Life cycle maintenance planning for deteriorated RC structure

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Introduction

Collapse of Bridges in Minnesota

1967: Open
1990: Inspection
- Deck patching
- Intensive inspection
2001: Inspection
- No performance problem
- Frequently inspection
2007: Collapse

Problem of current maintenance

Structural safety and maintenance program are evaluated by human judgment based on qualitative inspection

Progress of deterioration is predicted based on database of deterioration rate and Markov process

Life Cycle Maintenance Procedure

Concrete Structures

Setting up of Maintenance Plan
- Initial Inspection

Revision of Maintenance Plan
- Inspection
- Prediction of Progressive of Deterioration

Evaluation/Decision-making

Remedial Actions

Record
Inspection

• Visual Inspection
• Partial destructive testing
  • Penetration resistance
  • Pull out test
  • Pull off test
  • Break off test
• Coring
• Non destructive testing

Visual Inspection

• Initial inspection and periodic inspections (routine and regular inspection) are performed mostly by visual inspection
• It is not possible to perform detailed inspection of all parts of structures for all structures

What to be inspected? → Conditions and damages level of structure

Example of NDT applications (Uomoto2005)

Inspection – Non destructive test

• NDTs for Strength Evaluation
  Schmidt hammer, Ultrasonic
• NDTs for Rebar Detection
  Electromagnetic, RADAR, X-ray
• NDTs for Inspection of Internal Condition
  Ultrasonic, Impact echo, Thermograph, X-ray, Acoustic emission
• NDTs for Corrosion Checking
  Half-cell potential, polarization resistance

General Maintenance Procedure

Concrete Structures

Setting up of Maintenance Plan

Initial Inspection

Revision of Maintenance Plan

Inspection

Evaluation/Decision-making

Remedial Actions

Prediction of Progressive of Deterioration
Deterioration Mechanics of Chloride Attack

Stage 1: Initiation Stage
Up to time when chloride content at steel surface reaches the threshold

\[ C(t) = C_{\text{sat}} \]

Stage 2: Propagation Stage
From beginning of corrosion until the onset of corrosion crack

\[ W_{\text{r}}(t) = W_{\text{crit}} \]

Stage 3: Acceleration Stage
Corrosion crack occurs. Crack width increasing

\[ W_{\text{c}}(t) = W_{\text{lim}} \]

Stage 4: After being repaired
Deterioration of repaired structure

\[ \text{Re-deterioration of repairing system} \]

Prediction Program

FACOMP
Fly Ash CO\textsubscript{2}crete Mix Proportioning

Steel covering depth, mm
Actual result
Fitting result

We needed the probability based prediction to predict variation of the actual deteriorated condition of structure

Reality of Deterioration Degree

Example of variation of parameter value

Gamma(7.0478, 6.1951) Shift=+12.0433
Using actual inspection result in prediction

- Covering depth
- Chloride threshold
- Chloride diffusion coefficient
- Surface chloride content

Variation of inspection result

- After 10 years
- After 50 years

Deterioration Mechanisms of Chloride Attack

**Stage 1: Initiation Stage**
Up to time when chloride content at steel surface reaches the threshold

**Stage 2: Propagation Stage**
From beginning of corrosion until the onset of corrosion crack

**Stage 3: Acceleration Stage**
Corrosion crack occur. Crack width increasing

**Stage 4: After being repaired**
Deterioration of repaired structure

How to predict deterioration after repairing is conducted?

Affected Parameters after Repairing

<table>
<thead>
<tr>
<th>Parameters affected after repairing</th>
<th>Surface Coating</th>
<th>Patching</th>
<th>Cathodic Protection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chloride diffusion coefficient, D_{cl}</td>
<td>○</td>
<td>○</td>
<td>▲</td>
</tr>
<tr>
<td>Surface chloride content, C_{s}</td>
<td>○</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>Threshold chloride content, C_{lim}</td>
<td>×</td>
<td>▲</td>
<td>▲</td>
</tr>
<tr>
<td>Concrete strength, f_{c}</td>
<td>×</td>
<td>○</td>
<td>▲</td>
</tr>
<tr>
<td>Corrosion current, i_{corr}</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
</tbody>
</table>

