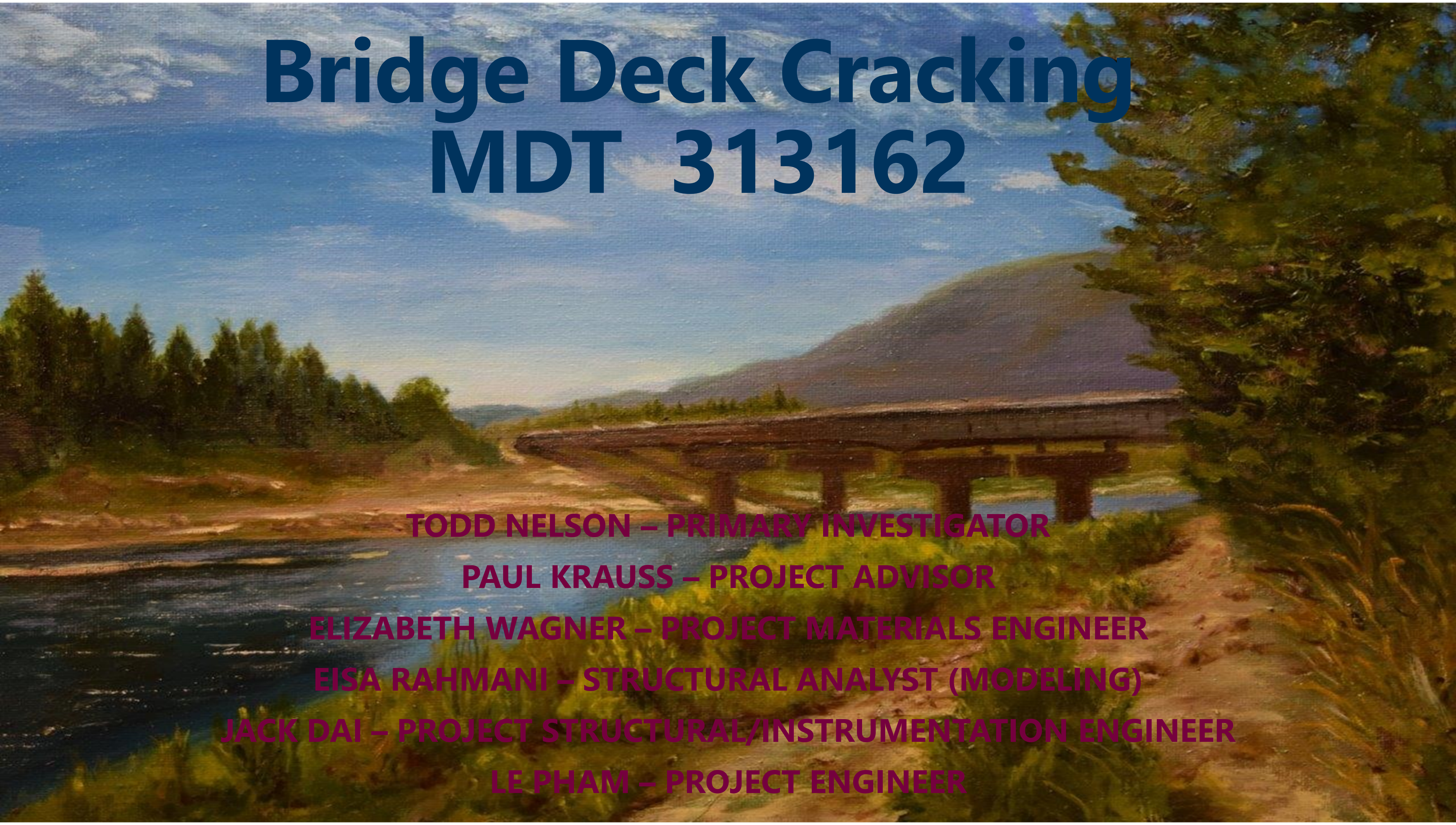

Bridge Deck Cracking
MDT 313162

TODD NELSON – PRIMARY INVESTIGATOR

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LE PHAM – PROJECT ENGINEER

Presentation Summary

- Introduction and Background on Bridge Deck Cracking
- Research Plan:
  - Item 4.1 – Literature Review
  - Item 4.4a – Field Inspections
  - Item 4.4b – Bridge Deck Instrumentation
  - Item 4.5a – Laboratory Evaluations
  - Item 4.5b – Finite Element Modeling
- WJE's Recommendations

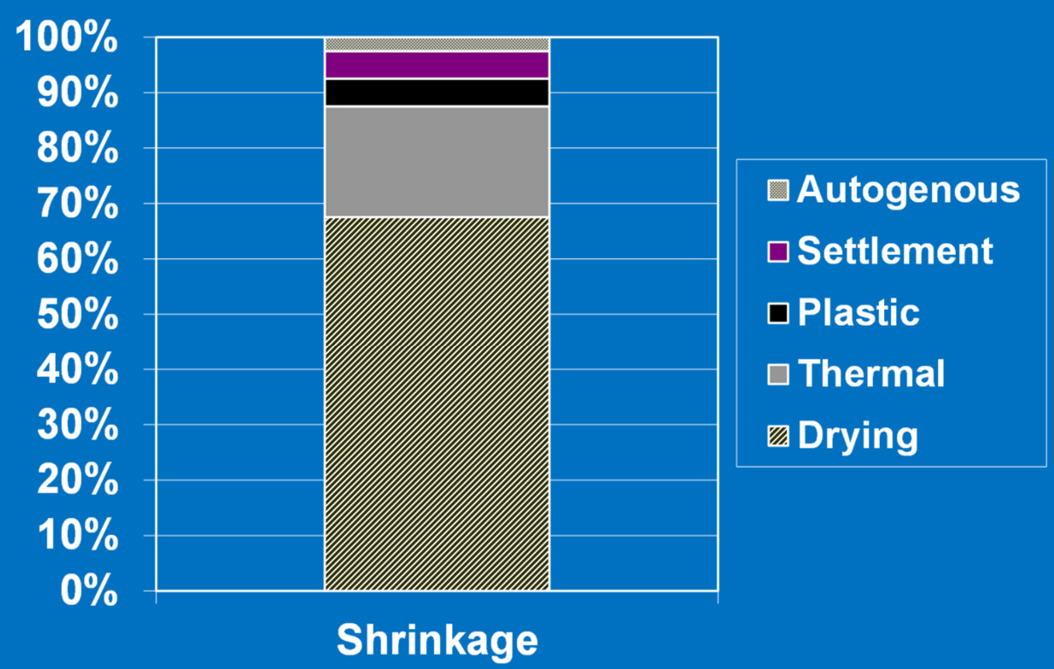
Introduction to Bridge Deck Cracking

- Types of Bridge Deck Cracking
  - Map cracking
  - Longitudinal cracking
  - Transverse

Introduction to Bridge Deck Cracking

- Complexity of contributing factors to transverse:
  - Autogenous shrinkage
  - Thermal changes and gradients
  - Drying shrinkage and moisture gradients
  - Importance of restraint
    - Internal restraint
    - External restraint
  - Construction practices and curing

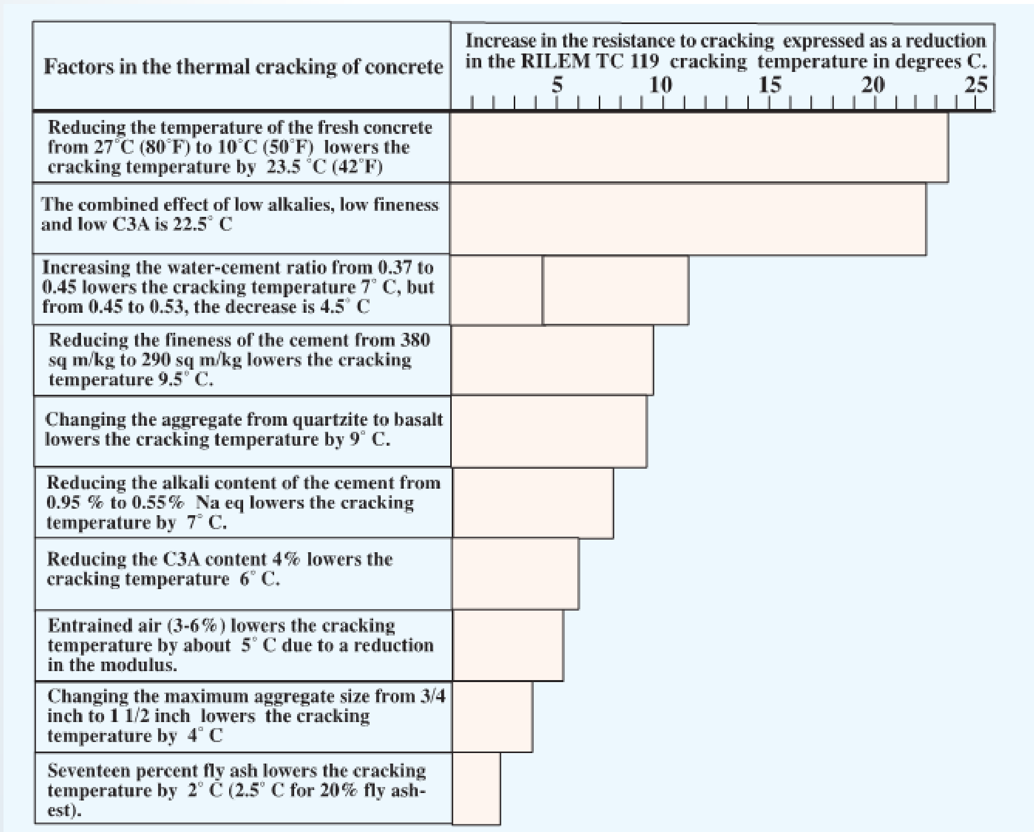
Introduction to Bridge Deck Cracking



Introduction to Bridge Deck Cracking

- Why are we still having these problems?
  - Changes in cement chemistry and fineness
  - Migration to low of w/cm
    - Low permeability but at a cost
  - HPC mixes require attention to curing
  - Low shrinkage mixes may not be sufficient

Introduction to Bridge Deck Cracking



WJE's Previous Studies (2016 to 2017)

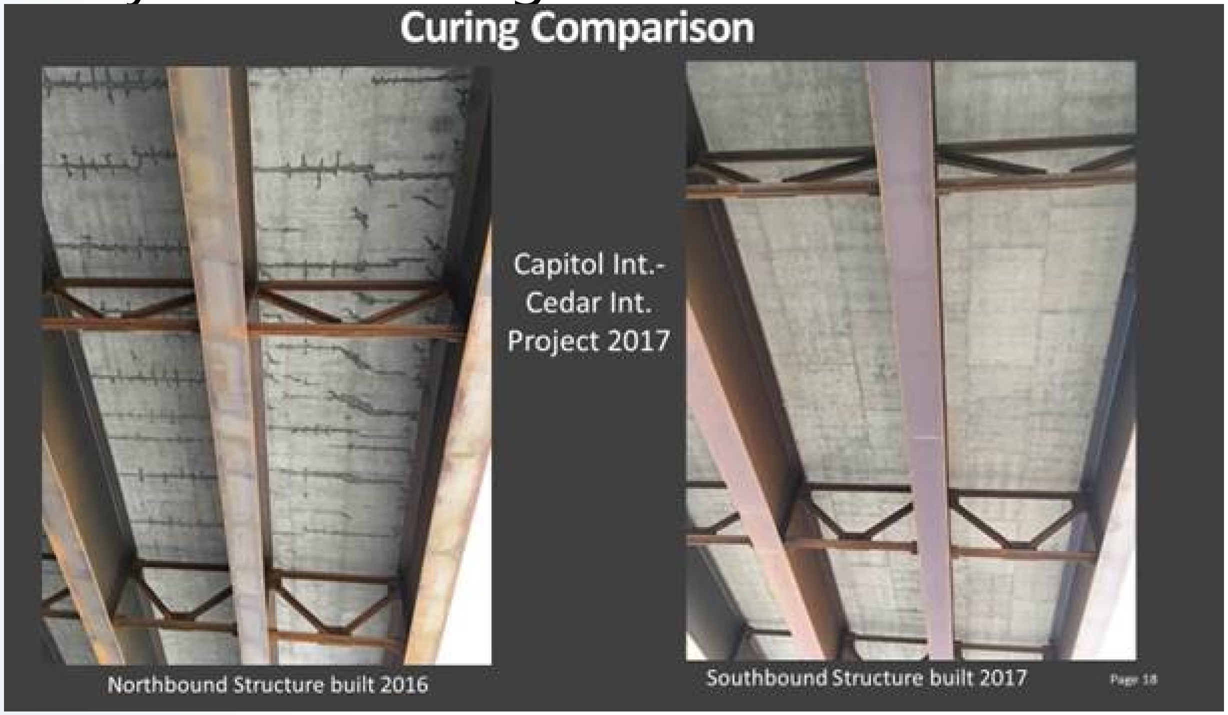
- WJE issued a report in April 2017 and found:
  - Closely spaced transverse cracks on numerous bridges in western Montana
  - Generally wider at the surface
  - Very early age development of the cracks
  - In some cases, through deck penetrations developed

