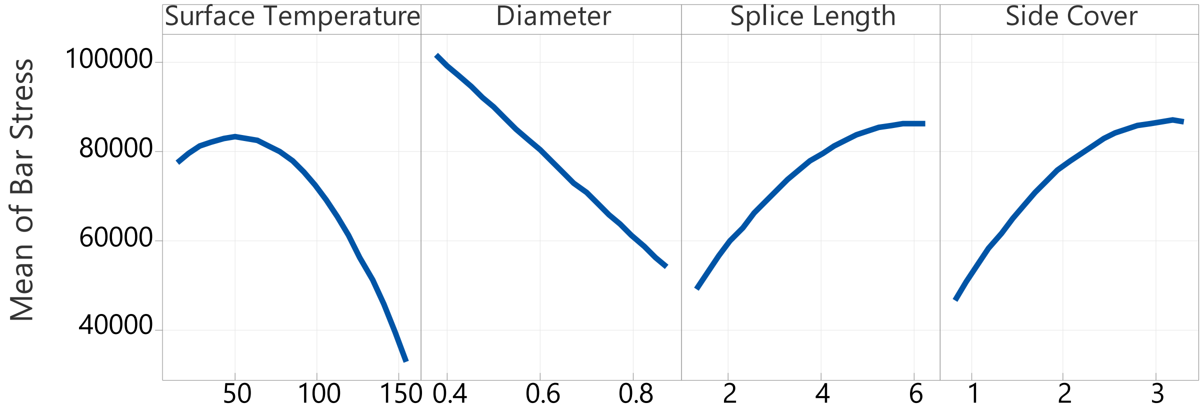
$$y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_{ii} x_i^2 + \sum_{i<j}^{k} \sum^{k} \beta_{ij} x_i x_j + \epsilon,$$

