Connecting visual inspection to load-carrying capacity for corroded concrete bridges

Tools for effective management of corroded concrete bridges

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BBT Workshop - Innovativa metoder för effektivare broförvaltning
29 MAY 2017, KTH

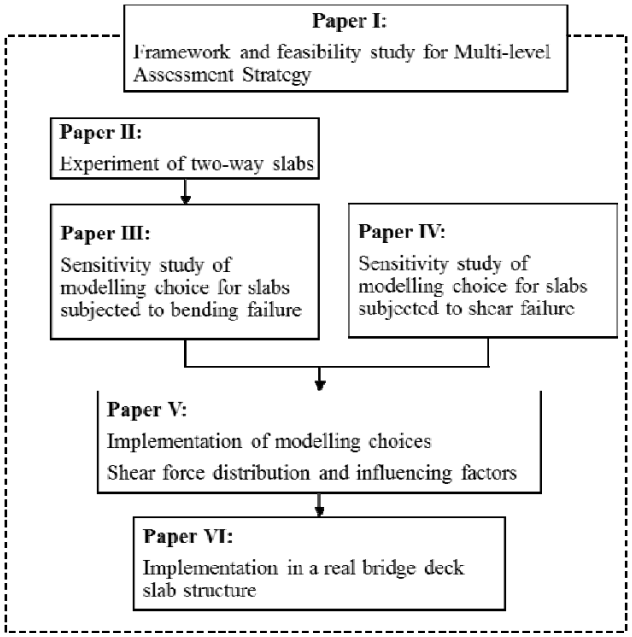
Bridge-related projects at Chalmers "Concrete Structure" funded by Trafikverket

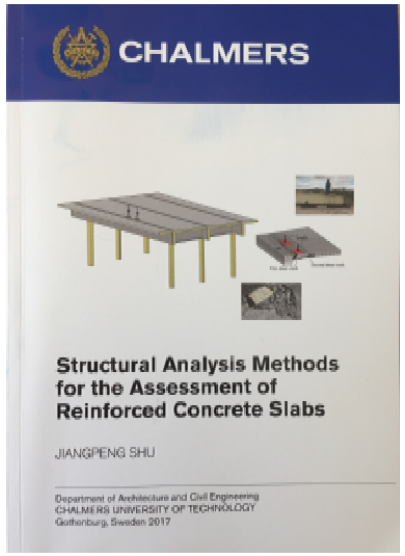
- **Stallbackabron** – Relating visual inspection to structural effects of natural corrosion in reinforced concrete structures (2014-2017)
- **Broplattor –** Load Carrying Capacity of Existing Bridge Deck Slabs (2012-2016)
- **ARC –** Tool for assessment and service-life evaluation of corroded bridges (2015-2018)
- **BIGBRO** – Decision support for maintenance and upgrading of existing transportation infrastructure (2016-2018)
- **Gullspång –** Assessment of the load-carrying capacity of existing structures with corroded smooth reinforcement bars (2017-2019)
- **UNICA (pre-study) –** Autonomous Non-Intrusive Condition Assessment of Infrastructure: *towards automation, system thinking, and complete solution* (2017)
- **SensIT (pre-study) –** Sensor driven and cloud based management of infrastructure (2017)

Stallbackabron
(Photo by Kamyab Zandi, 2011)

Broplattor – Load Carrying Capacity of Existing Bridge Deck Slabs (2012-2016)

- PhD project funded by TrV
- Objectives
  - Improved methods for assessment of the load carrying capacity
  - Increased understanding of load (effect) distribution
  - Assessment with analysis methods on different levels: Analytical, linear and non-linear FEM (shell + continuum)

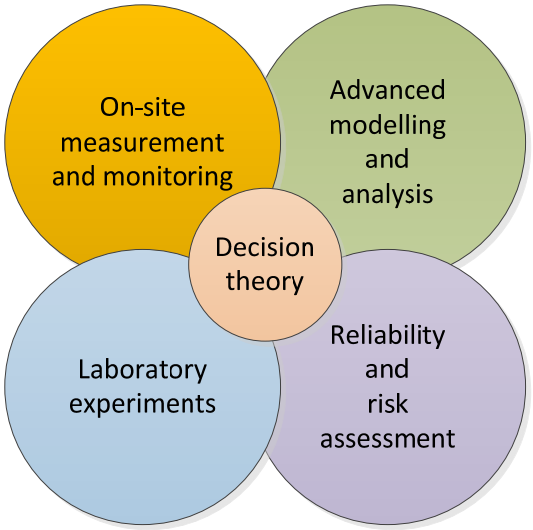




Structural Analysis Methods for the Assessment of Reinforced Concrete Slabs
Project members: **Shu Jiangpeng**, Mario Plos, Kamyab Zandi, Filip Nilenius, Morgan Johansson

