DTU Civil Engineering
Department of Civil Engineering

DANISH TECHNOLOGICAL INSTITUTE

CONCRETE EXPERTCENTRE

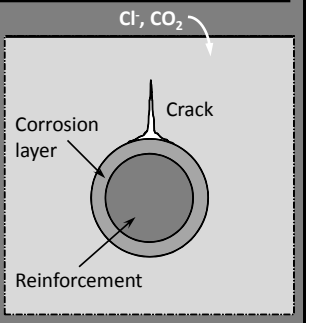
Improving corrosion-induced deterioration modeling approaches using novel experimental investigations

A summary of work preformed by:
Brad J. Pease, Alexander Michel, Anne-Emilie A. Thybo and Henrik Stang
(hs@byg.dtu.dk)

Prepared for:
Concrete Expert Centre Reference Group Meeting, Spring 2012, Høje Taastrup, Denmark, March 28, 2012

Difficulties in modeling corrosion-induced deterioration

- Complex, interdependent processes – transport, fracture & electrochemistry
- Numerous models developed, typical assumptions:
  - Uniform corrosion behavior
  - Elastic properties of corrosion products
  - Some corrosion products stored in concrete without stress in a corrosion accommodating region, CAR
- Models indicate CAR size has major impact on time-of-cracking estimates, **often used as a fitting parameter**

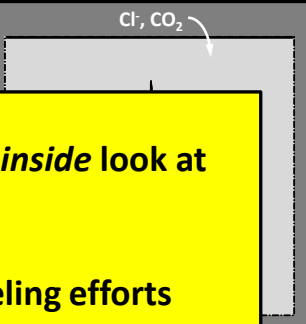


2

Difficulty in modeling corrosion-induced deterioration

- Complex process – transport,
- M
- M

parameter

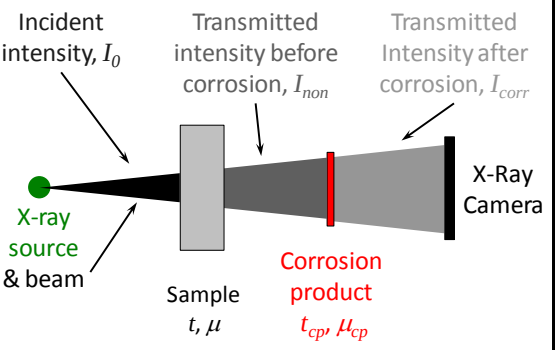


Experimental method providing an *inside* look at the corrosion process would:

- **Provide insights to improve modeling efforts**
- **Measure CAR size, parameters affecting CAR size**
- **And more…**

3

Monitoring corrosion products (CP) using x-ray attenuation measurement technique



X-ray photons attenuated by CP is directly related to con-centration of CP, Δc_{cp}

$$\Delta c_{cp} = -\frac{\rho_{cp}}{\mu_{ef,cp} \cdot t} \cdot \ln\left(\frac{I_{corr}}{I_{non}}\right)$$

$\mu_{ef,cp}$ – Effective atten. coeff. of CP

ρ_{cp} – Density CP, Fe_2O_3 assumed (5.24 g/cm^3)

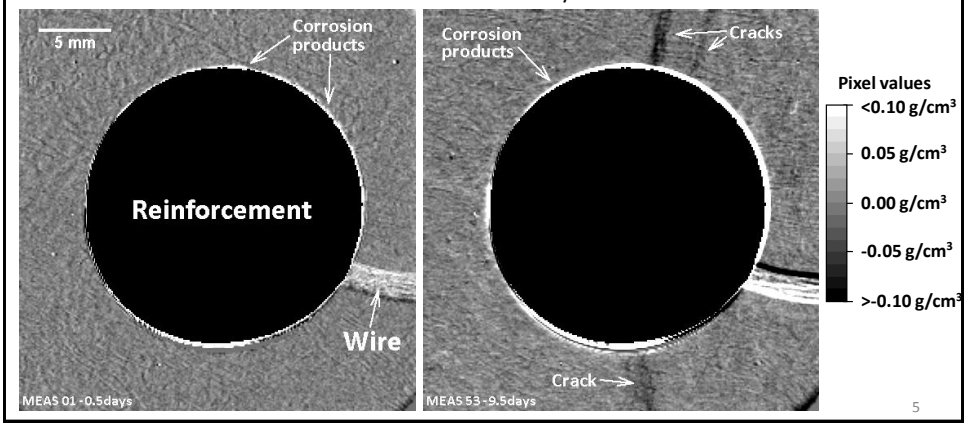
4

Inside look at corrosion-induced deterioration process

- Computed x-ray images provide:
  - Concentration and location of CP
  - Approximate time-of-cracking, difficult to pin-point

