SOLUTIONS FOR THE BUILT WORLD

Investigation of Concrete Bridge Deck Cracking

www.wje.com

Wiss, Janney, Elstner Associates, Inc.

ENGINEERS
ARCHITECTS
MATERIALS SCIENTISTS

Todd Nelson, P.E. – Associate Principal

February 27 and 28, 2018

- Project Background
- Field Investigations
- Laboratory Evaluations
- Thermal and Stress Modeling
- Recommendations
- Why are we still having these problems?

Comprehensive Investigation

- Hands-on practical and multi-disciplinary approach to investigate the problem AND provide reasonable recommendations:
  - Field Investigation
  - Laboratory Evaluations
  - Thermal and stress modeling

Project Background - General

- Outline
- **Project Background**
- Field Investigation
- Laboratory Evaluations
- Thermal and Stress Modeling
- Recommendations
- Why?

- MDT communicated to WJE that severe transverse cracking was noted on a number of bridge decks in western Montana
- In three bridges, cracking led to deck penetrations (holes in the deck)
- Concrete decks were only 1 to 9 years old
- MDT and FHWA commissioned WJE in early 2016 to investigate the problem

Project Background – MDT Documentation

- Outline
- **Project Background**
- Field Investigation
- Laboratory Evaluations
- Thermal and Stress Modeling
- Recommendations
- Why?

Background – Distress Reported by MDT

Background – Distress Reported by MDT

Background – Distress Reported by MDT

Background – Distress Reported by MDT

Background – Distress Reported by MDT

Project Background – Document Review

- Document Review – 22 bridges, most in western MT
- Problematic bridges were most commonly re-decks
- Concrete mixes varied:
  - Cement; cement/fly ash; cement/fly ash/ silica fume
  - W/cm from 0.36 to 0.40
  - Air entrained
- Decks constructed by many different contractors
- Construction types varied: prestressed beams, welded plate girders, varying span lengths, varying girder spacing, etc.

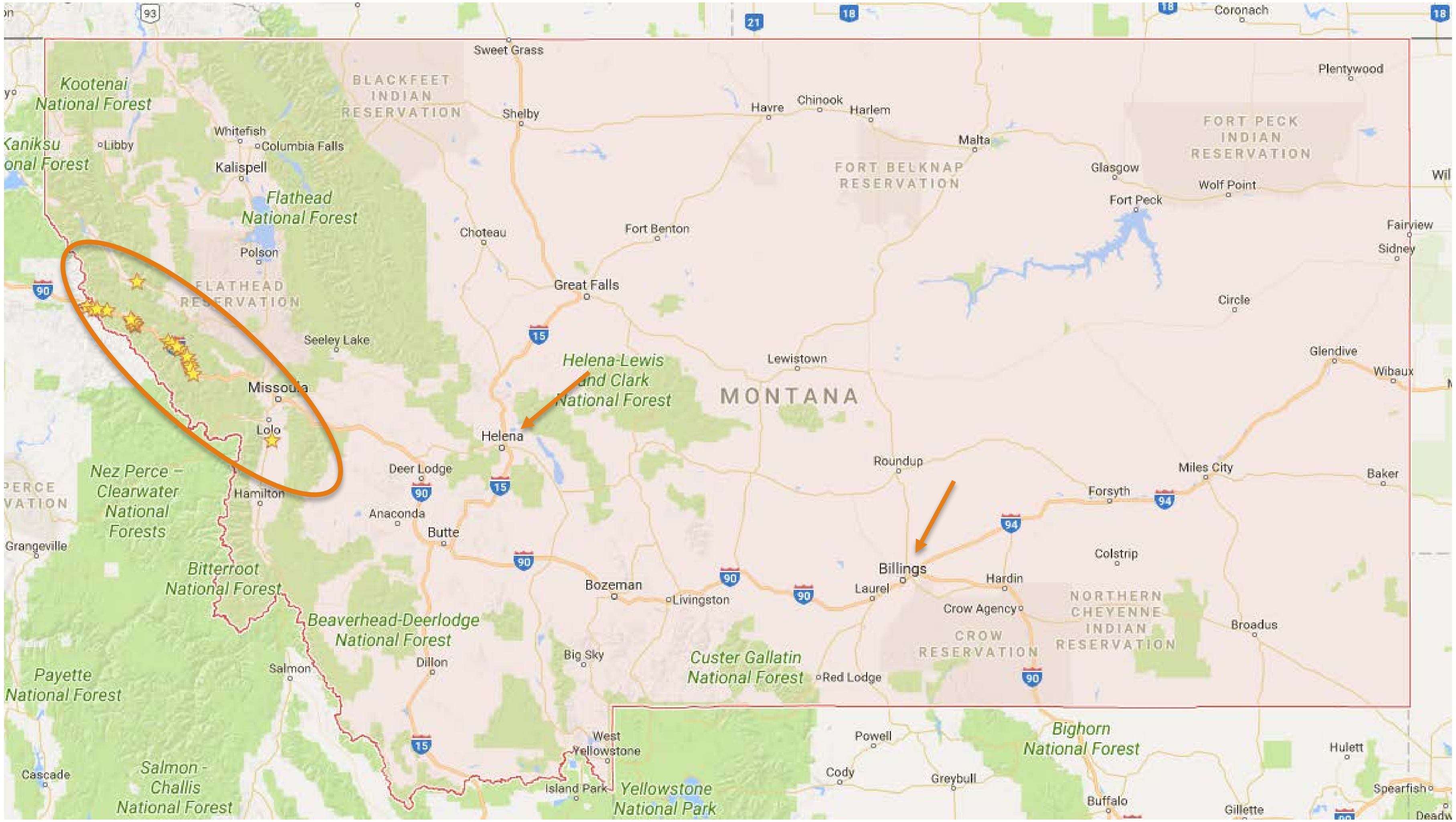
Project Background – Document Review

- Outline
- **Project Background**
- Field Investigation
- Laboratory Evaluations
- Thermal and Stress Modeling
- Recommendations
- Why?

- Total deck thicknesses varied from 6 ½ to 9 inches
- All of the re-decks included epoxy coated reinforcing steel
  - The typical transverse spacing was 6 inches for both top and bottom mats - #5s
  - Longitudinal spacing was typically 1’ 6” in top mat and 6 inches in bottom mat - #4s.
- Top cover is typically 2 3/8 inch
- Bottom cover is typically 1 inch

Project Background - Bridge Locations

- Outline
- Project Background
- **Field Investigation**
- Laboratory Evaluations
- Thermal and Stress Modeling
- Recommendations
- Why?



Project Background – Preliminary Lab Studies

- Concrete chunks were retrieved from MDT – fallen from LZ
- Based on photographs and information provided by MDT – WJE's original hypothesis - materials deterioration
- WJE performed preliminary petrographic analyses and chemistry
- Focus on any material related distress

Project Background – Preliminary Lab Studies

Project Background – Preliminary Evaluations

- No signs of internal distress (ASR, Freeze/Thaw, chemical attack, etc.)
- Aggregate quality good
- W/cm adequate
- High air content – 9 to 12 %
- White glaze on steel imprint and fractured surfaces
  - Consistent with leaching of the cement paste
- Weak paste-to-aggregate bond
- No direct contributing cause(s) to the cracking/deck penetration

Field Investigation

- Outline
- Project Background
- **Field Investigation**
- Laboratory Evaluations
- Thermal and Stress Modeling
- Recommendations
- Why?

Field Investigation

- Detailed investigation of four bridges
  - Crack mapping
  - Delamination survey
  - Infrared thermography
  - Drone (photographs, thermographic imagery, and video)
  - Ground penetrating radar
  - Concrete coring
  - Documentation performed in Plannotate
- Comparative investigations of eight additional bridges