BIGBRO – Decision support for maintenance and upgrading of existing transportation infrastructure

- 18 month project, 2016-2018
- Partners: RISE, Chalmers, KTH, LTH, NCC, Tyréns
- Coordinator: Dániel Honfi (RISE)
- Funding: 3827 kSEK (TrV, InfraSweden)
- Aim: Develop a framework for a decision support methodology that can be used for implementing maintenance strategies on a rational basis.



BIGBRO overall concept

Gullspång – Assessment of the load-carrying capacity of existing structures with corroded smooth reinforcement bars (2017-2019)

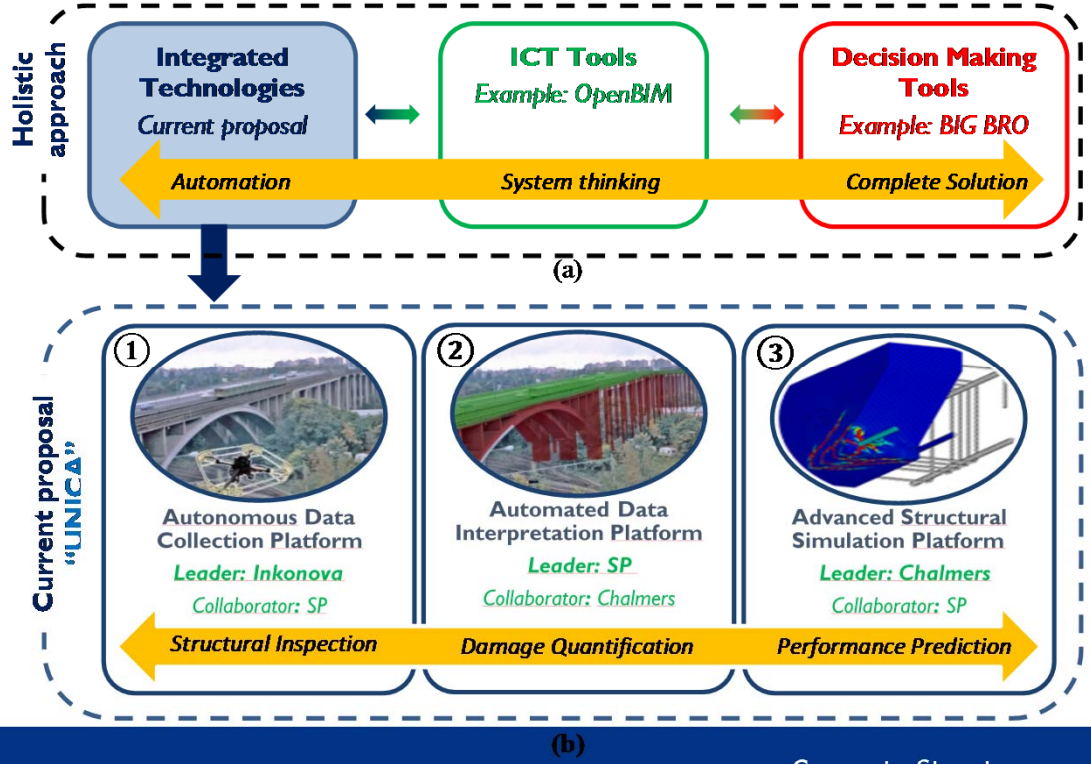
- PhD project of 3 years
  - Jan 2017 – Dec 2019
- Granted by FORMAS + TrV:
  - 3 mkr + 1.5 mkr
- Structural tests of the edge beams:
  - Load carrying capacity
  - Impact of hooks in the ultimate capacity
  - Bond behavior of corroded smooth bars

<u>Project members</u>
Samanta Robuschi
Karin Lundgren
Ignasi Fernandez Perez
Kamyab Zandi

UNICA – Autonomous Non-Intrusive Condition Assessment of Infrastructure

Towards automation, system thinking, and complete solution

- Pre-study granted by TrV (250 kkr)
  - Demo / feasibility
- Partners
  - Chalmers (Coord. Kamyab Zandi)
  - RISE (former SP)
  - Stockholms stad
  - Inkonova (SME)

