A SIMPLE DURABILITY DESIGN METHOD FOR CARBONATION-INDUCED CORROSION

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SUMMARY

• Scope
• Objective
• Preliminary discussions
• Analytical model
• Reliability analysis
• Proposed method
• Performance assessment
• Final remarks
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Scope

- Reinforcing steel corrosion is the prevailing deterioration mechanism in reinforced concrete structures
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- Reinforcing steel corrosion is the prevailing deterioration mechanism in reinforced concrete structures
- Reinforcing steel corrosion is generally induced by carbonation or chlorides

Although chloride induced corrosion is considered to be more severe, carbonation induced corrosion shall not be disregarded.
Scope

- Resistance against steel corrosion (durability) can be achieved if the cover of reinforcement has proper thickness and resistance to aggressive agents ingress.

- To achieve required durability two approaches can be considered:
  - Deemed-to-satisfy
  - Performance based specification
Scope

• Deemed-to-satisfy approach
  • Standard methodology
  • Simple
  • Limited flexibility
  • Doesn’t allow the quantification of consequences arising from deviations of what was prescribed
  • Not suitable for site control
Scope

- Performance based specification approach
  - Provides flexibility for mix design
  - Allows the quantification of consequences arising from deviations of what was prescribed
  - Suitable for site control

- More complex
- Requires accurate analytical models
Scope

• The trend is to use performance based specification approach to fulfil durability requirements

• Users require performance based specification methods to be:
  • Accurate
  • Simple
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Objective

- Development and proposal of a simple method for performance based design regarding carbonation induced corrosion
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**Preliminary discussions**

- Durability/service life
  - Minimum acceptable performance
  - Maximum acceptable deterioration
Preliminary discussions

- Durability/service life
  - Minimum acceptable performance
  - Maximum acceptable deterioration
    - Carbonation or chloride induced corrosion

![Diagram showing deterioration over time with stages of initiation, propagation, and service life]

Preliminary discussions

- Maximum acceptable deterioration

![Diagram showing deterioration over time with stages of collapse, spalling, cracking, and delamination]

8/27

9/27
Preliminary discussions

- Maximum acceptable deterioration

Accept higher levels of deterioration involves increasing the consequences
Preliminary discussions

- Accept higher levels of deterioration involves increasing the consequences
- To maintain the risk, the probability of occurrence must decrease
Preliminary discussions

- Depassivation Limit State
  - Simplicity (requires only one analytical model)
  - Disregard propagation stage may have large impact on production costs

The impact can be controlled making a reliability differentiation according to environmental classes taking into account the associated consequences.
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### Analytical model

- Several factors affecting carbonation must be taken into account
- User friendliness
Analytical model

• Several factors affecting carbonation must be taken into account
  • User friendliness

\[ x = K \sqrt{t} \]

\[ K = \frac{k_a}{k_e} \]

Concrete (intrinsic) factors

Environmental factors
Analytical model

\[ x = \frac{k_a}{k_o} \sqrt{t} \]

- \( k_a \): resistance to accelerated carbonation (mm/year\(^{0.5}\))
Analytical model

\[ x = \frac{k_e}{k_a} \sqrt{t} \]

- \( k_a \): resistance to accelerated carbonation (mm/year^{0.5})
  - XC3 \( \rightarrow k_e = 9.9 \)
  - XC4 \( \rightarrow k_e = 15.0 \)
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Reliability analysis

• Semi-probabilistic approach

$$R_c = \gamma_R S_c > 0$$
Reliability analysis

- Semi-probabilistic approach

\[ C_d - \gamma_s X > 0 \]

\[ C_d = C_{\text{nom}} - \Delta c \]
Reliability analysis

- Semi-probabilistic approach

\[ C_d - \gamma_S \frac{K_a}{K_e} \sqrt{f_{SL}} > 0 \]

\[ C_d = C_{nom} - \Delta c \]

\[ \gamma_S \rightarrow \text{Monte Carlo simulations} \]

\[ \beta = 1.50 \Rightarrow p_f = 0.066 \]
Reliability analysis

• $\gamma_S$ for environmental class XC4

$$p\left(\frac{\gamma_S \ k_a}{K_e} \sqrt{f_{SL}} > c_d \right) = 0.066$$

$k_a$ Normal distributed variable with C.o.V. = 13%

$k_e$ Normal distributed variable with $\mu = 15$ and $\sigma = 0.88$
Reliability analysis

