Service Life Evaluation of Concrete Structures

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Agenda

Part I: Introduction
  • Durability
  • Code-based vs performance-based design

Part II: Chloride-induced corrosion
  • Review of corrosion mechanism
  • Introduction of service life modeling

Part III: Service life evaluation
  • Diagnostic phase
  • Prognostic phase

Part IV: What’s next?
  • Artificial intelligence and digital twins
Part I
Durability

*Durabilitas* = Ability to last for a long time

ACI definition:

durability — the ability of a material to resist weathering action, chemical attack, abrasion, and other conditions of service.
Concrete durability

Various mechanisms of deterioration
• Freeze and thaw
• Abrasion
• Carbonation
• Chlorides
• Sulfates
• Alkali-silicates
• Etc.

(Millman and Giancaspro, 2015)
Concrete durability

Code-based, prescriptive design
Concrete durability

Performance-based design

![Graph showing the change in reliability with age of structure](image-url)
Part II
Chloride-induced corrosion

Ion flow

Anode

Cathode

Solution

Electron flow

Metal
Service life model

Corrosion initiation (or depassivation of the steel reinforcement)

Environmental exposure

Cover

Concrete porosity
Service life model

Corrosion initiation (or depassivation of the steel reinforcement)

Environmental exposure

Cover

Concrete diffusivity

Rust formation
Service life model

Corrosion propagation
Service life model

Corrosion propagation
Service life model

Corrosion propagation
Service life model

Corrosion propagation
Service life model

Tuutti, K., 1982, Corrosion of Steel in Concrete, Swedish Cement and Concrete Research Institute, Stockholm, Sweden
Part III
Service life evaluation

Goal: provide a holistic assessment from limited data points

https://www.newyorker.com/cartoons/daily-cartoon/friday-june-29th-heres-your-problem
Service life evaluation

Visual survey → Testing

Evaluate level of corrosion propagation

Estimate time to corrosion initiation

Diagnosis

Action plan

Treatment

Prognosis
Service life evaluation

- Materials
- Environment
- Design
- Execution
Diagnosis

Are there any sign of deterioration?
Diagnosis

Are there any construction defects?
Diagnosis

What is the source of chlorides?
Diagnosis

What type of protection do we have?
## Diagnosis

Has corrosion initiated?

<table>
<thead>
<tr>
<th>Test Location</th>
<th>Depth (in.)</th>
<th>Chloride content</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Pounds of chlorides per cubic yard</td>
<td>Percent of concrete weight</td>
</tr>
<tr>
<td>Column 1</td>
<td>1</td>
<td>7.67</td>
<td>0.202%</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>2.34</td>
<td>0.062%</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.42</td>
<td>0.011%</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>10.14</td>
<td>0.267%</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>7.01</td>
<td>0.184%</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>Column 2</td>
<td>1</td>
<td>3.37</td>
<td>0.089%</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.03</td>
<td>0.024%</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.74</td>
<td>0.019%</td>
</tr>
<tr>
<td>Column 3</td>
<td>1</td>
<td>1.23</td>
<td>0.032%</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.31</td>
<td>0.008%</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.10</td>
<td>0.003%</td>
</tr>
<tr>
<td>Roof Waffle North</td>
<td>1</td>
<td>1.23</td>
<td>0.032%</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.36</td>
<td>0.009%</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.10</td>
<td>0.003%</td>
</tr>
<tr>
<td>Roof Waffle South</td>
<td>1</td>
<td>0.10</td>
<td>0.003%</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.10</td>
<td>0.003%</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>6.10</td>
<td>0.161%</td>
</tr>
</tbody>
</table>

![Graph](image-url)
Diagnosis

Sounding and impact echo testing

ASTM C 1383

ASTM D 4580
Diagnosis

Half-cell potential testing

ASTM D 876

Position

Potential (mV)

-350
Diagnosis

Concrete electrical resistivity testing (Rilem, AASHTO)

<table>
<thead>
<tr>
<th>Concrete resistivity (kΩ–cm)</th>
<th>Risk of corrosion</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 10</td>
<td>High</td>
</tr>
<tr>
<td>10 to 50</td>
<td>Moderate</td>
</tr>
<tr>
<td>50 to 100</td>
<td>Low</td>
</tr>
<tr>
<td>&gt; 100</td>
<td>Negligible</td>
</tr>
</tbody>
</table>
Diagnosis

