Multi-scale testing of fibre reinforced concrete under corrosion deterioration

Victor Marcos Meson[123], Alexander Michel[1], Anders Solgaard[2], Carola Edvardsen[2], Gregor Fischer[1], Henrik Stang[1]

[1]DTU, Department of Civil Engineering, Lyngby, Denmark

[2]COWI A/S, Tunnel Department, Lyngby, Denmark

[3]VIA Building, Energy & Environment, VIA University College, Horsens, Denmark

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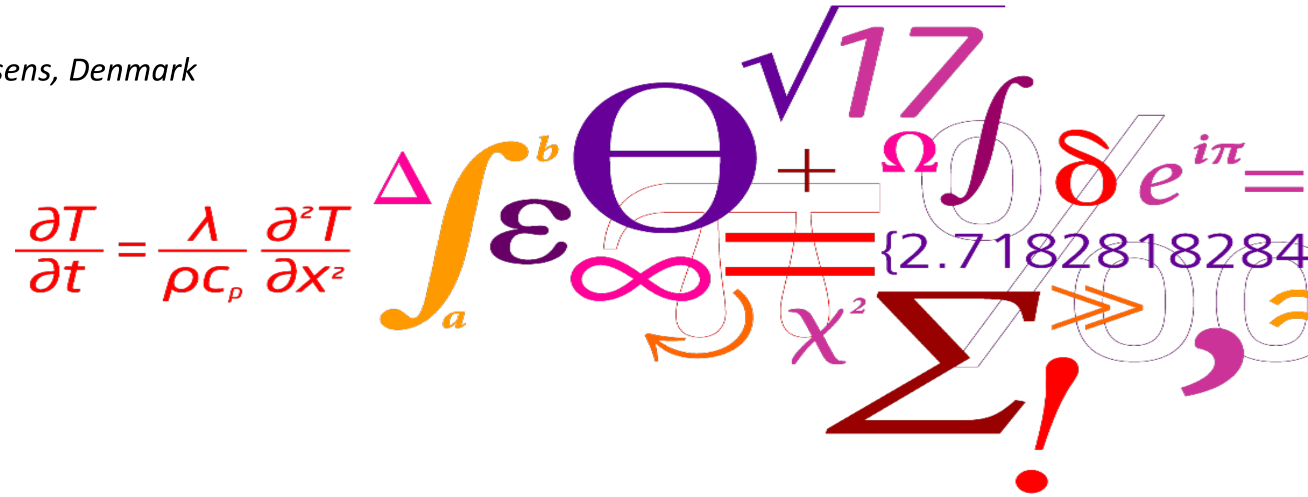

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- **Others**
  - Students: Jakob Jensen, Oliver Thorpe, Simon Bozick, Viktor Balaz
  - DTU 3D Imaging centre: Carsten Gundlach

Contents

1. Introduction

Background

Steel Fibre Reinforced Concrete is becoming an attractive solution for the industry:

- **Combined Reinforcement** Systems
- **Total substitution** of rebar by steel fibres

SFRC in compressed elements (Tunnel Linings)

- **Simplified production** processes
- Reduced **cracking during handling** and installation
- Reduction of **production failures** (insufficient cover)

Restrictions on standards and general concern

of SFRC structures under **limits design aggressive exposures** worldwide

Source: Solgaard A. (COWI)

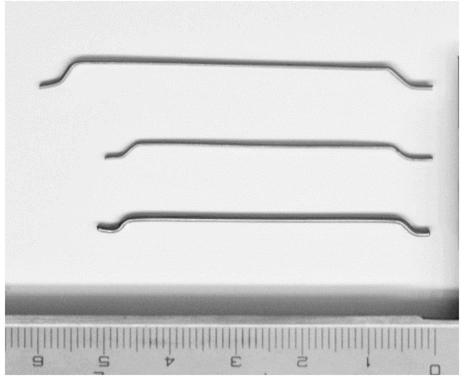
Revision of Eurocode-2 (Annex for SFRC)

1. Introduction

Status and problem formulation

Un-cracked SFRC

- **RESEARCH → durable** under **aggressive exposures** (surface damage)
- **STANDARDS →** agreement **allowing design** for **un-cracked SFRC on SLS**



Cracked SFRC

- **RESEARCH → Disagreement** regarding corrosion resistance for **cracks < 0.30mm**
  - Overall agreement on corrosion damage inside **cracks > 0.30mm**
  - Disagreement regarding corrosion damage inside **cracks < 0.30mm**
- **STANDARDS → Disagreement** on crack limitation for aggressive exposures
  - SFRC allowed for **small cracks** or un-cracked (SLS): *TR-63 (UK); ACI (US); AFTES (FR)*
  - Design allowed with **special provisions:** *EHE (ES); Testing; RILEM (FR)*
  - **Limitation for uncoated** low-carbon steel fibres: *UNI (IT); CRN-DT 204 (IT)*
  - **No consideration** of fibres for structural verification: *DBV/DafStb (DE); SFRC guidelines (DK)*
  - **No mentioning** of design restrictions: *Fib-Model code (FR)*

2. Project description

Aim and objectives

Aim

- Evaluate the **durability of SFRC** for prefabricated tunnel lining segments exposed to **aggressive corroding environments**

Objectives

- Characterise the **design and service conditions** leading to steel fibre corrosion in cracked SFRC.
- Identify the **mechanisms governing** the deterioration of SFRC subjected to corrosive environments
- Quantify the **impact of steel fibre corrosion** on the **mechanical behaviour** of SFRC.

