Relevance of crack width requirements due to durability aspects of conventional reinforcement

E39 Seminar; Trondheim, 5th January 2018

Tobias Danner

Mette R. Geiker
Outline

• Background and motivation

• Results from field investigations
  • Impact of cracks on chloride ingress and carbonation
    – de-iced structures
  • Impact of cracks on chloride ingress
    – marine structures

• Summary
• Further plans
Research Team

E39 WP 7.1.1: Relevance of crack width and decompression requirements (limits) due to durability aspects of conventional reinforcement

E39 WP 7.1.3: Evaluation and improvement of crack width calculation methods for large-scale concrete structures

Presentation of WP 7.1.3 8th February 2018
E39 WP 7.1.1: Relevance of crack width and decompression requirements (limits) due to durability aspects of conventional reinforcement

Objectives:

Collecting long-term field data on the

• Impact of cracks on chloride ingress
• Impact of cracks on extent of corrosion
Causes of concrete cracking

<table>
<thead>
<tr>
<th></th>
<th>1 hour</th>
<th>1 day</th>
<th>1 week</th>
<th>1 month</th>
<th>1 year</th>
<th>50 years</th>
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</thead>
<tbody>
<tr>
<td><strong>Loading, service</strong></td>
<td></td>
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<tr>
<td><strong>ASR</strong></td>
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<tr>
<td><strong>Corrosion</strong></td>
<td></td>
<td></td>
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<tr>
<td><strong>Drying shrinkage</strong></td>
<td></td>
<td></td>
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</tr>
<tr>
<td><strong>Early thermal contraction</strong></td>
<td></td>
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</tr>
<tr>
<td><strong>Plastic shrinkage</strong></td>
<td></td>
<td></td>
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<tr>
<td><strong>Plastic settlement</strong></td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

*CEB Design guide, Durable Concrete Structures (1989)*


NTNU

E39 Seminar, Tobias Danner & Mette Geiker; Trondheim, 5th January 2018
Crack width limitations for reinforced concrete structures in standards

NS-EN-1992-1-1 (Eurocode 2), DIN 1045-1, ...:
0.3 mm for exposure classes XC, XD and XS

Reasons for crack width limitations (servicability & condition/durability limit states)

- Aesthetics
- Permeability/Tightness
- Durability
  - Reinforcement corrosion
  - Chloride ingress
  - Carbonation

*Foto: Tobias Danner*
*Foto: Øystein Vennesland (TKT4225)*
*Foto: Mette Geiker*
# Crack width impact, guidelines

*fib* Model Code for service life design (2006)

## Chloride ingress

<table>
<thead>
<tr>
<th>Surface</th>
<th>Exposure</th>
<th>Crack</th>
<th>Crack width limitation</th>
<th>Protective Measure</th>
<th>Service Life</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizontal</td>
<td>From top</td>
<td>On Top</td>
<td>Crack</td>
<td>Special measures</td>
<td>≥ 10 years</td>
</tr>
<tr>
<td>Vertical/Horizontal</td>
<td>From bottom</td>
<td>Water not leaking through cracks</td>
<td>≤ 0.3 mm</td>
<td>High quality concrete (cover &gt; 50mm; w/c ≤ 0.5)</td>
<td>≥ 50 years</td>
</tr>
</tbody>
</table>

“It should also be noted that, from the point of view of corrosion control, the permissible crack width of 0.3 mm specified in CP110 * (or indeed any other width) cannot be justified in any logical way from test evidence: it is simply a guess.”