0.50 w/c, 100 μA/cm² (1.16 mm/yr)

Video | After 9.5 days accelerated corrosion

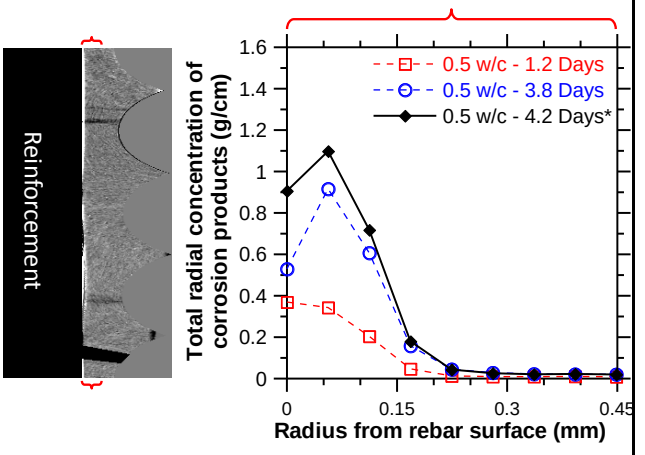


5

Polar transformation and corrosion product concentration profiles

- Radial concentration profiles
- CP penetrates into concrete prior to cracking
- Increased CP conc. with time

0.50 w/c, 100 μA/cm² (1.16 mm/yr)

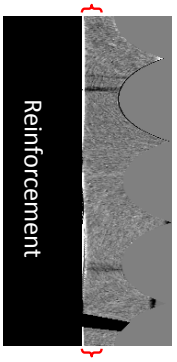


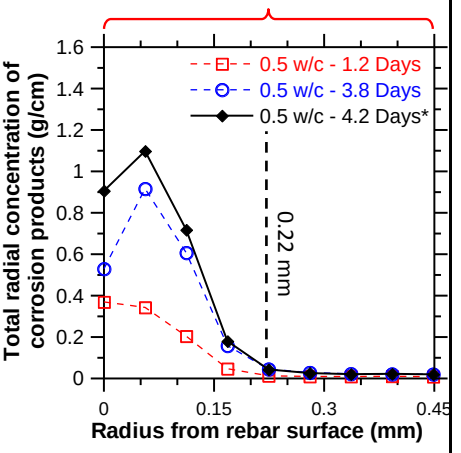
* Indicates profile at time of observed cracking

6

Polar transformation and corrosion product concentration profiles

- Radial concentration profiles
- CP penetrates into concrete prior to cracking
- Increased CP conc. with time
- Corrosion accommodating region (CAR) size 0.22 mm



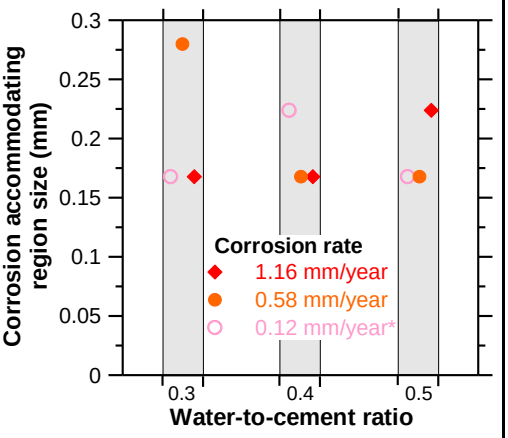


* Indicates profile at time of observed cracking

7

Impact of water-to-cement ratio, corrosion rate

- Minimum CAR size of 0.17 mm, but no clear effect of w/c or corrosion rate
- CAR size in literature (determined by model fitting):
  - **0.002-0.12 mm**

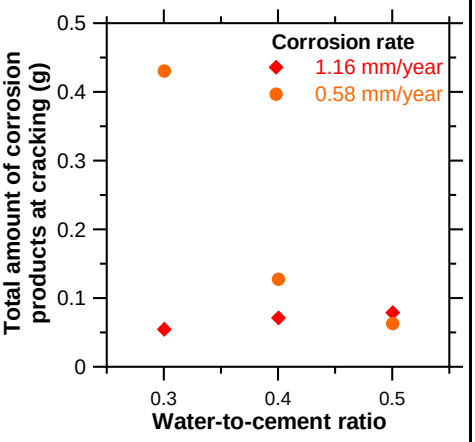


* No cracks observed in 0.12 mm/year specimens, data from 93 days

8

Impact of water-to-cement ratio, corrosion rate

- Total mass of CP penetrating concrete at cracking time indicates:
  - Minimal impact with rapid corrosion
  - Additional strength of lower w/c increases required amount of CP to induce cracking