Understand and update the background

- **Provide an updated background** based on scientific and technical literature
- Provide a coherent **basis explaining the existing limits** found in the regulation

↓

Produce consistent experimental data

- Assess the **durability of cracked SFRC** and compare the damage with traditional reinforced concrete
- **Relate the damage** observed on **single fibres** to the **structural effects on SFRC**

↓

Propose recommendations

- Provide **design recommendations** for maximum allowed crack width and risk of corrosion propagation on SFRC
- **Assist the development** of future guidelines with updated knowledge and tools

2. Project description

Experimental programme

Macro-scale Experiments

- **Wet-Dry cycles (2 years)**
- Combination of **exposure and crack conditions**
- Post-crack behaviour on **bending and direct tension**

Micro-scale Experiments

- **Single fibre pull-out** and x-ray **Micro-CT** (Micro-Tomography)
- **Electrochemical testing** on single fibres
- **Thin sections** and microstructure analysis

Numerical Modelling

- **Deterioration model** based on the Microscale study (fibre pull-out)
- **Validation with the data** from the Macroscale study

Conditions leading to fibre corrosion

Understand and **quantify fibre corrosion**

Damage in SFRC due to fibre corrosion

DESIGN STRATEGY

Macro Study
Conditions

Modelling

Micro Study
Mechanisms

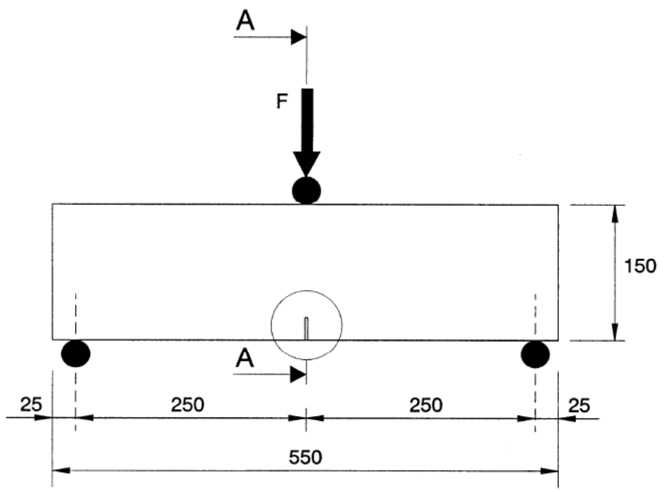
2. Project description

Macro-scale study

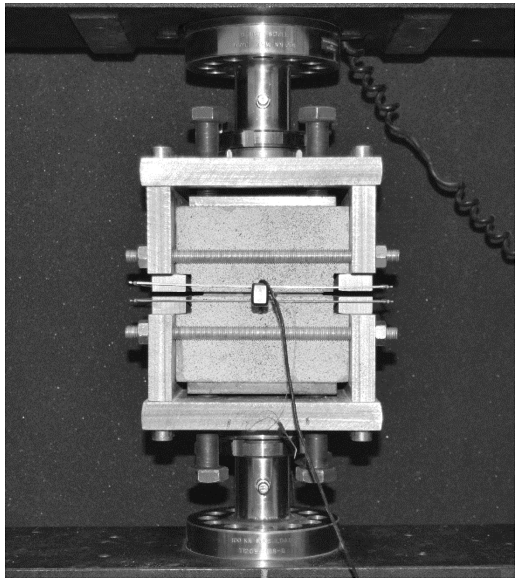
3-Point Bending Test
(EN 14651)
Load – Deflection
Load - CMOD

