SHRP2 Service Life Design for Bridges (R19A)

Oregon DOT Early Adopter Funding Award
1. Ochoco Bridge Service Life Design
2. Chloride Deck Corrosion Study
3. Design-Build Service Life Design Specs

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State Bridge Engineer

June 28, 2018
Service Life Design for Routine Structures

- Select Target Service Life
- Exposure Zones (Load Cases)
- Environmental Loading (Demand)
- Material Properties (Capacity)
- Detailing (Capacity)
- Capacity vs. Demand
- Document the Service Life Evaluation/Plan
Project Background
Service Life Design

- Define Exposure Zones
  - Buried Zone w/ Seasonal GWT (blue)  Pile Cap
  - Atmospheric w/o Deicing (green)  Int. Slabs
  - Atmospheric w/ Mod. Deicing (yellow)  Ext. Slabs/Dia.
  - Atmospheric w/ Direct Deicing (red)  Deck/Rail/Panel
# Exposure Conditions and Deterioration Mechanisms for Reinforced Concrete Elements

<table>
<thead>
<tr>
<th>Exposure Zone</th>
<th>Elements</th>
<th>Exposure conditions</th>
<th>Potential Deterioration Mechanisms</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atmospheric zone without de-icing solutions</td>
<td>Interior PC/PS Slabs</td>
<td>Atmospheric $O_2$ and $CO_2$.</td>
<td>DEF, Sulfate, Freeze-Thaw, Leaching</td>
</tr>
<tr>
<td></td>
<td>CIP End Diaphragm</td>
<td>Indirect exposure to chlorides from de-icing solutions with alternating wetting and drying. Freeze and thaw.</td>
<td></td>
</tr>
<tr>
<td>Atmospheric zone with moderate or indirect de-icing solutions</td>
<td>Exterior PC/PS Slabs</td>
<td>Atmospheric $O_2$ and $CO_2$.</td>
<td>DEF, Sulfate, Freeze-Thaw, Leaching</td>
</tr>
<tr>
<td></td>
<td>CIP End Diaphragm</td>
<td>Indirect exposure to chlorides from de-icing solutions with alternating wetting and drying. Freeze and thaw.</td>
<td></td>
</tr>
<tr>
<td>Atmospheric zone with direct application of magnesium chloride de-icing solutions</td>
<td>Bridge Railing</td>
<td>Atmospheric $O_2$ and $CO_2$.</td>
<td>DEF, Sulfate, Freeze-Thaw, Leaching</td>
</tr>
<tr>
<td></td>
<td>CIP Concrete Deck &amp; Sidewalk</td>
<td>Indirect exposure to chlorides from de-icing solutions with alternating wetting and drying. Freeze and thaw.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Precast Concrete End Panels</td>
<td>Indirect exposure to chlorides from de-icing solutions with alternating wetting and drying. Freeze and thaw.</td>
<td></td>
</tr>
<tr>
<td>Buried zone with seasonal groundwater</td>
<td>Pile Cap</td>
<td>Soil contact and seasonal exposure to groundwater with limited chlorides and sulfates.</td>
<td>DEF, Sulfate, Freeze-Thaw, Leaching</td>
</tr>
</tbody>
</table>

**AAR** - Alkali-aggregate reaction  
**DEF** - Delayed ettringite formation
Service Life Design

• Chloride Induced Corrosion (Load Case)
  – Focal point of the service life design
  – Demand dictated by chloride surface concentration
    • Soil
    • Deicing

• Environmental Loading (Demand)
  – Qualitative before quantitative
  – District Transportation Maintenance Manager
    • Medium deicer application rate (H/M/L)
    • 30 Gallons magnesium-chloride per lane mile
    • 30-40 applications per year
  – Expect moderate surface concentration.
Service Life Design

Chloride Profile Fit Using

\[ C(x, t) = C_o + (C_3 - C_o) \cdot \left(1 - \text{erf} \left( \frac{x}{2 \sqrt{D_{app} \cdot t}} \right) \right) \]

