Life Cycle Cost Analysis Based on Service Life Modeling for NX Infrastructure

John Lawler, Ph.D., P.E.
Wiss, Janney, Elstner Associates, Inc.
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Corrosion Mitigation

- Consequences of corrosion can not be ignored

- Available Strategies
  - Corrosion Resistant Reinforcing Steels
  - High Performance Concrete
Troubleshoot existing structures
  - Have perspective on what causes failures and how to prevent them

Research history of alternatives to black bar
  - Field performance investigations with various DOTs and CRSI – service life models
Life Cycle Cost Analysis

- Recommended by FHWA as method for choosing between alternatives

- This study compares **Annualized Costs**
  1. Performance in typical bridge deck modeled based on bar properties
  2. Total direct costs calculated over life of bridge
     - Includes construction, maintenance, but no User costs
  3. Convert to equivalent annual cost
Model for Damage

- Corrosion Initiation at Chloride Threshold ($C_T$)
- Chloride Accumulation
- Initiation Time ($t_i$)
- Propagation Time ($t_p$)
- Time

Surface Damage

Deterioration at a single location
**Chloride Penetration**

- Ingress of chloride governed by Fick’s Law Sol’n:

$$C(x, t, C_s, D) := (C_s - C_0) \cdot \left(1 - \text{erf}\left(\frac{x}{2 \cdot \sqrt{D \cdot t}}\right)\right) + C_0$$

**Effect of Depth**

- 1 in.  
- 2 in.  
- 3 in.

**Effect of $C_s$**

- 26 lb/yd³  
- 13 lb/yd³
Corrosion Initiation Model

- Initiation time ($t_i$) modeled based on Chloride threshold ($C_T$) and cumulative distribution functions based on field data for:
  - Surface concentration ($C_s$)
  - Diffusion coefficient ($D_0$)
  - Cover depth

- Considered cracks over 5% of area as 5x Diffusion coefficient elsewhere
Modeling challenges

- Determination of Inputs ($C_T$, $t_p$)
  - Corrosion resistant bars require long or accelerated tests; most do not assess $t_p$
  - Wide variety of opinions in industry

- Stainless clad bar
  - Effect of bar ends, breaks in cladding
    - Clad bar treated as 316 stainless with bar ends performing as black bar in 1.4% of deck area
Model inputs

- Cover a range of expected performance (pessimistic to optimistic)

<table>
<thead>
<tr>
<th>Case</th>
<th>Corrosion Threshold, CT (lbs/yd³)</th>
<th>Propagation time, tp (yrs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Black</td>
<td>1, 1.5</td>
<td>5</td>
</tr>
<tr>
<td>ECR</td>
<td>3, 6, 9, 12</td>
<td>15</td>
</tr>
<tr>
<td>MMFX-II</td>
<td>3, 4.5, 6</td>
<td>9</td>
</tr>
<tr>
<td>Stainless Clad (SCR)</td>
<td>10, 15, 25</td>
<td>25</td>
</tr>
<tr>
<td>304 SS</td>
<td>7.5, 15</td>
<td></td>
</tr>
<tr>
<td>316 SS</td>
<td>10, 15, 25</td>
<td>25</td>
</tr>
</tbody>
</table>
## Model Inputs

Concrete and Exposure Distributions:

<table>
<thead>
<tr>
<th>Bridge Property</th>
<th>Average (Coef. of Var.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete Cover (Bridge Construction)</td>
<td>3 in. (10%)</td>
</tr>
<tr>
<td>Diffusion Coefficient (Concrete Quality)</td>
<td>0.15 in$^2$/yr, 0.025 in$^2$/yr for HPC (45%)</td>
</tr>
<tr>
<td>Surface Chloride Concentration (Exposure Conditions)</td>
<td>26 lbs/yd$^3$ (22%)</td>
</tr>
</tbody>
</table>

*Values based on WJE field studies in Iowa and Virginia of 9 decks, but severe exposure*
Damage limit for repair

Damage Fraction (%) vs. Time (yrs.)