Uniaxial Tension Test
(Fischer. et al.)
Load - CMOD

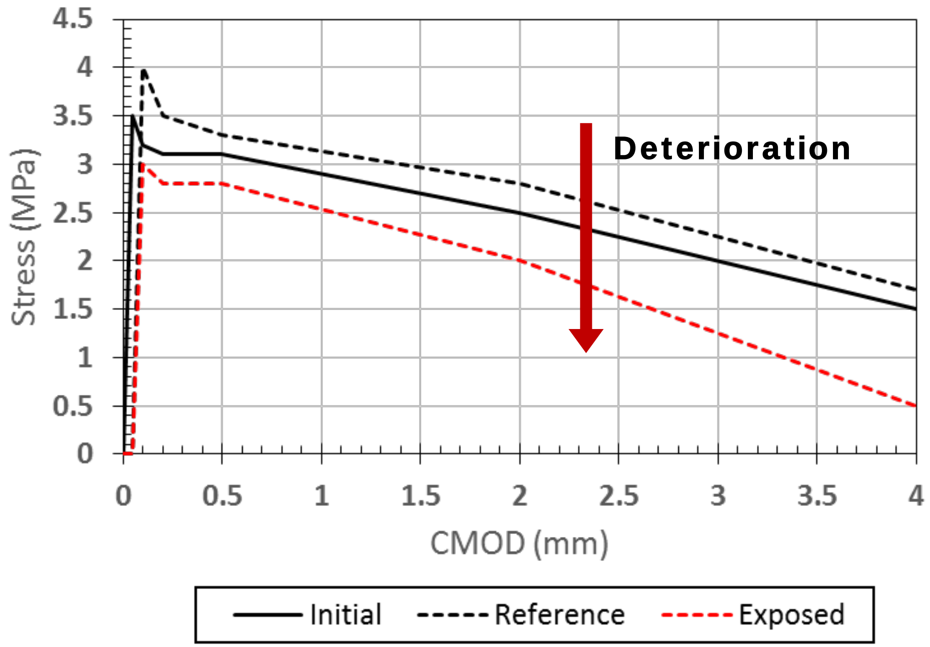
AIM
Identify changes in the residual tensile strength (toughness) after exposure



Source: EN 14651

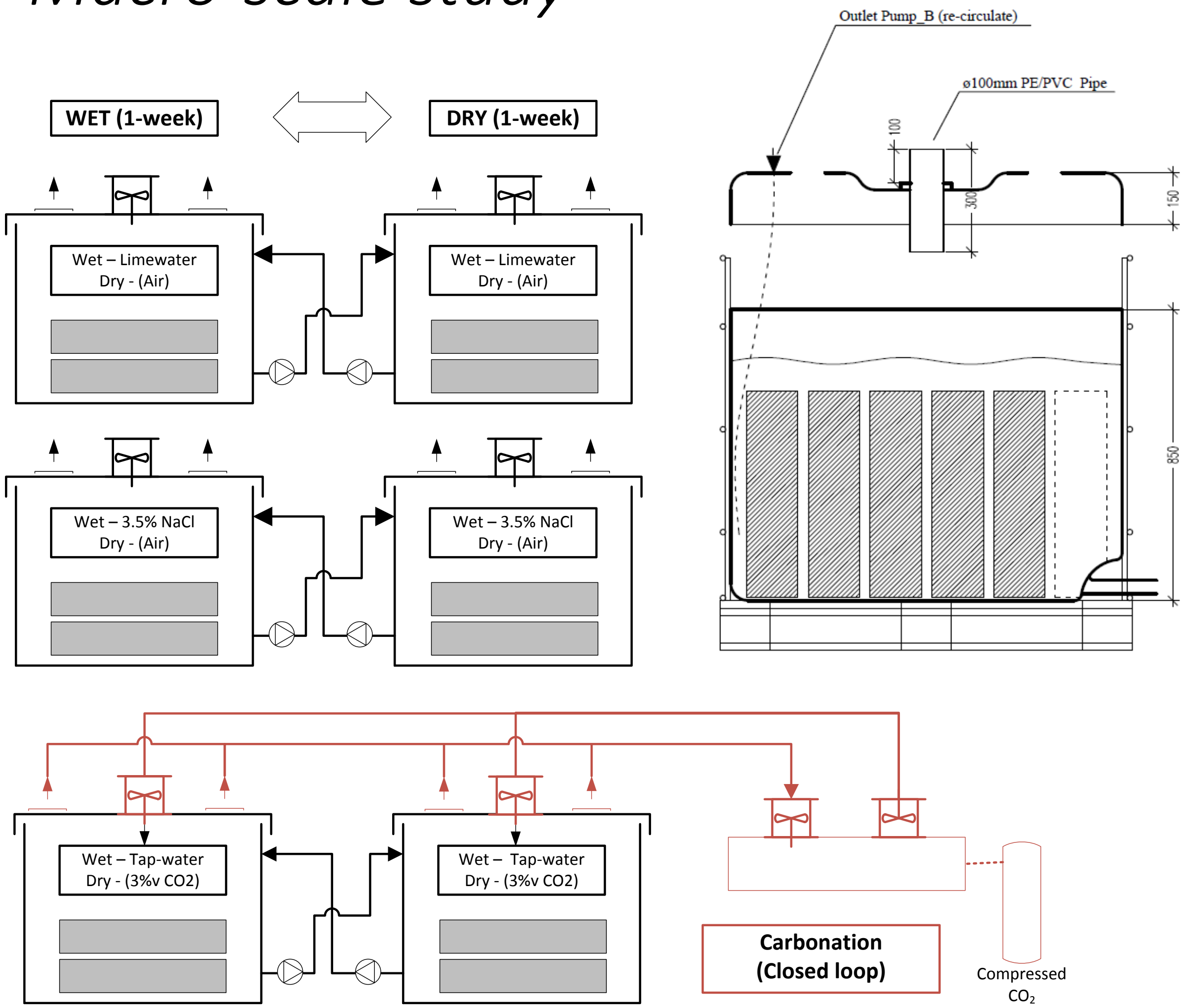


Source: Peagle I., Fischer G. (DTU)