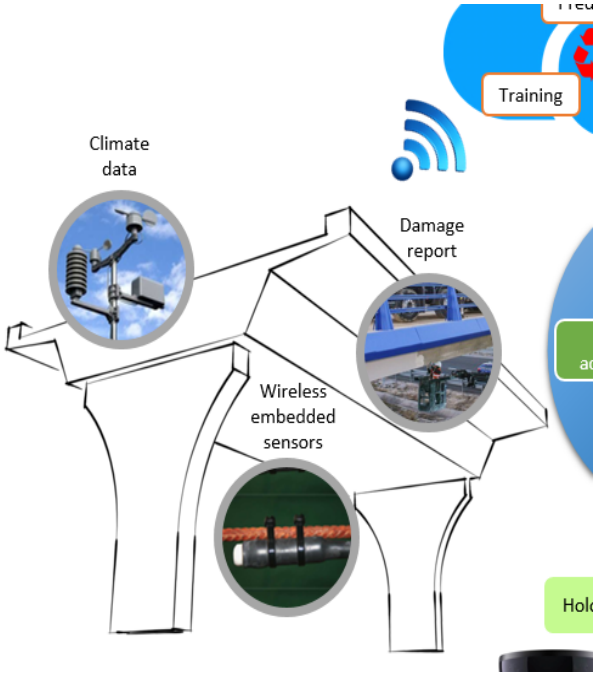


SensIT – Sensor driven and cloud based management of infrastructure

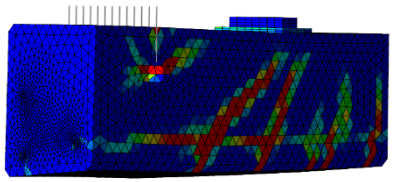
- Pre-study granted from TrV – 250 kkr
  - Writing a report to assess the potential of sensor management of infrastructures
  - Impact for the different agents in the building environment

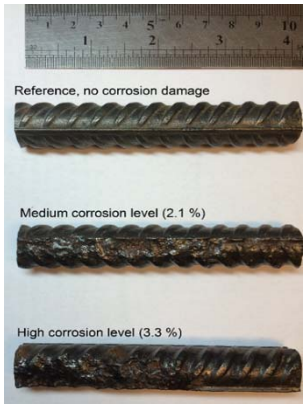
- SBE application in collaboration with:

  (Budget 750 kkr)
  - Chalmers (coord. R. Rempling) - Tietto
  - Trafikverket - NCC
  - WSP - Microsoft



RELATING VISUAL INSPECTION TO STRUCTURAL EFFECTS OF NATURAL CORROION IN REINFORCED CONCRETE STRUCTURES



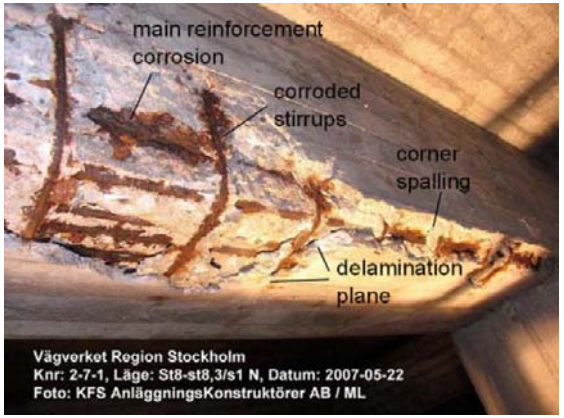


Motivation

Hammersmith Flyover Corrosion Problems
Photo by FESI NEWS

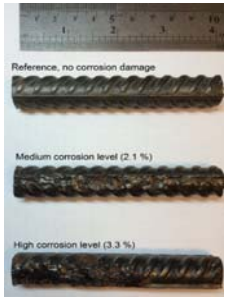
Motivation

Skurubron, Stockholm, Sweden
Photo by Magnus Lindqvist

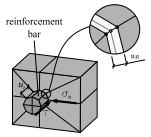


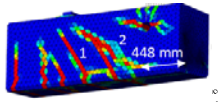
Motivation

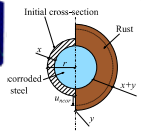
Structural tests of RC beams with natural corrosion