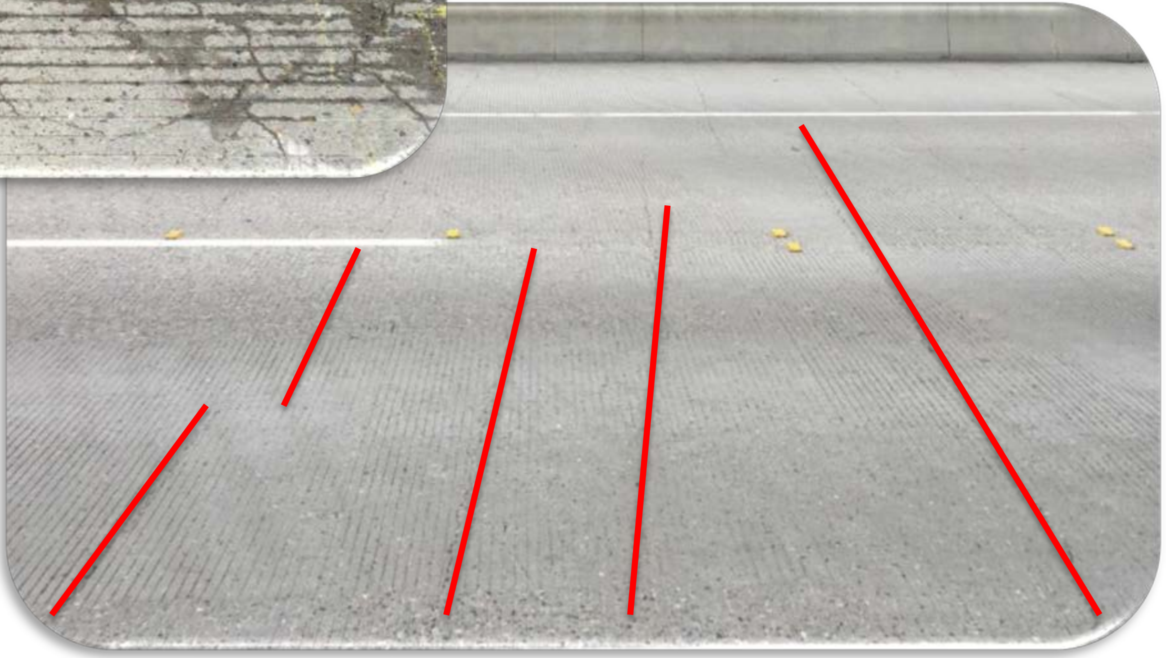
Field Investigation - Bridge Locations

Bridge Location	Year of Construction (Reconstruction)	Specified Deck Thickness	Transverse Bar Spacing: Top and Bottom Mats	Longitudinal Bar Spacing: Top Mat	Longitudinal Bar Spacing: Bottom Mat
Florence-East, MP 10.640	2014	8”	7 1/4”	1’-6”	7 3/8”
Lozeau-Tarkio, MP 57.472 EB	1967 (2011 - redeck)	7 1/4” to 8”	7” or 7 1/2”	1’-6”	7 1/2”
Lozeau-Tarkio, MP 58.550 EB	1967 (2011 - overlay)	7 1/4” to 8” (+)	6” or 10 1/2”	1’-3” or 1’-8”	5” or 6”
Lozeau-Tarkio, MP 58.550 WB	1967 (2011 - redeck)	7 1/2” to 8 1/4”	7” or 7 3/4”	1’-6”	7” or 7 1/2”
Lozeau-Tarkio, MP 57.472 WB	1967 (2011 - redeck)	7 1/4” to 8”	7” or 7 1/2”	1’-6”	7 1/2”
Henderson-West, MP 22.013	1980 (2007 - redeck)	7 1/2”	5 3/4”	1’-5 3/4”	6 1/8”
Henderson-East, MP 25.393	1980 (2008 - overlay)	7” to 7 3/4”	5”, 5 3/4”, or 6 1/4”	1’-6”	5”, 6”, or 7”
Henderson-East, MP 24.603	1980 (2008 - redeck)	6 5/8”	6 1/8”	1’-5 3/4”	6”
Henderson-East, MP 23.325	1979 (2009 - redeck)	8 1/4”	5”	1’-5 3/4”	3 1/2”
Superior Area, MP 49.397 EB	1966 (2010 - redeck)	7 1/2” to 8 1/4”	6 1/4” or 7”	1’-6”	6 7/16” or 7 11/16”
Superior Area, MP 49.397 WB	1960 (2011 - redeck)	6 3/4” to 7”	6” or 6 1/2”	1’-6”	4 1/4” or 7 1/8”
Thompson River, MP 55-56	2015	9”	6 1/4” (top) 9 3/4” (bottom)	1’-6”	9”

Field Investigation – Types of Cracking

- Outline
- Project Background
- **Field Investigation**
- Laboratory Evaluations
- Thermal and Stress Modeling
- Recommendations
- Why?

Map cracking

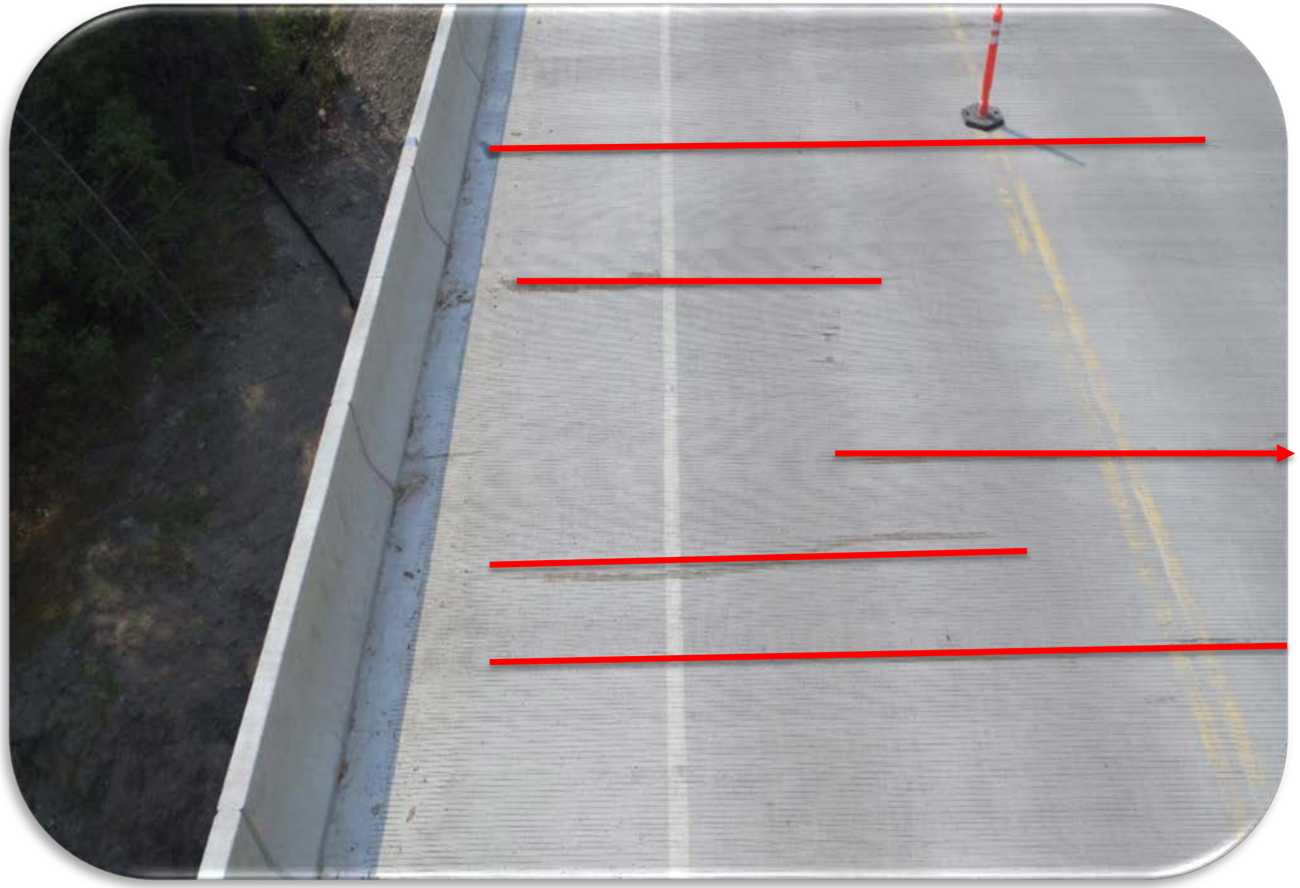


Transverse cracking

Field Investigations – Transverse Cracking

Field Investigation – Transverse Cracking

- Outline
- Project Background
- **Field Investigation**
- Laboratory Evaluations
- Thermal and Stress Modeling
- Recommendations
- Why?



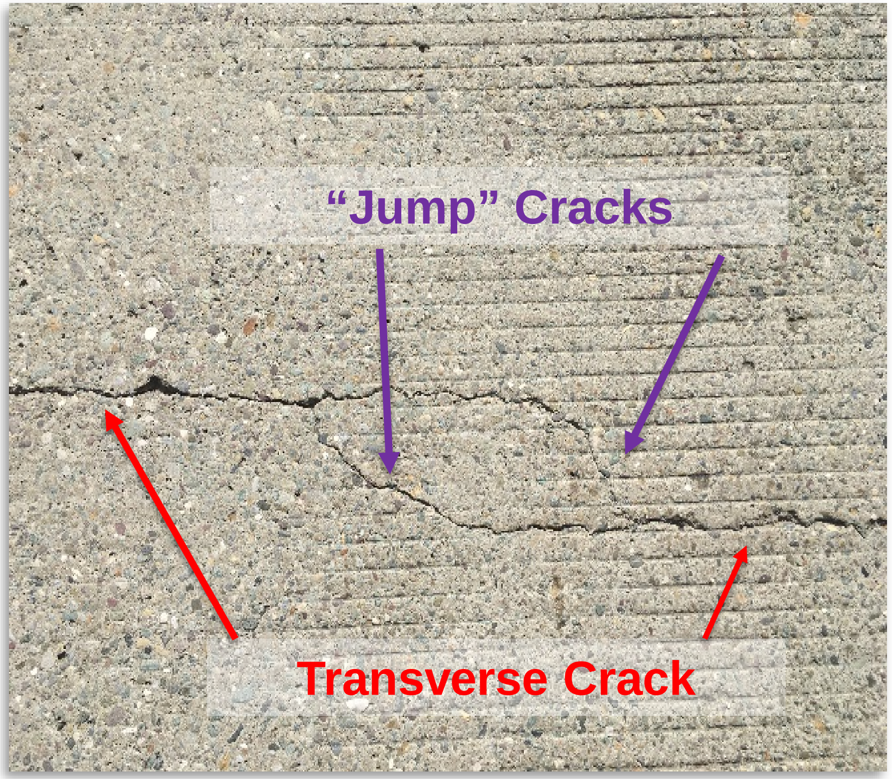
Transverse cracking

Field Investigation – Transverse Cracking

Transverse cracking - Underside

Field Investigation - Characteristic Cracking

- Outline
- Project Background
- **Field Investigation**
- Laboratory Evaluations
- Thermal and Stress Modeling
- Recommendations
- Why?