2. Project description

Macro-scale study



Exposure method

- Wet-dry cycles (48h-cycle)
- 2 years (1-year, 2-year test)
- ≈9m³ total capacity (10 IBC tanks)

Amount of specimens

- 230 beams (150x150x600mm)
- 230 cubes (150mm)
- Total 3.8m³ (≈9 ton.)

Experiment variables

- Crack width: 150µm, 300µm
- Chloride exposure: 3.5%NaCl, 7.0%NaCl
- CO_2 exposure: 0% CO_2, 1% CO_2
- Exposure time: 1-year, 2-year

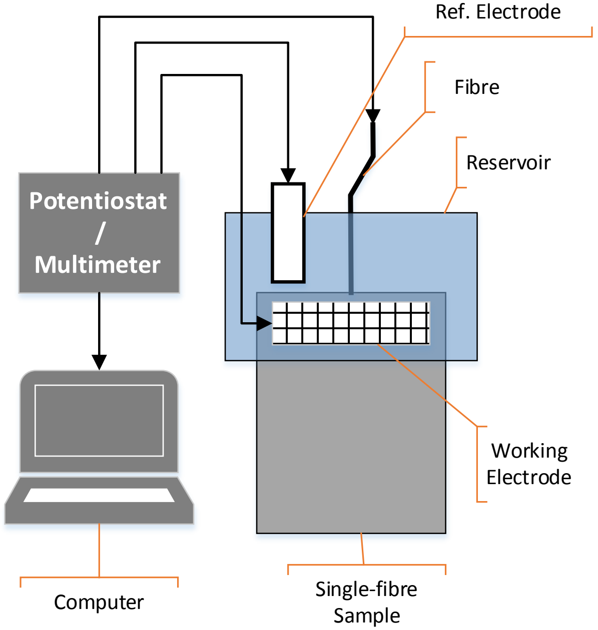
2. Project description

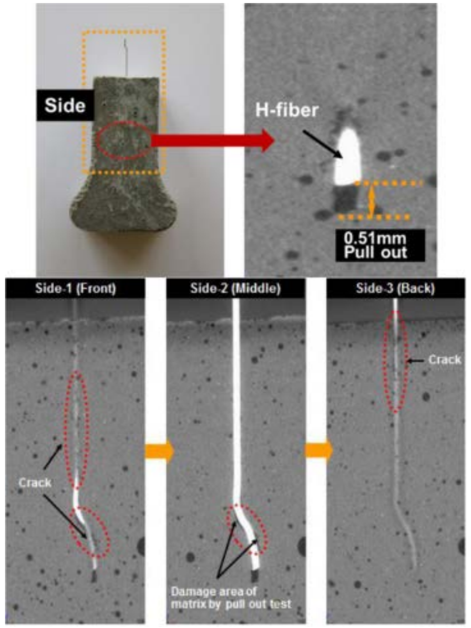
Micro-scale study

Single fibre pull-out tests
+
Exposure

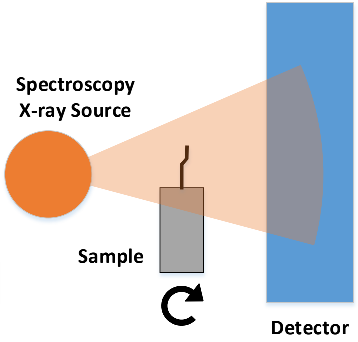
Linear Polarization Resistance
+
Electrochemical Impedance Spectroscopy