- Black
Black

MMFX-II

Damage limit for repair

Time (yrs.)

Damage Fraction (%)

0 10 20 30 40 50

0 2 4 6 8 10 12 14 16 18 20
Damage fraction (%) vs. time (yrs.)

- Black
- MMFX-II
- ECR
- Black w/HPC

Damage limit for repair
Damage limit for repair

304 SS

Time (yrs.)

Damage Fraction (%)
Damage limit for repair

304 SS

SCR
Damage limit for repair

Damage Fraction (%)

Time (yrs.)

304 SS

SCR

316 SS
Economic Analysis Inputs

- Maintenance Program
  - Patching starts at 1% damage and deck is patched up to 10% of the area before an overlay is placed.
  - Deck is overlaid when damage level reaches 10%.
  - After two overlays, the deck service life is complete.
  - Total life span of all decks is terminated at 100 years.
Economic Analysis Inputs

- Real discount rate (corrected for inflation):
  - 2.8% - 2008 US OMB Circular A-94
  - 4%

- Overlay (finite life span):
  - 7 yrs.
  - 15 yrs. – Average based on WJE survey
  - 25 yrs.
Economic Analysis Inputs

- **Bridge costs** determined based on “average”-sized bridge (FHWA report)

- **Bar costs** used for initial bridge deck costs based on April 08 pricing provided by NX Infrastructure

<table>
<thead>
<tr>
<th>Bar Type</th>
<th>Black</th>
<th>ECR</th>
<th>MMFX-II</th>
<th>Clad</th>
<th>304 SS</th>
<th>316 SS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost ($/lb) – Fab’d and Delivered</td>
<td>0.94</td>
<td>1.15</td>
<td>1.13</td>
<td>2.90</td>
<td>3.46</td>
<td>4.95</td>
</tr>
</tbody>
</table>

- **HPC cost** - Material 150% of that for conventional conc.
Deck Life Spans (Overlay Life=15 yrs)
Range of Costs

*Disc. Rate* = 2.8%
*Overlay* = 15 yrs.

Service Life Inputs shown: $C_t$ in lbs./yd.³, $T_p$ in yrs.

Annualized Life Cycle Cost ($)
Effect of Overlay Life

- Longer Overlay Life = Decreased Annualized Cost
- Most corrosion resistant alternatives appear better if overlay life is short
- Regardless of overlay life, SCR (25 lbs/yd³) has lowest Annualized Cost
Effect of Discount Rate

- Higher discount rate = Increased Annualized Cost
  - Future costs weighted less heavily versus initial costs

- For 2.8% discount rate, SCR (25 lbs/yd³) has lowest Annualized Cost

- For ≥4% discount rate, ECR (12 lbs/yd³) has lowest Annualized Cost
Best Estimate for SCR

- Overlay = 15 yrs., Rate = 2.8%

- Consider Annualized Cost for Optimistic corrosion resistance:
  - SCR is 43% less than Black Bar
  - SCR is 10% less than ECR
  - SCR is 17% less than Solid 316 SS
Conclusions

- Modeled Range of Inputs Due to Uncertainties: Corrosion resistance, Material Costs, Discount Rate, Overlay life, **User Cost**

- SCR showed lowest Annualized Cost (2.8%, 15 yrs.) even with bar ends treated as black

- Model is available for specific projects
Questions?

John Lawler

JLAWLER@WJE.COM
Effect of User Costs

- User Costs - $ value assigned to public

- Simple Example
  - Traffic congestion on average bridge due to:
    - 150-day construction
    - 45-day rehabilitation
  - Assumed delay time, $/hr
Effect of User Costs

- Results of User Cost analysis
  - Produces 4-6x increase in Annualized costs
  - Benefits of more corrosion resistant alternatives greater
  - SCR (25 lb/yr) still least expensive choice
  - 316 SS replaces ECR as 2\textsuperscript{nd} best alternative