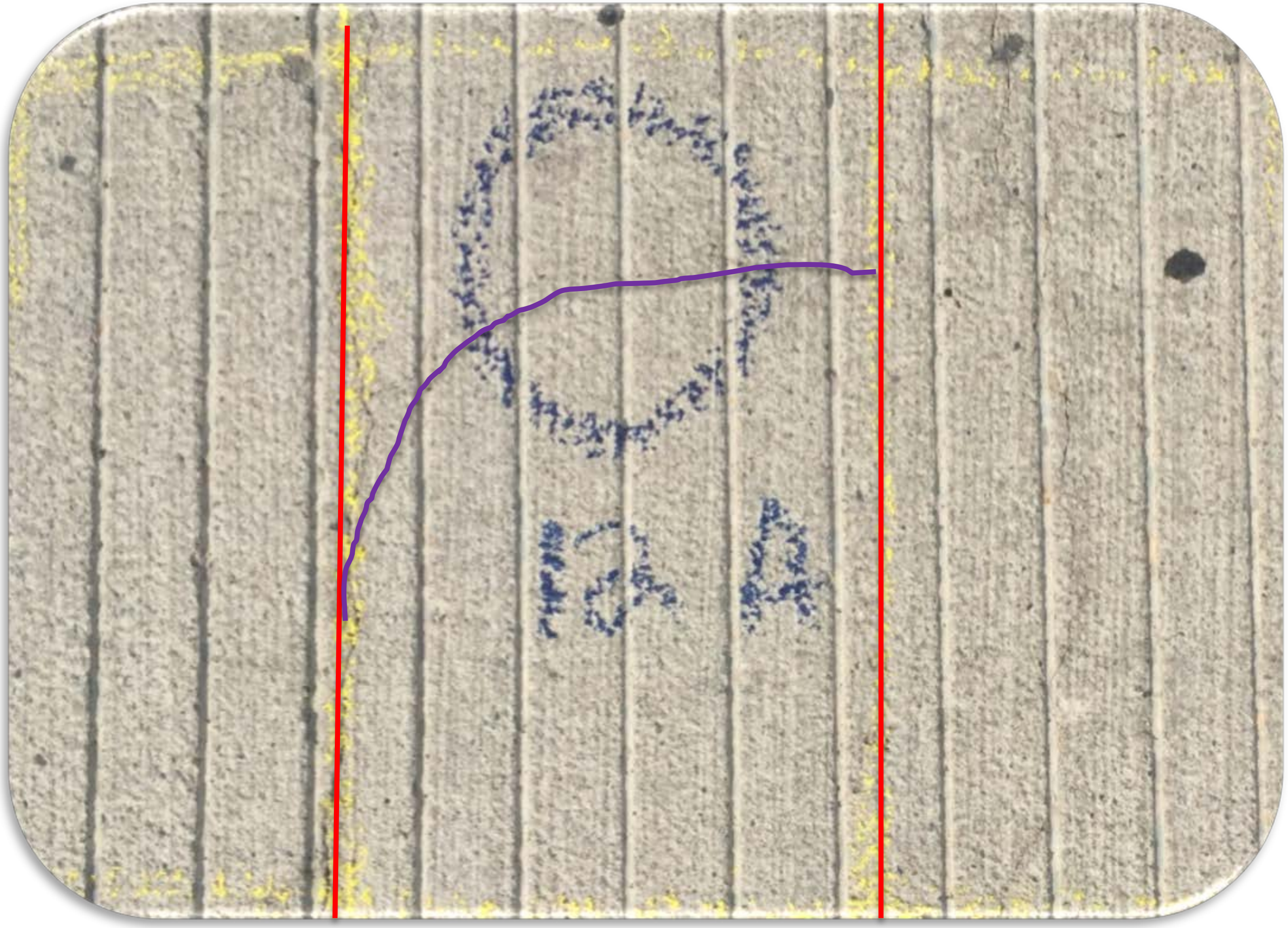
"Jump" cracking

Field Investigation - Characteristic Cracking

- Hypothesis on crack progression:
  1. Transverse cracks develop, likely early
  2. Transverse cracks progress over time
  3. Closely-spaced transverse cracks form “jump” cracks
  4. Continued volumetric movement and traffic loading - widen and ravel transverse and “jump” crack
  5. Deck penetrations may develop at “jump” cracks with the right conditions:
     - ➢ Deck penetrations more prone to occur with top and bottom mats aligned
     - ➢ The more closely spaced the transverse cracks, the more likely deck penetrations will occur
     - ➢ Driving lanes and under wheel paths more susceptible

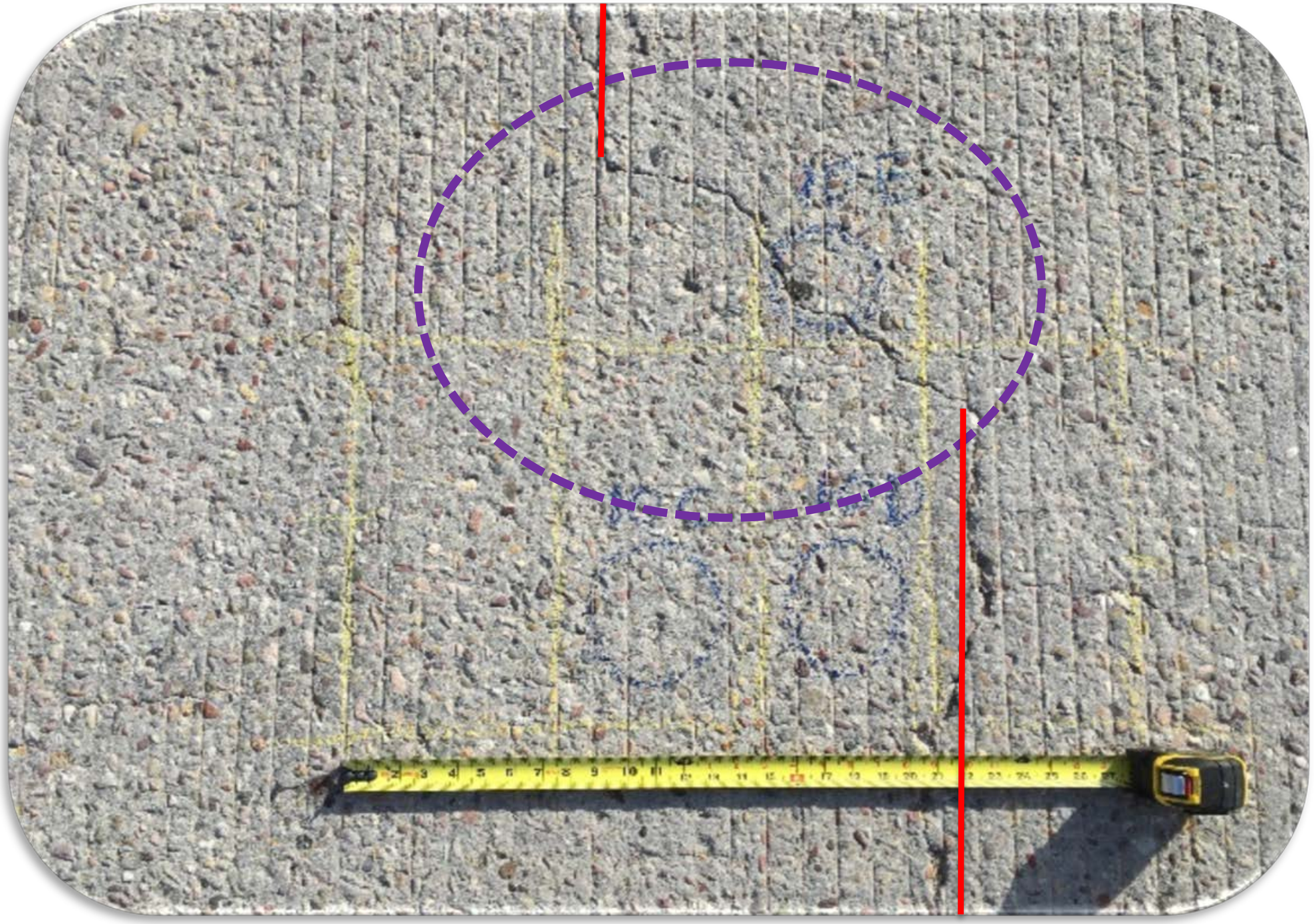
Field Investigation - Characteristic Cracking

- Outline
- Project Background
- **Field Investigation**
- Laboratory Evaluations
- Thermal and Stress Modeling
- Recommendations
- Why?