Single-fibre Pull-out Test
+
Micro X-ray computed tomography





Source: Kim D.J. et al, 2014



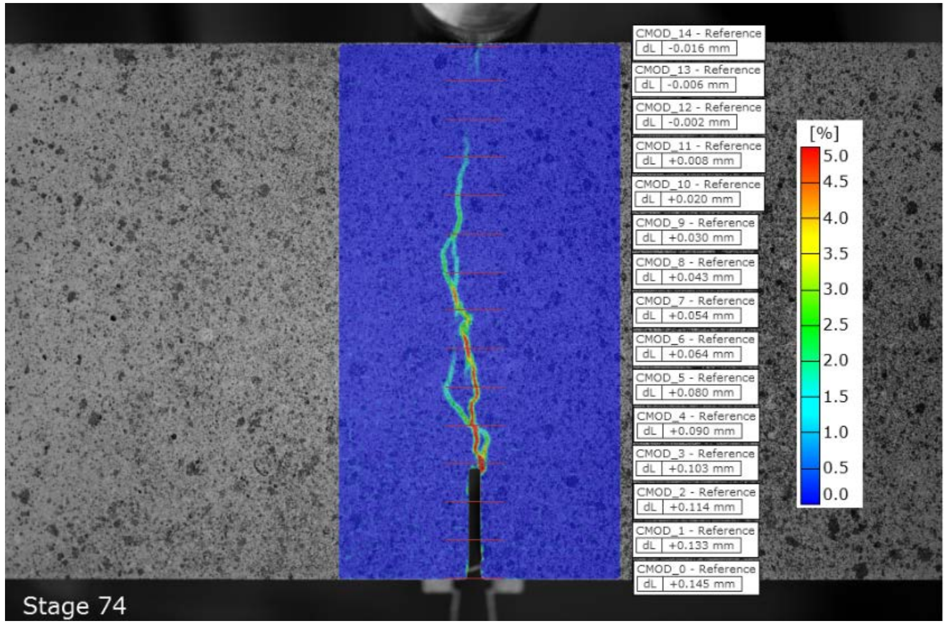
3. Preliminary results

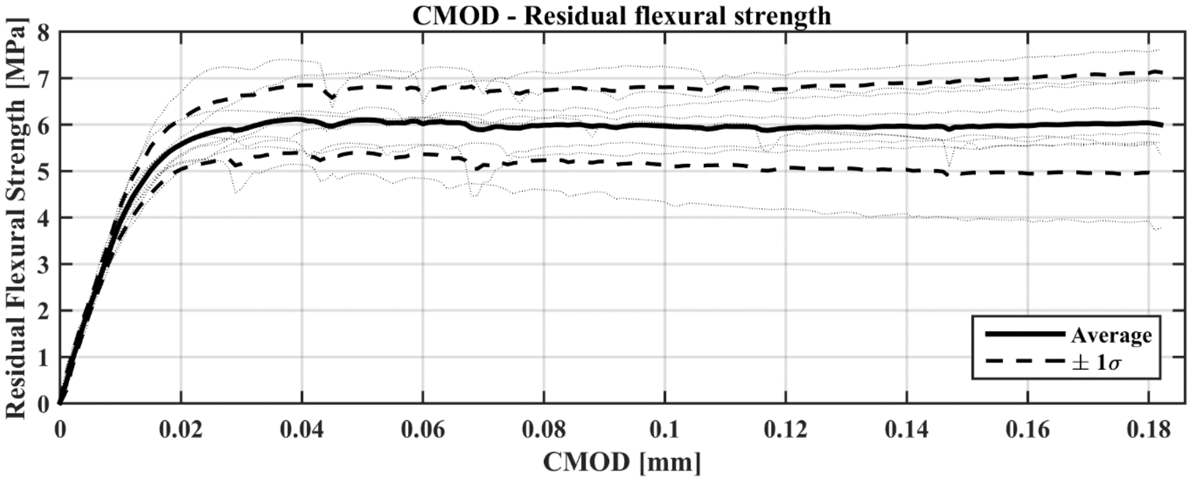
Macro-scale study

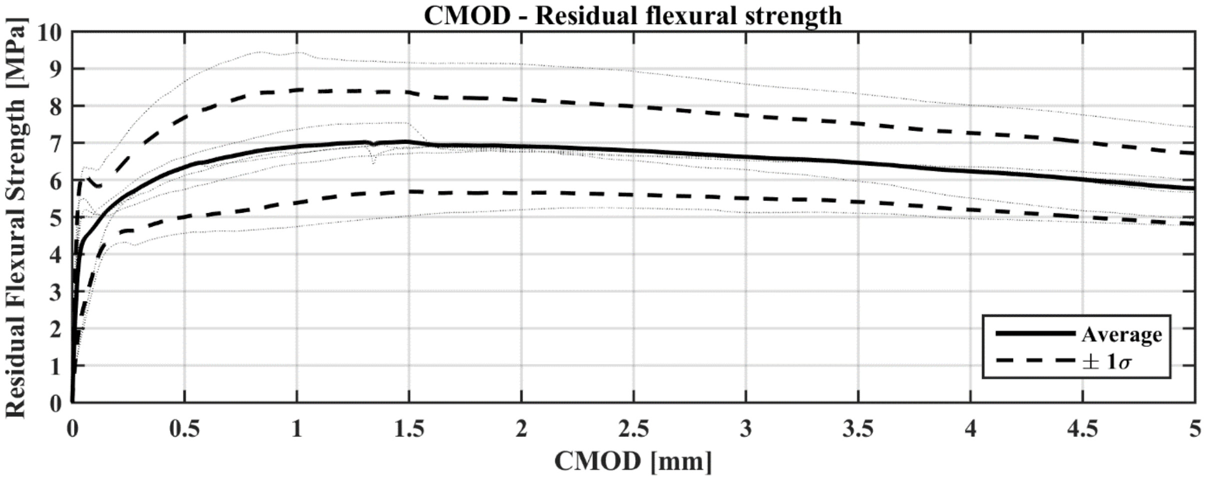
Preparation of specimens (cracking)