○ = Be affected, ▲ = Possible be affected, × = Not be affected

Deterioration of surface coating

- Crack of surface coating
- Trace of crack on surface coating

Deterioration of Patching Repair

- Macrocell corrosion of patching repair
- Trace of macrocell corrosion
- Macrocell corrosion
- Patching repair section
- High chloride content
  - Macrocell corrosion
  - Trace of macrocell corrosion
Maintenance planning and life cycle cost

Life cycle cost (LCC)

\[ C_t = C_i + C_{ins} + C_r + C_f \]

- \( C_i \): Initial construction cost
- \( C_{ins} \): Inspection cost
- \( C_r \): Repairing cost
- \( C_f \): Failure cost

Example of Practical Application

**Target structure**

- Inspection program: Parameters, and number of samples

- Variation of structural performance

- Deterioration prediction model: Before and after repairing

- Probability based prediction deterioration degree

- What is the appropriate user or failure cost?

- \( C_T \): Total repairing cost

- How much is repairing quantity and repairing cost?

- User cost

- Example of Practical Application

**Example of Practical Application**

- Target structure

- Inspection program: Parameters, and number of samples

- Variation of structural performance

- Deterioration prediction model: Before and after repairing

- Probability based prediction deterioration degree

- What is the appropriate user or failure cost?

- \( C_T \): Total repairing cost

- How much is repairing quantity and repairing cost?

User cost

(As used in case of national bridge)

\[ C_u(t) = Time\text{value} \cdot t_{ave}(t) \cdot V(t) \]

- \( C_u(t) \): Annual user cost

- \( t_{ave}(t) \): Time value of user, US$/vehicle-minute

- \( V(t) \): Loss of user depending on deterioration degree of structure

- What is the appropriate user or failure cost?

- \( C_T \): Total user cost during service life

- \( n \): Service life

- \( V \): Discount rate
Example 1

Covering depth
- Method: Electro magnetic
- Be careful
  - Depth of steel
  - Alignment of steel
  - Adjacent magnetic field
  - Smooth concrete surface

Chloride content
- Method: JSCE G573
  - Drilling 2-4 adjacent holes with 14mm diameter each
  - Collect the sample powder at 0-2, 2-4, 4-6, 6-8, and 8-10cm

Compressive strength
- Method: Rebound hammer
- No. of sample:
  - 20 points per sample
  - 3cm distance between each point
- Be careful
  - Angle of testing
  - Surface condition

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Number of sample</th>
<th>Specified value</th>
<th>Mean</th>
<th>COV, %</th>
<th>Distribution</th>
<th>Inspection result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Covering depth</td>
<td>915</td>
<td>50mm</td>
<td>24.3mm</td>
<td>10.60</td>
<td>Gamma (12.25, 5.05)</td>
<td>Required 50mm</td>
</tr>
<tr>
<td>Chloride diffusion coefficient</td>
<td>3</td>
<td>-</td>
<td>1.34 y/year</td>
<td>10.15</td>
<td>Normal (1.34, 1.35)</td>
<td>Required 0.75 kg/m³</td>
</tr>
<tr>
<td>Surface chloride content</td>
<td>3</td>
<td>-</td>
<td>0.75 kg/m³</td>
<td>-</td>
<td>Uniform (0.74, 0.75)</td>
<td></td>
</tr>
<tr>
<td>Compressive strength</td>
<td>252</td>
<td>24MPa</td>
<td>14.30</td>
<td>10.35</td>
<td>Estimate value (14.30, 5.50)</td>
<td>5% less than required</td>
</tr>
</tbody>
</table>

Case studies: Bad structure

Site of Inspection: Case studies

Bangkok

Number of Sample | Specified value | Mean | COV, % | Distribution          | Inspection result |
<table>
<thead>
<tr>
<th></th>
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<th></th>
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Case studies: Bad structure – Pf