9

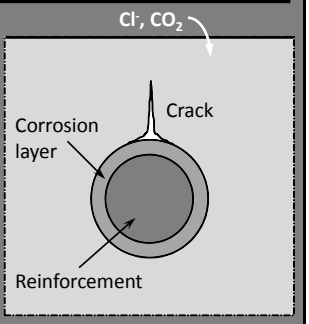
Conclusions from an inside look at corrosion process

- X-ray attenuation measurements quantify location and amount of corrosion products and provide one measure of time-of-cracking
- Corrosion product profiles provide vital information to develop realistic corrosion-induced deterioration models
- Results contradict assumption of uniform penetration of corrosion products
- Existence of CAR proven, measured CAR sizes are larger than values estimated from models

10

Difficulties in modeling corrosion-induced deterioration

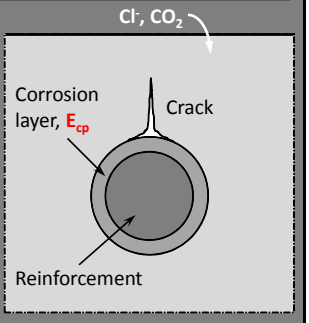
- Complex, interdependent processes – transport, fracture & electrochemistry
- Numerous models developed, typical assumptions:
  - Uniform corrosion behavior
  - Elastic properties of corrosion products
  - Some corrosion products stored in concrete without stress in a corrosion accommodating region, CAR
- Models indicate CAR size has major impact on time-of-cracking estimates, **often used as a fitting parameter**



11

Difficulties in modeling corrosion-induced deterioration

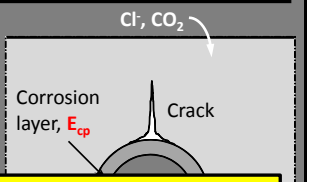
- Complex, interdependent processes – transport, fracture & electrochemistry
- Numerous models developed, typical assumptions:
  - Uniform corrosion behavior
  - Elastic properties of corrosion products
  - Some corrosion products stored in concrete without stress in a corrosion accommodating region, CAR
- Elastic modulus of corrosion products directly effects imposed deformations, **methods needed to quantify**



12

Difficulties in modeling corrosion-induced deterioration

- Complex, interdependent processes – transport, fracture & electrochemistry



- **Quantifying corrosion-induced deformations of concrete provides a method to:**

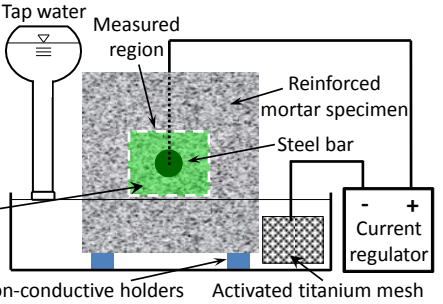
  - estimate elastic properties of corrosion products
  -calibrate mechanical models applying non-uniform corrosion distribution and CAR
- **-characterize crack propagation**

quantify

13

Digital image correlation (DIC) measurements of corrosion-induced deformations

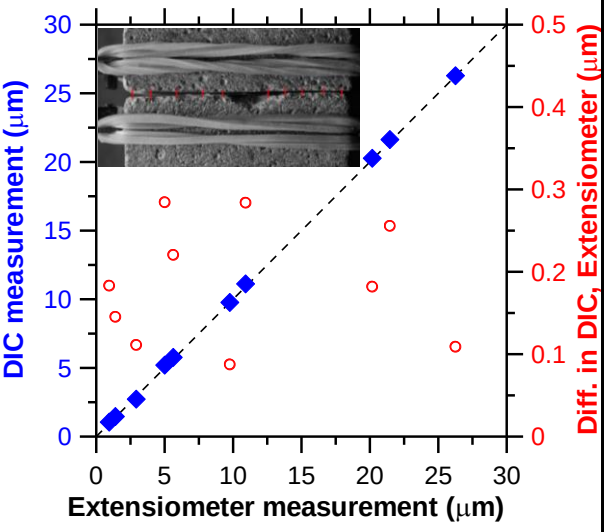
- 24.5 megapixel camera used for DIC during accelerated corrosion testing
- Each pixel corresponds to 7.8×7.8 μm^2 of specimen surface
- Identical conditions, companion specimens to x-ray investigation underway
- **Initial test** – 0.50 w/c and 100 $\mu A/cm^2$ (1.16 mm/yr) corrosion rate