Table 2.1 - Chloride Content in Existing Bridge

<table>
<thead>
<tr>
<th>Test Sample</th>
<th>Chloride Mass</th>
<th>Chloride Surface Concentration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core #1 (NW)</td>
<td>0.50 kg cl- /m³</td>
<td>0.15% chloride / cement</td>
</tr>
<tr>
<td>Core #2 (SW)</td>
<td>1.31 kg cl- /m³</td>
<td>0.39% chloride / cement</td>
</tr>
<tr>
<td>Core #3 (SE)</td>
<td>0.55 kg cl- /m³</td>
<td>0.16% chloride / cement</td>
</tr>
<tr>
<td>Core #4 (NE)</td>
<td>0.29 kg cl- /m³</td>
<td>0.09% chloride / cement</td>
</tr>
<tr>
<td>Mean</td>
<td>0.66 kg cl- /m³</td>
<td>0.27% chloride / cement</td>
</tr>
</tbody>
</table>
Service Life Design

- Environmental Load
  - Demand assessment complete

- Service Life Design (Capacity)
  - Material Selection
    - Concrete
    - Reinforcement Type
  - Detailing
    - Reinforcement Cover

- Key Question - How do ODOT mixes perform?
  - NTBuild 492 Test for Chloride Migration Coefficient
Service Life Design

**Figure 3.1** – NT Build 492 Test Results by Concrete Product

**Figure 3.2** – NT Build 492 Test Results by Mix Design
Service Life Design

- Service Life Design (Capacity)
  
  - Detailing
    - Reinforcement Cover

  - Material Selection
    - Concrete
      - Resistance to chloride intrusion
    - Reinforcement Type
      - Corrosion threshold

  - Next Step → Chart Solutions

State Practice +/-

Standard/Special Mix Design

SS, GFRP, EC, MMFX, Black
Service Life Design

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 + >20%FA
Age factor 0.6 = mean, std = 0.25

Capacity - QA Deck Concrete, Class HPC4000 (Slag) - \( D_{RCM} = 0.60 \text{ in}^2/\text{year} \) - 2.5" Clear ----> 1.75%cem
Demand - \( C_s = 0.39\% \text{ wt. cement} \)
Service Life Design Documentation

• Calculation Book documentation of service life demand and resistant materials/detailing for selected service life based on probabilistic time to corrosion initiation

• Life Cycle Preservation Plan with projected actions for permanent and replaceable or maintainable elements
Sample Project Specifications Reviewed:

- Tappan Zee Hudson River Crossing – Nov 2012
- The East End Crossing (Louisville-Southern Indiana Ohio River Bridges) – July 2012
- Goethals Bridge Replacement (The Port Authority of New York and New Jersey) – Feb 2013
- Columbia River Crossing (OR-WA) Draft 2014
Corrosion Loading

- Will be assessed by the project team and recommended to the owner for approval for specific site conditions

- Current general recommendations (% of chlorides by weight of concrete)
  - 1.1% for heavy exposure areas
    - Siskiyou Mountains in SW Oregon
    - Coastal areas with direct exposure to the ocean
  - 0.12% for moderate exposure
    - Portland Metro and the Willamette Valley

- Expected to be modified as we gather additional data
Specification Highlights

- Design Service Life – Non-Replaceable Components

  - Major Bridges 100 years
  - Other Bridges 75 years

Note that Design Service Life would typically be the same for all non-replaceable components.
### Specification Highlights

- **Design Service Life – Replaceable Components**

<table>
<thead>
<tr>
<th>Component</th>
<th>Major Bridges</th>
<th>Other Bridges</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete Bridge Barriers</td>
<td>40 years</td>
<td>40 years</td>
</tr>
<tr>
<td>Steel Bridge Rail Elements</td>
<td>40 years</td>
<td>30 years</td>
</tr>
<tr>
<td>Deck Wearing Surface</td>
<td>25 years</td>
<td>25 years</td>
</tr>
<tr>
<td>Bridge Bearings</td>
<td>40 years</td>
<td>40 years</td>
</tr>
<tr>
<td>Expansion Joints</td>
<td>30 years</td>
<td>30 years</td>
</tr>
<tr>
<td>Coating Systems</td>
<td>20 years</td>
<td>20 years</td>
</tr>
</tbody>
</table>
**Specification Highlights**

- **Service Life and Corrosion Protection Plan**

  - Provide a detailed Service Life and Corrosion Protection plan for all bridges, prepared by or under the direction of a qualified Professional Engineer licensed in the State of Oregon and bearing the engineer’s signature, seal, and expiration date.
Specification Highlights