- No repair
- Patching
- Patching + Coating
- Cathodic protection

*Probability of failure vs. Time, year*

Case studies: Bad structure – LCC

- No repair
- Patching
- Patching + Coating
- Cathodic protection

*Remaining service life 57 years*

Case studies: Good structure

<table>
<thead>
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<th>Parameters</th>
<th>Number of sample</th>
<th>Specified value</th>
<th>Specified result</th>
<th>COV, %</th>
<th>Distribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coating depth</td>
<td>334</td>
<td>75mm</td>
<td>25.38mm</td>
<td>22.10</td>
<td>Weibull (6.68, 120.67)</td>
</tr>
<tr>
<td>Chloride diffusion coefficient</td>
<td>6</td>
<td>0.6</td>
<td>0.98</td>
<td>98.09</td>
<td>Normal (6.82, 19.09)</td>
</tr>
<tr>
<td>Surface chloride content</td>
<td>6</td>
<td>-</td>
<td>3.34 kg/m²</td>
<td>19.34</td>
<td>Uniform (3.08, 14.30)</td>
</tr>
<tr>
<td>Compressive strength</td>
<td>1495</td>
<td>30MPa</td>
<td>19MPa</td>
<td>19.00</td>
<td>Extreme value (19.35, 6.68)</td>
</tr>
</tbody>
</table>

**Case studies: Good structure – Pf**

- No repair
- Patching
- Patching + Coating
- Cathodic protection

**Case studies: Good structure – LCC**

- No repair
- Patch+Coat: Fixed budget
- Patch+Coat
- Patch
- Patch: Fixed budget
- Patch

**Maintenance with Fixed budget**

(Assumed repairing budget is limited to 50,000 US$ during the service life)

**Methods and schedule of repairing are decided by LCC**

- No repairing is needed during the service life

**Methods and schedule of repairing are decided by LCC**

- Two times of cathodic protection at year 47th and 80th causes the lowest LCC

**Methods and schedule of repairing are decided by LCC**

- Allocation of repairing budget can be adjusted based on the different of LCC

- Repairing cannot be conducted because of fixed repairing budget. Then, failure cost is increase as well as LCC.
**Guideline for service life**

- Service life is assumed to be the time that total repairing cost is equal to initial construction cost.

**Good Quality**
- Assumed initial cost = 75,000 US$

**Bad Quality**
- Assumed initial cost = 50,000 US$

![Graph showing life cycle cost over time](image)

**Repairing cost**
- 9,960 US$

**Time, year**
- 0 100 200 300 400 500 600 700

**Life cycle cost**
- 0 50000 100000 150000 200000 250000

**Example 2**

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**Introduction**

- What is the cause of cracks?
- Is this building still safe?
- How long structure can be used?

**Visual Inspection**

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**Crack Inspection: Preparation (2)**
Crack Inspection: Preparation (2)

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Crack Mapping

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Result of Crack Mapping Block 3-4

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What is the likely cause of this cracking?

- All cracks is from support to support
- Crack spacing is approximately same.
- Most of the crack is in one direction
- Not depend on carrying load

Shrinkage crack

Estimation of Concrete Shrinkage (JSCE)

\[ \varepsilon_{sh}^f(t, t_0) = 1 - \exp(-0.108(t - t_0)^0.56) \cdot \varepsilon_{sh}^0 \]

- \( \varepsilon_{sh}^f(t, t_0) \): Final value of shrinkage strain (x10^-5)
- \( \varepsilon_{sh}^0 \): Shrinkage strain of concrete from age of \( t_0 \) to \( t \) (x10^-5)
- \( RH \): Relative humidity (% (45% \leq RH \leq 80%))
- \( W \): Unit water content (kg/m^3) (130kg/m^3 \leq W \leq 230kg/m^3)
- \( V \): Volume (mm^3)
- \( S \): Surface area in contact with outside air (mm^2)
- \( V/S \): Volume-surface ratio (mm) (100mm/V/S \leq 300mm)

Shrinkage induce cracking
**Estimation of Concrete Shrinkage**

\[ \varepsilon_{sh} = -50 + 78 \left[ 1 - \exp \left( \frac{RH}{100} \right) \right] + 38 \log W - 5 \left[ \log \left( \frac{V}{S} \right) \right] \]

**Assumption:**

- Relative humidity: 75%
- Unit water content: 200 kg/m³
- Average slab size: 3160mm x 4630mm

\[ \varepsilon'_{sh} = 27.39 \times 10^{-2} \]