14

Precision of DIC measurement

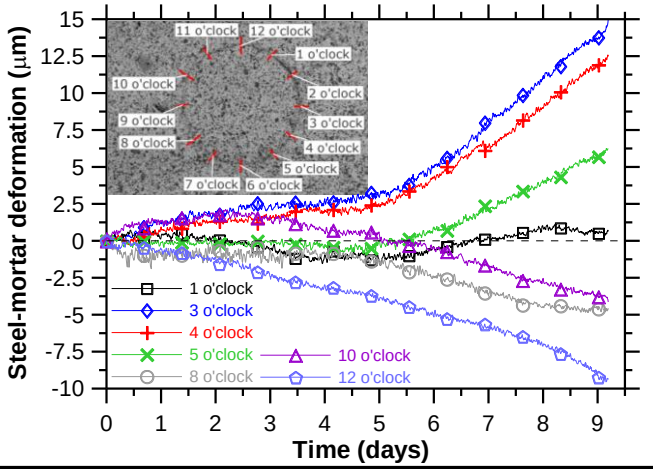
- Two mortar prisms separated in controlled steps, DIC and extensiometer measurements compared
- DIC measured separation averaged from 10 locations
- Max deviation of 0.29 μm between DIC, extensiometers



15

DIC results – Separation at steel/mortar interface

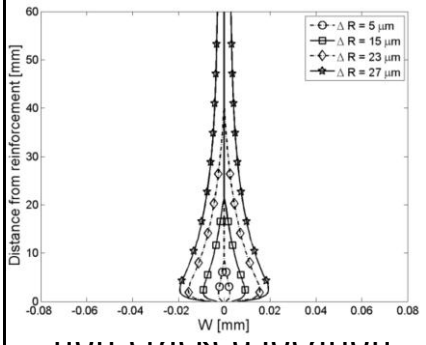
- Similar to x-ray, non-uniform separations observed
  - Max increased separation at 3 o'clock, max contraction nearby at 12 o'clock

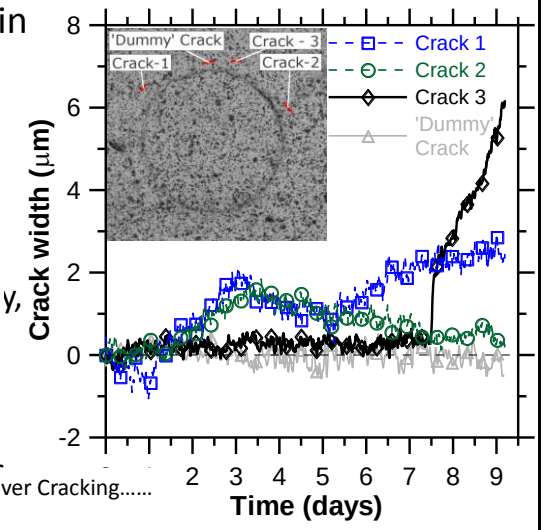


16

DIC results – (Micro)crack formation

- Cracks 1 & 2 formed at approx. 1.5 days, remain near rebar surface





From: Anders Solgaard et al.: Concrete Cover Cracking……

+0.004 μm

17

Summary and conclusions

- X-ray attenuation and DIC measurement techniques provide vital information on corrosion process for developing and verifying realistic models
- Penetration of corrosion products, resulting concrete deformations are non-uniform under DC accelerated corrosion testing
- A corrosion accommodating region (CAR) was observed, minimum size of approx. 0.17 mm
- DIC measured separations and (micro)cracking offer a means for verifying model results, establishing elastic properties of corrosion products and calibrate the cracking process

18

Acknowledgements

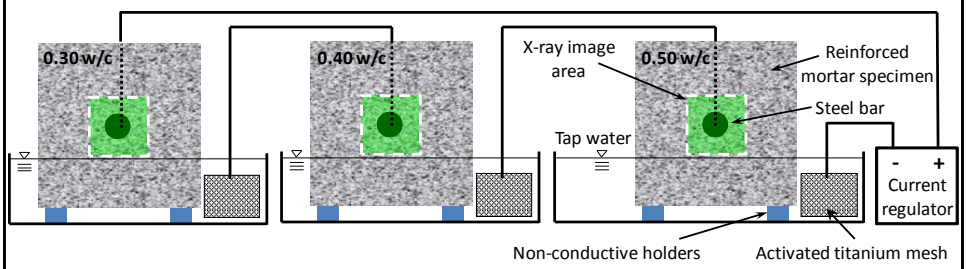
Experimental methods for improving current service life design practices for reinforced concrete structures

NICe : Project no. 08190 SR "Sustainable rehabilitation of civil and building structures"

19

Accelerated corrosion experimental setup

- DC accelerated corrosion:
  - 10, 50, 100 μA/cm^2 (0.12, 0.58, 1.16 mm/year)
- Water-to-cement ratio:
  - 0.30, 0.40, 0.50
- X-ray images recorded every 24, 12, 4 hours



20