- **Full Probabilistic Models**
  - Model the chloride-induced corrosion process in concrete components based on the fib Bulletin 34 approach using a full probabilistic model.
  - Test the concrete transport properties of the concrete mixes used in the permanent works using a test consistent with the chosen model. Use the NT Build 492 test if the modeling is performed according the fib Bulletin 34 chloride-induced corrosion model.
Project Objectives

- Develop an AASHTO Guide Specification for Service Life Design of Highway Bridges
- Develop Case Studies to demonstrate the application of the proposed Guide
Overview of Guide Specification

Section 1 – Introduction

Section 2 – Bridge Classification

Section 3 – General Design Guidelines

Section 4 – Concrete Structures

Section 5 – Steel Structures

Section 6 – Foundations and Retaining Walls

Section 7 – Renewable Elements

Section 8 – LCCA

Appendices – Probabilistic Framework and Case Studies

- Philosophy, approach, etc.
- Classification of target service life, environment, etc.
- General design guidance

- Major organization by material, then component
- Guidance on deterioration mechanisms, protective measures, detailing, and construction within each section

- In development

NCHRP 12-108 Phase II Meeting
Three tiered approach is the basis of the methodology, separating practice into:

- **Good**
- **Better**
- **Best**

**Example: Decks**

- **Good**: low-permeability concrete mixture, explicit curing requirements, concrete cover per LRFD specifications.
- **Better**: use of waterproofing membranes and/or low permeability overlays, prestressing of concrete, enhanced concrete cover dimensions.
- **Best**: combination of previous practices plus use of non-corroding reinforcement and/or bi-directional prestressing.

Majority of the methodology consists of:

- Deemed-to-satisfy
- Avoidance-of-deterioration

Supplemented by probabilistically calibrated deemed-to-satisfy provisions where applicable

- **Chloride-induced corrosion**
Target Service Life Categories

- **Renewable**
  - Elements designed for replacement

- **Normal = 75 years**
  - Matches probabilistic basis of LRFD calibration

- **Enhanced = 100 years**
  - Often used in project specific criteria, improvement over standard practice

- **Maximum = 150 years**
  - At or beyond practical ability to predict

<table>
<thead>
<tr>
<th>Category</th>
<th>Bridge Component Type</th>
<th>Bridge Description</th>
<th>Level of Qualitative Practice</th>
<th>Target Service Life(^1) (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Renewable</td>
<td>Bearings, joints, etc.</td>
<td>All</td>
<td>Replaceable</td>
<td>&lt; 50</td>
</tr>
<tr>
<td>Normal</td>
<td>All other components</td>
<td>Typical bridges</td>
<td>Good</td>
<td>75</td>
</tr>
<tr>
<td>Enhanced</td>
<td>All other components</td>
<td>Bridges with high cost, high ADT, social context, etc.</td>
<td>Better</td>
<td>100</td>
</tr>
<tr>
<td>Maximum</td>
<td>All other components</td>
<td>Bridges with higher cost, higher ADT, social context, etc.</td>
<td>Best</td>
<td>150</td>
</tr>
</tbody>
</table>

Notes:

\(^1\)Assuming a mild environment
Exposure Zones

- **Rural/Mild/Non-Aggressive**: little to no exposure to airborne or applied salts. Low pollution/humidity/precipitation.
- **Industrial/Moderate**: occasional exposure to airborne salts or deicing salt runoff. Industrial areas with pollution.
- **Marine**: coastal areas with exposure to airborne salts or direct contact with sea water/brackish water.
- **Deicing**: region where de-icing salts are used with low to high application rate.

**Macro Exposure Zones (Atmospheric)**

*Fig. 1.6 Road Salt Usage in the United States*  
Weyers et al. (1994)
Exposure Zones

- Direct Deicing Zone
  - Directly exposed to de-icing salts
- Indirect Deicing Zone
  - Indirectly exposed to de-icing salt thru roadway splash/spray
- Atmospheric Zone
  - Not exposed to soil, water, or de-icing salts
- Splash/Spray Zone
  - Region above tidal zone subject to splash/spray
- Tidal Zone
  - Not permanently submerged in water, subject to wet/dry cycles
- Submerged Zone
  - Permanently submerged in water, below tidal zone
- Buried Zone
  - Permanently buried in soil, below the mudline (after consideration of all applicable scour)
3.1 Service Life Design Strategies