WJE's Previous Studies (2016 to 2017)

- WJE's previous Recommendations
  - Curing
    - Application of insulation blankets shortly after peak hydration
    - Movement of placement times to the afternoon
  - Mixture Proportions
    - w/cm of 0.42 to 0.45
    - Limit total cementitious to 600 lb./yd^3 or less
    - Limit silica fume to maximum of 5%
    - Lower plastic concrete temperatures to < 75F

WJE's Previous Studies (2016 to 2017)

- In 2017 and 2018, WJE's recommendations were implemented on approximately 24 new bridge decks



WJE's Previous Studies (2016 to 2017)

- However, even though the early development of transverse cracks was mitigated, MDT reported significant later age development of transverse cracks.
- Commissioned WJE for additional applied research in 2019 to investigate the later age development of transverse cracking

Item 4.1 – Literature Review

- Federal Studies:
  - FHWA
  - NCHRP
  - NIST
- DOT-Funded Studies:
  - California
  - **Colorado**
  - **Idaho**
  - **Iowa**
  - **Kansas**
  - **Minnesota**
  - **Montana**
  - **New Jersey**
  - Nevada
  - North Dakota
  - Oregon
  - **Pennsylvania**
  - **Wisconsin**

Item 4.1 – Literature Review

Summary of Factors Affecting Bridge Deck Cracking

Factor	Factors Affecting Bridge Deck Cracking
Concrete Mixture Design	• Type II cements, fly ash, and slag reduce thermal and autogenous shrinkage • Type III cements increase heat of hydration and shrinkage • Coarse aggregates with low COTE reduce thermal movement • Low paste contents reduce shrinkage • Conflicting information regarding w/cm → WJE recommends w/cm between 0.42 and 0.45 to reduce autogenous shrinkage
Concrete Strength	• High-strength concrete has greater tendency to crack (higher MOE)

Item 4.1 – Literature Review

Summary of Factors Affecting Bridge Deck Cracking

Factor	Factors Affecting Bridge Deck Cracking
Restraint Conditions	• Restraint is greatest in interior spans and at integral abutments • Simply-supported or pin connections reduce crack tendency • Curved girders and skew increase restraint
Element Design	• Cracking increases when girders are stiffer than deck (thin decks, composite steel plate girders, wide flanges, and cross-framing) • Larger girder spacing and thicker decks (> 8.5 in.) reduce crack tendency • Concrete girders provide less restraint than steel girders • Offsetting top and bottom reinforcing mats reduces risk of full-depth cracking • Increased cover increases crack width but reduces frequency

Item 4.1 – Literature Review

Summary of Factors Affecting Bridge Deck Cracking

Factor	Factors Affecting Bridge Deck Cracking
Construction Practices	• Practices that limit evaporation reduce potential for early-age plastic shrinkage cracking • Mechanical vibration can close plastic shrinkage cracks • Roller screeding can increase risk of near-surface autogenous shrinkage cracking • Large temperature variations during placement exacerbate thermal stresses

Item 4.4a – Field Inspections

- Visual inspection
- Crack mapping
- Crack width measurement
- Crack data analysis
- Delamination survey (chain dragging)
- Ground Penetrating Radar (GPR)

Item 4.4a – Field Inspections

- Bridges were selected based on recency in construction, implementation of WJE's previous recommendations, and exposure conditions.
- Documentation accumulated for each bridge deck: drawings, specifications, mix designs, concrete temperature monitoring records, environmental conditions during construction, quality control results, and weather data.

Item 4.4a – Field Inspections

- Two inspection trips were performed:
  - 2019 inspection: December 2 to 7, 2019
    - Inspected 9 bridges
    - Analyzed ortho mosaic photos of 1 bridge
  - 2020 inspection: August 25 to 30, 2020
    - Inspected 14 bridges
    - Document of any progression in cracking from 2019 and additional bridges recently constructed

Deck Overall Visual Rating

Bridge ID	Bridge Short Name	Overall Visual Rating[1]
07006	Russell Street Bridge - Phase I (NB)	3.0
07006	Russell Street Bridge - Phase II (SB)	1.5
06253	Garrison Bridge	1.0
05943	Whitehall Bridge	1.0
01642	Capitol-Cedar Bridge - Phase I (NB)	4.0
01641	Capitol-Cedar Bridge - Phase II (SB)	3.0
01434	Bonner Bridge - Phase I (EB)	1.5
01435	Bonner Bridge - Phase II (WB)	1.0
01741	West Laurel Bridge - Phase 1 - (EB)	3.0
01742	West Laurel Bridge - Phase 2 - (WB)	1.5 (2020 only)
01104	Rarus-Silver Bow Creek - Phase I - Bridge A	1.0 (2019) 1.5 (2020)
01105	Rarus-Silver Bow Creek - Phase II - Bridge B	1.0 (2020 only)
01106	Rarus-Silver Bow Creek - Phase I - Bridge C	1.5
01107	Rarus-Silver Bow Creek - Phase II - Bridge D	1.5 (2020 only)

[1] Same ratings in 2019 and 2020 unless otherwise noted.

Bonner Bridge – Phase 2 (WB)

- Overall Visual Rating = 1

Placement #	Crack Density (ft/ft2)	Crack Severity (mil*ft/ft2)
1	0.04	0.19
2	0.04	0.19
3	0.03	0.17
4	0.02	0.10
5	0.05	0.23
All	**0.03**	**0.17**

- Cracks very difficult to see
- Cracks less than 10 mils

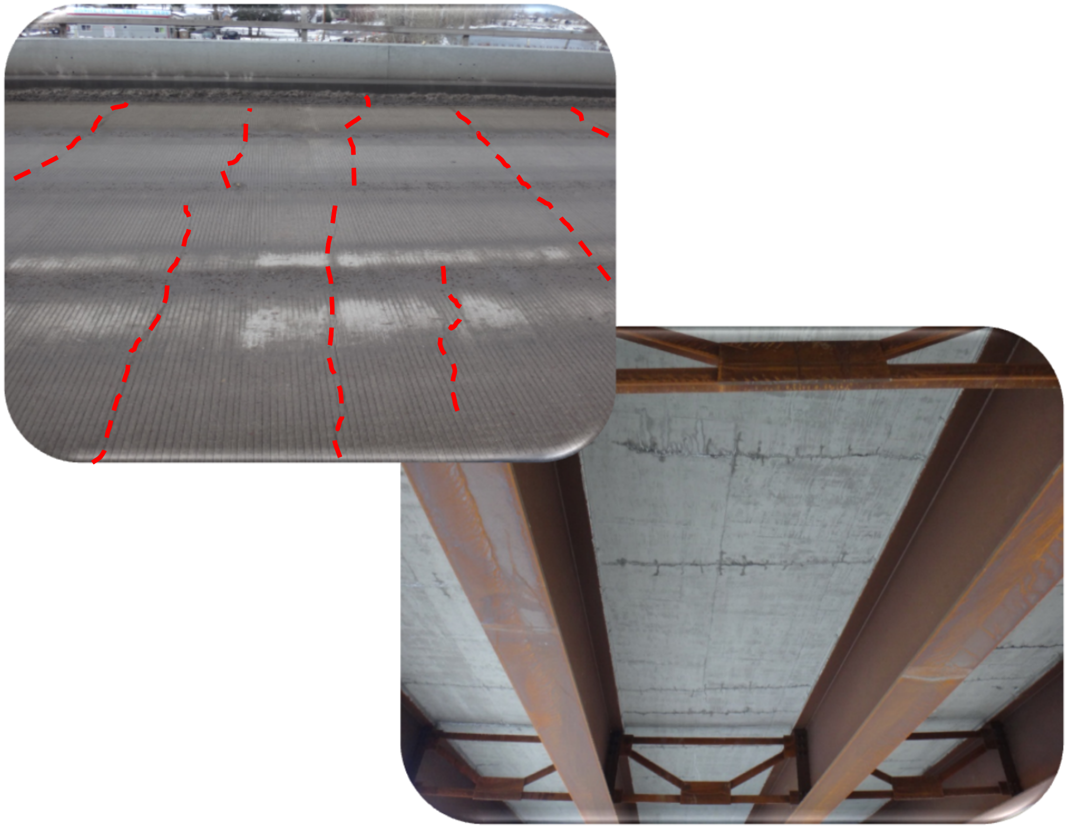
Bonner Bridge Phase II (WB) - 2019 Inspection - Typical deck underside condition, Span 2 - Looking east.

Russell Street Bridge – Phase 1 (NB)

- Overall Visual Rating = 3

Placement #	Crack Density (ft/ft²)	Crack Severity (mil*ft/ft²)
1	0.27	6.95
2	0.23	6.62
3	0.21	3.48
4	0.28	3.99
5	0.30	3.63
All	**0.26**	**4.88**

- Frequent transverse cracks, 15 to 25 mils



Russell Street Bridge - Phase I, 2019 Inspection - Placement 3, underside. Typical transverse cracks at arrows

Crack Data Analysis

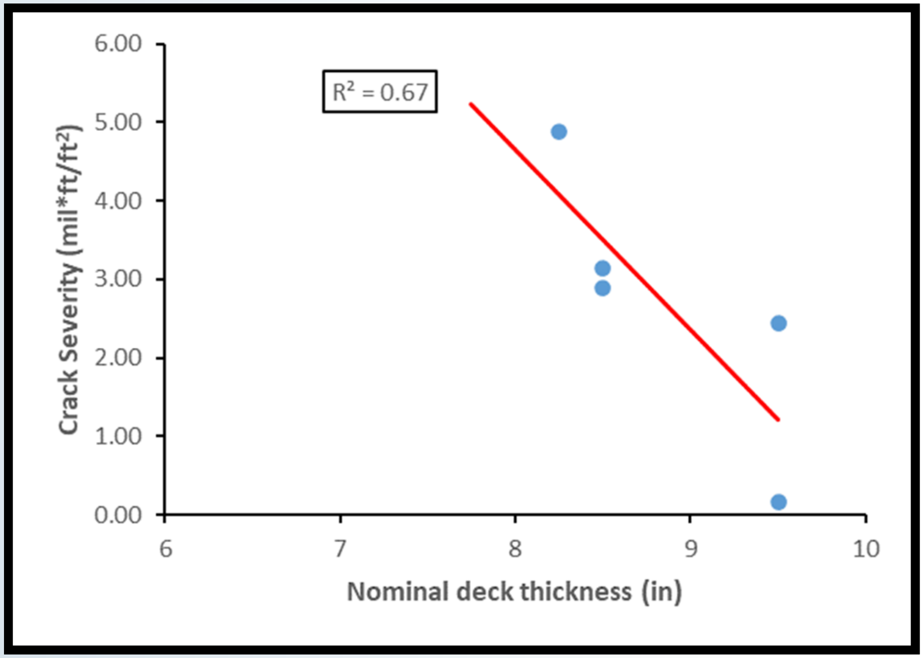
- Cracking frequency and density were analyzed versus bridge bearing type, span length, span bearing type, placement location, placement length, deck thickness, placement
- Quantity of bridges (14) likely not statistically significant, but correlations were developed.

