SHRP2 R19-A Service Life Implementation Update

AASHTO SCOBS T-9 Technical Committee Meeting Spokane, WA – June 13, 2017

Mike Bartholomew, P.E., Bridge Design Practice Lead/ CH2M
Presentation Overview

• Quick Review of Service Life Design
• SHRP2 R19A Implementation Action Program
  – Program Goals
  – Work Focus Areas
  – Participating Agency (Lead Adopter) Projects
  – Lessons Learned
Review of Service Life Design
Service Life Design (SLD)

• Design approach to resist deterioration caused by environmental actions
  – Also called Durability Design
  – Often referred to as Design for 100-Year Service Life

• Introduces concepts that extend beyond typical structural engineering design
Review of SLD

• Similar to strength design to resist structural failure caused by external loads
  – External Loads ↔ Environmental Actions
  – Material Strength ↔ Durability Properties

• Both strength and Service Life Designs satisfy scientifically based modeling equations
Review of SLD

• Historically, durability issues have been addressed through prescriptive specifications and practices
  – Concrete cover for different exposure zones
  – Epoxy coated reinforcement
  – Painting/coating structural steel

• Known as “Deemed to Satisfy” method
  – Approach has not been quantifiable
“Deemed to Satisfy” method often leads to inadequate performance
Review of SLD

• Durability issues have also been addressed by specifying materials with extremely high resistance to deterioration
  – Stainless Steel reinforcement

• Known as “Avoidance of Deterioration” method
  – Often at a much higher cost
  – Can result in unnecessary over design
Review of SLD

• Industry needs better ways to evaluate/predict structure performance over time
  – Deterioration behavior models
    • All materials deteriorate with time
    • Deterioration rate is dependent on:
      – Environmental exposure conditions
      – Material protective systems – durability properties
  – Known as “Design Based on Deterioration from the Environment”
Environmental Exposure

- Chlorides from sea water or de-icing chemicals
- \( \text{CO}_2 \) from many wet / dry cycles & manufacturing process emissions
- Temperature / relative humidity
- Freeze-thaw cycles
- Abrasion (ice action on piers, studded tires on decks)
- Internally from Alkali-Silica reaction
Material Resistance

• For Concrete Bridges in Chloride Exposure
  • Resistance to Chloride Ingress is significantly influenced by concrete mix proportions:
    – Type of Cement
    – Water/Cement Ratio
    – Supplemental Cementitious Materials
      • Fly Ash (FA)
      • Ground Granulated Blast Furnace Slag (GGBFS)
      • Silica Fume (SF)
    – Depth of Cover
Deterioration Model

- **Chloride Ingress – Fick’s 2\textsuperscript{nd} Law of Diffusion to Corrosion Initiation**

\[
C_{\text{crit}} \geq C(x = a, t) = C_0 + (C_s, \Delta x - C_0) \cdot \left[ 1 - \text{erf} \left( \frac{a - \Delta x}{\sqrt{2D_{\text{app}},C \cdot t}} \right) \right]
\]

\[
D_{\text{app},C} = k_e \cdot D_{\text{RCM},0} \cdot k_t \cdot A(t)
\]

\[
k_e = \exp \left( b_e \left( \frac{1}{T_{\text{ref}}} + \frac{1}{T_{\text{real}}} \right) \right)
\]

\[
A(t) = \left( \frac{t_0}{t} \right)^\alpha
\]

- **Red – Environmental Loading**
  - \(C_0\) & \(C_s\) are the Chloride Background and Surface Concentrations
  - \(T_{\text{real}}\) is the annual mean Temperature at the project site

- **Green – Material Resistance**
  - \(D_{\text{RCM},0}\) is the Chloride Migration Coefficient, \(\alpha\) is the Aging Exponent, both are functions of the concrete mix
  - \(a\) is the Concrete Cover
Design Standard

- International Federation of Structural Concrete
  - Establishes design procedures
    - To resist deterioration
    - From environmental actions
  - Also recognizes
    - “Deemed to Satisfy”
    - “Avoidance of Deterioration”
Review of SLD

- Growing interest by the industry to make bridges more durable with longer expected lives

- Influenced by political motivation – popular to state that a new bridge will last 100+ years…

- Evident by requirements in recent Owner’s RFPs – particularly on Design Build projects

- Expectations of SLD requirements often unclear
Review of SLD

• A more robust definition was needed for SLD

• FHWA in conjunction with AASHTO and TRB through the 2\textsuperscript{nd} Strategic Highway Research Program (SHRP2) initiated project R19A