Decisions made at **all stages** of the design process impact durability

- Planning
- Span layout and number/location of joints
- Design details
- Material selection

![Diagram of joint types](image)

NCHRP (2003)

DMRB (2001)
3.3 General Durability Considerations

Good **detailing** practices that are essential to service life

- Drainage
- Deck detailing
- Joints
- Bearings
- Utilities and Appurtenances
- Wildlife
- Access and Inspection
- Construction and Preservation
## Development of Cover Table

<table>
<thead>
<tr>
<th>Exposure Class</th>
<th>Description</th>
<th>Examples</th>
<th>75 years</th>
<th>100 years</th>
<th>125 years</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>nom. cover</td>
<td>Concrete</td>
<td>Reinforcing</td>
</tr>
<tr>
<td><strong>Direct Deicing Salts - High</strong></td>
<td>Direct exposure to deicing salts with high application rate of deicing salts</td>
<td>Top of decks, curbs, sidewalks, barriers</td>
<td>2.0</td>
<td>Any</td>
<td>ss</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2.5</td>
<td>OPCFA</td>
<td>black</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>3.0</td>
<td>OPCFA</td>
<td>black</td>
</tr>
<tr>
<td><strong>Direct Deicing Salts - Low</strong></td>
<td>Direct exposure to deicing salts with medium to low application rate of deicing salts</td>
<td>Top of decks, curbs, sidewalks, barriers</td>
<td>2.0</td>
<td>Any</td>
<td>ss</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2.0</td>
<td>OPCFA+SF</td>
<td>black</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2.5</td>
<td>OPCFA</td>
<td>black</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>3.0</td>
<td>GGBS+SF</td>
<td>black</td>
</tr>
<tr>
<td><strong>Indirect Deicing Salts</strong></td>
<td>Surfaces exposed or potentially exposed to drainage water containing deicing salts or roadway spray</td>
<td>Surfaces below expansion joints or drains, deck, fascia, substructure surfaces near a roadway</td>
<td>2.0</td>
<td>Any</td>
<td>ss</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2.0</td>
<td>OPCFA+SF</td>
<td>black</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2.5</td>
<td>OPCFA</td>
<td>black</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>3.0</td>
<td>GGBS</td>
<td>black</td>
</tr>
<tr>
<td><strong>Atmospheric in a deicing salts environment</strong></td>
<td>Surfaces exposed to airborne chlorides</td>
<td>Abutments, piers, pile caps, pier caps, girders, underside deck overhang</td>
<td>2.0</td>
<td>Any</td>
<td>black</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1.5</td>
<td>OPCFA</td>
<td>black</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1.0</td>
<td>GGBS+SF</td>
<td>black</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Underside of deck (interior bays)</td>
<td>1.5</td>
<td>Any</td>
<td>black</td>
</tr>
<tr>
<td><strong>Marine - Tidal or spray zone</strong></td>
<td>Surfaces in contact with salt water either in the tidal zone or spray zone</td>
<td></td>
<td>3.0</td>
<td>Any</td>
<td>ss</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>3.5</td>
<td>GGBS+SF</td>
<td>black</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>3.5</td>
<td>OPCFA</td>
<td>black</td>
</tr>
<tr>
<td><strong>Marine - Submerged or Buried, Corrosive Soils</strong></td>
<td>Surfaces permanently submerged or buried with salt water present, corrosive soils</td>
<td>Piles, foundations</td>
<td>4.0</td>
<td>GGBS</td>
<td>black</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>3.5</td>
<td>GGBS+SF</td>
<td>black</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>3.0</td>
<td>OPCFA</td>
<td>black</td>
</tr>
<tr>
<td><strong>Marine - Atmospheric Chlorides</strong></td>
<td>Surfaces exposed to airborne chlorides</td>
<td>Superstructure</td>
<td>2.5</td>
<td>Any</td>
<td>black</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2.0</td>
<td>OPCFA</td>
<td>black</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1.5</td>
<td>GGBS</td>
<td>black</td>
</tr>
<tr>
<td><strong>Non-corrosive soils, fresh water</strong></td>
<td>Surfaces in contact with fresh water or non-corrosive soils</td>
<td>Piles, foundations, abutments</td>
<td>3.0</td>
<td>Any</td>
<td>black</td>
</tr>
<tr>
<td><strong>Non-aggressive environment</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Interior exposure</strong></td>
<td>Shattered surfaces, mostly dry conditions</td>
<td>Up to no.11 bars</td>
<td>1.5</td>
<td>Any</td>
<td>black</td>
</tr>
<tr>
<td></td>
<td></td>
<td>no.14 and 18 bars</td>
<td>2.0</td>
<td>Any</td>
<td>black</td>
</tr>
<tr>
<td><strong>Other exterior exposure</strong></td>
<td></td>
<td></td>
<td>2.0</td>
<td>Any</td>
<td>black</td>
</tr>
</tbody>
</table>