INFLUENCE OF PRIMER

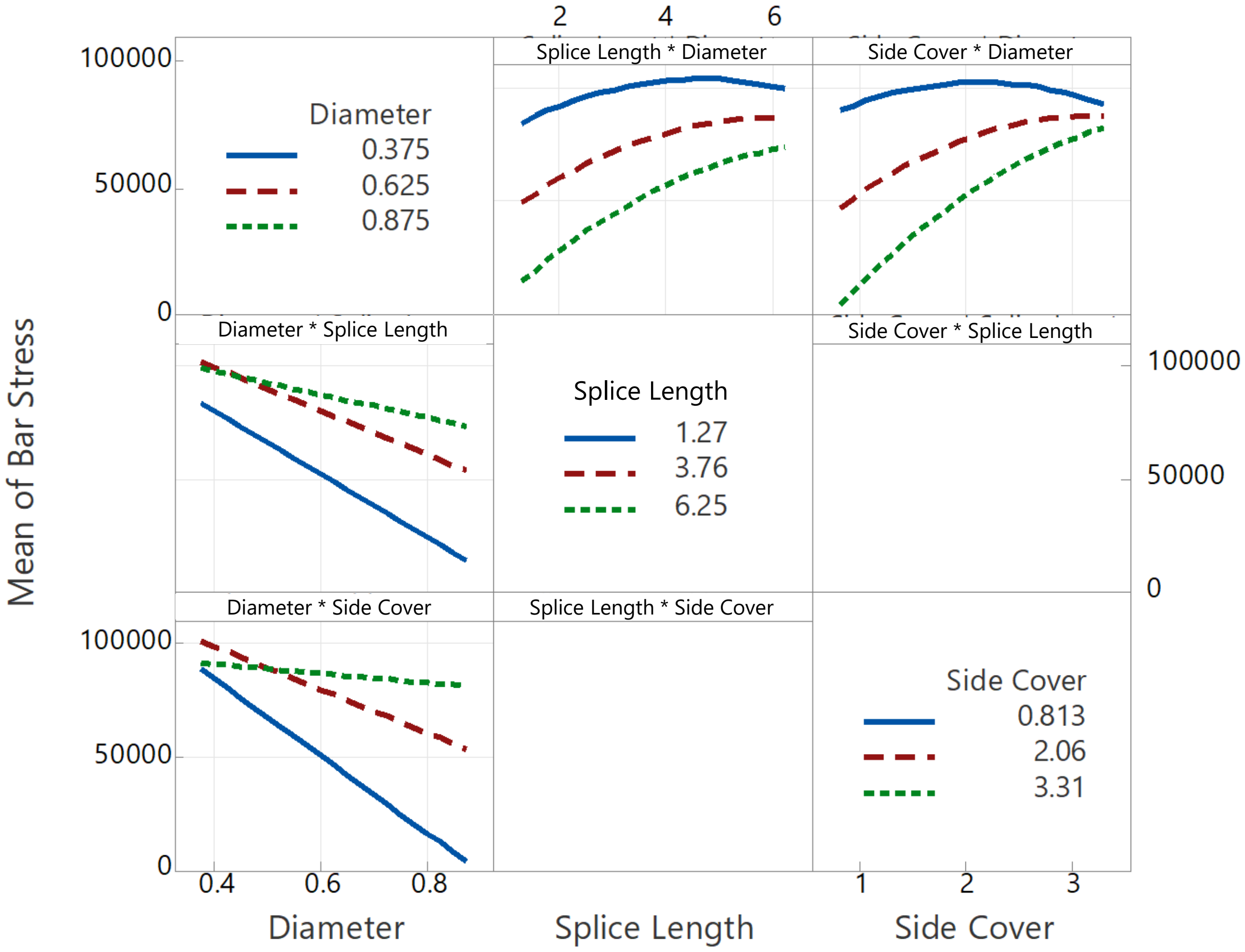


BAR STRESS

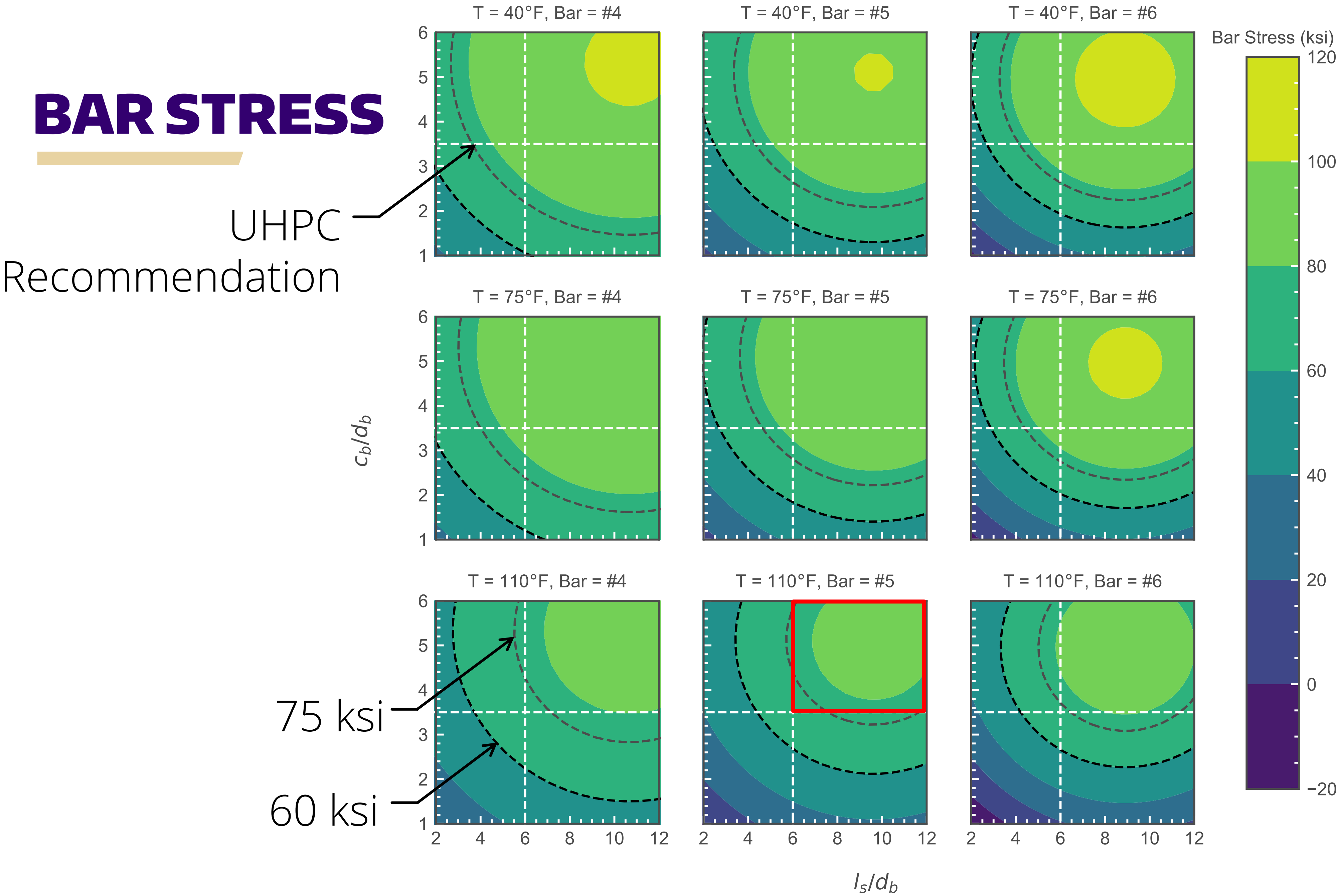
Main effects



Interactions



BAR STRESS



UHPC Recommendation
75 ksi
60 ksi
T = 40°F, Bar = #4
T = 40°F, Bar = #5
T = 40°F, Bar = #6
T = 75°F, Bar = #4
T = 75°F, Bar = #5
T = 75°F, Bar = #6
T = 110°F, Bar = #4
T = 110°F, Bar = #5
T = 110°F, Bar = #6
Bar Stress (ksi)
120
100
80
60
40
20
0
−20
c_b/d_b
l_s/d_b

RESEARCH OBJECTIVES

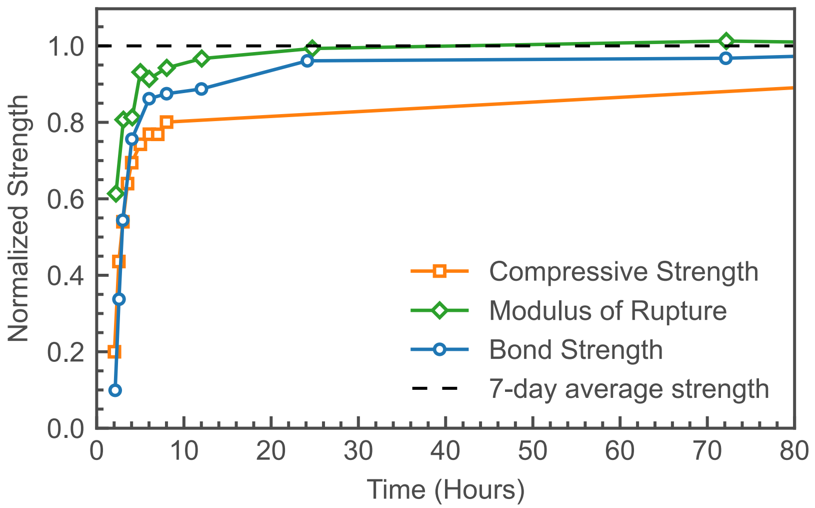