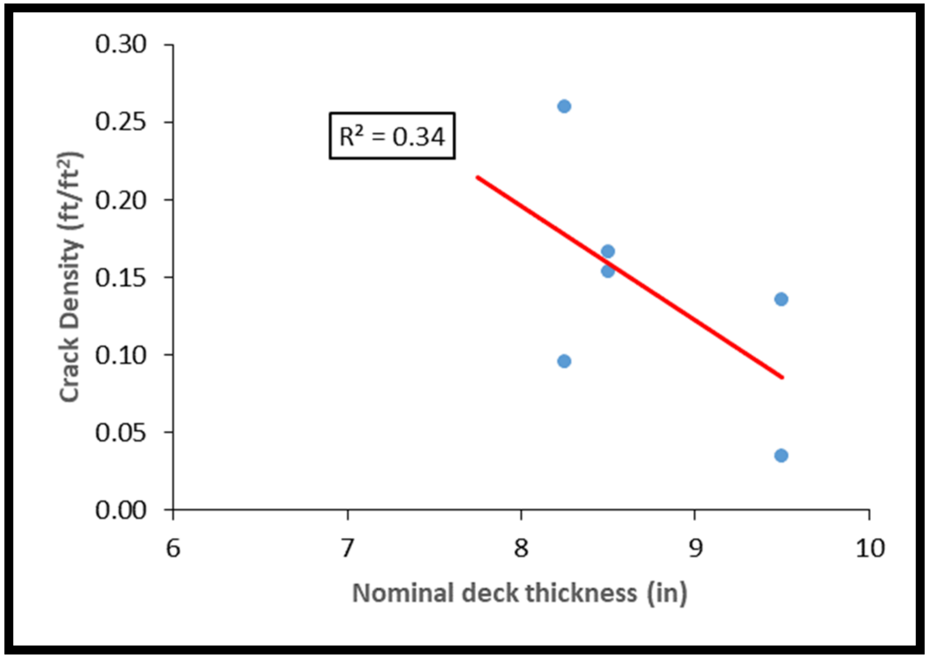
Crack Data Analysis

- Differences in cracking condition between spans and placements within the same bridge were observed; however, the trends were not consistent on every bridge deck.
- The following factors did not yield any consistent trends in the development of transverse cracking severity: bridge bearing type, span length, span bearing type, placement location, and placement length.

Crack Data Analysis

- Cracking appears to be less severe in decks with greater deck thicknesses.

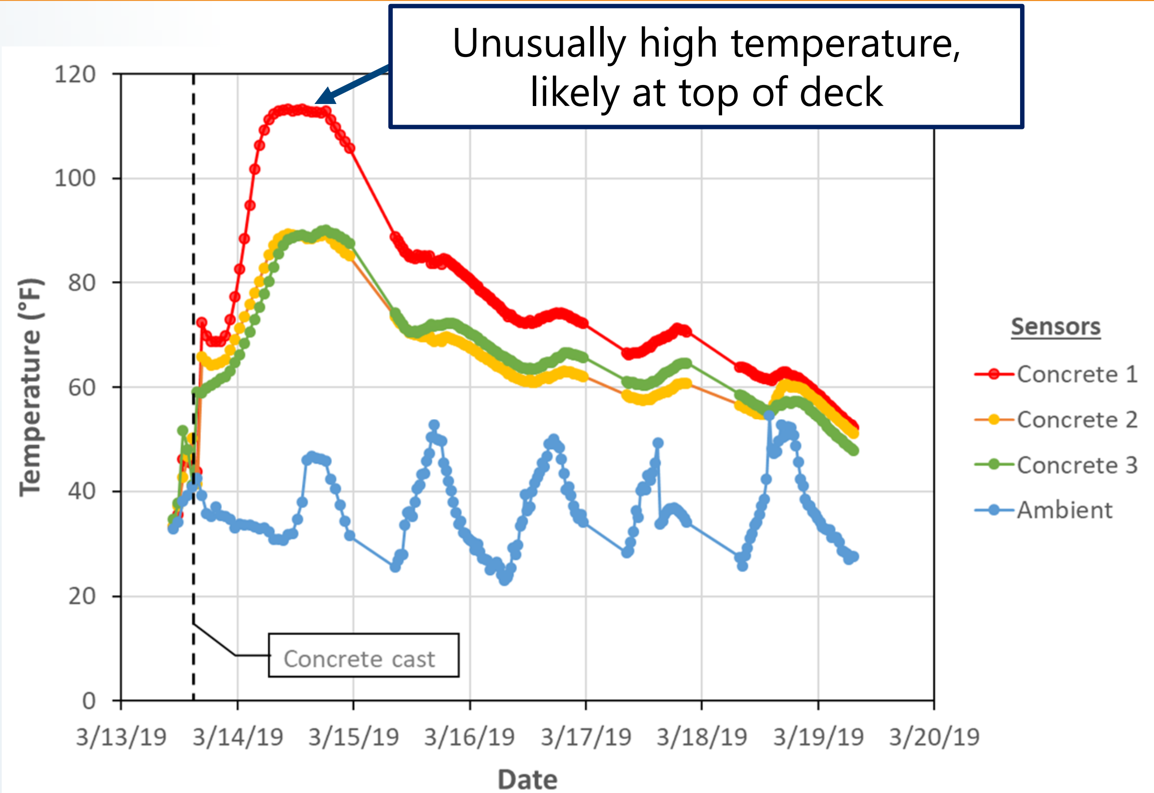




Cracking Analysis - Winter Curing

- The placement of concrete during the winter months, actively heated from the top, is likely a contributing factor to transverse cracking severity at Russel Street Phase I (potentially Phase II as well).
- Alternatively, Rarus/Silver Bow Creek Structure, Bridge D, was cast in the winter but heated from the bottom, including the steel girders, and exhibited very little transverse deck cracking.

Curing with Heating on Top of Deck



Curing temperature data with heating hoses on top of concrete. Russell Street Bridge Phase I (NB), Placement 1, sensor location 3.

Other Findings

- Cracking conditions in 2019 and 2020 were generally similar at most of the bridges without significant progression of the cracking.
- GPR surveys at transverse crack locations on the topside of the bridge decks indicate that the transverse cracks were generally in line with the transverse (topmost) deck reinforcement.
- Based on observations from both the deck topside and underside, it appears that the majority of transverse cracks are through the deck thickness.

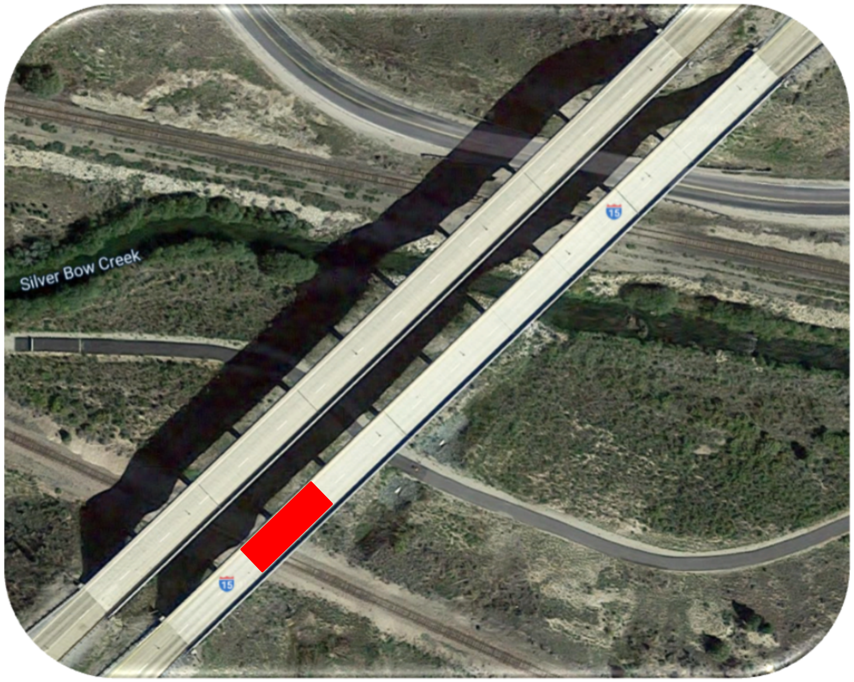
Item 4.4b - Instrumentation

- Goal to understand the impact of environmental changes on the internal deck temperatures, relative humidity (RH), and strains.

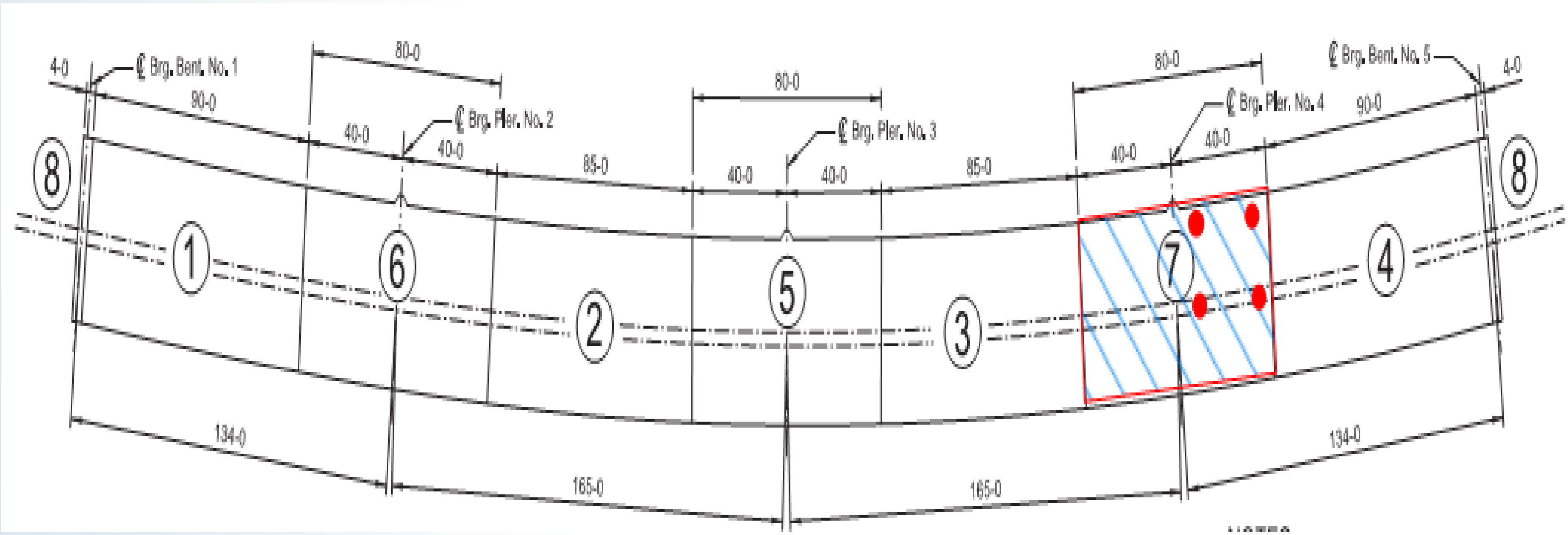
- Bridge Deck Instrumented for:
  - Strain (vibrating wire SG's)
  - Temperature
  - Relative Humidity (resistive)
  - Ambient conditions – temperature, relative humidity, wind speed, and solar radiation

Item 4.4b - Instrumentation

- Rarus/Silverbow Creek, Bridge D, was selected for instrumentation
  - Butte, MT
  - Four-span bridge
  - 7 ¾ inch deck thickness
  - Deck replacement
  - Constructed in Winter 2019