Max Allowable Chloride Migration Coefficients (m²/s):
- OPC = 12.5x10⁻¹²
- OPCFA = 8.0x10⁻¹²
- OPCFA+SF = 4.7x10⁻¹²
- GGBS = 5.0x10⁻¹²
- GGBS+SF = 2.3x10⁻¹²

Crack width should be kept below a characteristic value – fib Bulletin 34
Model Limitations

Concrete oriented in the vertical position

- i.e., not bridge decks

Uncracked concrete

- Crack width should be kept below a characteristic value – fib Bulletin 34
- Research shows cracking increases chloride diffusion, but magnitude of effect is not clear due to the number of influencing factors

- This is currently the best model we have to work with
- How to address cracking of horizontal concrete members (i.e., bridge decks)?
- How do you design for cracking?
- This is an open issue to be further addressed in Phase III by examining current state of research related to cracking and chloride diffusion
- There are ongoing internal discussions within the Research Team on how to approach this issue
### Deemed-to-satisfy provisions by exposure class

<table>
<thead>
<tr>
<th>Service Life Category</th>
<th>Mild (C2)</th>
<th>Moderate (C3)</th>
<th>Severe (C5-I)</th>
<th>Seacoast (C5-M)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Good</td>
<td>Coated ASTM A709 Gr 50</td>
<td>Coated ASTM A709 Gr 50</td>
<td>Coated ASTM A709 Gr 50</td>
<td>Coated ASTM A709 Gr 50</td>
</tr>
<tr>
<td>Better</td>
<td>Galvanized ASTM A709 Gr 50</td>
<td>Galvanized ASTM A709 Gr 50</td>
<td>Galvanized ASTM A709 Gr 50</td>
<td>Galvanized ASTM A709 Gr 50</td>
</tr>
<tr>
<td></td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Uncoated ASTM A1010</td>
</tr>
<tr>
<td>Best</td>
<td>Uncoated ASTM A709 Gr 50W</td>
<td>Uncoated ASTM A709 Gr 50W</td>
<td>Uncoated ASTM A709 Gr 50W</td>
<td>Galvanized ASTM A709 Gr 50</td>
</tr>
<tr>
<td></td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Uncoated ASTM A1010</td>
</tr>
</tbody>
</table>
Specifications have been developed for the following foundation elements:

1. Spread foundations
2. Driven Piles
3. Micropiles
4. Drilled shafts

Each foundation type is organized as follows:

- Deterioration environment
- Protection strategies

Deterioration environment is based on ground aggressiveness

- Usually in terms of electrochemical properties (pH, resistivity, sulfates, and chlorides)

Protection strategies vary depending on foundation type and C-factor

- Minimum concrete cover, sacrificial steel, level of integrity testing, etc.
## Schedule

<table>
<thead>
<tr>
<th>Task</th>
<th>Submission</th>
<th>Review completed</th>
<th>Phase</th>
</tr>
</thead>
<tbody>
<tr>
<td>8 – Interim Report No. 2</td>
<td>April 30, 2018</td>
<td>May, 2018</td>
<td>II</td>
</tr>
<tr>
<td>11 &amp; 12 – Revisions and Final Deliverables</td>
<td>January 1, 2019</td>
<td>February, 2019</td>
<td>IV</td>
</tr>
<tr>
<td>End of project</td>
<td></td>
<td>February 28, 2019</td>
<td></td>
</tr>
</tbody>
</table>

Proposed Bridge Committee Coordination and Outreach: T-5, T-10, T-14, T-18 mid-year meetings and Webinars Fall-Winter 2018