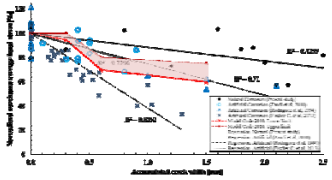
Calibrating numerical models

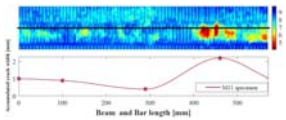






Providing new assessment methods





Outline

Introduction
- Corrosion damage
- Motivation

Experiments
- Tests of naturally corroded RC specimens
- Bond and anchorage behavior
- Corrosion level measurements

Investigations of correlations
- Inspection data vs. structural damage
- Comparisons

Conclusions and future research

Test specimens

Specimens from edge beams of Stallbacka Bridge:

- First test series
  8 specimens

- Second test series
  13 Specimens

Specimen classifications

Based on visible corrosion damage:

Reference, no visible surface damage

Specimen (R4)

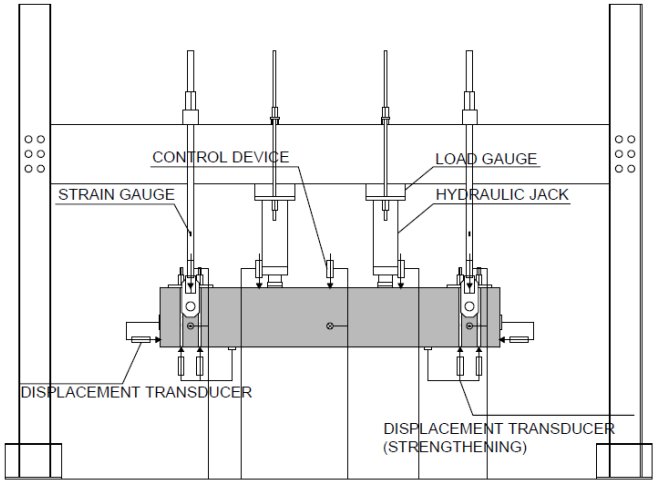
Medium damaged, splitting cracking

Specimen (M11)

Highly damaged, spalling of cover

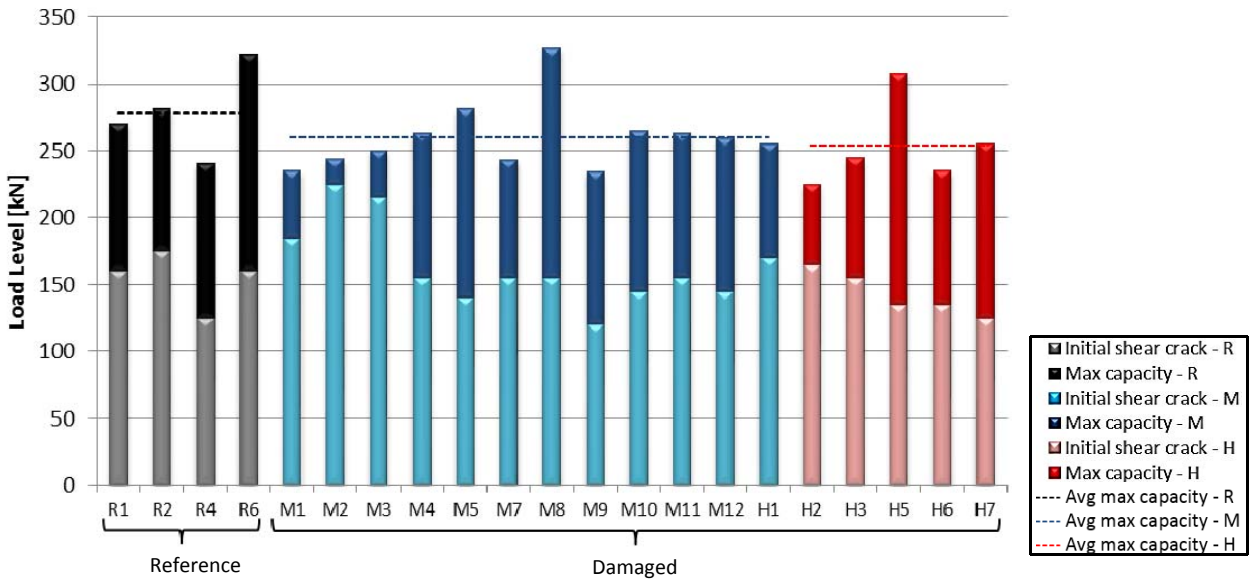
Specimen (H7)