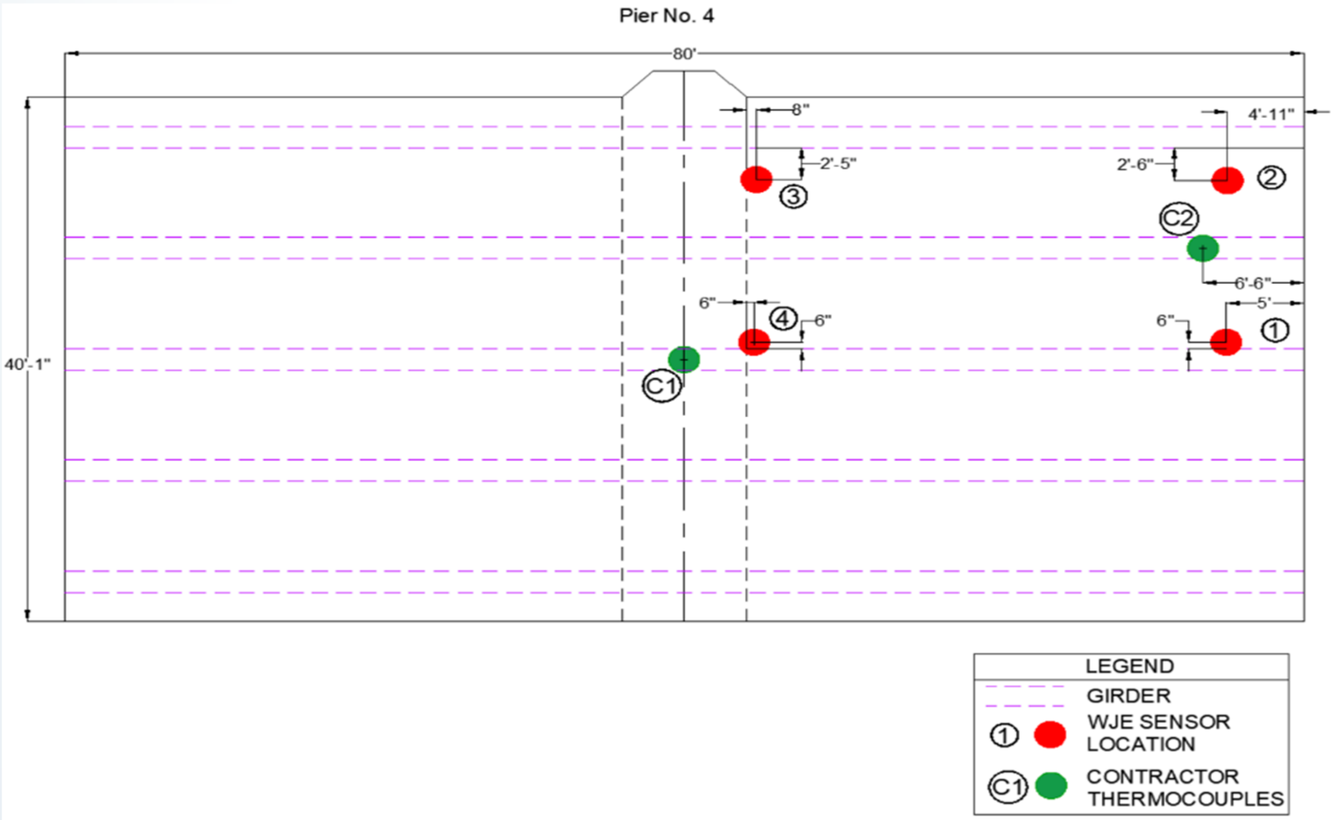


Instrumentation Plan



Placement 7 was selected for instrumentation

Instrumentation Plan

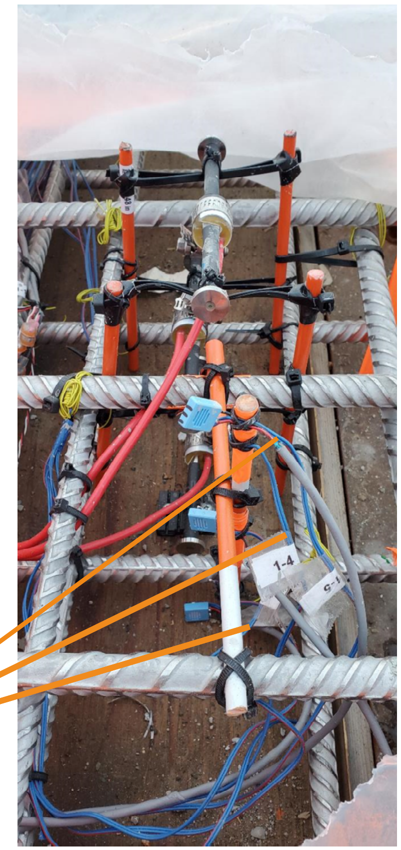


Bridge Deck Instrumentation

Vibrating wire strain gages

RH Sensors

Thermocouples



Instrumentation Hardware

Bridge Deck Instrumentation

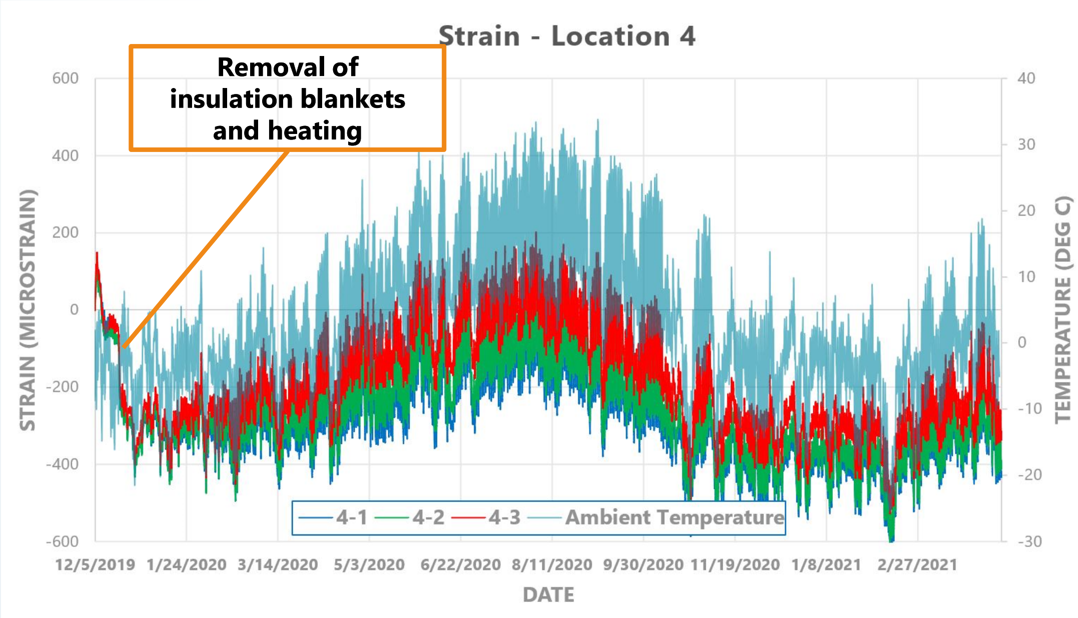
- Concrete Deck placement on December 5, 2019

Instrumentation Plan

- A total of x chan, recording every 5 minutes for the first
- All channels are still active and WJE will continue to monitor and download

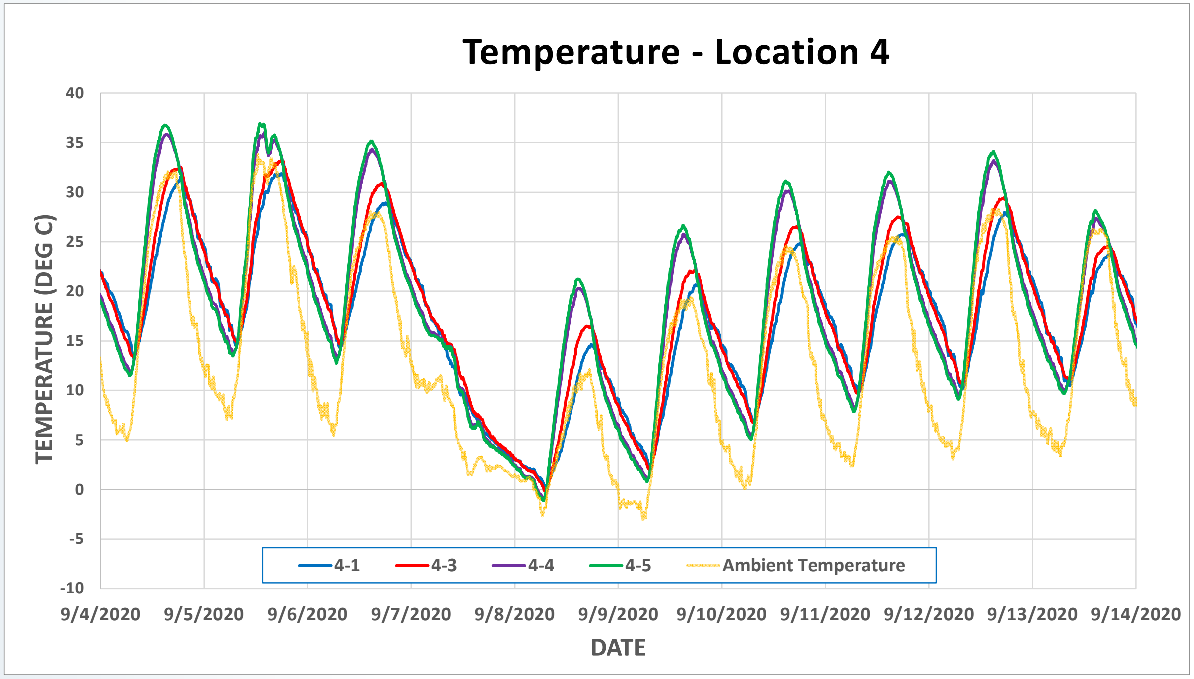
Strain

- Strain gages did not show indication of cracking (sudden change in strain)
- No tensile strains developed during the winter wet-curing methods (11 days)
- Compressive strain developed in deck after removal of insulation and heating



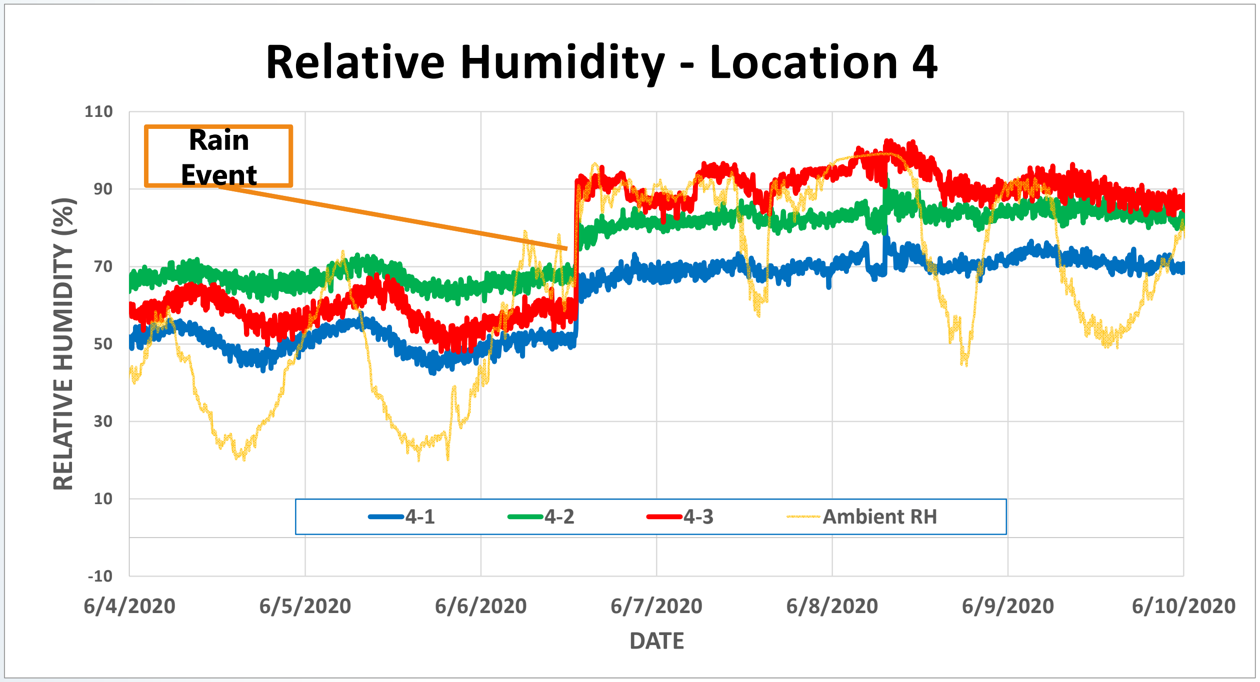
Temperature

- Large daily temperature changes observed (ΔT=+55 to 70˚F)
- Temperature gradient within the deck, 20F



Relative Humidity

- Large daily RH changes observed
- RH gradient within the deck



Instrumentation Summary

- None of the installed strain gages showed any indication of cracking (sudden change in strain)
- No tensile strains developed in the deck during the curing period
- Removal of heating created a pre-compression of the deck
- Large daily ambient temperature changes were recorded with extremes at 55 to 60F, creating gradients within the deck
- Large daily ambient humidity changes, creating gradients within the deck as large as 30 percent