  – Bridges for Service Life Beyond 100 Years: Innovative Systems, Subsystems and Components
SHRP2 Project R19A
SHRP2 Process

RESEARCH – TRB

IMPLEMENTATION – FHWA/AASHTO

SUBJECT MATTER EXPERTS / LOGISTICS SME LEAD – CH2M
TECHNICAL SMEs – COWI

LEAD ADOPTER AGENCIES
Research Work Completed

• Project R19A – Service Life Design Guide

http://www.trb.org/Main/Blurbs/168760.aspx
Implementation Leads:

- Patricia Bush, AASHTO Program Manager for Engineering, pbush@aashto.org
- Raj Ailaney, FHWA Senior Bridge Engineer, Raj.Ailaney@dot.gov

Subject Matter Expert Team:

- Mike Bartholomew, CH2M, mike.bartholomew@ch2m.com
- Anne-Marie Langlois, COWI North America, amln@cowi.com
IAP Lead Adopter Agencies

Oregon

Central Federal Lands (project in Hawaii)
IAP Lead Adopter Agencies

Iowa

Maine

Pennsylvania

Virginia
IAP Team Leaders

• **FHWA Central Federal Lands**  
  – Bonnie Klamerus, Mike Voth

• **Iowa DOT**  
  – Ahmad Abu-Hawash, Norm McDonald

• **Oregon DOT**  
  – Bruce Johnson, Paul Strauser, Zach Beget, Ray Bottenberg, Andrew Blower, Craig Shike

• **Pennsylvania DOT**  
  – Tom Macioce

• **Virginia DOT**  
  – Prasad Nallapaneni

• **Maine DOT**  
  – Dale Peabody
IAP Goals

• Promote SLD concepts through:
  – Marketing, outreach & training
  – 5 regional Peer Reviews planned for 2017-18

• Assist Lead Adopter agencies in developing in-house SLD skills

• Build a strong technical foundation
  – Develop training & reference materials
  – Develop “Academic Toolbox”
  – Lessons learned summaries
Current Work Focus Areas

- Performing tests on material durability properties of concrete mix designs
  - Concrete chloride diffusion coefficients (NT Build 492)
  - Measurement of as-constructed concrete cover
Current Work Focus Areas

• Tests on existing bridges to assess environmental loading and material behavior
  – Taking concrete cores to measure chloride loading from de-icing chemicals or sea water

Source: Germann Instruments
Current Work Focus Areas

• Developing design tools and processes to aid in SLD
  – Excel spreadsheet for chloride profiling

<table>
<thead>
<tr>
<th>d</th>
<th>Depth from surface [mm]</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
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<th>10</th>
<th>15</th>
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<tbody>
<tr>
<td>C_m</td>
<td>Test Values [mass %]</td>
<td>0.368</td>
<td>0.450</td>
<td>0.410</td>
<td>0.326</td>
<td>0.266</td>
<td>0.231</td>
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<td>0.132</td>
<td>0.124</td>
<td>0.117</td>
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<td>0.078</td>
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<tr>
<td>C_r</td>
<td>Fit Data to C_m, D_app,c [mass %]</td>
<td>0.530</td>
<td>0.458</td>
<td>0.391</td>
<td>0.329</td>
<td>0.275</td>
<td>0.230</td>
<td>0.192</td>
<td>0.162</td>
<td>0.199</td>
<td>0.122</td>
<td>0.089</td>
<td>0.085</td>
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<td>(C_m - C_r)^2</td>
<td>Sum of least squares</td>
<td>6.72E-05</td>
<td>3.76E-04</td>
<td>1.10E-05</td>
<td>9.01E-05</td>
<td>1.55E-06</td>
<td>2.93E-04</td>
<td>4.34E-04</td>
<td>5.00E-05</td>
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<td>4.90E-05</td>
<td>2.22E-03</td>
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<td>C_m</td>
<td>Initial chloride content (measured) [mass %]</td>
<td>0.085</td>
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<tr>
<td>t</td>
<td>Exposure time [yr]</td>
<td>1</td>
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<tr>
<td>C_s</td>
<td>Chloride content at exposed face [mass %]</td>
<td>0.605</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>D_app,c</td>
<td>Apparent coefficient of chloride diffusion [mm²/yr]</td>
<td>15.324</td>
<td></td>
<td></td>
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Implementation Products – Dedicated Webpage

http://shrp2.transportation.org/Pages/ServiceLifeDesignforBridges.aspx
IAP Projects - Round 4
Initiated Fall 2014
• Tropical Coastal Exposure on North Shore, Island of Kauai, HI
  – 3 bridge replacements - 500’ to 1,000’ from the coastline
• Testing brackish water salinity