1. Characterize the mechanical properties of FRPC at multiple temperatures and ages
2. Characterize the splice performance of deformed bars embedded in FRPC materials at multiple temperatures
3. Develop preliminary design recommendations for the use of FRPC in closure joints for ABC applications

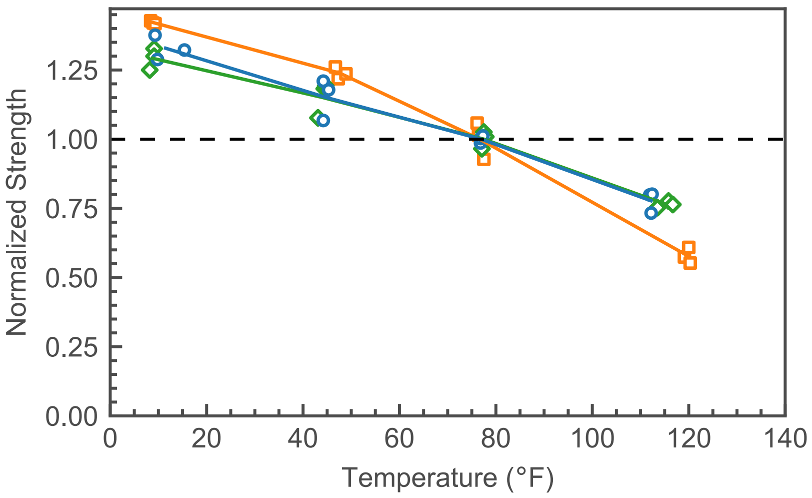
CONCLUSIONS

> Strength gain over time depends on curing temperature and can be tailored to specific needs by varying amount of accelerator