**Estimation of Concrete Shrinkage**

\[ \sigma'_c = \frac{1 - \exp \left[ -0.108 \left( t - t_0 \right)^{0.56} \right]}{t - t_0} \cdot \varepsilon'_c \]

\[ t - t_0 = \sum_{i=1}^{n} \Delta t_i \cdot \exp \left[ 13.65 - \frac{4000}{273 + T(T_i)} \right] \]

\( \Delta t_i \) : Number of days when the temperature is \( T \) (°C)

\( T_0 \) : 1°C

**Assumption:**

| Temperature | 25°C |

**Estimation of Crack Width**

**Assumption:**

- Compressive strength: 280 ksci
- Modulus of rupture: 2.0(1) ksci
- Young’s modulus: 2.75 x 10^5 ksci
- Restrain condition: 98% restrained
- Time: 10 years

\[ \sigma_c = \frac{2}{3} \sigma'_c \cdot E_c = 75.39 \text{ksci} \]

**Estimated crack width = 0.71 mm**

**Cumulative crack width Block 1-2**

Average = 0.7mm

**Measurement – Covering depth**

- Probe parallel to steel reinforcement
- Move the probe at low speed
- Mark the location of reinforcing steel
- Record the covering depth
**Result: Covering depth Block 3-4**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Number of sample</th>
<th>Specified value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Covering depth</td>
<td>307</td>
<td>20mm</td>
</tr>
</tbody>
</table>

**Inspection result**

<table>
<thead>
<tr>
<th>Mean (mm)</th>
<th>COV (%)</th>
<th>Distribution Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>20.47</td>
<td>17.45</td>
<td>Normal</td>
</tr>
</tbody>
</table>

**Measurement – Rebound number**

- Locate the location of steel
- Select the location and Smoothing the surface
- Marking the test location
- Testing perpendicular to surface

**Result: Schmidt hammer Block 3-4**

\[ f_c' = -18 + (1.27 \times RN) \]
\[ f_c = 392 \text{ ksc} \]

**Measurement**

- Locate the location of steel
- Marking the measure location
- Measuring the velocity

**Result: Slab**

<table>
<thead>
<tr>
<th>ตัวอย่าง</th>
<th>( t_1 ) (μ)</th>
<th>( t_2 ) (μ)</th>
<th>ความลึกรอยรอย (mm)</th>
<th>หมายเหตุ</th>
</tr>
</thead>
<tbody>
<tr>
<td>S5-1</td>
<td>77.7</td>
<td>121.7</td>
<td>43.69</td>
<td>-</td>
</tr>
<tr>
<td>S5-2</td>
<td>78.2</td>
<td>144.3</td>
<td>25.10</td>
<td>-</td>
</tr>
<tr>
<td>S6-1</td>
<td>76.3</td>
<td>135.35</td>
<td>31.52</td>
<td>-</td>
</tr>
<tr>
<td>S6-2</td>
<td>83.7</td>
<td>149.4</td>
<td>30.51</td>
<td>-</td>
</tr>
<tr>
<td>S7-1</td>
<td>114.8</td>
<td>129.5</td>
<td>115.05</td>
<td>-</td>
</tr>
<tr>
<td>S7-2</td>
<td>82.8</td>
<td>149.3</td>
<td>28.83</td>
<td>-</td>
</tr>
<tr>
<td>S14-1</td>
<td>92.25</td>
<td>149.65</td>
<td>45.79</td>
<td>-</td>
</tr>
<tr>
<td>S14-2</td>
<td>68.7</td>
<td>168.9</td>
<td>34.16</td>
<td>-</td>
</tr>
<tr>
<td>S15-1</td>
<td>72.2</td>
<td>108.8</td>
<td>65.39</td>
<td>-</td>
</tr>
<tr>
<td>S15-2</td>
<td>86.3</td>
<td>131.6</td>
<td>56.20</td>
<td>-</td>
</tr>
<tr>
<td>S16-1</td>
<td>58.7</td>
<td>73.7</td>
<td>56.14</td>
<td>-</td>
</tr>
<tr>
<td>S16-2</td>
<td>90.8</td>
<td>84.7</td>
<td>56.14</td>
<td>-</td>
</tr>
</tbody>
</table>