• Coring of existing abutments at water line / splash zone for surface chloride concentration

• NT Build 492 tests being performed on baseline concrete mix designs at the University of Hawaii
• New Bridge at Site with Extreme De-Icing Spray Exposure

– Using A1010 High Chromium Structural Steel
– Lab and field testing A1010 for steel corrosion resistance performance
Iowa DOT

- Replacement of Twin Structures on I-35 over South Skunk River near Ames
  - Chloride profile testing on existing structures
  - NT Build 492 tests on concrete mix designs
  - SB Bridge – Constructed to current Iowa DOT policies
  - NB Bridge – Currently under design using SLD “Avoidance of Deterioration” methodology
• Replacement of Twin Structures on I-35 over South Skunk River near Ames

– Final Product – Side-by-side comparison report to include:
  • Estimate of Service Life Duration and Cost
  • Comparison of both structures
• **Bridge Deck Evaluation in Various Chloride Exposure Zones**
  - Performed chloride profile testing and categorization of chloride loading by geographic/climatic zones (Pacific Coast, Willamette Valley, Cascade Mountains and east)
• I-5 Columbia River Crossing Design/Build – Portland to Vancouver
  – Evaluate/modify RFP requirements for contractor to design/document to a 100-year service life

• Replacement Bridge over Ochoco Creek in Prineville
Oregon DOT – Ochoco Creek
• NT Build 492 Test (Chloride Migration Coefficient, $D_{RCM}$) performed on all concrete elements during construction (~33 cylinders total)

  – Deck – HPC4000 w/Flyash
    • $D_{RCM} = 0.64 \text{ in}^2/\text{yr}$

  – Deck (Alternative) – HPC4000 w/Slag
    • $D_{RCM} = 0.54 \text{ in}^2/\text{yr}$
Oregon DOT – Ochoco Creek

SERVICE LIFE DESIGN - GRAPHICAL SOLUTION

Calculations as per fib Bulletin 34 - fully probabilistic design
Service Life = 100 years
Beta = 1.3, Probability of failure = 10%
Critical chloride concentration: black bars - 0.6%cem.
Initial chloride concentration : 0.1%cem.

Temperature: mean = 49.1F, std = 12.1F
Exposure Zones: Splash/Deicing Salts
Concrete Type: OPC + >20%FA
Age factor 0.6 = mean, std = 0.25

Capacity 1.6% wt. cement

Demand, $C_s = 0.6\%$ wt. cement

HPC 4000
$D_{RCM} = 0.64 \text{ in}^2/\text{yr}$

2.5" Cover
SERVICE LIFE DESIGN - GRAPHICAL SOLUTION

Calculations as per fib Bulletin 34 - fully probabilistic design
Service Life = 100 years
Beta = 1.3, Probability of failure=10%
Critical chloride concentration: black bars - 0.6%cem.
Initial chloride concentration: 0.1%cem.

Temperature: mean = 49.1°F, std = 12.1°F
Exposure Zones: Splash/Deicing Salts
Concrete Type: OPC+30% GGBS
Age factor: mean = 0.40, std = 0.15

Capacity 0.8% wt. cement

2.5" Cover

Demand, $C_s = 0.6$% wt. cement

HPC 4000 (Alt.)
$D_{REM} = 0.54$ in²/yr
Pennsylvania DOT

- **Statewide Evaluation of Chloride Resistance of Concrete**
  - Performed NT Build 492 tests on 106 samples from 7 ready mix and 2 precast concrete suppliers

![Figure 1: Company location map relative to PennDOT districts](image)
PennDOT Concrete Classifications tested