Test set-up



- Indirectly supported four-point bending test
  - Least damage to the beams during preparations
  - Avoiding support pressure

Shear cracking and ultimate capacity



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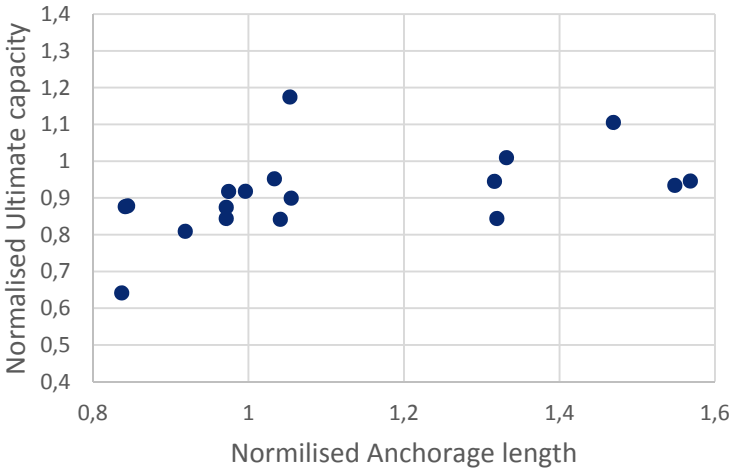
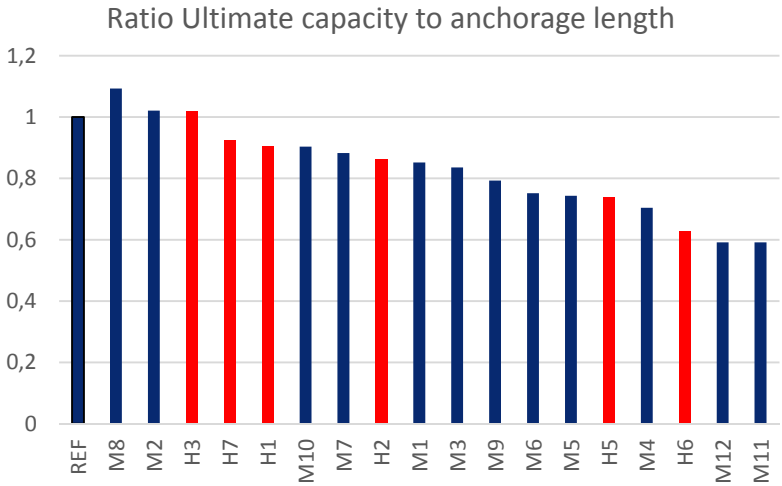
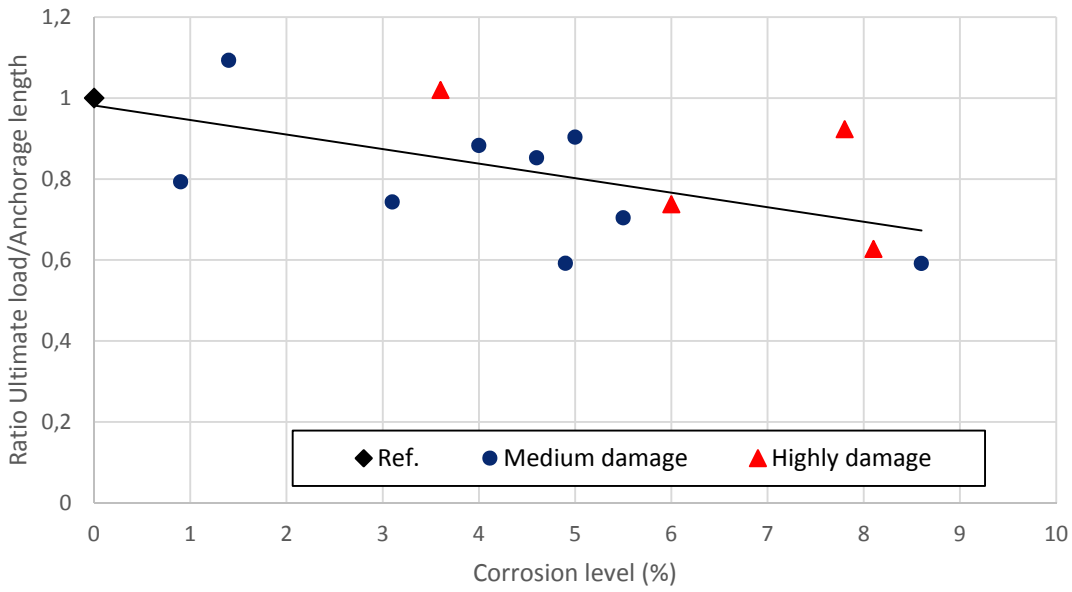