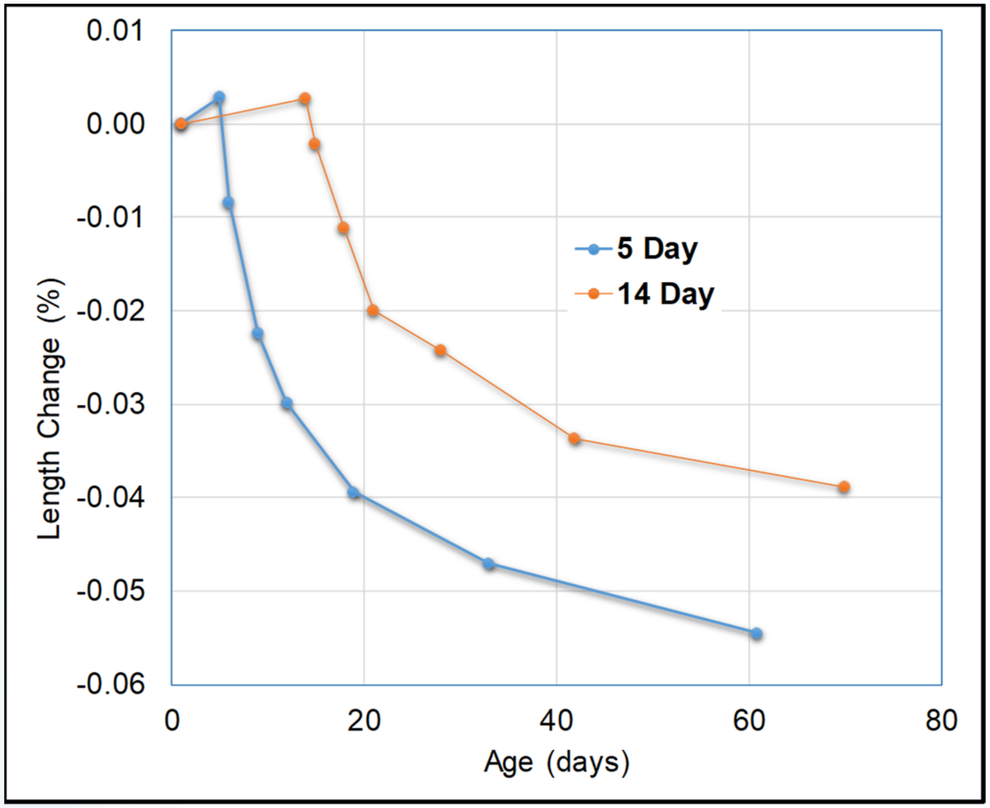
Item 4.5a – Laboratory Testing

- Laboratory batching performed on concrete mix design from Rarus/Silverbow Creek bridge
- Raw materials shipped to WJE for the following tests
  - Compressive strength, tensile strength, modulus of elasticity, maturity, drying shrinkage, creep, and coefficient of thermal expansion
- Data used for FE modeling inputs and sensitivity analysis

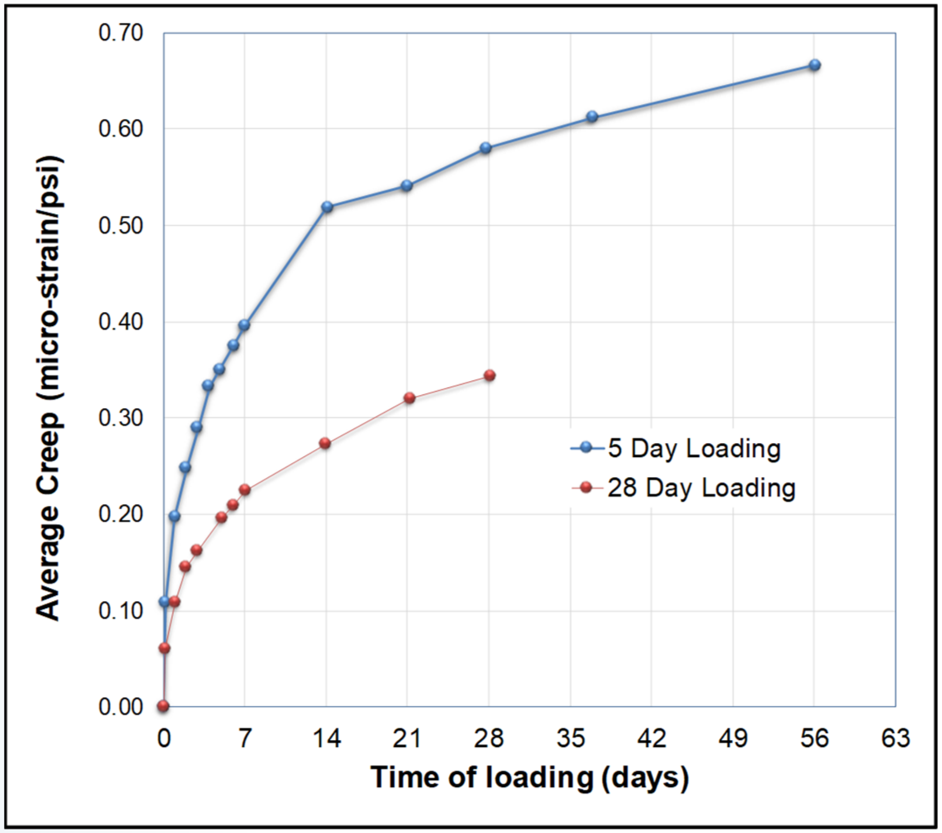
Laboratory Evaluations - Results

Age (days)	Compressive Strength (psi)	Modulus of Elasticity (ksi)	Splitting Tensile Strength (psi)	Concrete Coefficient of Thermal Expansion ($x10^{-6}/°F$)
1	1,480	2,470	200	4.14
3	3,100	2,900	350	4.14
5	3,530	3,325	355	4.14
21	5,070	4,000	NA	4.14
28	5,380	4,400	580	4.14
90	6,400	4,575	590	4.14

Drying Shrinkage



Concrete Creep



Laboratory Evaluations - Summary

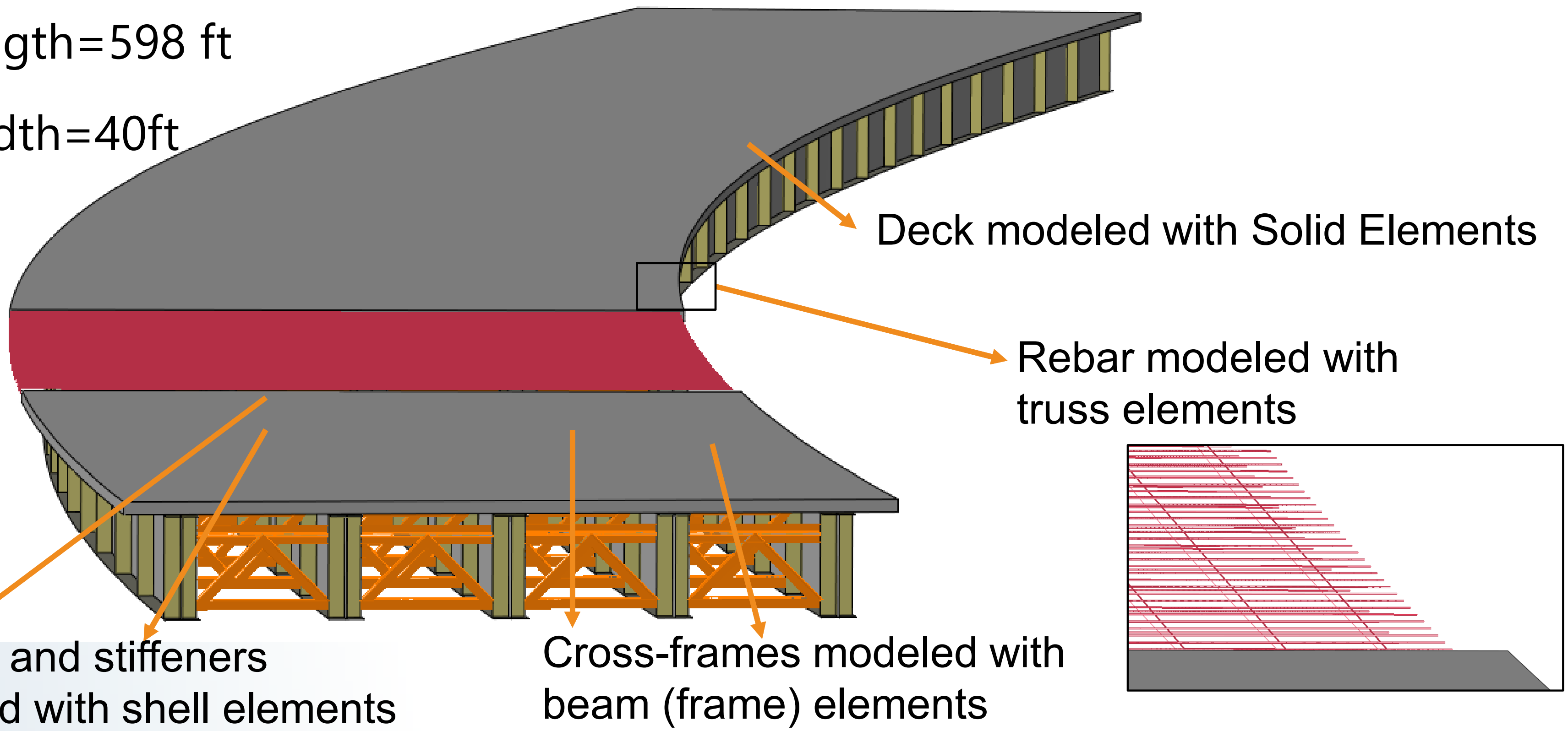
- Drying shrinkage significantly reduced with longer wet-curing, 5 to 14 days
- Concrete creep is greater at early ages
- Need to assess mixes for cracking potential with varying SCMs, curing periods, and for optimal curing

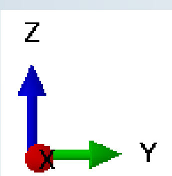
Item 4.5b - Bridge FE Model Overview

- Full scale 3D Model of Rarus/Silver Bow Creek – Bridge D created in Abaqus/CAE 2020
- 4-span bridge, 5 steel plate girders with 7.75” composite deck
- Bridge superstructure is curved orienting North-South
- FE model included full-length deck geometry, girders, and lateral braces

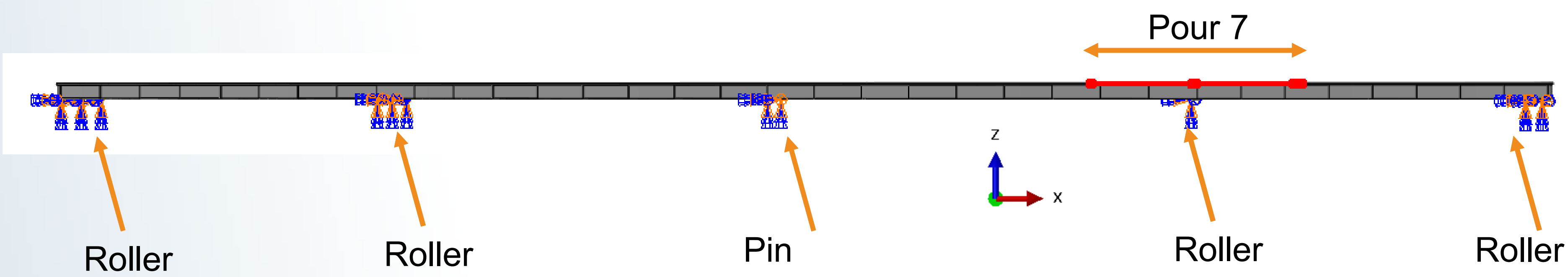
Model Assembly

- Total length=598 ft
- Deck width=40ft





Model Interactions and Boundary Conditions



- WJE instrumentation placed at Placement No. 7 (Pour 7) region.
- Pour 7 region was modeled with refined mesh.
- Rebar elements were embedded in solid concrete elements (full bond)
- Contact with rough friction was used at concrete deck and girder interface to model composite action (no slippage allowed)

FE Model Material Calibration

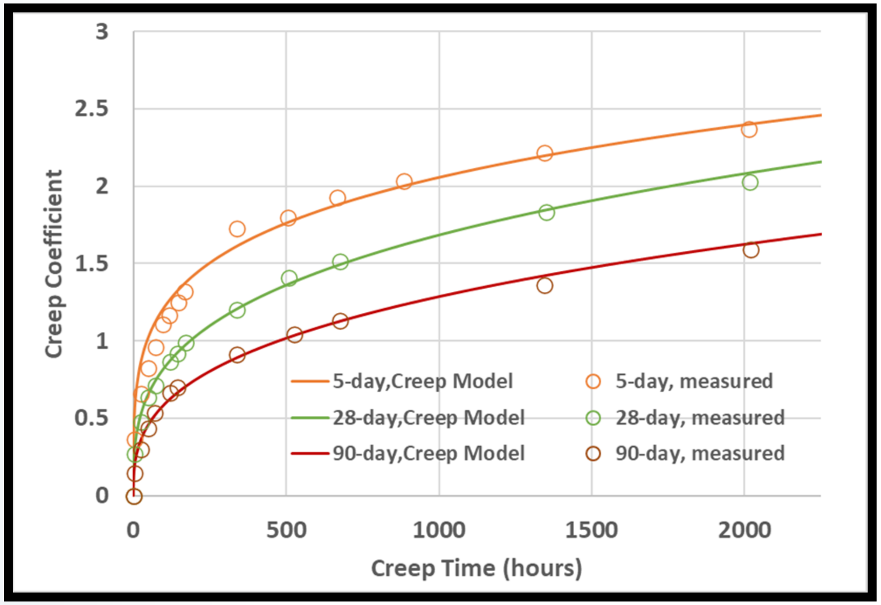
- Deck Concrete- Linear elastic with aging viscoelasticity (creep)