Field Investigation - Characteristic Cracking

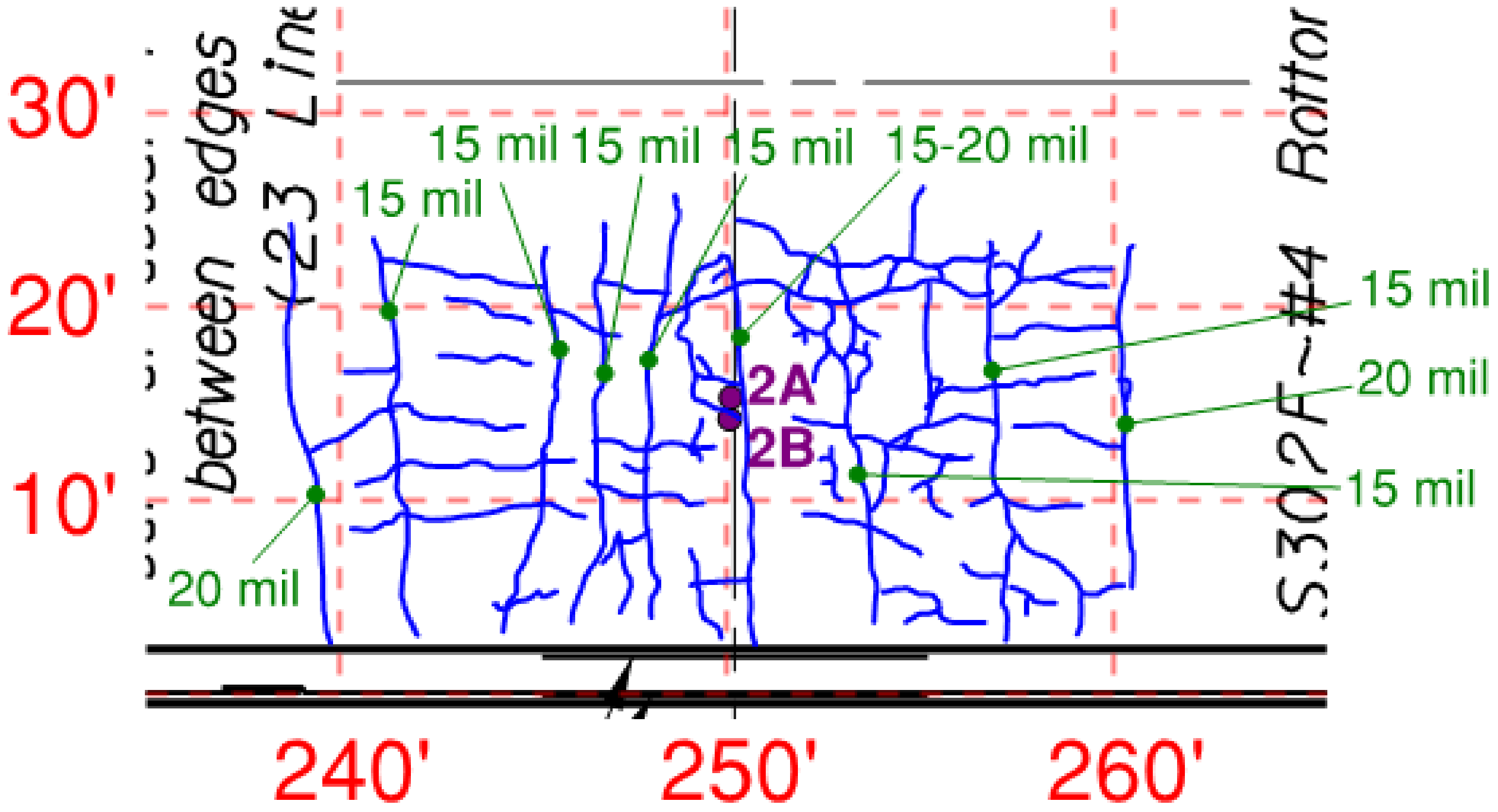
- Outline
- Project Background
- **Field Investigation**
- Laboratory Evaluations
- Thermal and Stress Modeling
- Recommendations
- Why?



Field Investigation – Deck Penetration

Field Investigation – Crack Mapping

- Outline
- Project Background
- **Field Investigation**
- Laboratory Evaluations
- Thermal and Stress Modeling
- Recommendations
- Why?



Field Investigation – Cracking

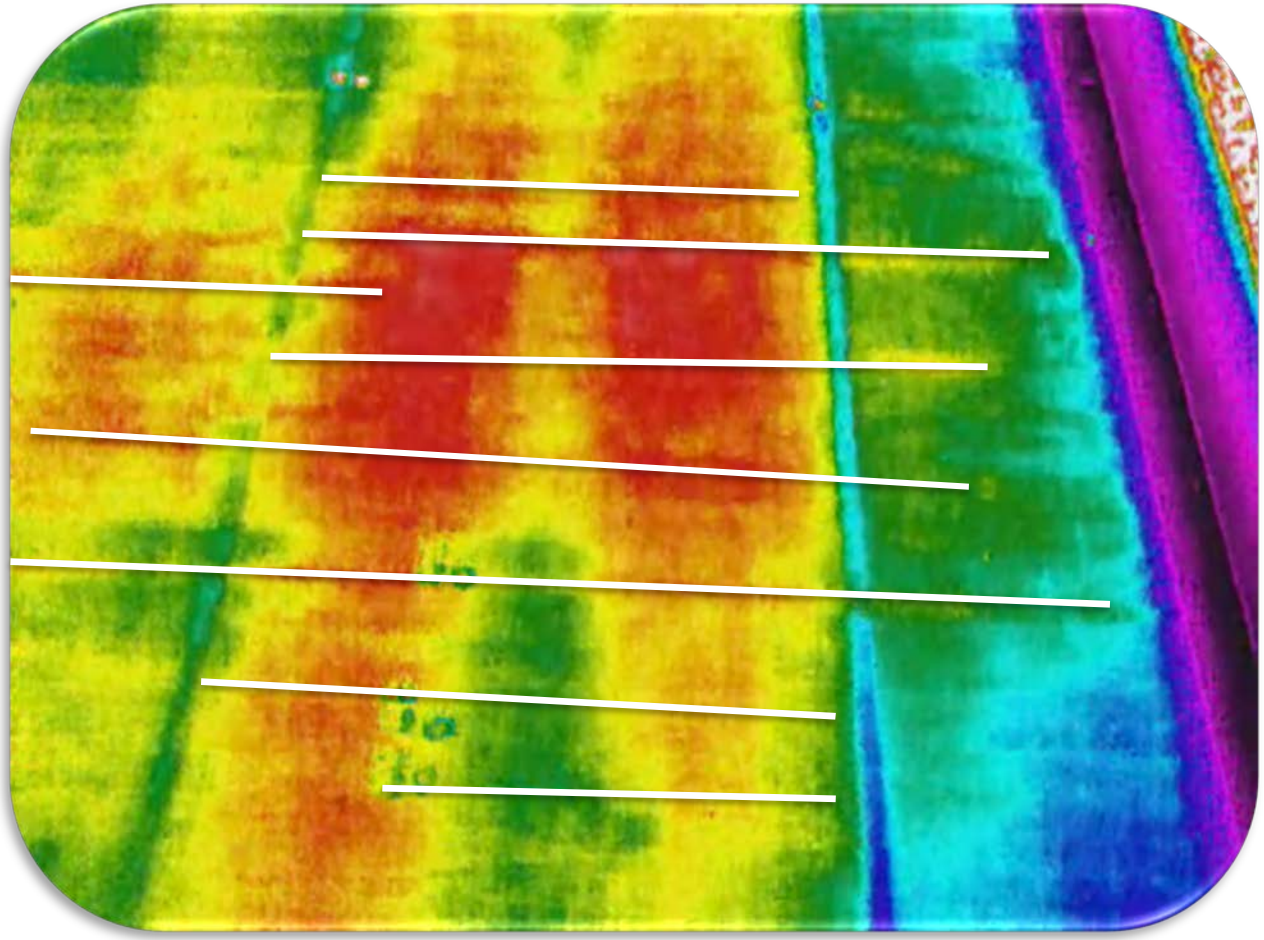
- Transverse crack spacing varied from 2 to 4 feet on most bridges
  - More frequent then typical
- Transverse cracks predominately over transverse bars (GPR)
- Width of transverse cracks were typically 15 to 25 mils
- Plastic shrinkage cracking noted on some decks, most severe on Florence-East MP 10.640 - 1 year old and contained silica fume concrete.
- Longitudinal cracking noted, but not significant