> Tradeoff between working time and rapid strength gain

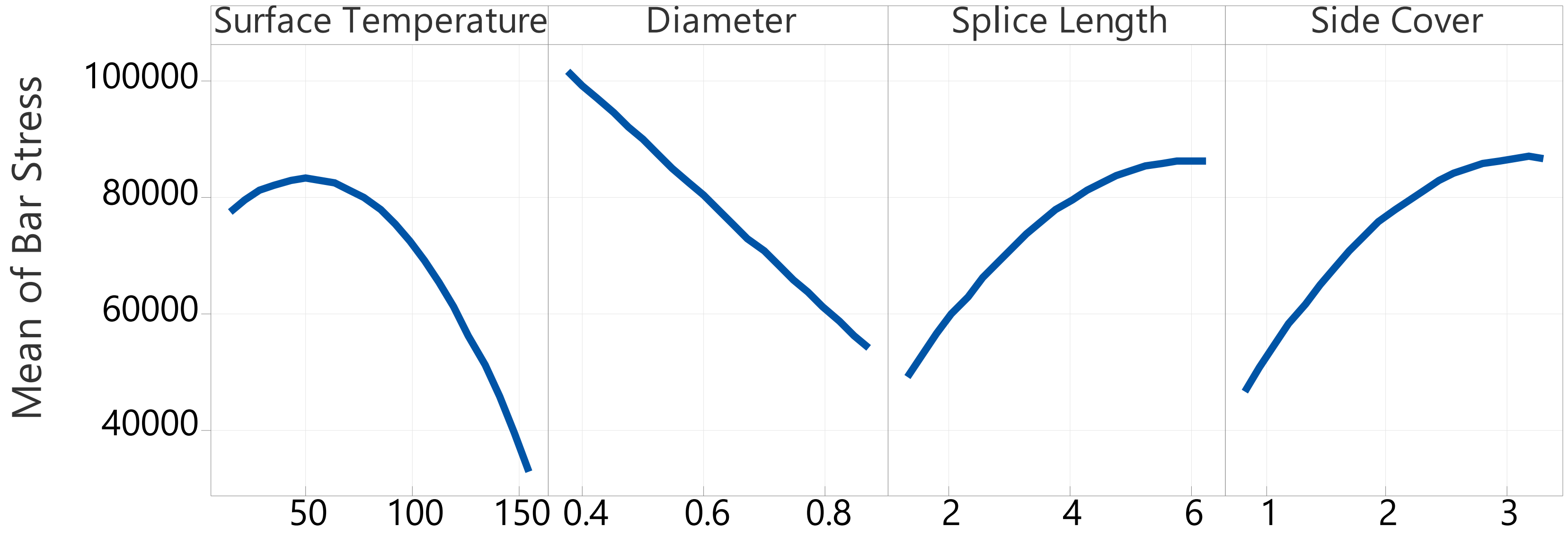
> Mechanical properties of FRPC are significantly influenced by temperature





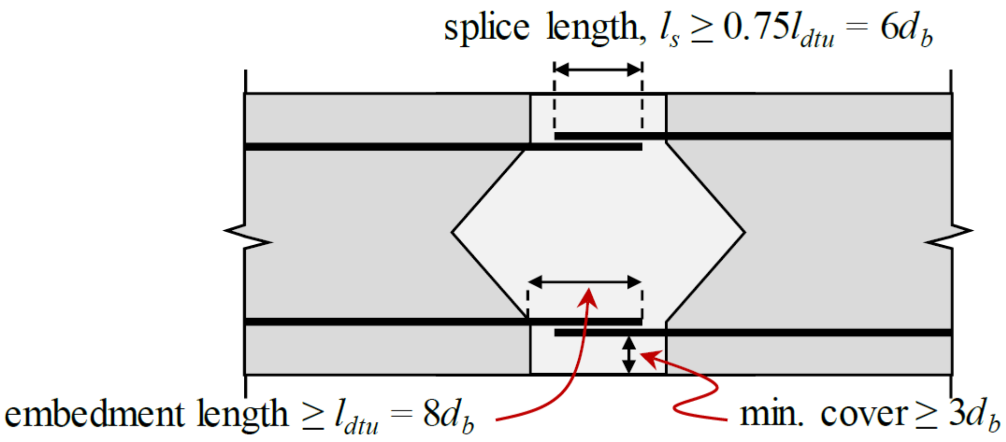
CONCLUSIONS

- Primer in non-contact splice tests had a minor influence in bond strength (up to 10% increase). Did not assess concrete to HCSC interface strength.
- Splice strength increases with larger splice lengths and larger cover. Bar stress decreases with higher temperatures