Characterization of **crack propagation**

- Digital Image Correlation (DIC)







3. Preliminary results

Macro-scale study

Exposure method

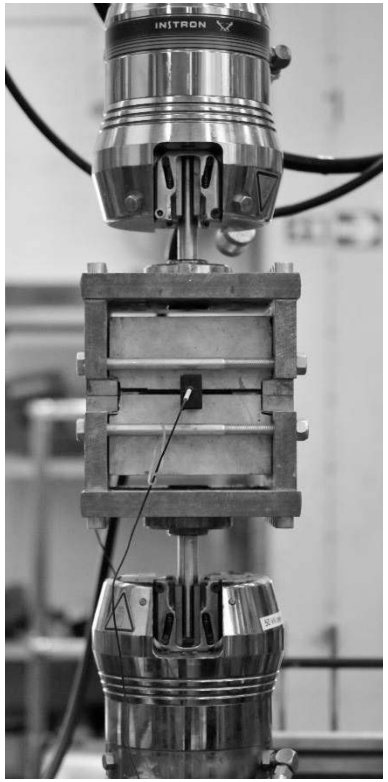
- Wet-dry cycles (48h-cycle)
- 60 cubes (150mm)
- 5 replicates per group

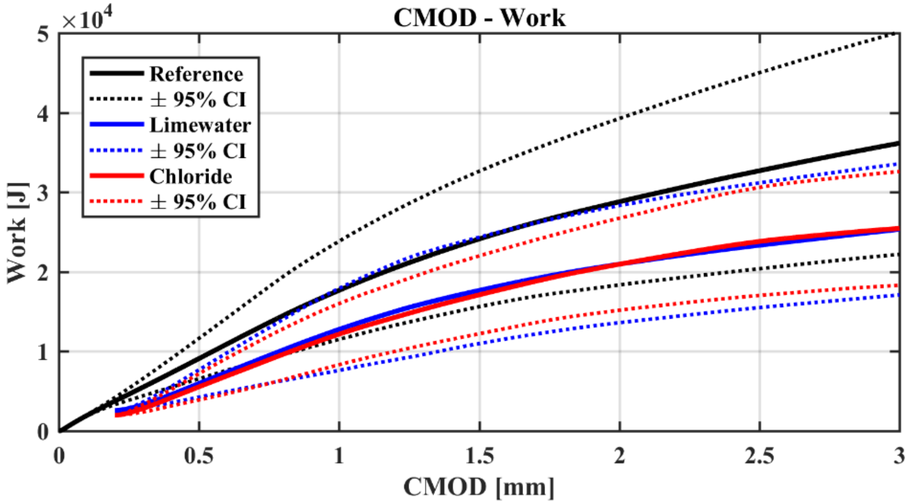
Experiment variables

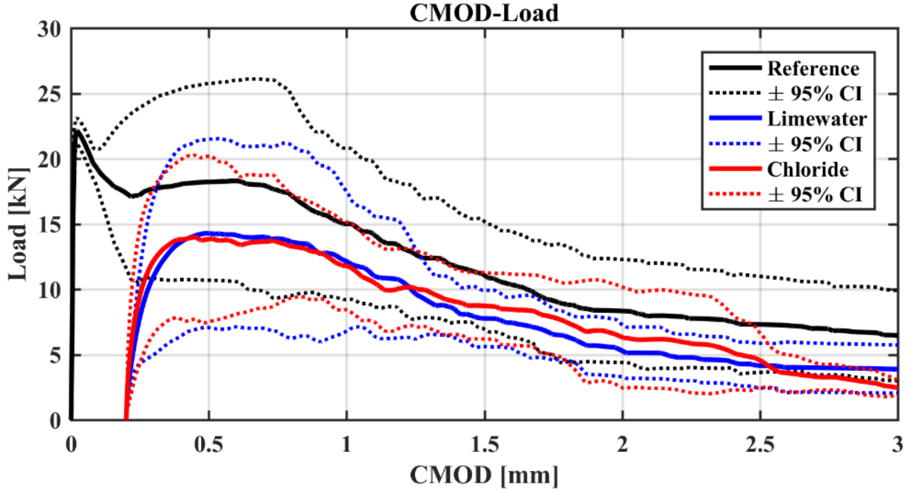
- Crack width: 100µm, 200µm
- Chloride exposure: 7.0%NaCl
- Exposure time: 2 months