Age (days)	Compressive Strength (psi)	Modulus of Elasticity (ksi)	Splitting Tensile Strength (psi)	Concrete Coefficient of Thermal Expansion ($x10^{-6}/°F$)	Girder Steel Coefficient of Thermal Expansion ($x10^{-6}/°F$)
1	1480	2470	200	4.14	6.94
3	3100	2900	350	4.14	6.94
5	3530	3325	355	4.14	6.94
21	5070	4000	NA	4.14	6.94
28	5380	4400	580	4.14	6.94
90	6400	4575	590	4.14	6.94

- Tabular number show averages from the measured WJE lab tests

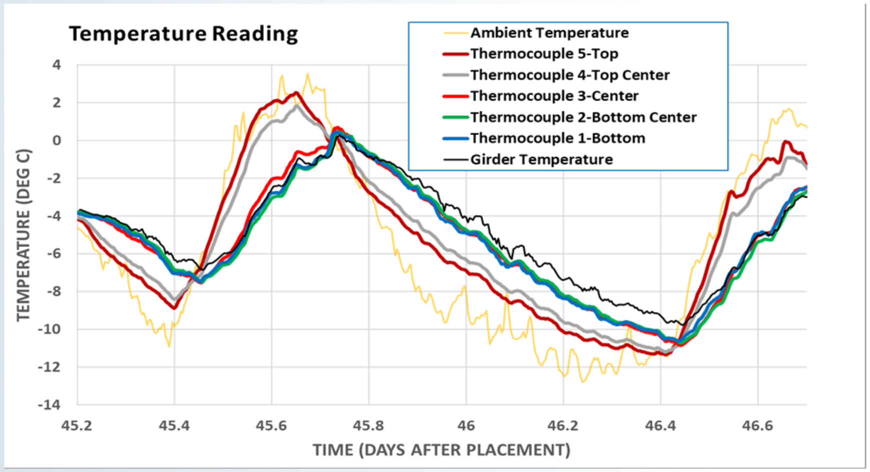
FE Model Material Calibration (cont.)

- Deck Concrete- Creep Model Calibration
  - Abaqus built-in creep model was utilized and calibrated to in-house measured creep data

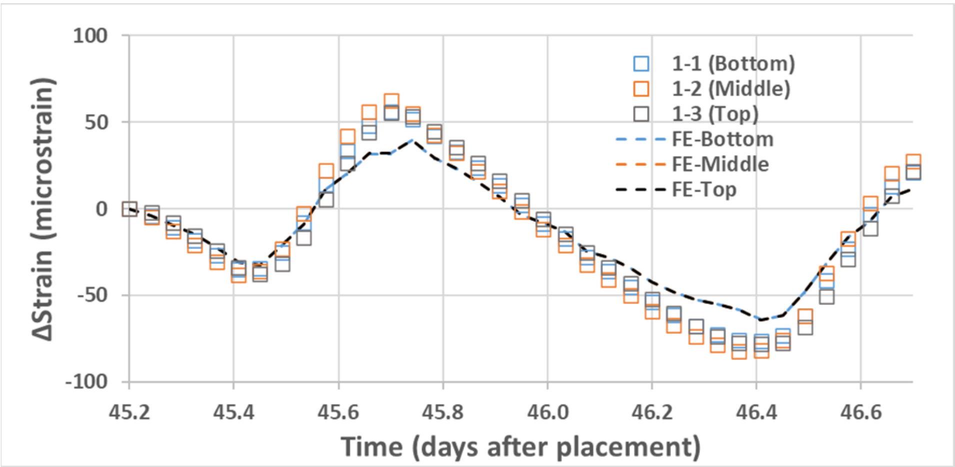


FE Model Validation

- Model was validated against field-measured strain gauge data
  - The goal was to verify the global FE model trend VS. actual field behavior



Temperature input for FE Model



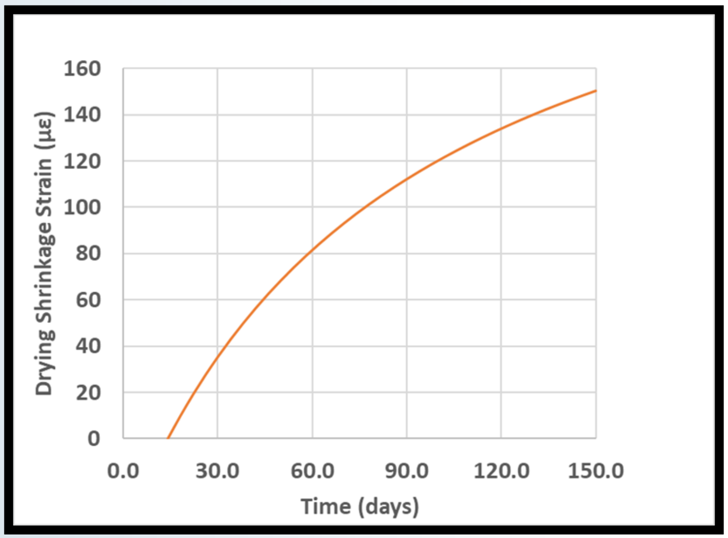
Strain output from FE Model against field-measured strain data

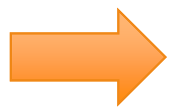
Analysis Scenarios

- Later-age Analyses (typically 90 days after placement)
- Early-age Analyses (24 hour to 14 days after placement)
- Factors investigated:
  - Drying shrinkage
  - Temperature histories (sharp drop or increase)
  - Relative humidity (moisture) histories (sharp drop or sharp increase)
  - Wet-curing time with summer or winter placements
  - Sensitivity on deck thickness and girder restraint

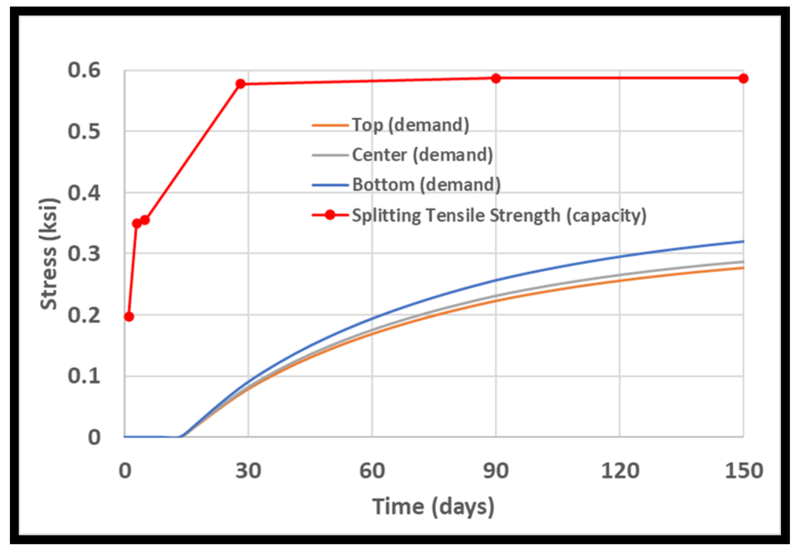
Drying Shrinkage

Drying Shrinkage based on ACI 209 approach





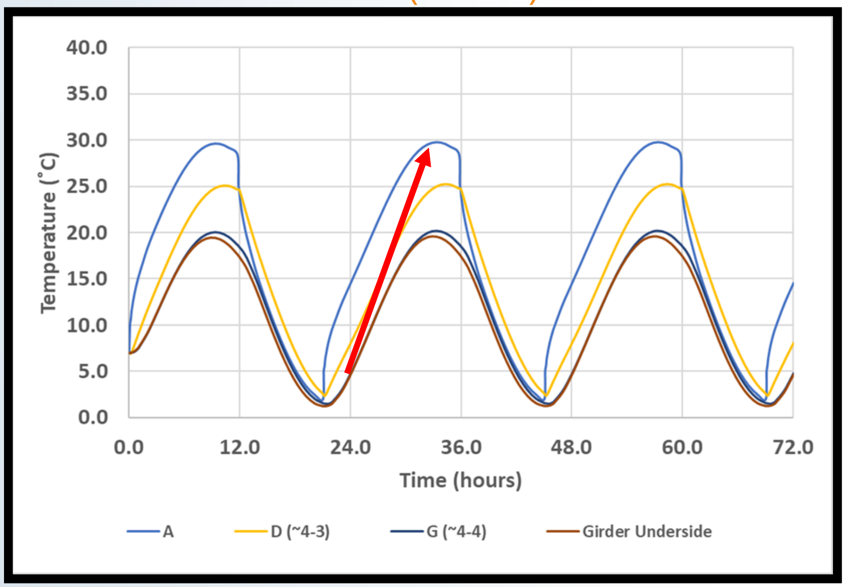
Average Resultant Longitudinal Stress vs time



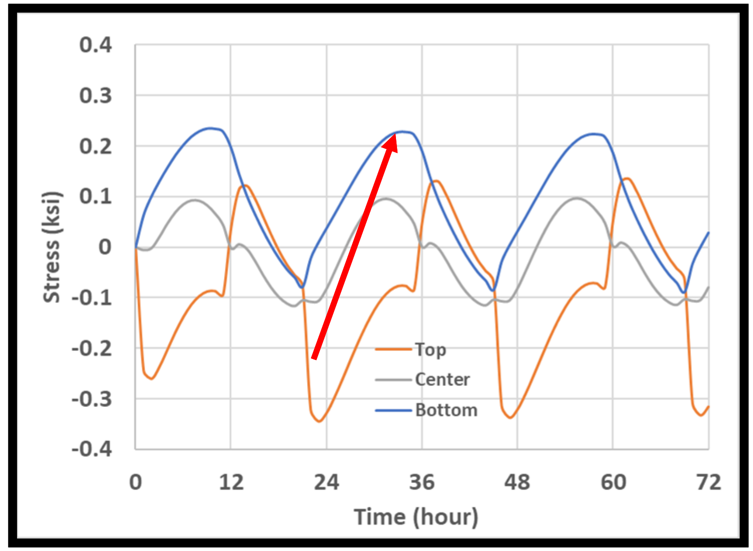
- Due to restraint drying shrinkage, tensile stresses as high as 300 psi can be developed within 150 days after placement

Later-age Summer Temperatures

Typical simulated summer temperature with max ΔT=+30˚C (+55˚F)



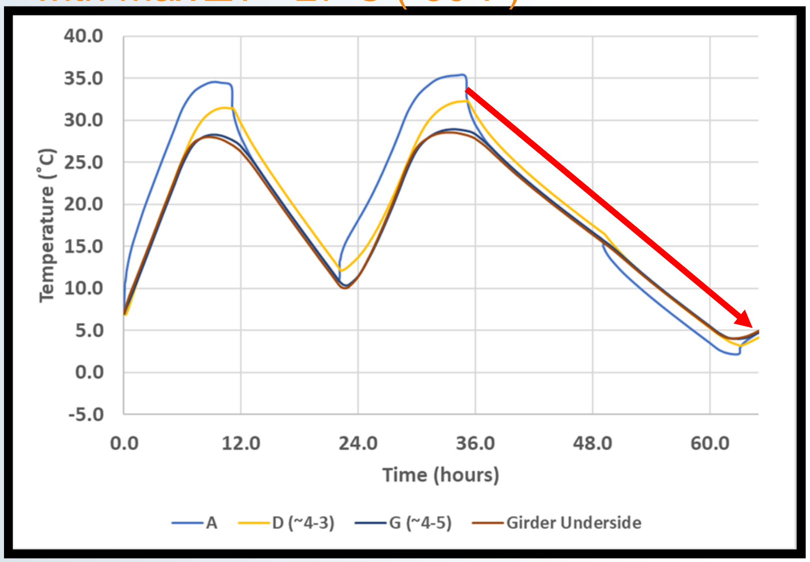
Average Resultant Longitudinal Stress vs time