Shear cracking and ultimate capacity

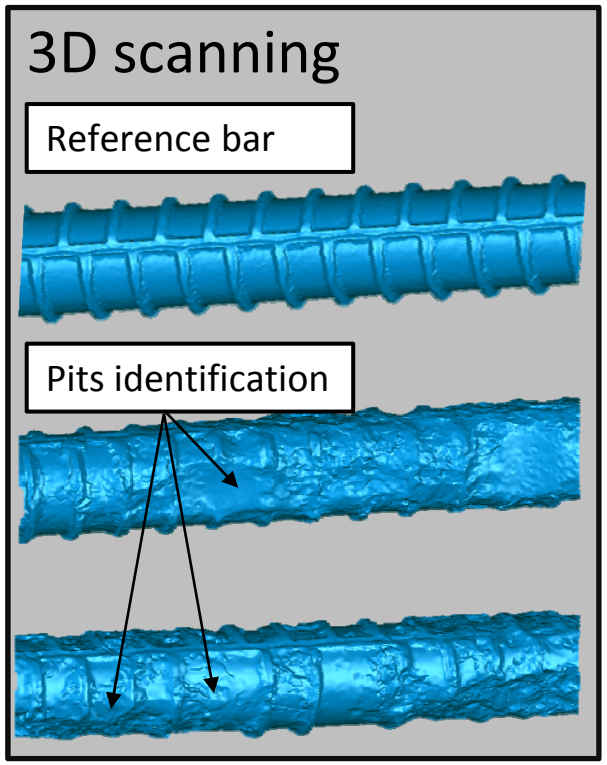


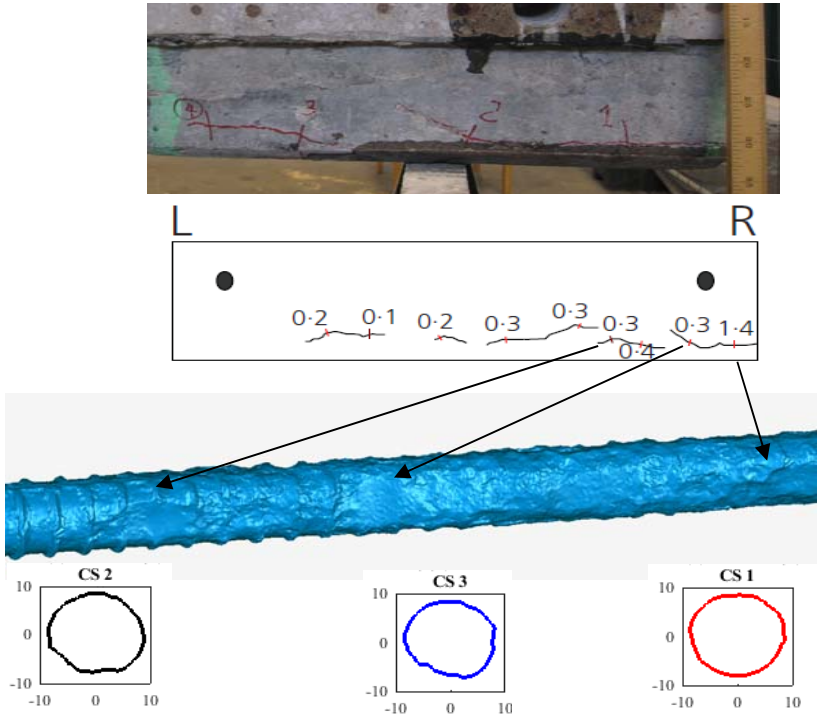
Corrosion level assessment

Weight loss

$$\text{CL (\%)} = \frac{W_{avg,Ref} - W_{bar}}{W_{avg,Ref}} \times 100$$