Observations

- Limited impact of exposure
- Large variability within groups
- Limited corrosion inside crack







3. Preliminary results

Micro-scale study

Description

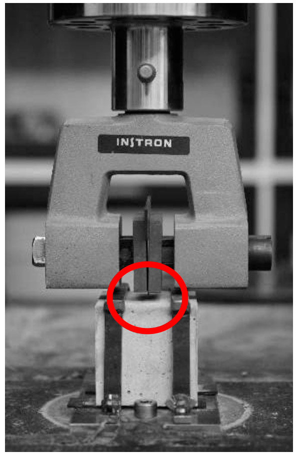
- 120 pull-out cubes (70mm)
- 10 replicates per group
- Bond restoration on partially-pulled fibres

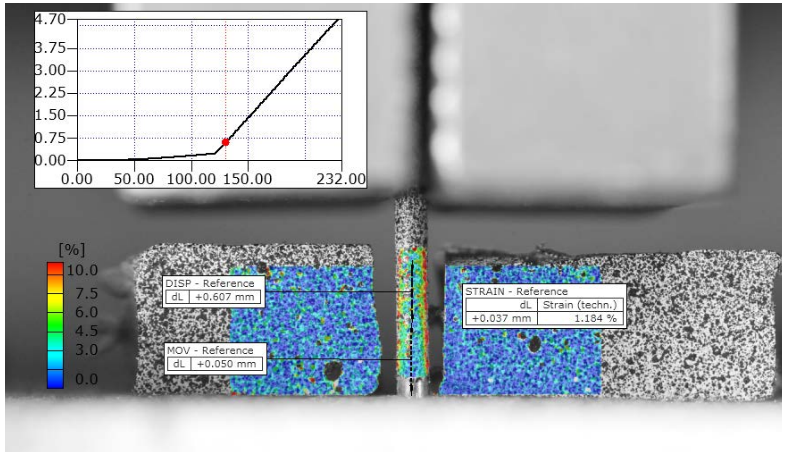
Experiment variables

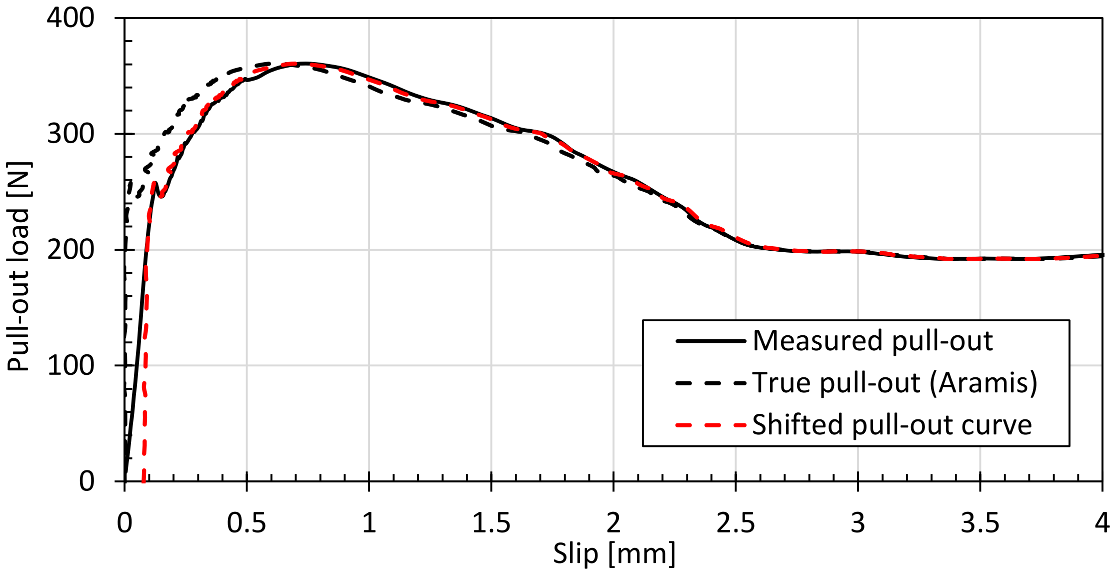
- Pull-out: 150µm, 300µm
- Limewater exposure → Bond restoration

Observations

- Underestimation of bond stiffness (DIC)
- Error≈80µm → Important under SLS!!
- Restoration of initial bond after healing







