Investigation of Concrete Bridge Deck Cracking

Todd Nelson, P.E. – Associate Principal
Investigation of Concrete Bridge Deck Cracking

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

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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
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

- 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 Plannote
  - Comparative investigations of eight additional bridges
### Field Investigation - Bridge Locations

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

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

Map cracking

Transverse cracking
Field Investigation – Transverse Cracking

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Transverse cracking
Field Investigation – Transverse Cracking

Transverse cracking - Underside
Field Investigation - Characteristic Cracking

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“Jump” Cracks

Transverse Crack

“Jump” 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
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- 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?
Transverse crack spacing varied from 2 to 4 feet on most bridges
  - More frequent than 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

Why?

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?

<table>
<thead>
<tr>
<th>Bridge</th>
<th>Range</th>
<th>Depth of Slab (inch)¹</th>
<th>Top Transverse Bar Location (inch)</th>
<th>Bottom Transverse Bar Location (inch)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Entire length</td>
<td>8</td>
<td>7 3/4</td>
<td>8 1/4</td>
</tr>
<tr>
<td>2</td>
<td>0' to 117&quot;-3&quot;</td>
<td>7 1/4</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>117&quot;-3&quot; to 198&quot;-9&quot;</td>
<td>7 3/4</td>
<td>-</td>
<td>7 5/8</td>
</tr>
<tr>
<td></td>
<td>198&quot;-9&quot; to 296'</td>
<td>8</td>
<td>7 1/8</td>
<td>-</td>
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<tr>
<td>3</td>
<td>Overlay</td>
<td>Not measured</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>Not measured</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Entire length</td>
<td>7 1/2</td>
<td>7</td>
<td>-</td>
</tr>
<tr>
<td>7</td>
<td></td>
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<td></td>
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<tr>
<td>8</td>
<td></td>
<td>Not measured</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td></td>
<td>Not measured</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>0' to 75'</td>
<td>8 1/4</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>75' to 725'</td>
<td>7 1/2</td>
<td>7 1/2</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>725' to 800'</td>
<td>8 1/4</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>11</td>
<td>0' to 75'</td>
<td>7</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>75' to 725'</td>
<td>6 3/4</td>
<td>6 1/4</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>725' to 800'</td>
<td>7</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>12</td>
<td>Entire length</td>
<td>9</td>
<td>8 1/4</td>
<td>-</td>
</tr>
</tbody>
</table>

¹: Measurements in inches.
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

- 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

- 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 of 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, and 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

Bridge 1

Max. Deck Temperature (°F)

Date/Time

- Blue: 6:00 AM
- Green: 12:00 PM (noon)
- Red: 6:00 PM
- Dashed Red: 2:00 AM (Actual)
- Gray: Ambient

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Thermal and Stress Modeling

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- Why?

Bridge 6

35 °F difference!

Max. Deck Temperature (°F)

Date/Time


6:00 AM 12:00 PM (noon)
6:00 AM 7:00 AM (Actual)

Ambient
Thermal and Stress Modeling

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

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
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
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

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

- **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?**

![Graph showing Max. Deck Temperature (°F) over time for Bridge 1]

- 6:00 AM
- 6:00 PM
- 12:00 PM (noon)
- 2:00 AM (Actual)
- Ambient
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./yd³ or less
  - Optimized gradation and crushed aggregates

- Why are these important?
Specific Recommendations

- **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
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

- 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!
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

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