- $\gamma_S$ for environmental class XC4

\[
p\left(\frac{\gamma_S k_a}{k_e}\sqrt{f_{SL}} \geq c_d\right) = 0.066
\]

$k_e$ Normal distributed variable with C.o.V. = 13%

$k_e$ Normal distributed variable with $\mu = 15$ and $\sigma = 0.88$

$\gamma_S = 1.25$

Reliability analysis

- $\gamma_S$ for environmental class XC3
Reliability analysis

- $\gamma_S$ for environmental class XC3

$$t_{SL} = t_i + t_p$$

- $t_p = 45$ years

- $t_{SL} = 200$ years
Reliability analysis
• $\gamma_S$ for environmental class XC3

\[
\begin{align*}
t_{SL} &= t_i + t_p \\
t_p &= 45 \text{ years} \\
t_{SL} &= 200 \text{ years} \\
t_i &= 155 \text{ years}
\end{align*}
\]

\[
p\left(\frac{\gamma_S k_a}{K_e} \sqrt{t_i} > c_a\right) = 0.066
\]
Reliability analysis

• $\gamma_S$ for environmental class XC3

$$p\left(\frac{\gamma_S k_a}{k_e} \sqrt{t_i} > c_d\right) = 0.066$$

$k_a$ Normal distributed variable with C.o.V. = 13%

$k_e$ Normal distributed variable with $\mu = 9.9$ and $\sigma = 0.61$
Reliability analysis

- $\gamma_S$ for environmental class XC3

\[
p \left( \frac{\gamma_S}{k_e} \sqrt{t_i} > c_d \right) = 0.066
\]

$k_e$ Normal distributed variable with C.o.V. = 13%

$k_e$ Normal distributed variable with $\mu = 9.9$ and $\sigma = 0.61$

$\gamma_S = 1.00$

Reliability analysis

- For $\gamma_S = 1$

\[
p \left( \frac{k_e}{k_e} \sqrt{t_{SL}} > c_d \right) = 0.50
\]

$\beta = 0$
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Proposed method

\[ k_a = \frac{c_d k_e}{\gamma_s \sqrt{t_{SL}}} \]

• \( k_a \) - resistance to accelerated carbonation (mm/year^{0.5})
Proposed method

\[ k_a = \frac{c_d \cdot k_a}{\gamma_s \cdot \sqrt{t_{SL}}} \]

- \( k_a \) - resistance to accelerated carbonation (mm/year^{0.5})
- \( c_d \) - reinforcement cover design value \( c_d = c_{nom} - 10 \) (mm)

- \( t_{SL} \) - specified service life (year)
Proposed method

\[ k_a = \frac{c_d k_p}{\gamma_s \sqrt{t_{SL}}} \]

- \( k_a \) - resistance to accelerated carbonation (mm/\text{year}^{0.5})
- \( c_d \) - reinforcement cover design value, \( c_d = c_{\text{nom}} - 10 \) (mm)
- \( t_{SL} \) - specified service life (year)

<table>
<thead>
<tr>
<th></th>
<th>( k_e )</th>
<th>( \gamma_s )</th>
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</thead>
<tbody>
<tr>
<td>XC3</td>
<td>9.9</td>
<td>1.00</td>
</tr>
<tr>
<td>XC4</td>
<td>15.0</td>
<td>1.25</td>
</tr>
</tbody>
</table>

\[ X C 3 \]

\[ X C 4 \]

\[ 19/27 \]
Proposed method

- XC4

![Graph showing proposed method](image)