Field Investigation – Other Observations

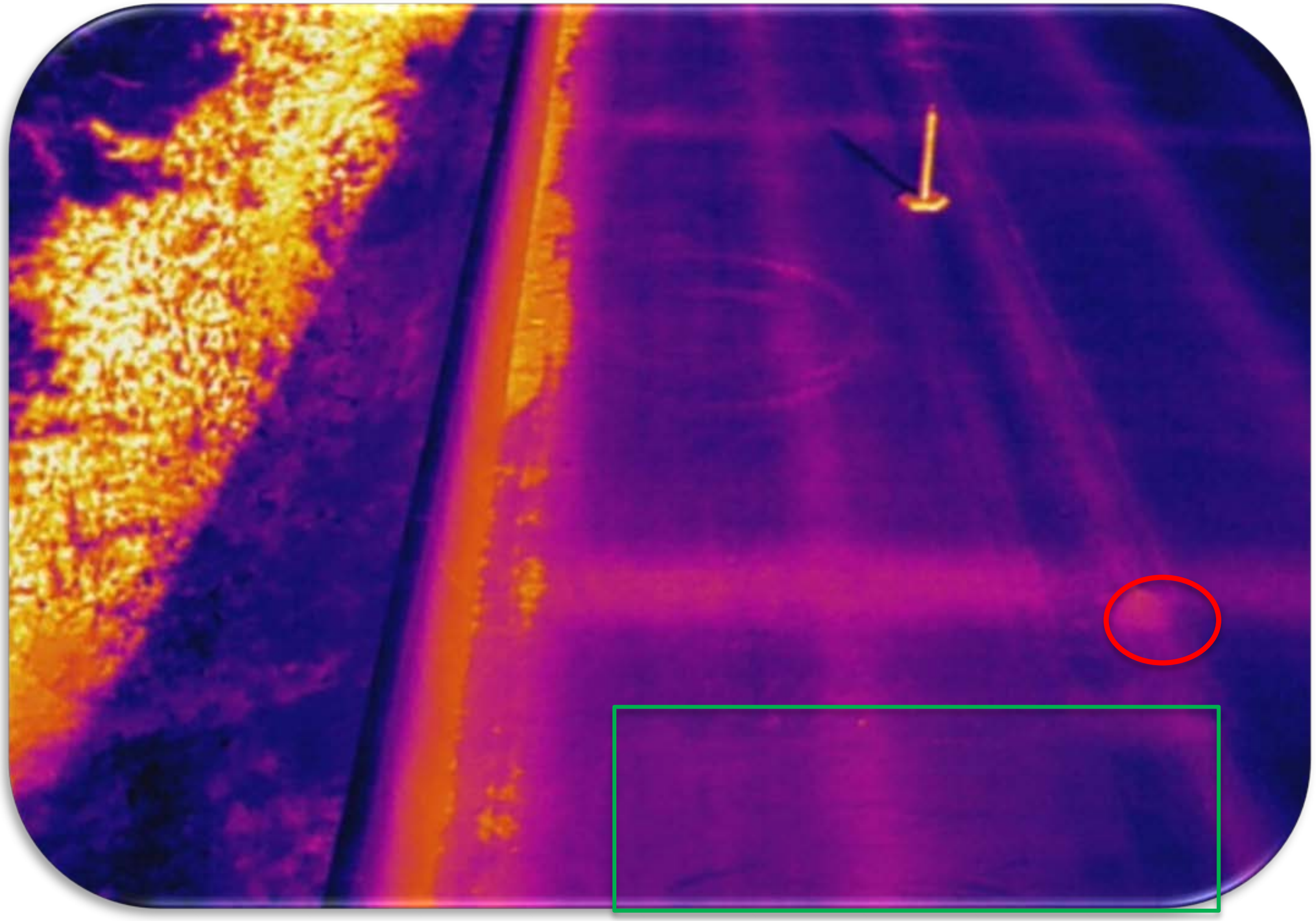
- Very little delamination noted on any of the bridges
  - Based on chain dragging and infrared images of representative areas
- Deck overlays appear to be performing well
  - 3 of the inspected bridges had overlays (as opposed to re-decks)
  - Much less cracking – transverse cracking 5 to 8 feet apart
  - Very little delamination noted
  - Overlays appeared to be cementitious/silica fume mix

Field Investigation – Drone Photographs

Field Investigation – Infrared Thermography



Field Investigation – Infrared Thermography



Field Investigations – Deck Temperatures

- Concrete deck surface and underside temperatures were measured
  - Surface temperatures varied from 42 F to 104 F
  - Underside temperatures varied from 40 to 58 F
  - Very high temperature swings! Fairly unique to Montana
  - Relevant to subsequent thermal analysis and modeling

Field Investigation – GPR

- Outline
- Project Background
- **Field Investigation**
- Laboratory Evaluations
- Thermal and Stress Modeling
- Recommendations
- Why?

Bridge	Range	Depth of Slab (inch)[1]			Top Transverse Bar Location (inch)			Bottom Transverse Bar Location (inch)		
		Spec.	Est.	Meas.	Spec.	Est.	Meas.	Spec.	Est.	Meas.
1	Entire length	8	7 3/4	8 1/4	2 3/8	2 1/2	2 1/2, 2 5/8	6 3/8	-	7 1/8, 6 5/8
2	0' to 117'-3"	7 1/4	-	-	2 3/8	-	-	5 5/8	-	-
	117'-3" to 198'-9"	7 3/4	-	7 5/8	2 3/8	-	2 1/2	6 1/8	-	6 1/4
	198'-9" to 296'	8	7 1/8		2 3/8	2 1/8	-	6 3/8	-	-
3	*Overlay*									
4	*Not measured*									
5	*Not measured*									
6	Entire length	7 1/2	7	-	2 3/8	2 1/4	2 5/8	5 7/8	-	-
7	*Overlay*									
8	*Not measured*									
9	*Not measured*									
10	0' to 75'	8 1/4	-	-	2 3/8		-	6 5/8	-	-
	75' to 725'	7 1/2	7 1/2	-	2 3/8	2 3/4	-	5 7/8	-	6 3/8
	725' to 800'	8 1/4	-	-	2 3/8	-	-	6 5/8	-	-
11	0' to 75'	7	-	-	2 3/8	-	-	5 3/8	-	-
	75' to 725'	6 3/4	6 1/4	-	2 3/8	2 1/8	2 5/8	5 1/8	4 7/8	-
	725' to 800'	7	-	-	2 3/8	-	-	5 3/8	-	-
12	Entire length	9	8 1/4	-	2 3/8	2 1/2	-	7 3/8	-	-

Field Investigations – Concrete Cores

- Outline
- Project Background
- **Field Investigation**
- Laboratory Evaluations
- Thermal and Stress Modeling
- Recommendations
- Why?

Concrete Core Extraction

- A total of 43 cores were extracted from 8 bridges
- Cores were extracted over "jump" cracks, transverse cracks, and no cracks
- Tried to capture progression of cracks
- Sampled from decks with straight cement and SCMs
- Sampled from two overlay bridges
- Varying severity of transverse cracks

Laboratory Evaluations

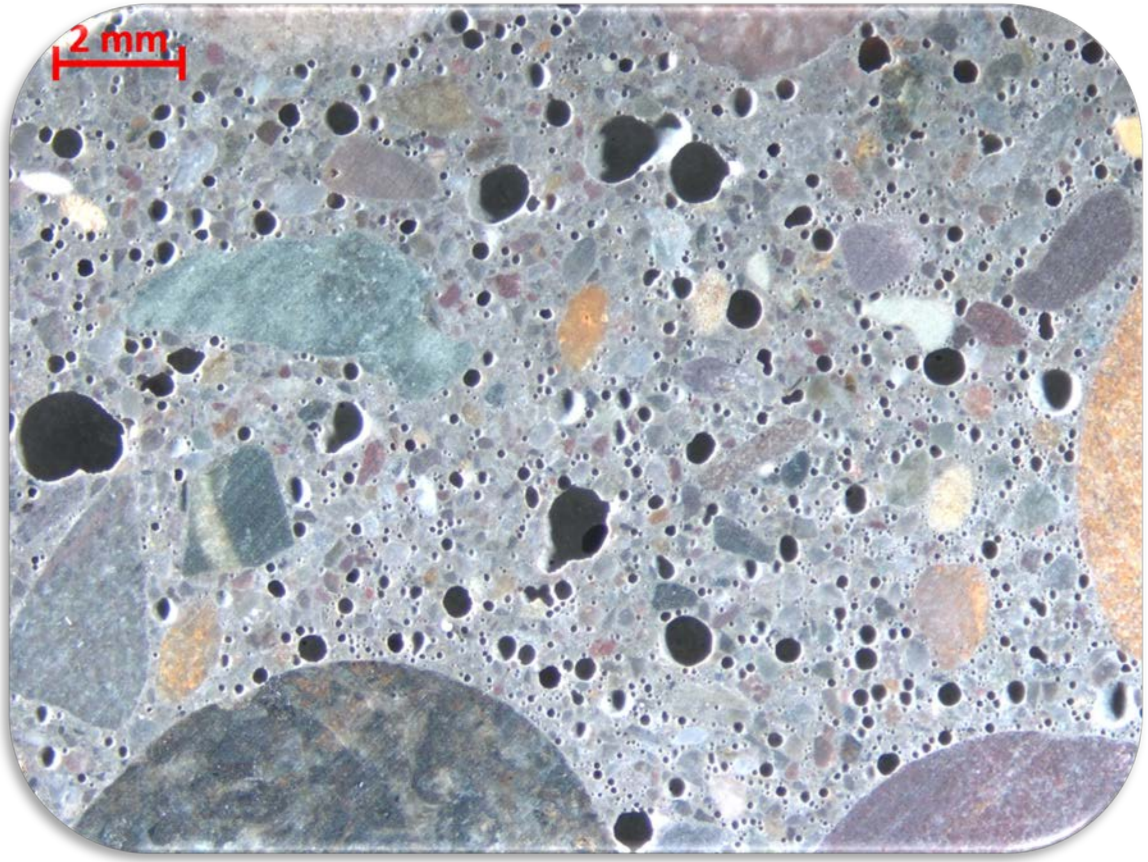
- Laboratory Evaluations
  - Petrographic Analyses (ASTM C856)
  - Physical Properties
    - Compressive Strength (ASTM C42)
    - Splitting Tensile Strength (ASTM C469)
    - Thermal property evaluation (COTE)
  - Others (Chloride ion content, x-ray diffraction, SEM)