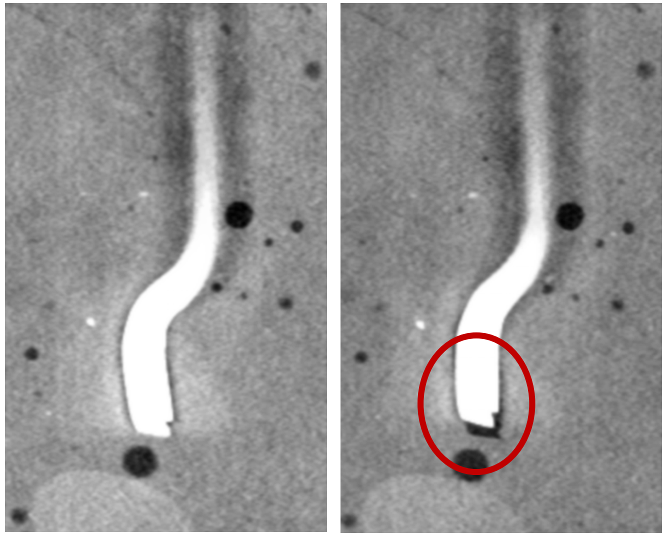
2. Preliminary results

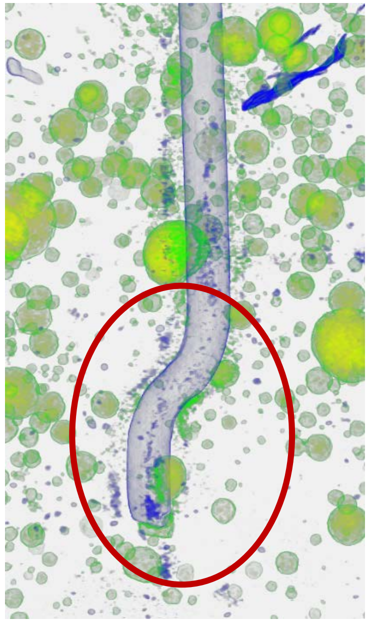
Micro-scale study

Interfacial damage characterized by **X-ray computed micro-tomography (µCT)**

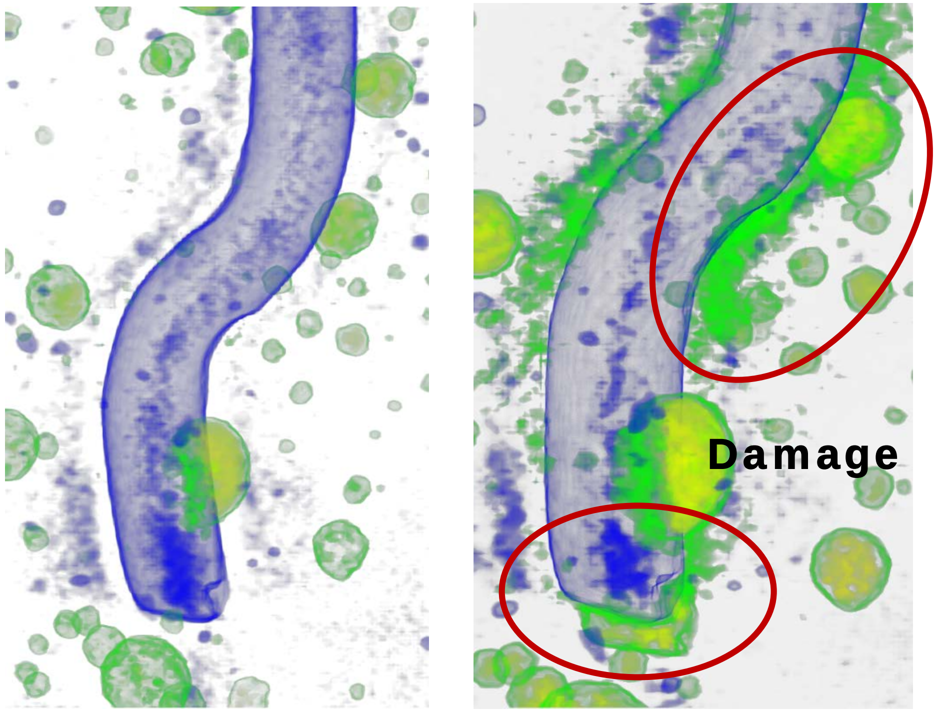
- DTU 3D Imaging centre (Carsten Gundlach)
- Resolution 45µm *(ZEISS XRadia 410 Versa)*

Original | **Pull-out** (300µm)





Original | **Pull-out** (300µm)



Damage at interface can be measured **without invasive/destructive methods**

4. Summary

- **Discrepancies** regarding **durability of SFRC** exposed to **chlorides and carbonation** limit the use of **SFRC in civil infrastructure**
- Former research **does not focus** on **damage mechanisms** and provides a **limited explanation** for the damage reported
- Multiscale investigation combines **performance data (macro-scale)** with **explanation of mechanisms (Micro-scale)** trough **numerical modelling**
- Preliminary **Macro-scale** results show **a large variability** within same SFRC group and **limited corrosion damage** at short exposures
- Preliminary **Micro-scale** results reveal **underestimation of fibre-matrix bond stiffness** and show **damage at fibre-matrix interface** during pull-out

THANK YOU