*Beeby (1978a)*

* Code of practice for the structural use of concrete. Design, materials and workmanship (British Standard)
Reinforcement corrosion

Carbonation induced corrosion

\[ \text{pH} < 10 \]

\[ \text{Ca(OH)}_2 + \text{CO}_2 \rightarrow \text{CaCO}_3 + \text{H}_2\text{O} \]

diagram from cement.org, (2017)

General corrosion

diagram from duromac-cp.de (2017)

Chloride induced corrosion

diagram from dti.dk, (2017)

Pitting corrosion

diagram from duromac-cp.de (2017)
Service Life

• Reinforcement corrosion in uncracked concrete
  – **Initiation Period**: Ingress of chlorides and CO$_2$
  – **Propagation Period**: Corrosion of the reinforcement with a certain rate

*after Tuutti (1982)*
Impact of cracks on chloride ingress and corrosion initiation

Facilitate chloride ingress in cracks
Reduce time for corrosion initiation

Crack width: 0.15 mm
Exposure: 3% NaCl solution, 2 weeks

Concrete surface sprayed with AgNO$_3$

Bertolini, Elsner et al. (2013) based on CEB (1989)

Foto: Tobias Danner
Impact of cracks on chloride ingress and corrosion initiation

Michel, A. et al., 2013

Exposure: 3% NaCl solution
Concrete surface sprayed with AgNO₃

a) Half-cell potential
b) Corrosion rate
c) Modelled slip and separation
Impact of cracks on corrosion propagation

Observations

Corrosion rate depends on cover thickness more than on the crack width

For relatively small cracks (< 0.5 mm), reduced corrosion rate or even re-passivation for long term exposure

Recent reviews, e.g.: (Pease 2010), (Šavija 2014), (Käthler, Angst et al. 2017)
Self-healing of concrete

Research questions:
- **Exposure**: water most important factor for self-healing
- **Crack width**: crack width upper limit for self-healing
- **Binder type**: Effect of pozzolanic reaction

*after de Rooij et al. (2013)*

de Rooij et al. (2013);
*Concrete Society, Technical report 44 (2015)*
Service Life

Reinforcement corrosion in cracked concrete

- **Initiation Period:**
  - A: Faster Ingress of chlorides and CO$_2$

- **Propagation Period:**
  - B: Faster corrosion rate
  - C: Same corrosion rate
  - D: Initial faster corrosion rate, but slowing down after some time

Uncracked concrete

Cracked concrete, after *(Pease, Michel et al. 2012), (Käthler, Angst et al. 2017)*

![Graph showing the degradation level over time for both uncracked and cracked concrete, illustrating the initiation and propagation periods.](image)
Project goals E39 WP 7.1.1

E39 Project, “Relevance of crack width and decompression requirements (limits) due to durability aspects of conventional reinforcement”, W.P. 7.1.1

Collecting **long-term field data** on the

- Impact of cracks on chloride ingress
- Impact of cracks on extent of corrosion
- Impact of exposure, binder type and crack width on self-healing of concrete
# Field studies in 2017

<table>
<thead>
<tr>
<th>Structure</th>
<th>Cecilie Bridge</th>
<th>Täsen Tunnel</th>
<th>Moholt Bridge</th>
<th>DNV Field Station</th>
<th>Hafsfjord Bridge</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Type</strong></td>
<td>Beam (Box-girder) Bridge</td>
<td>Kulvert</td>
<td>Slab bridge</td>
<td>Concrete column</td>
<td>Beam Bridge, NIB</td>
</tr>
<tr>
<td><strong>Location</strong></td>
<td>Trondheim</td>
<td>Oslo</td>
<td>Trondheim</td>
<td>Bergen</td>
<td>Stavanger</td>
</tr>
<tr>
<td><strong>Structural part</strong></td>
<td>Edgebeam</td>
<td>Tunnel wall</td>
<td>Edgebeam</td>
<td>Column</td>
<td>Foundation</td>
</tr>
<tr>
<td><strong>Age (years)</strong></td>
<td>16</td>
<td>20</td>
<td>25</td>
<td>33</td>
<td>50</td>
</tr>
<tr>
<td><strong>Exposure</strong></td>
<td>De-icing salt (minor)</td>
<td>De-icing salt (minor)</td>
<td>De-icing salt (minor)</td>
<td>Tidal seawater (heavy)</td>
<td>Tidal seawater (heavy)</td>
</tr>
<tr>
<td><strong>Climate</strong></td>
<td>Inland</td>
<td>Inland</td>
<td>Inland</td>
<td>Marine</td>
<td>Marine</td>
</tr>
<tr>
<td><strong>Concrete</strong></td>
<td>C55, SV-40</td>
<td>C45</td>
<td>C60</td>
<td>B35</td>
<td></td>
</tr>
<tr>
<td><strong>Cover</strong></td>
<td>55</td>
<td>50</td>
<td>50</td>
<td>50</td>
<td>90</td>
</tr>
</tbody>
</table>