**Flexural capacity analysis - Slab**

- Two-ways slab
- Slab thickness - 200mm, Covering – 20mm
- Reinforcing steel - DB12@150mm Top and Bottom

\[
C = 31.83 \text{ mm}^2
\]

<table>
<thead>
<tr>
<th>d</th>
<th>174mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>d</td>
<td>61mm</td>
</tr>
<tr>
<td>( A_s )</td>
<td>678mm²</td>
</tr>
<tr>
<td>b</td>
<td>1000mm</td>
</tr>
<tr>
<td>( f_s' )</td>
<td>280ksc</td>
</tr>
<tr>
<td>( f_{cc} )</td>
<td>4000ksc</td>
</tr>
</tbody>
</table>
**Remaining load carrying capacity**

<table>
<thead>
<tr>
<th>Type</th>
<th>σ (unit)</th>
<th>σ (unit)</th>
<th>σ (unit)</th>
</tr>
</thead>
<tbody>
<tr>
<td>R&amp;M</td>
<td>4335.00 lb/ft²</td>
<td>4335.00 lb/ft²</td>
<td>4335.00 lb/ft²</td>
</tr>
<tr>
<td>S&amp;M</td>
<td>2688.00 lb/ft²</td>
<td>2688.00 lb/ft²</td>
<td>2688.00 lb/ft²</td>
</tr>
</tbody>
</table>

**Carbonation**

\[ C \geq \gamma_i \cdot x_c \]

\[ x_c = \alpha_1 \cdot \alpha_2 \cdot k \cdot \sqrt{t} \]

**Estimation of Carbonation Depth**

**Estimation of Carbonation Depth**

\[ k = 17.5 \cdot (w/b)^3 \]

**Estimation of Carbonation Depth**

\[ \text{Percentage of replacement} \]

\[ \alpha_2 \]

\[ \begin{array}{c|c|c|c|c|c|c|c|c|c|c} \text{Percentage of replacement} & \alpha_2 \\ \hline 0 & 0.0 \\ 0.5 & 0.05 \\ 1.0 & 0.10 \\ \end{array} \]
### Parameters value

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma_i$</td>
<td>1.1</td>
</tr>
<tr>
<td>$\alpha_1$</td>
<td>1.0</td>
</tr>
<tr>
<td>$\alpha_2$</td>
<td>0.65</td>
</tr>
<tr>
<td>$k_r$</td>
<td>OPC concrete</td>
</tr>
<tr>
<td>$w/b$</td>
<td>0.60</td>
</tr>
<tr>
<td>$k$</td>
<td>3.78 mm/yr^{0.5}</td>
</tr>
</tbody>
</table>

### Carbonation depth of cracked concrete

$$C \geq \gamma_i \cdot X_C$$

<table>
<thead>
<tr>
<th>Percentile</th>
<th>Covering depth (mm)</th>
<th>Corrosion initiation time (year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>28.73</td>
<td>137</td>
</tr>
<tr>
<td>50</td>
<td>40.50</td>
<td>272</td>
</tr>
<tr>
<td>95</td>
<td>52.21</td>
<td>452</td>
</tr>
</tbody>
</table>

### Prediction – Corrosion Initiation Time

### Prediction – Corrosion Cracking Time

### Repairing for uncracked concrete

- Carbonation will reach reinforcement in next 55 years
- If structure is expected to use less than 55 years, no repairing is required
- If structure is expected to use more than 55 years, repairing is conducted
- Concrete surface coating may be conducted to prevent CO$_2$
Concrete surface coating

- There is a chance of crack propagation

Repairing for cracked concrete

- Carbonation has already reached the reinforcement since 2 years after crack initiated
- However, there is no sign of corrosion due to no contact with high moisture source such as rain
- Monitoring result after 2 months shows low possibility of damage progress
  - Long-term monitoring should be conducted, or
  - Close the cracking opening by surface coating (there is chance of crack propagation) or crack injection (no further crack propagation)

Thank you

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