Laboratory Evaluations - Petrography

Laboratory Evaluations - Petrography

Laboratory Evaluations - Petrography

- All transverse and “jump” cracks appeared to have initiated very early – cracks propagate around aggregates
- No signs of internal distress
- Air void system is good for freeze/thaw durability
  - Excessively high on some cores – 12%
- Aggregates are sound
- W/cm ratios were adequate, occasionally slightly elevated



Laboratory Evaluations – Physical Properties

- Compressive strength
  - 5,090 to 7,370 psi (specified 4,500 psi)
- Modulus of Elasticity
  - 3.3 to 4.5 $x10^6$ psi
- Splitting tensile strength
  - 600 to 770 psi
- Coefficient of thermal expansion
  - 3.6 to 5.0 $x 10^{-6}$

Thermal and Stress Modeling

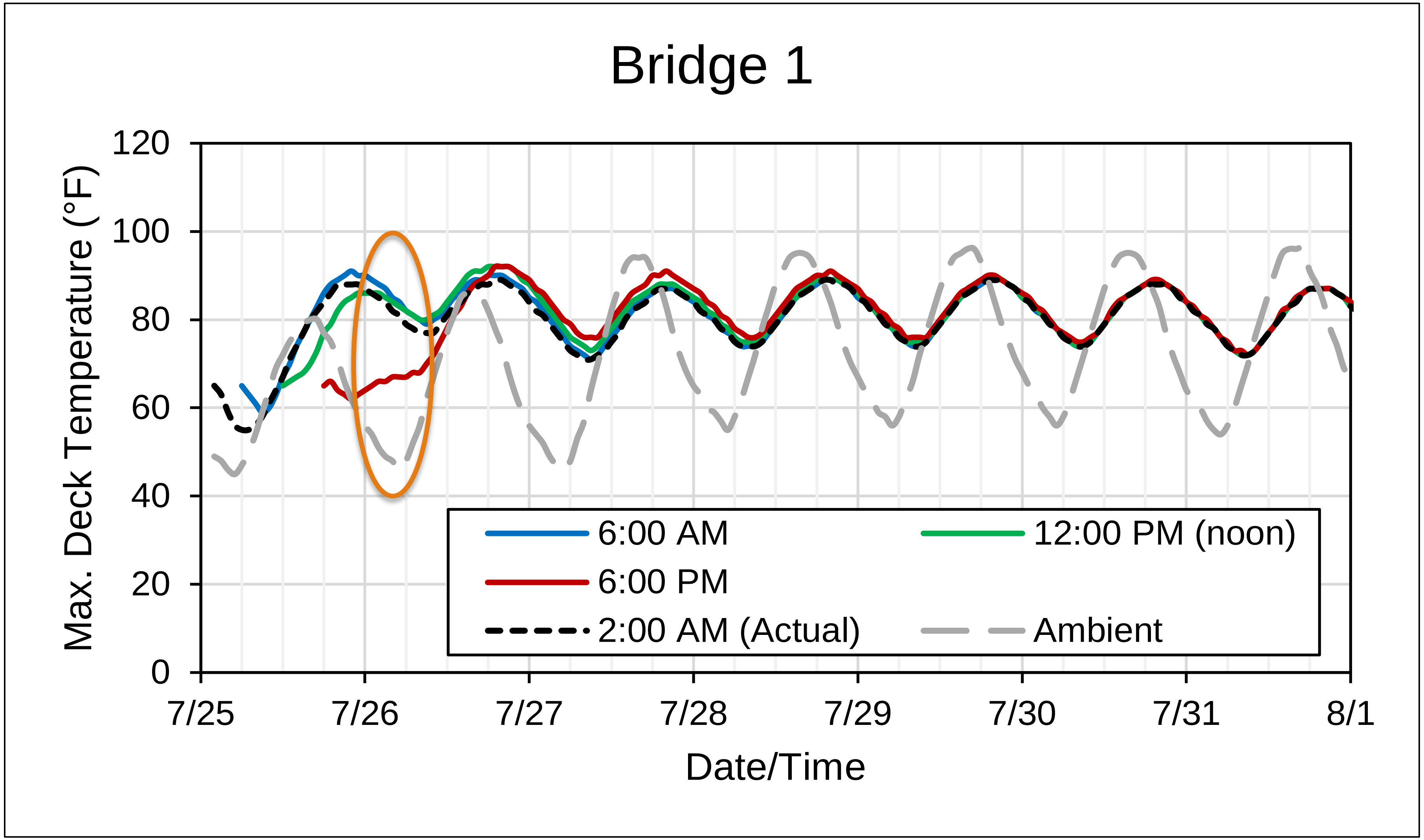
- Thermal and stress modeling on three bridges
  - Temperature model: ConcreteWorks
  - Stress model: Mathcad tool based on Zuk (1961)[1]
- Why?
  - Have a better understanding f early age temperature changes and gradients
  - Have a better understanding of early age stress
  - Sensitivity analysis – most important variables
  - Results to help guide recommendations

[1]Zuk, W. "Thermal and Shrinkage Stresses in Composite Beams," *Journal of the American Concrete Institute*, (1961): 327-340.

Thermal and Stress Modeling

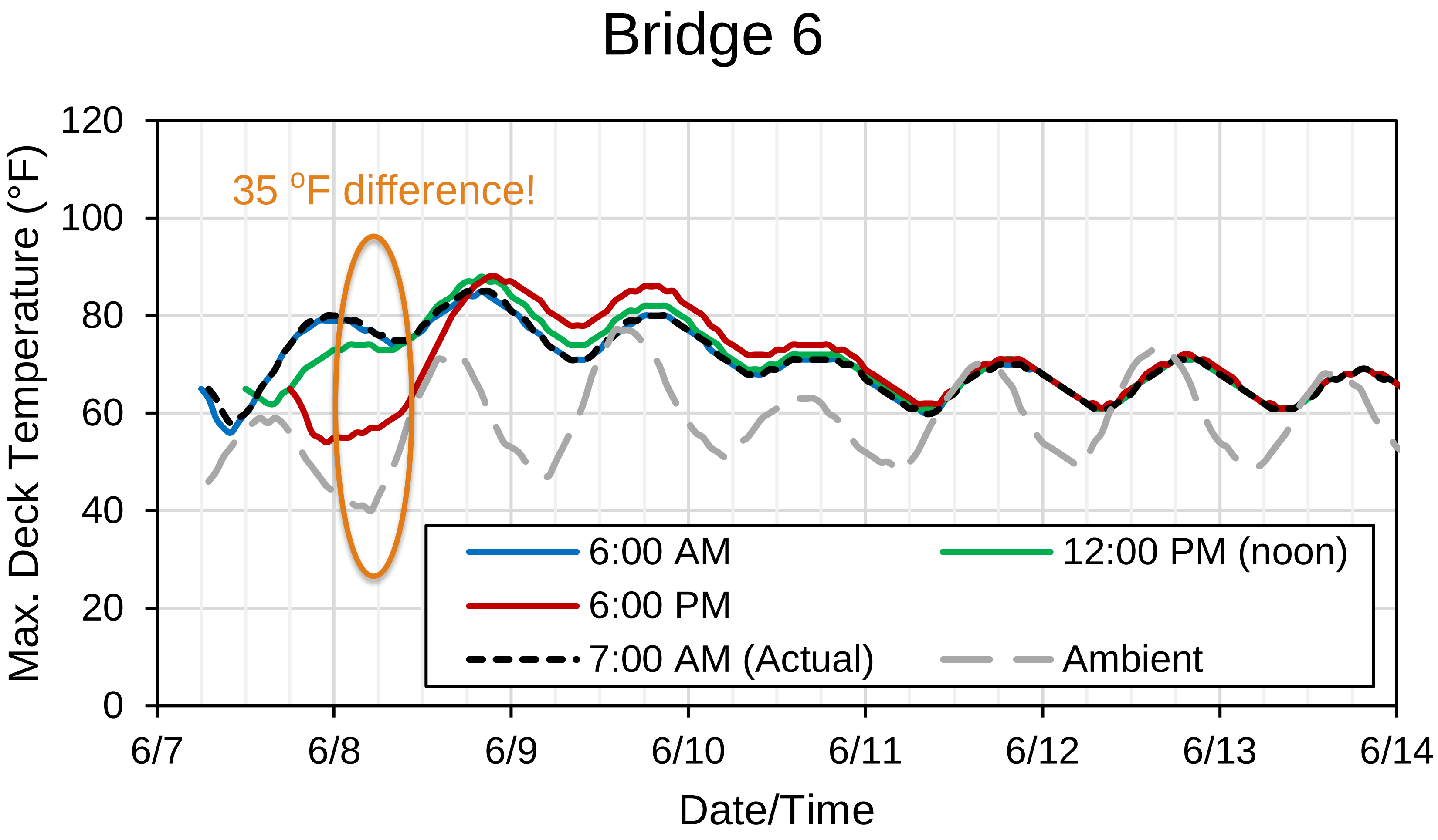
- Used ConcreteWorks to simulate peak temperature-time histories for 3 bridge decks
  - Deck geometry based on drawings
  - Heat generation simulated based on mix designs and cement compositions
  - Ambient temperature, wind speed, ans solar radiation based on historic records (NCDC)
  - Assumed placement temperature of 65 degrees F based on available batch ticket information
  - Varied placement times