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[Image showing structures: Cecilie Bridge, Täsen Tunnel, Moholt Bridge, DNV Field Station, Hafsfjord Bridge]
## Field studies in 2017

### Samples with cracks

<table>
<thead>
<tr>
<th>Structure</th>
<th>Amount of cores</th>
<th>Concrete surface</th>
<th>Crack type</th>
<th>Crack width</th>
<th>Crack orientation</th>
<th>Exposure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cecilie Bridge</td>
<td>1 (5)</td>
<td>Horizontal</td>
<td>Shrinkage</td>
<td>0.45</td>
<td>Vertical</td>
<td>De-icing</td>
</tr>
<tr>
<td>Tåsen Tunnel</td>
<td>1</td>
<td>Vertical</td>
<td>Restraint</td>
<td>0.45</td>
<td>Vertical</td>
<td>De-icing</td>
</tr>
<tr>
<td>Moholt Bridge</td>
<td>3</td>
<td>Horizontal</td>
<td>Shrinkage</td>
<td>0.00</td>
<td>Vertical</td>
<td>De-icing</td>
</tr>
<tr>
<td>DNV Field Station</td>
<td>6</td>
<td>Vertical</td>
<td>Dynamic, bending</td>
<td>0.00</td>
<td>Horizontal</td>
<td>Marine, tidal</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.20</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.55</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hafsfjord Bridge</td>
<td>6</td>
<td>Vertical</td>
<td>Shrinkage,</td>
<td>0.00</td>
<td>Vertical</td>
<td>Marine, tidal</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>temperature</td>
<td>0.20</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.45</td>
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</tr>
</tbody>
</table>
µ-XRF at NTNU

Sample Chamber: WxDxH: 60 cm x 35 cm x 26 cm
Sample: 1.5 kg concrete sample; 20 cm x 5 cm x 2 cm

- Spatial resolution: 25 μm
- Max. sample weight: 5 kg
- Max. sample size: 20 x 15 x 10 cm
- Limited or no sample preparation

Bruker (2016)
Elemental mapping of concrete using μ-XRF

Mapping size: 50 x 150 mm

Surface crack width: 0.5 mm

St = Stirrup

Danner et al. (2017)
Impact of cracks on chloride ingress and carbonation in cracks – De-iced structures

Cecilie Bridge
Age: 16 years
Surface: Horizontal
Crack width: 0.45 mm

μ-XRF Chloride ingress

Carbonation

Publication in preparation

Foto: Andreas Rygg
Impact of cracks on chloride ingress and carbonation in cracks – De-iced structures

Tåsen Tunnel:
**Age**: 20 years; **Surface**: Vertical; **Crack width**: 0.45 mm

Publication in preparation

Corrosion imprint in steel-concrete interface
Impact of cracks on chloride ingress and carbonation in cracks – De-iced structures

Moholt Bridge
Age: 25 years
Surface: Horizontal
Crack width: 0.55 mm

General corrosion on steel surface
Corrosion imprint in steel-concrete interface

Reinforcement after cleaning with hydrochloric acid (HCl)

Publication in preparation

Foto: Andreas Rygg
### Chloride ingress and carbonation

#### De-iced structures

<table>
<thead>
<tr>
<th>Structure</th>
<th>Age (years)</th>
<th>Cover (mm)</th>
<th>Surface</th>
<th>Crack orientation</th>
<th>Crack Width (mm)</th>
<th>Chloride ingress higher in cracks</th>
<th>Carbonation in crack</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cecilie Bridge</td>
<td>16</td>
<td>55-70</td>
<td>Horizontal</td>
<td>Vertical</td>
<td>0.45</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Tåsen Tunnel</td>
<td>20</td>
<td>50</td>
<td>Vertical</td>
<td>Vertical</td>
<td>0.45</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Moholt Bridge</td>
<td>25</td>
<td>50</td>
<td>Horizontal with small inclination</td>
<td>Vertical</td>
<td>0.00</td>
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<td>Yes</td>
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<tr>
<td></td>
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<td></td>
<td>0.20</td>
<td>No</td>
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<tr>
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<td></td>
<td></td>
<td>0.55</td>
<td>No</td>
<td></td>
</tr>
</tbody>
</table>