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Performance assessment

- Comparative study with Portuguese standard E 465

<table>
<thead>
<tr>
<th>Scenario</th>
<th>$c_d$ (mm)</th>
<th>$t_{SL}$ (years)</th>
<th>Environmental class</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>25</td>
<td>50</td>
<td>XC3</td>
</tr>
<tr>
<td>B</td>
<td>25</td>
<td>100</td>
<td>XC3</td>
</tr>
<tr>
<td>C</td>
<td>30</td>
<td>50</td>
<td>XC4</td>
</tr>
<tr>
<td>D</td>
<td>30</td>
<td>100</td>
<td>XC4</td>
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</table>

Performance assessment

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**Scenario A**

**Scenario C**

---

<table>
<thead>
<tr>
<th>$L_{\text{con}}$ (mm)</th>
<th>X2</th>
<th>X3</th>
<th>X4</th>
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<tr>
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<td>80</td>
<td>12</td>
<td>88</td>
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<table>
<thead>
<tr>
<th>$L_{\text{res}}$ (mm)</th>
<th>X2</th>
<th>X3</th>
<th>X4</th>
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<tr>
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<td>148</td>
<td>351</td>
<td>281</td>
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<table>
<thead>
<tr>
<th>$k_1$</th>
<th>$n$</th>
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<tbody>
<tr>
<td>0.20</td>
<td>0.09</td>
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<table>
<thead>
<tr>
<th>$k_{\text{h1}}$</th>
<th>$n_{\text{h1}}$</th>
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<tbody>
<tr>
<td>0.77</td>
<td>0.02</td>
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<table>
<thead>
<tr>
<th>$k_{\text{h2}}$</th>
<th>$n_{\text{h2}}$</th>
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<tbody>
<tr>
<td>0.41</td>
<td>0.085</td>
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</table>
Performance assessment

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<table>
<thead>
<tr>
<th>$R_{\text{max}}$ (kg/ano/m$^2$)</th>
<th>X2</th>
<th>X3</th>
<th>X4</th>
<th>X5</th>
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</thead>
<tbody>
<tr>
<td>betão com cura normalizada</td>
<td>61</td>
<td>30</td>
<td>14</td>
<td>78</td>
</tr>
<tr>
<td>(Clave extracierta a solubilidad)</td>
<td>153</td>
<td>23</td>
<td>184</td>
<td>60</td>
</tr>
<tr>
<td>(Clave extracierta a solubilidad)</td>
<td>106</td>
<td>20</td>
<td>229</td>
<td>65</td>
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<td>(Clave extracierta a solubilidad)</td>
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<td>25</td>
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<tr>
<td>(Clave extracierta a solubilidad)</td>
<td>60</td>
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<td>640</td>
<td>64</td>
</tr>
</tbody>
</table>

Scenario B

Scenario D

Performance assessment

- Comparative study with Portuguese standard E 465

$$K_s = \frac{1000}{\sqrt{R_{\text{C50}}}}$$
Performance assessment

- Comparative study with Portuguese standard E 465

\[ k_s = 1000 \sqrt{\frac{2 \cdot 0.09}{R_{C65}}} \]

<table>
<thead>
<tr>
<th>Scenario</th>
<th>E 465</th>
<th>Proposed</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>57</td>
<td>35</td>
</tr>
<tr>
<td>B</td>
<td>41</td>
<td>24</td>
</tr>
<tr>
<td>C</td>
<td>50/45</td>
<td>50</td>
</tr>
<tr>
<td>D</td>
<td>35/33</td>
<td>36</td>
</tr>
</tbody>
</table>

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• Implications of considering a Depassivation Limit State for carbonation-induced corrosion were discussed

• The consequences of disregarding relevant propagation periods (XC3) were balanced by means of considering a lower reliability index
Final remarks

• Implications of considering a Depassivation Limit State for carbonation-induced corrosion were discussed.

• The consequences of disregarding relevant propagation periods (XC3) were balanced by means of considering a lower reliability index.

• A practical and suitable method was proposed.
Final remarks

• Main features of the method
  • Use of only one analytical model
  • Analytical model calibrated with long term results
  • Analytical model requiring just two parameters