Artificial intelligence, drones and laser scanning
Diagnosis

Damage mapping
Diagnosis

Color-coded map of test results
Prognosis

Corrosion initiation

$$C(x, t) = C_0 \left(1 - erf \frac{x}{2\sqrt{D_t t}} \right)$$

Environment

Geometric properties

Material properties
Prognosis

Corrosion initiation modeling

\[ C(x, t) = C_0 \left( 1 - erf \frac{x}{2\sqrt{D_c t}} \right) \]

Environmental factors:
- Chloride binding coefficient
- Carbonation
- Temperature
- Relative Humidity
- Corrosion inhibitor content
- Type of steel
- Admixture in concrete
- Porosity
- Cement composition
- Geographic location
- Type of structure
- Effect of co-existing ions

Material properties:
- Life-35
- STADIUM
- ConcreteWorks
- DURACRETE
- CHLODIF
- ClinConc
- NIST CIKS
- NCHRP 558

Modeling Corrosion-Related Service Life of Existing Concrete Materials Performance Magazine October 2019 (bluetoad.com)
Prognosis

Time to corrosion initiation

Surface chloride concentration

<table>
<thead>
<tr>
<th>Source</th>
<th>Wave Splashing Zone</th>
<th>Coastal Atmospheric Zone</th>
<th>Offshore Atmospheric Zone</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACI-365</td>
<td>18.4</td>
<td>23(2.3)</td>
<td>13.8(0.92)</td>
</tr>
<tr>
<td>JSCE</td>
<td>14.95</td>
<td>10.35</td>
<td>2.3</td>
</tr>
<tr>
<td>DuraCrete</td>
<td>12.42</td>
<td>4.11</td>
<td>4.11</td>
</tr>
<tr>
<td>GB/T51355-2019</td>
<td>17</td>
<td>11.5</td>
<td>2.57</td>
</tr>
<tr>
<td>Bamforth</td>
<td>18</td>
<td>12</td>
<td>6</td>
</tr>
<tr>
<td>McGee</td>
<td>-</td>
<td>2.95</td>
<td>1.69</td>
</tr>
</tbody>
</table>

https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7288091/
Prognosis

Ground penetrating radar (ASTM, AASHTO, ACI)
Prognosis

Concrete apparent diffusivity (ASTM C 1556)
ACI 318 chloride limits:

- Exposure class C0
- Exposure class C1
- Exposure class C2

Prognosis

Probabilistic analysis

Figure 2-2. Life-cycle performance profile under uncertainty. 
Source: Adapted from Biondini and Frangopol (2016). 

(Biodini and Frangopol, 2020)
Prognosis

Evaluation of residual service life

<table>
<thead>
<tr>
<th>Time (years)</th>
<th>Damage level (%)</th>
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<tr>
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% damage / year
Prognosis

Evaluation of residual service life

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Time (years)
Prognosis

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<td></td>
<td></td>
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<tr>
<td>Calculated time to corrosion initiation</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Expected residual life with no intervention</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Acceptable damage level</td>
<td></td>
<td></td>
<td></td>
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<th>Acceptable damage level</th>
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**Prognosis**

**Evaluation of residual service life**

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<tr>
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<tr>
<td></td>
<td>Calculated time to corrosion initiation</td>
</tr>
<tr>
<td></td>
<td>Expected residual life with intervention</td>
</tr>
</tbody>
</table>

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**Acceptable damage level**

**Calculated time to corrosion initiation**

**Expected residual life with intervention**
Prognosis

Evaluation of residual service life

Damage level (%)

Acceptable damage level

Observed damage

% damage / year

Calculated time to corrosion initiation

Age of the structure at time of survey

Predicted additional service life

Time (years)
Prognosis

Evaluation of residual service life

<table>
<thead>
<tr>
<th>Damage level (%)</th>
<th>Observed damage</th>
<th>% damage / year</th>
<th>Calculated time to corrosion initiation</th>
<th>Age of the structure at time of survey</th>
<th>Predicted additional service life</th>
<th>Time (years)</th>
</tr>
</thead>
</table>

Challenges:
- Coatings
- Cracking
- Repairs
Part IV
What's next?