- Class A – Structures & Misc., 3000 psi (31 samples)
- Class AA – Structures & Misc., 3500 psi (36 samples)
- Class AAAP – Bridge Decks, 4000 psi (30 samples)
- Class HES – High Early Strength, 3500 psi (3 samples)
- SCC – Self-Consolidating, must meet requirements of above classifications (6 samples)
<table>
<thead>
<tr>
<th>Class of Concrete</th>
<th>Use</th>
<th>Cement Factor&lt;sup&gt;(3)(5)&lt;/sup&gt; (lbs/cu. yd.)</th>
<th>Maximum Water Cement Ratio&lt;sup&gt;(6)&lt;/sup&gt; (lbs/lbs)</th>
<th>Minimum Mix&lt;sup&gt;(2,9)&lt;/sup&gt; Design Compressive Strength (psi) Days</th>
<th>Proportions Coarse&lt;sup&gt;(1)&lt;/sup&gt; Aggregate Solid Volume (cu. ft./cu. yd.)</th>
<th>28-Day Structural Design Compressive Strength (psi)</th>
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<tr>
<td></td>
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<td>Min.</td>
<td>Max.</td>
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<td>AAAP</td>
<td>Bridge Deck</td>
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<td>690</td>
<td>0.45</td>
<td>—</td>
<td>3,000</td>
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<tr>
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<td>Bridge Deck</td>
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<td>0.45</td>
<td>—</td>
<td>3,000</td>
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<tr>
<td>AAA&lt;sup&gt;(4)&lt;/sup&gt;</td>
<td>Other</td>
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<td>752</td>
<td>0.43</td>
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<td>Slip Form Paving&lt;sup&gt;(7)&lt;/sup&gt;</td>
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<td>3,750</td>
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<td>Paving</td>
<td>587.5</td>
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<td>0.47</td>
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<td>3,750</td>
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<td>AA</td>
<td>Accelerated Patching&lt;sup&gt;(8)&lt;/sup&gt;</td>
<td>587.5</td>
<td>800</td>
<td>0.47</td>
<td>—</td>
<td>—</td>
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<td>AA</td>
<td>Structures and Misc.</td>
<td>587.5</td>
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<td>2,750</td>
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<td>752</td>
<td>846</td>
<td>0.40</td>
<td>3,000</td>
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Chloride Migration Coefficient by Concrete Class

- A: 6.970
- A: 20.019
- A: 9.889
- A: 9.995
- A: 7.043
- A: 7.340
- A: 7.157
- AA: 14.984
- AA: 10.040
- AA: 8.344
- AA: 10.914
- AA: 4.939
- AA: 5.219
- AA: 3.985
- HES: 8.380
- SCC: 7.551
- HES: 1.219
Chloride Migration Coefficient by Concrete Supplier
Final Service Life Design Workshop held late August 16, 2016

- Overview of Service Life Design for Bridges
- Chloride Induced Corrosion Modeling
- Concrete Deterioration Mechanisms
- Implications of Cracks in Concrete on Service Life
- Service Life Design Requirements for RFPs
- Service Life Design for Steel Structures
• Statewide Evaluation of Chloride Surface Loading and Resistance of Concrete
  – Compared historic chloride surface loading to fib-34 methods
  – Performed NT Build 492 tests on over 20 ongoing bridge construction projects around the state
  – Developing a database of reference values specific to Virginia for use in modeling
Categorization of chloride loading by zones

- Historical data (Williamson, 2007)
- *fib 34-predicted*
• Final Service Life Design Workshop Agenda scheduled for late August, 2017

– Overview of SLD – SME Team
– Concrete Material Testing Program – Virginia Tech
– Chloride Profiling of Existing Bridges – Virginia Tech
– Specifications on Corrosion Resistant Reinforcing – VDOT
– SLD Tools developed – SME Team
– SLD for Alternative Delivery Projects – SME Team
– R19A work done by other agencies – SME Team
IAP Projects - Round 7
Selected Summer 2016
• Thin Deck Overlays as a Bridge Preservation Action
  – Evaluation of structures on US-18 corridor
  – Kick-off Meeting to take place on June 20, 2017
Maine DOT

- Replacement of Beals Island Bridge in cold weather coastal environment
  - Chloride profiling on existing bridge
  - NT Build 492 tests on proposed concrete specifications
Lessons Learned

- Chloride profiling on core samples produce much better results than powder samples from rotary drilling
- Deicing application is minimal in the Willamette Valley – Corrosion from chlorides insignificant
- Need to develop contour maps of de-icing chloride loading
- Chloride migration tests (NT Build 492) are relatively easy to implement
  - Virginia and Iowa performing in-house testing
Lessons Learned

• Many state concrete classifications are flexible in w/c ratio, and % fly ash or slag replacing cement
• Mix design flexibility ≠ Consistent durability properties
  – Chloride migration test values (NT Build 492)
  – Aging coefficients (need ≥ 20% flyash to benefit)
• Need to develop guidelines for more consistent concrete specifications for SLD
Thank You

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