**Chloride ingress and carbonation**

De-iced structures

- **Cecilie Bridge**
- **Moholt Bridge**
- **Tåsen Tunnel**
Impact of cracks on chloride ingress in cracks – Marine Exposure

DNV Field station:
Age: 33 years; **Surface:** Vertical; **Crack width:** 0.15 – 0.50 mm
Impact of cracks on chloride ingress in cracks – Marine Exposure

DNV Field station:
• 3 reinforcement nets
• Dynamic loading → bending cracks in tidal zone
• Cracks parallel to stirrups

Impact of cracks on chloride ingress in cracks – Marine Exposure

normalised chlorine intensity (%)

St = Stirrup
R = reinforcement

Publication in preparation
Self-healing of cracks

DNV Field station:

Surface

\( w = 0.50 \text{ mm} \)

Atomic ratio: \( \text{Mg/Ca} \approx 1/1 \)

Publication in preparation
Impact of cracks on chloride ingress in cracks – Marine Exposure

Hafsfjord Bridge:
Age: 50 years; Surface: Vertical; Crack width: 0.2 – 0.45 mm
Hafrsfjord Bridge

Coring

1: N2U; w: 0.40 mm
2: N2D; w: 0.20 mm
3: N1D; w: 0.20 mm
Impact of cracks on chloride ingress in cracks – Marine Exposure

Hafrsfjord Bridge: Cores - open cracks

1: N2U; w: 0.40 mm
2: N2D; w: 0.20 mm
3: N1D; w: 0.20 mm
Hafsfjord Bridge: Cores

μ-XRF Chloride ingress:

- w: 0.40 mm
- w: 0.20 mm
- w: 0.20 mm

No impact of cracks on chloride ingress

Publication in preparation
Hafsfjord Bridge: Cores
μ-XRF Mg and S mapping

N2U

N2D

N1D

Publication in preparation
## Impact of cracks on chloride ingress in cracks – Marine Exposure

<table>
<thead>
<tr>
<th>Structure</th>
<th>Cover (mm)</th>
<th>Concrete Surface</th>
<th>Crack orientation</th>
<th>Crack Width (mm)</th>
<th>Chloride ingress higher in cracks</th>
<th>Carbonation in crack</th>
<th>Self-healing</th>
</tr>
</thead>
<tbody>
<tr>
<td>DNV Field Station</td>
<td>50</td>
<td>Vertical</td>
<td>Horizontal</td>
<td>0.0</td>
<td>No</td>
<td>n.d.*</td>
<td>Yes</td>
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<tr>
<td></td>
<td></td>
<td></td>
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<td>0.2</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.5</td>
<td>No</td>
<td>n.d.</td>
<td></td>
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<tr>
<td>Hafrsfjord Bridge</td>
<td>90</td>
<td>Vertical</td>
<td>vertical</td>
<td>0.0</td>
<td>No</td>
<td>n.d.</td>
<td>Precipitation on crack surface, no crack closing</td>
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<tr>
<td></td>
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<td>0.2</td>
<td>No</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td></td>
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<td></td>
<td></td>
<td>0.45</td>
<td>No</td>
<td>No</td>
<td></td>
</tr>
</tbody>
</table>