Thermal and Stress Modeling



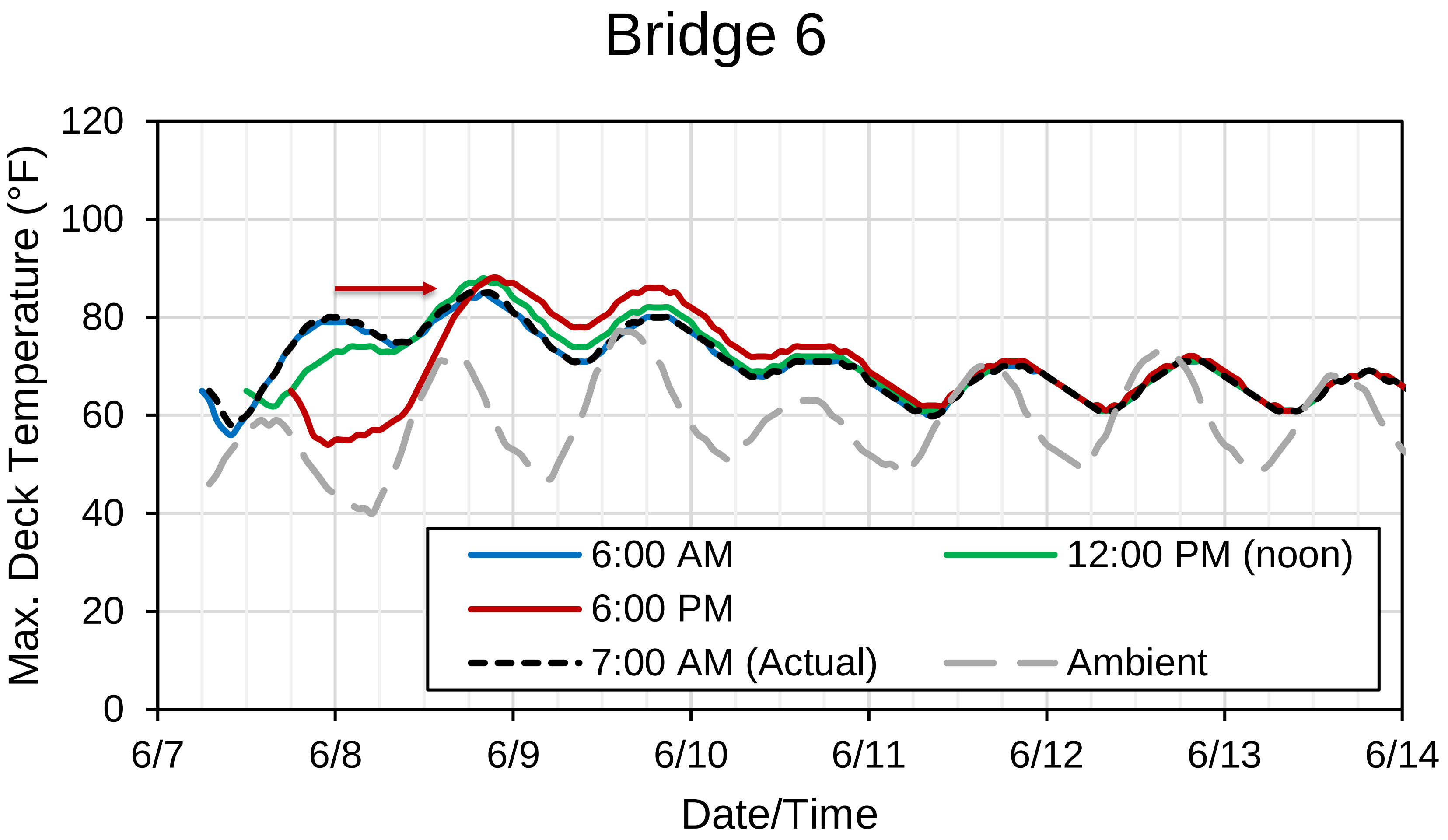
Thermal and Stress Modeling

- Outline
- Project Background
- Field Investigation
- Laboratory Evaluations
- **Thermal and Stress Modeling**
- Recommendations
- Why?



Thermal and Stress Modeling

- Outline
- Project Background
- Field Investigation
- Laboratory Evaluations
- **Thermal and Stress Modeling**
- Recommendations
- Why?



Placing concrete in late afternoon shifts peak temperature difference to Day 2 or 3.

Thermal and Stress Modeling

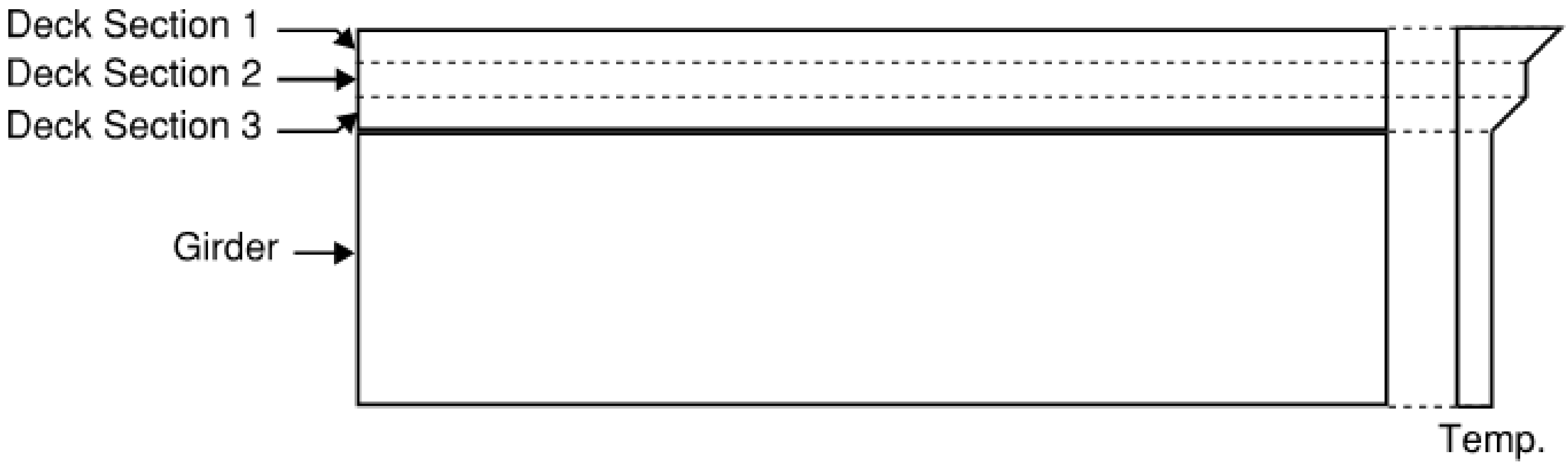
- Outline
- Project Background
- Field Investigation
- Laboratory Evaluations
- **Thermal and Stress Modeling**
- Recommendations
- Why?

- Stress analyses were performed using Mathcad, based on first-principles model by Zuk (1961)
  - Developed for composite bridge decks
  - Calculate free strain in each segment due to all volume changes (temperature, shrinkage, etc.
  - Calculate stresses generated by compatibility along interfaces

Zuk, W. "Thermal and Shrinkage Stresses in Composite Beams," *Journal of the American Concrete Institute*, (1961): 327-340.