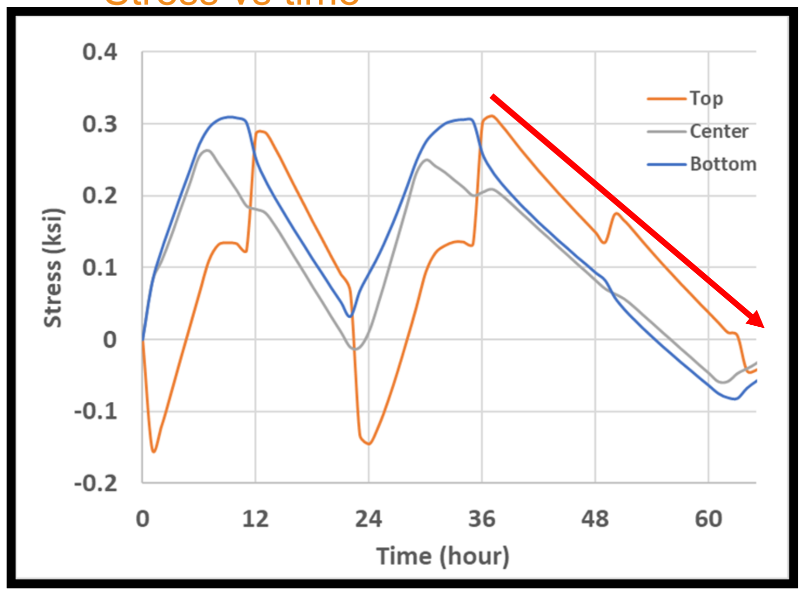
- **Tensile stress amplitude of 400 psi can develop due to nonlinear temperature rise**

Later-age Winter Temperatures

Typical simulated winter temperature with max ΔT=-27˚C (-50˚F)



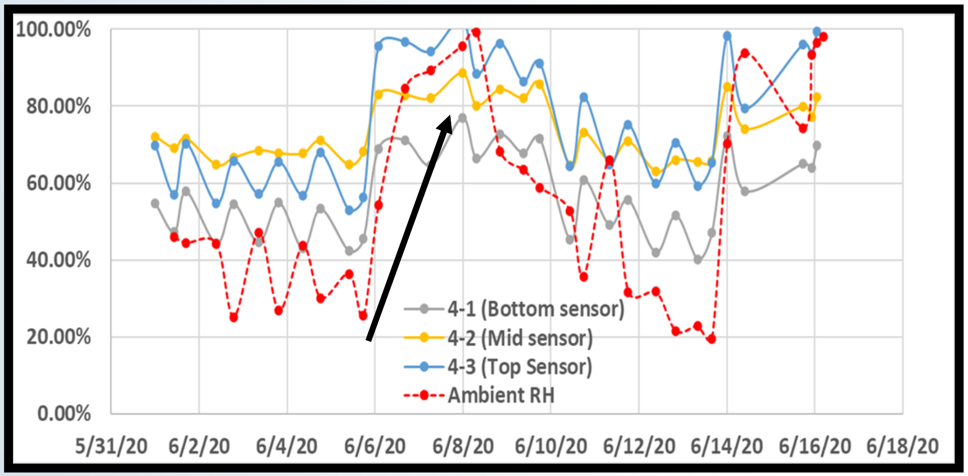
Average Resultant Longitudinal Stress vs time



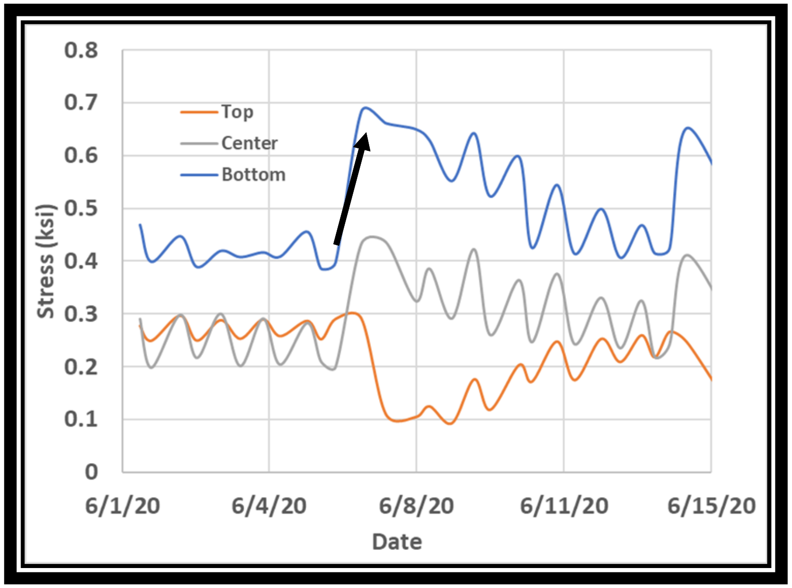
- **At the end of negative temperature swing, stresses are mostly compressive**.

Later-age Moisture Gradient

Recorded Relative Humidity at deck cross section and ambient

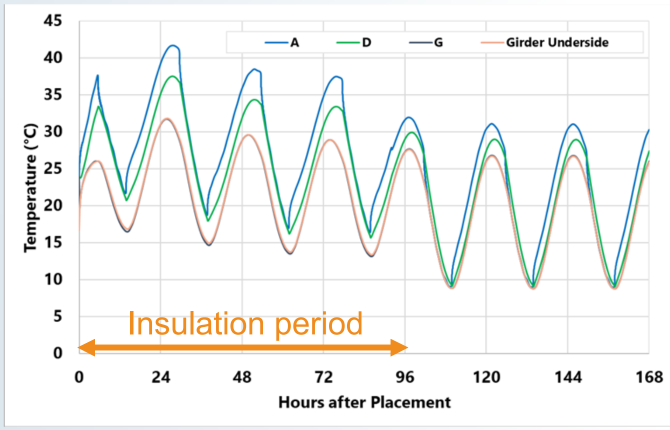


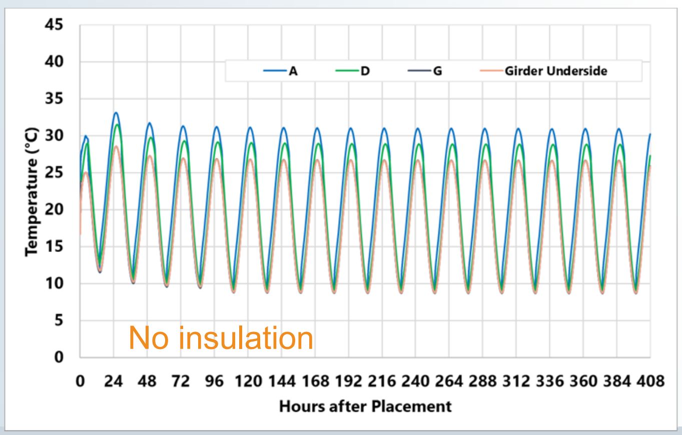
Average Resultant Longitudinal Stress vs time



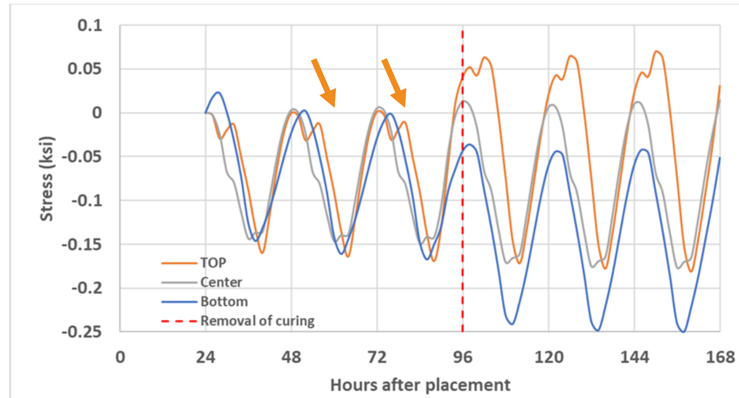
- Higher RH gradient existed after rain event.
- Elevated tensile stresses at the bottom of the deck.
- Combined effect of temperature and moisture gradient can be subtractive.

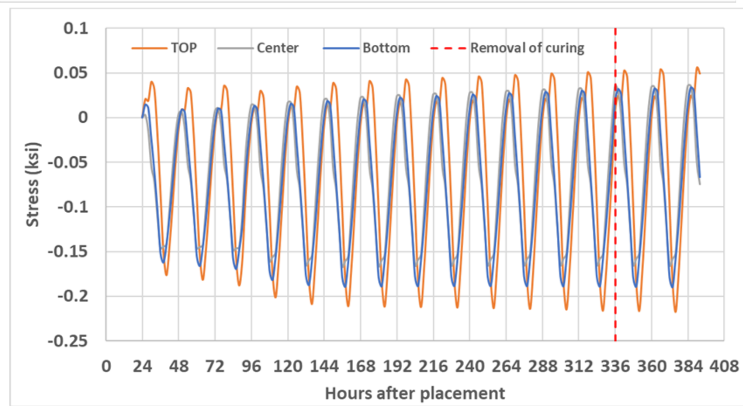
Early-age Summer Placement





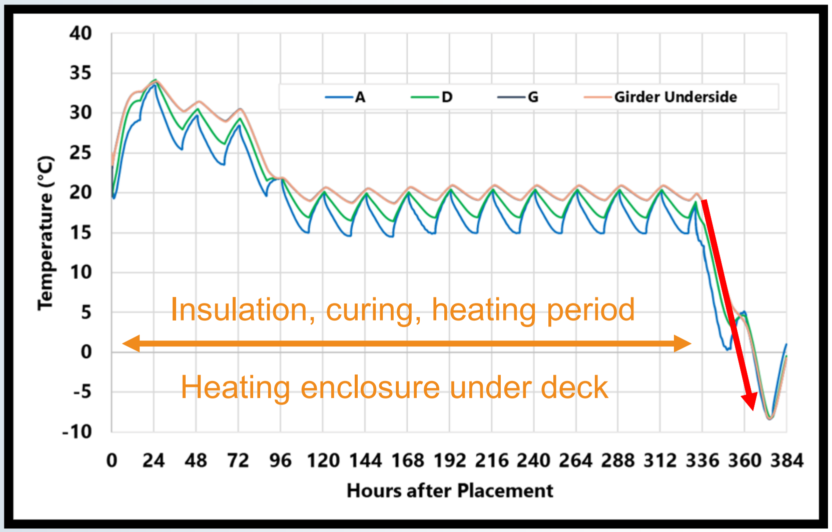
Increase in early age tensile stresses with no insulation



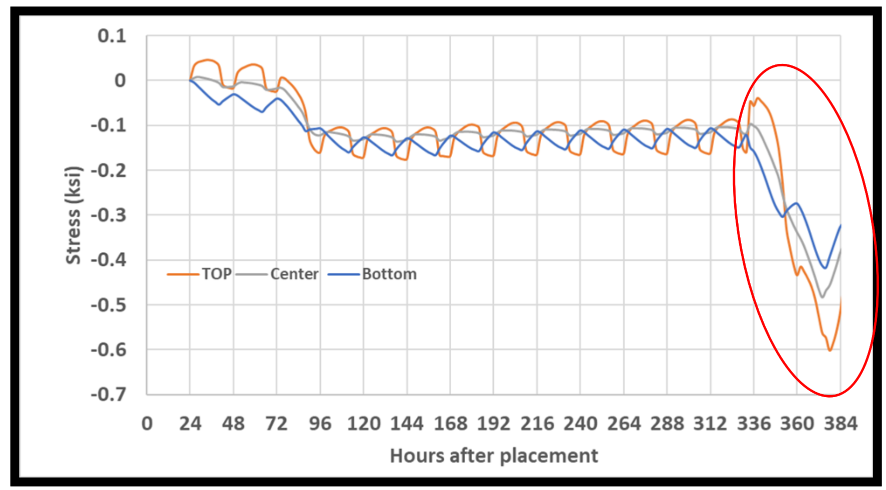


Early-age Winter Placement

Simulated winter placement temperature



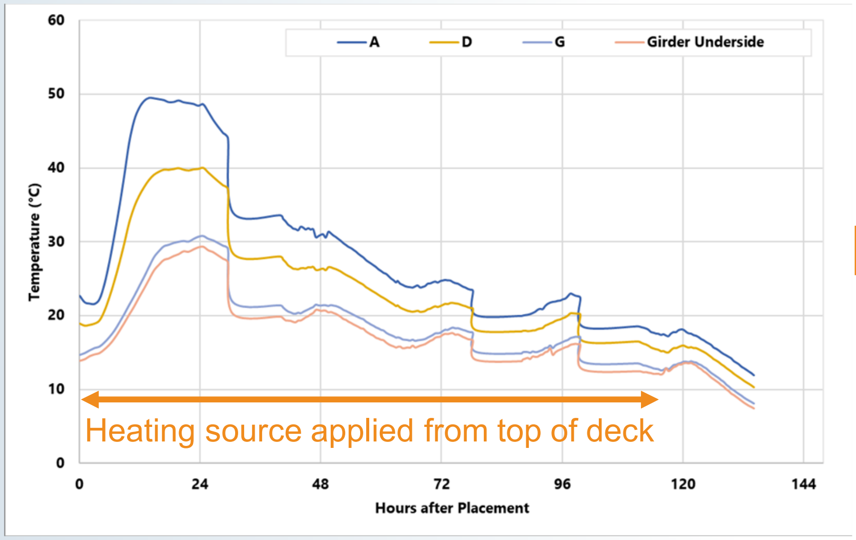
Average Resultant Longitudinal Stress vs time



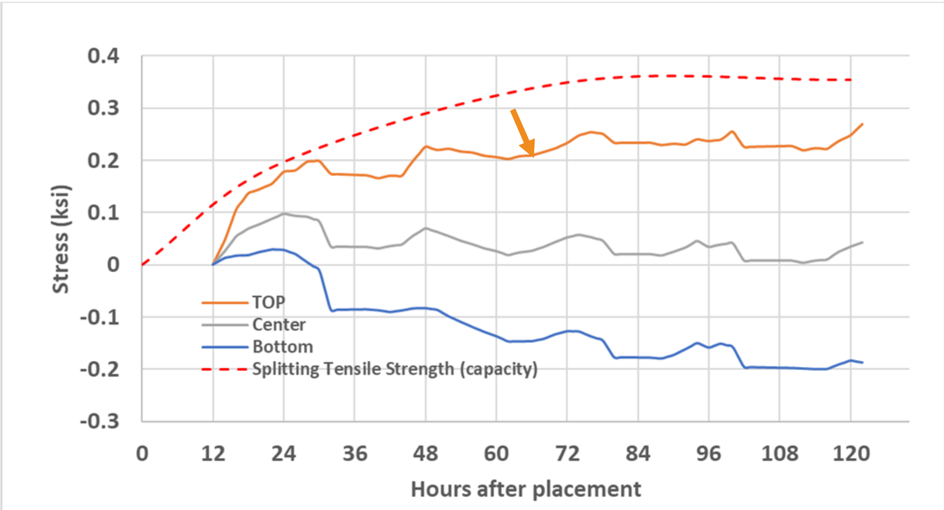
- Heated from the bottom.
- No tensile stresses developed after removal of curing measures.
- Large beneficial compressive forces develop.