PRELIMINARY DESIGN RECOMMENDATIONS

- Initial testing supports direct replacement of UHPC with HCSC for *in-service HCSC temperatures* ≤ 110 °F
- For higher temperatures, additional splice length would be required



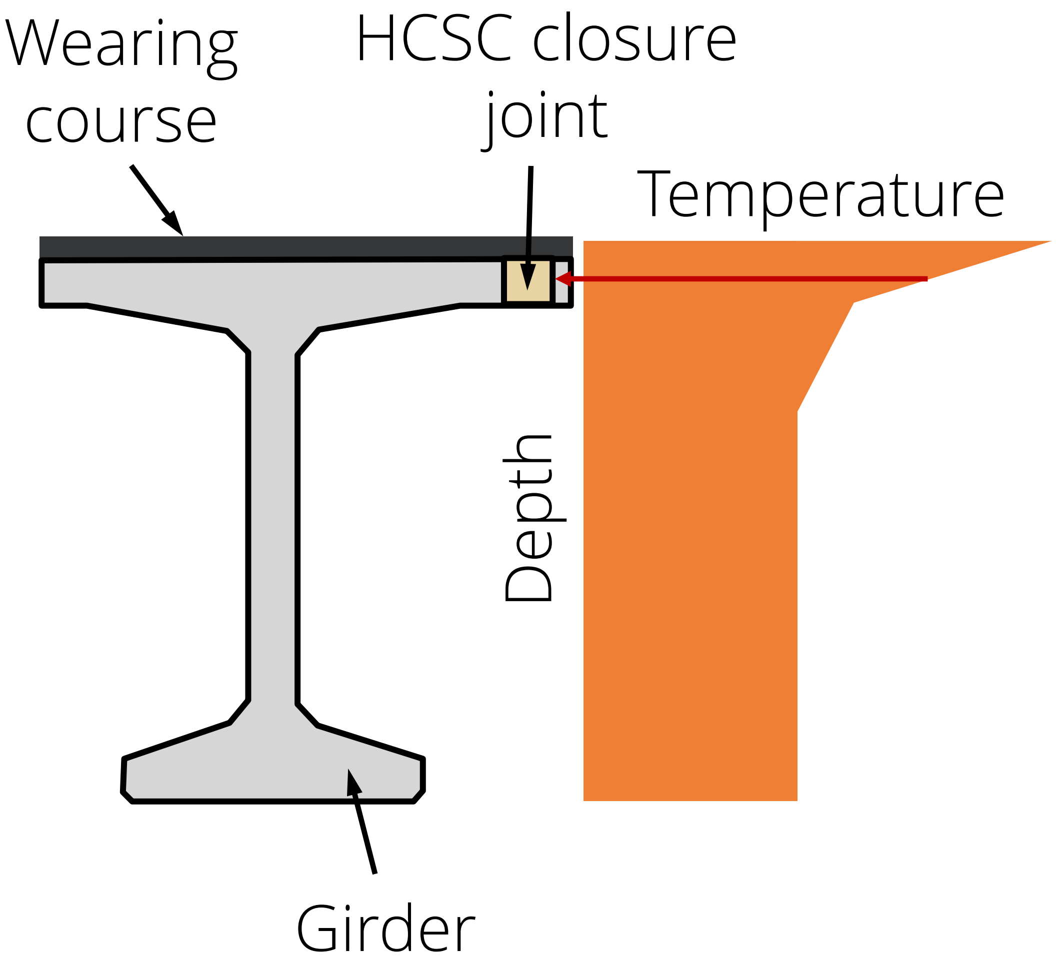


Image: Garber, D., and E. Shahrokhinasab. (2019). "ABC-UTC Guide for: Full-Depth Precast Concrete (FDPC) Deck Panels."

OUTLOOK & FUTURE WORK

> HCSC is a promising alternative closure pour material

> Service and Ultimate level joint testing is needed
  - Full-scale at various test temperatures
  - Repeated cycling at Service level

> Influence of time/rate-dependent properties

> Ongoing PennDOT Project Lafayette WO 001 ”Precast Bridge Deck Panel Testing” David Mante, Lafayette College

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