* n.d. = not determined
## Field studies 2017 - Summary

<table>
<thead>
<tr>
<th>Structure</th>
<th>Age (years)</th>
<th>Cover (mm)</th>
<th>Crack orientation</th>
<th>Crack width (mm)</th>
<th>Chloride ingress higher in cracks</th>
<th>Carbonation in crack</th>
<th>Self-healing</th>
<th>Corrosion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cecilie Bridge</td>
<td>16</td>
<td>55-70</td>
<td>Vertical</td>
<td>0.45</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>N/A</td>
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<tr>
<td>Tåsen Tunnel</td>
<td>20</td>
<td>50</td>
<td>Vertical</td>
<td>0.45</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Moholt Bridge</td>
<td>25</td>
<td>50</td>
<td>Vertical</td>
<td>0.0</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
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<td>0.2</td>
<td>No</td>
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<td>Yes</td>
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<td>0.55</td>
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<td>DNV Field Station</td>
<td>33</td>
<td>50</td>
<td>Horizontal</td>
<td>0.0</td>
<td>n.d.</td>
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<td>Yes</td>
<td>CP</td>
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<td>0.2</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>CP</td>
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<td></td>
<td></td>
<td></td>
<td>0.5</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>CP</td>
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<tr>
<td>Hafrsfjord Bridge</td>
<td>50</td>
<td>90</td>
<td>Vertical</td>
<td>0.0</td>
<td>n.d.</td>
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<td>No</td>
<td>No</td>
<td>No</td>
<td>N/A</td>
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<td></td>
<td></td>
<td></td>
<td>0.45</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>N/A</td>
</tr>
</tbody>
</table>
Take home message - impact of cracks on durability

Ingress
• Open cracks facilitate ingress

Reinforcement corrosion
• Cracks may shorten the initiation period (depending on surface orientation)
• Long-term impact of cracks on corrosion propagation not understood

Self-healing
• Cracks may self-heal (depending on orientation and width; \( w < 0.5 \) mm)

Field data
• The shown results are from a limited amount of samples and structures
• Need for further long-term field data on the impact of cracks on ingress and reinforcement corrosion
Acknowledgements

- Coastal Highway Route E39 Project for financing the research
- Statens Vegvesen for providing access to Moholt Bridge, Hafsfjord Bridge, and Tåsen tunnel
- Trondheim Kommune for allowing access to Cecilie Bridge
- DNV GL for providing concrete columns from their field station
- NTNU lab technicians for support in the field and laboratory
Publications/Presentations

Publications:
Danner, Tobias; De Weerdt, Klaartje; Geiker, Mette Rica. (2017) \( \mu \)-XRF – CHARACTERISATION OF CHLORIDE INGRESS AND SELF-HEALING IN CRACKED CONCRETE. NORDIC CONCRETE RESEARCH. Proceedings of the XXIII Nordic Concrete Research Symposium; Aalborg, Denmark

Danner, Tobias; Hornbostel, Karla; Michel, Alexander; Geiker, Mette (2018); Self-healing and chloride ingress in cracked concrete exposed to marine environment for 33 years; to be submitted

Danner, Tobias; Geiker, Mette (2018); IMPACT OF CRACKS AND EXPOSURE ON CHLORIDE INGRESS AND SELF-HEALING; SLD4 Conference – RILEM week 2018, Delft, Netherlands, Abstract submitted and accepted, paper in preparation.

Hornbostel, Karla; Geiker, Mette (2017); Influence of cracking on reinforcement corrosion; Nordic mini-seminar: Crack width calculation methods for large concrete structures, Oslo, Norway

Oral presentations:
Danner, Tobias; Hornbostel, Karla; De Weerdt, Klaartje; Geiker, Mette Rica (2017); Ongoing Investigations, E39 WP, 7.1.1 - Test Methods, Lab and Field Investigations. DACS - Durable Advanced Concrete Solutions; 2017-06-20; NTNU

De Weerdt, Klaartje; Danner, Tobias (2017); \( \mu \)XRF at NTNU/SINTEF. Nordic Concrete Federation mini seminar/workshop on Repair of chloride infected concrete; 2017-01-31; NTNU

Danner, Tobias; Geiker, Mette (2017); Relevans av rissviddekrav, hvor viktig er dette for bestandighet?; E39 Betongworkshop – Miniworkshop på NTNU; 2017-12-11; NTNU
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Thank you for your attention