Thermal and Stress Modeling

- Modifications:



- Creep was implicitly modeled by reducing the elastic modulus of concrete

Thermal and Stress Modeling

- Sensitivity Analysis
  - **Autogenous shrinkage**
  - **Drying shrinkage**
  - **Temperature changes in deck and girder**
  - Compressive strength of deck concrete
  - Thickness of deck
  - Girder spacing

Thermal and Stress Modeling

- Sensitivity Analysis: Key Findings
  - High sensitivity to tensile stresses caused by early-age **temperature drops**
  - Stresses due to **thermal gradients** (e.g., cooling of deck surfaces) are greater magnitude than stresses due to uniform temperature changes
  - Strains due to **temperature** generally larger than strains due to **autogenous shrinkage** for bridges investigated
  - **Drying shrinkage** may be significant at later ages

Thermal and Stress Modeling

- Simulations also performed for “realistic” temperature distributions
  - Assumed top 1/3 of deck is cooled 10 degrees F relative to interior
    - Simulated tensile stresses reached up to **130 psi** at 3 days (after cooling)
    - Steeper substantial gradients may have existed in actual deck
  - Tensile capacity of the concrete may be exceeded by “realistic” thermal and shrinkage effects
  - Simulated stresses generally correlated with observed crack severity

Conclusion

- Transverse cracks are initiating at early ages
  - Driven by early age temperature gradients
- Cracks continue to propagate
- "Jump" cracks occur with tightly spaced transverse cracks
- Deck penetrations occur under right conditions
  - Deck penetrations more prone to occur with top and bottom mats aligned
  - The more closely spaced the transverse cracks, the more likely deck penetrations will occur
  - Driving lanes and under wheel paths more susceptible

Recommendations

- Goals and Desired Outcomes:
  - Reduce the potential for early age transverse cracking/ reduce frequency
  - Reduce the potential for plastic shrinkage cracking (lower priority)
  - Increase service life of bridge decks
  - Decrease maintenance costs
  - Practical and reasonable approach to these recommendations

Recommendations

- Outline
- Project Background
- Field Investigation
- Laboratory Evaluations
- Thermal and Stress Modeling
- **Recommendations**
- Why?

- How do we accomplish these goals?
  - Reduce early age thermal stresses
  - Reduce autogenous shrinkage
  - Reduce the potential for early age and long term drying shrinkage
  - Maintain low permeability concrete
  - Maintain durability and service life
  - Work with MDT to achieve practical implementation

Specific Recommendations

- Outline
- Project Background
- Field Investigation
- Laboratory Evaluations
- Thermal and Stress Modeling
- **Recommendations**
- Why?

Placement Times

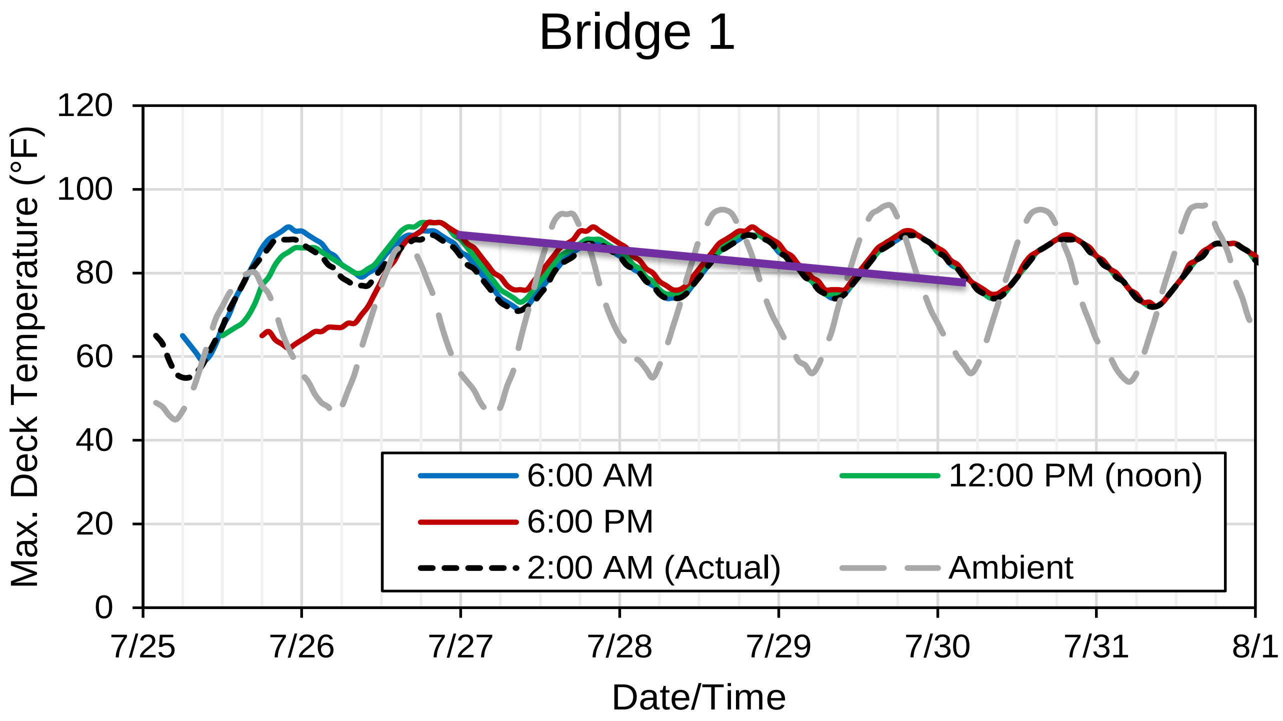
- Move placement times to afternoon
  - Based on modeling, late afternoon likely best
- Prevents peak hydration temperatures to occur during peak ambient temperatures
- Moves peak concrete temperature to 2 to 3 days later - concrete has higher tensile strength
- Peak concrete temperature aligns with cooler night temperatures

Specific Recommendations

- **Curing**
  - Immediately fog mist placements until wet curing media is in place
  - Contractor to measure evaporation rate
  - Apply wet-curing methods immediately after finishing
    - Pre-Wet burlap, cotton blankets, but no plastic!
  - Why is this important?

Specific Recommendations

- **Curing**
  - Monitor in-place concrete temperatures: at multiple depths and beginning/end of placement
  - Apply insulating blankets immediately after peak hydration
  - Why?



Specific Recommendations

- **Curing**
  - When concrete temperatures are within 5ºF of ambient and vertical temperatures through deck thickness are uniform - remove all curing
  - Minimum of 72 hours old (or 96 hours old if concrete contains silica fume), remove all curing and allow deck to dry.
  - After the surface has dried, white-pigmented curing compounds may be applied.

Specific Recommendations

- **Decrease plastic concrete temperatures**
  - Recommend maximum plastic temperature of 80F, preferably lower
  - Work with suppliers to help reduce concrete temperatures
  - Sprinkling aggregates, shading, chill water, adding ice, etc.

Specific Recommendations

- **Mixture Proportions Recommendations**
  - Limit silica fume replacement to 5%
  - Specify w/cm between 0.42 and 0.45
  - Limit cementitious material contents to 600 lb./yd^3 or less
  - Optimized gradation and crushed aggregates
  - Why are these important?

Specific Recommendations

- Outline
- Project Background
- Field Investigation
- Laboratory Evaluations
- Thermal and Stress Modeling
- **Recommendations**
- Why?

- **Design Considerations**
  - Increase design thickness of decks to 8 inches minimum
  - Modify specifications to require staggering of top and bottom transverse reinforcing mats
  - Why are these important?

Why are we still having these problems?

- Trend has been to lower the water to cementitious ratio, add SCMs (HPC), and control total cementitious content:
  - Lower water and chloride permeability and increase chloride resistance = increased durability
  - Lower drying shrinkage = lower transverse cracking
  - Increase service life
  - However, bridges can still crack significantly!
    - No longer have intended service life and long durability

Why are we still having these problems?

- Compared to 25 years ago, the potential for volume change has increased: increase in cement fineness, C3A, and alkalis – schedule driven
- Too low of w/cm is not better
  - Autogenous shrinkage
- Creating low drying shrinkage mixes may not be sufficient – thermal/autogenous can play a primary role in early age cracking
- HPC mixes require critical attention to early age curing
- However, longer wet-curing periods increase potential for transverse cracking!

Final Thoughts

- Outline
- Project Background
- Field Investigation
- Laboratory Evaluations
- Thermal and Stress Modeling
- Recommendations
- **Why?**

- Awareness/education on current cement characteristics and implications: fineness
- Keep our w/cm around 0.42
- Use of SCMs are recommended, keep moderate
- Limit total cementitious content
- Curing, curing, curing!

Special Thanks!

- **Matt Needham – MDT**
- **Paul Bushnell – MDT**
- **Paul Krauss – WJE**
- **Elizabeth Nadelman - WJE**

Questions?

Thanks for very much for the opportunity!

Implementation

- WJE's Recommendations implemented on 3 new bridge decks since early 2017
  - MDT reports limited transverse cracking. Typically over bents, if observed.
  - WJE briefly inspected one new deck placed in the Helena area (built in summer of 2017), approximately three weeks after placement – transverse cracks were difficult to find (very tight) and spaced far apart
  - Future inspections and assignments are needed

Recommendations

- Outline
- Project Background
- Field Investigation
- Laboratory Evaluations
- Thermal and Stress Modeling
- **Recommendations**
- Why?