Public Law No: 117-58 (11/15/2021)
Infrastructure Investment and Jobs Act

Among other provisions, this bill provides new funding for infrastructure projects, including for:

- roads, bridges, and major projects;
- passenger and freight rail;
- highway and pedestrian safety;
- public transit;
- broadband;
- ports and waterways;
- airports;
- water infrastructure;
- power and grid reliability and resiliency;
- resiliency, including funding for coastal resiliency, ecosystem restoration, and weatherization;
- clean school buses and ferries;
- electric vehicle charging;
- addressing legacy pollution by cleaning up Brownfield and Superfund sites and reclaiming abandoned mines; and
- Western Water Infrastructure.
Big picture goal

- Monitoring
- Digital twins
- Diagnosis
- Prognosis
Big picture goal

- Monitoring
- Diagnosis
- Prognosis
- Digital Twins
- Preventative Maintenance
- Early Treatment
Digital twins

Image Lungs and Create 3D Model

Run Sims of Blood and Oxygen Flow

Train AI with Simulation Data

Predict Ventilation Requirements

Update Digital Twin

Digital twins
Preventative maintenance

Time (years)

Damage

End of service life / failure

Do nothing
Preventative maintenance

- **Time (years)**
- **Damage**

- **End of service life / failure**
- **Do nothing**
- **React**
Preventative maintenance

Reactive maintenance is the state of the art

End of service life / failure

Do nothing

React
Preventative maintenance

<table>
<thead>
<tr>
<th>Time (years)</th>
<th>Damage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Do nothing</td>
<td>React</td>
</tr>
<tr>
<td>Prevent</td>
<td></td>
</tr>
</tbody>
</table>

End of service life / failure

Reactive maintenance is the state of the art

Do nothing

React

Prevent
Preventative maintenance

<table>
<thead>
<tr>
<th>Damage</th>
<th>Time (years)</th>
</tr>
</thead>
<tbody>
<tr>
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<td>React</td>
</tr>
<tr>
<td>Prevent</td>
<td>End of service life / failure</td>
</tr>
</tbody>
</table>

Reactive maintenance is the state of the art

Strive for preventative maintenance

ICRI Concrete Repair
Preventative maintenance

- Reactive maintenance is the state of the art
- Strive for preventative maintenance
- Early monitoring is key

Damage vs. Time (years)

- End of service life / failure
- Do nothing
- React
- Prevent
Machine learning

Problem categories that benefit from machine learning: 

- **a** Clustering
- **b** Classification
- **c** Regression
- **d** Rule extraction

Proof of concept

Analogy

Independent variables:
• Age
• Chest pain type
• Resting blood pressure
• Serum cholesterol
• Max heart rate achieved
• Etc.

Can ML be used to predict if the patient has a heart condition or not?

Proof of concept

Analogy

Independent variables

Dependent variable

Linear Regression RMS Error= 0.33 or 33% determines goodness of fit for the model

Logistic Regression Confusion Matrix

<table>
<thead>
<tr>
<th></th>
<th>True Positive</th>
<th>False Positive</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>140</td>
<td>18</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>False Negative</th>
<th>True Negative</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>27</td>
<td>109</td>
</tr>
</tbody>
</table>

Error=0.15 or 15%
Machine learning for service life evaluation

Dataset from inspection reports

<table>
<thead>
<tr>
<th>ID</th>
<th>Year 1</th>
<th>Year 2</th>
<th>...</th>
<th>Year i</th>
<th>...</th>
<th>Year n</th>
</tr>
</thead>
<tbody>
<tr>
<td>ID 1</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ID 2</td>
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<tr>
<td>ID n</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Type
Age
Condition 1
Condition 2
...
Amount of damage
Rating
Repair Y/N
Conclusions

• Focus on chloride-induced corrosion of steel reinforcement

• Review of service life modeling

• Overview of state-of-the-art methodology for diagnosis and prognosis of reinforced concrete structures

• Discussion on how innovation can add value to evaluating the residual life of existing structures
Questions?

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