Early-age Winter Placement

Winter placement temperature
estimated from Russel street bridge



Average Resultant Longitudinal
Stress vs time



- **Heated from the top**
- **Elevated tensile stresses developed within the first few days after placemen, sufficient to exceed tensile capacity.**

FE Modeling

- Deck thickness analysis
- Restraint analysis

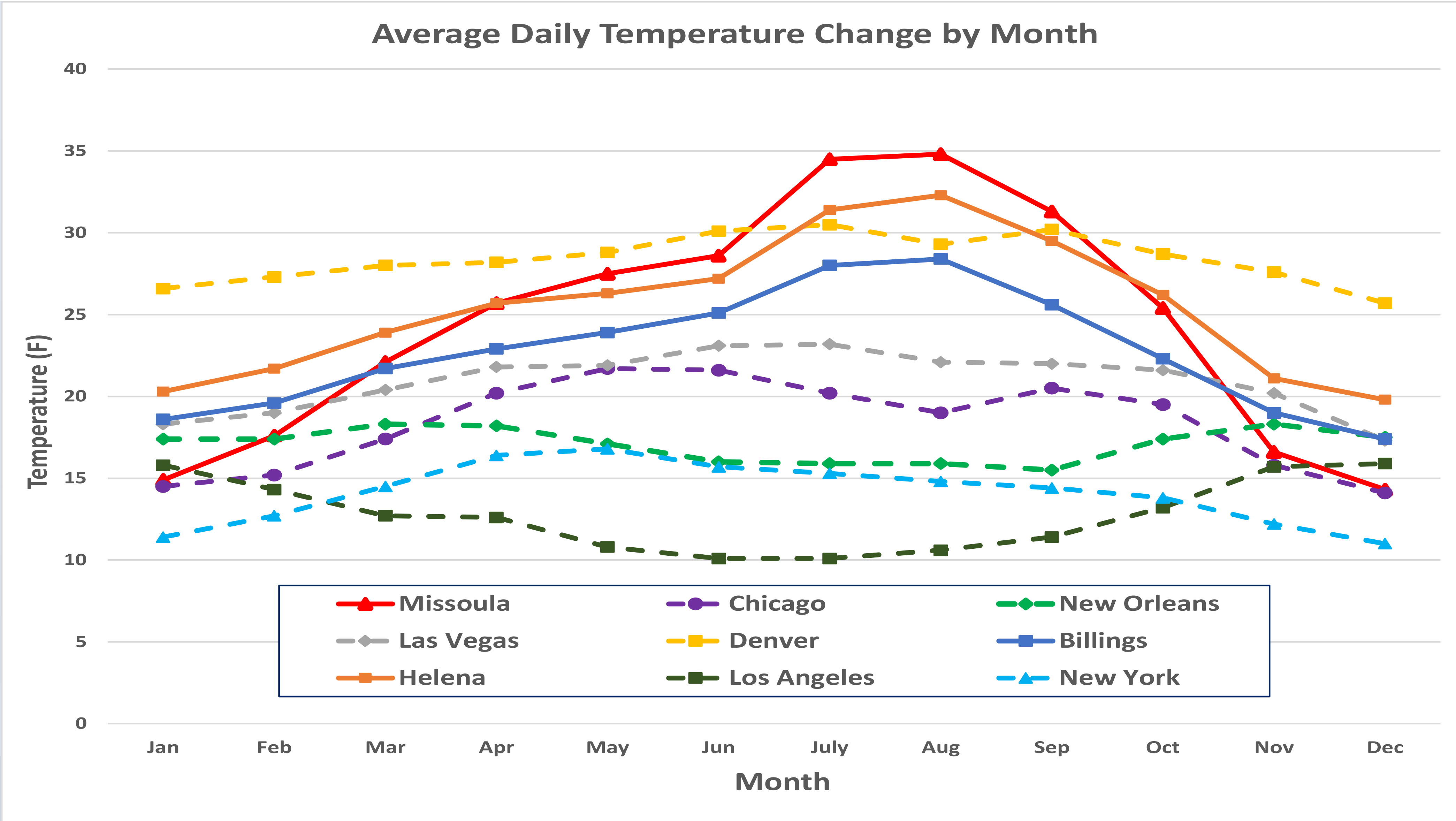
FE Modeling Summary

- Drying shrinkage can contribute up to 300 psi in tensile stress, long term
- Large temperature rises can create an increase in tensile stresses by as much as 400 psi, underside of deck
- Large changes in relative humidity can create an increase in tensile stresses by as much as 300 psi, underside of deck
- The contributions from the thermal and moisture gradients can be subtractive
- Winter curing, heating from below is preferred to heating from the top

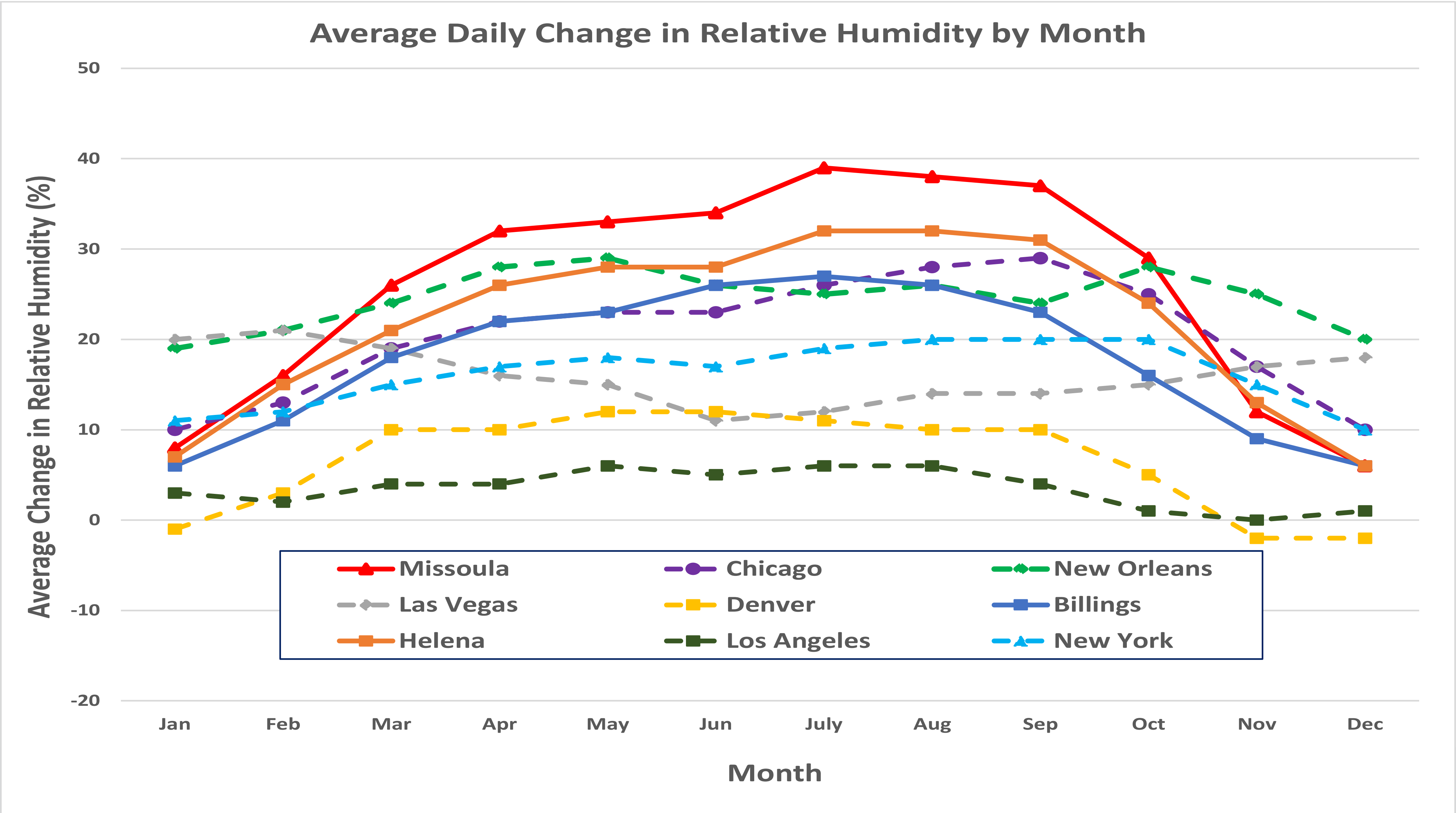
WJE's Recommendations

- Three primary goals of recommendations
  1. Reduction in drying shrinkage
  2. Reduction in thermal gradients
  3. Reduction in moisture gradients

Reduction in volumetric movement



Average Daily Temperature Change by Month
40
35
30
25
20
15
10
5
0
Temperature (F)
Missoula
Chicago
New Orleans
Las Vegas
Denver
Billings
Helena
Los Angeles
New York
Jan
Feb
Mar
Apr
May
Jun
July
Aug
Sep
Oct
Nov
Dec
Month


Average Daily Change in Relative Humidity by Month
50
40
30
20
10
0
-10
-20
Average Change in Relative Humidity (%)
Missoula
Chicago
New Orleans
Las Vegas
Denver
Billings
Helena
Los Angeles
New York
Jan
Feb
Mar
Apr
May
Jun
July
Aug
Sep
Oct
Nov
Dec
Month

WJE's Recommendations

- Mixture Proportioning
  - Reduction in total cementitious to preferably less than 600 and ideally below 550 lb/yd^3
  - W/cm between 0.40 and 0.45
  - Optimized SCM contents: low heat, low permeability and low shrinkage
  - Design consideration for 56-day strength, instead of 28 day
  - Shrinkage reducing admixtures (SRAs): reduction in drying shrinkage and potential gradients

WJE's Recommendations

- Mixture Proportioning
  - Limit silica fume use to a maximum of 5 percent
  - Optimized aggregate gradation, likely needed for reduction in cementitious content
  - Investigation in the use of lightweight aggregates (LWAs): internal cure vs. possible moisture gradient reduction. Thermal gradients?
  - Mixture optimization for use of SCMs, SRAs, aggregate gradations, and LWAs for cracking resistance

WJE's Recommendations

- Design and Construction Practices
  - Minimum deck thickness of 8 inches
  - Reduction in moisture gradients on bottom side of deck: research recommended into barrier coatings and stay-in-place (SIP) forms
  - Reduction in moisture gradients from the top: research the use of thin-polymer overlays

WJE's Recommendations

- Design and Construction Practices
  - Summer curing:
    - Continue WJE's curing procedures with insulated blankets
    - Optimization of moisture curing length performed in conjunction with mix optimization for cracking resistance
  - Winter curing:
    - Heat cure from underside is preferable, and provides additional pre-compression benefit
    - Slow removal of curing and heating from the deck

For more information, visit wje.com or call 800.345.3199

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