Corrosion level assessment





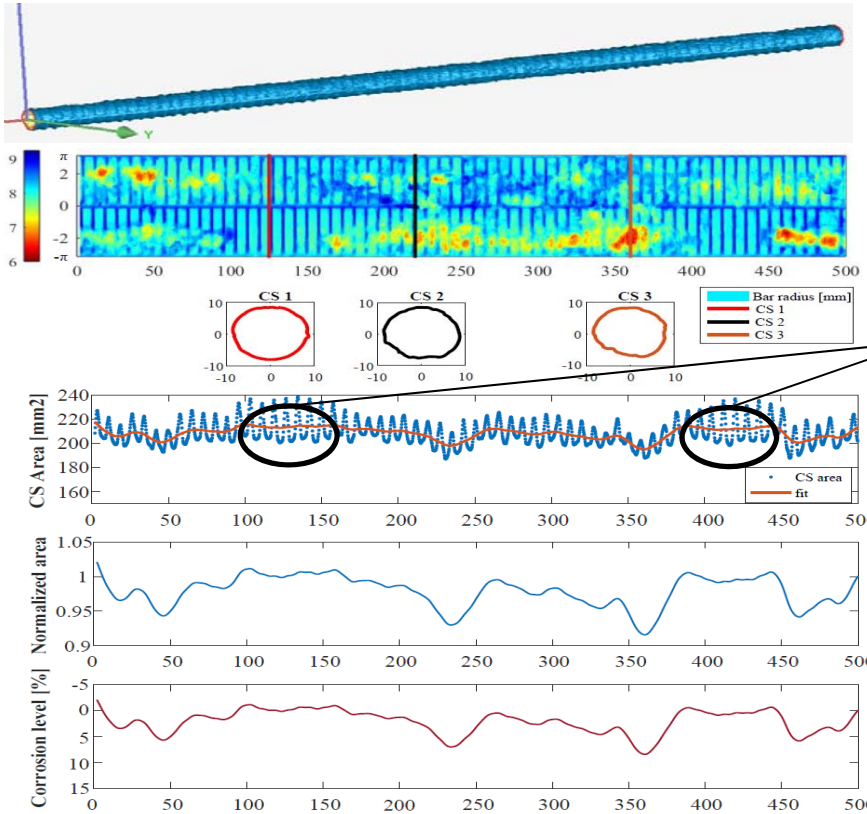
Methods for corrosion level evaluation

Step 1

Step 2

Step 3

Step 4

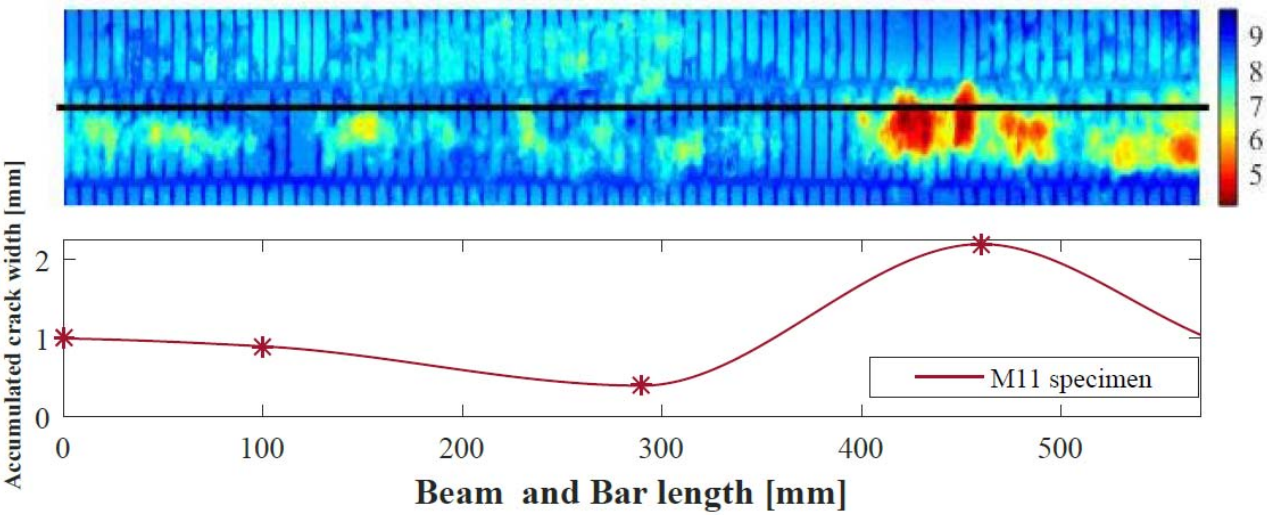


Identification of the uncorroded zones

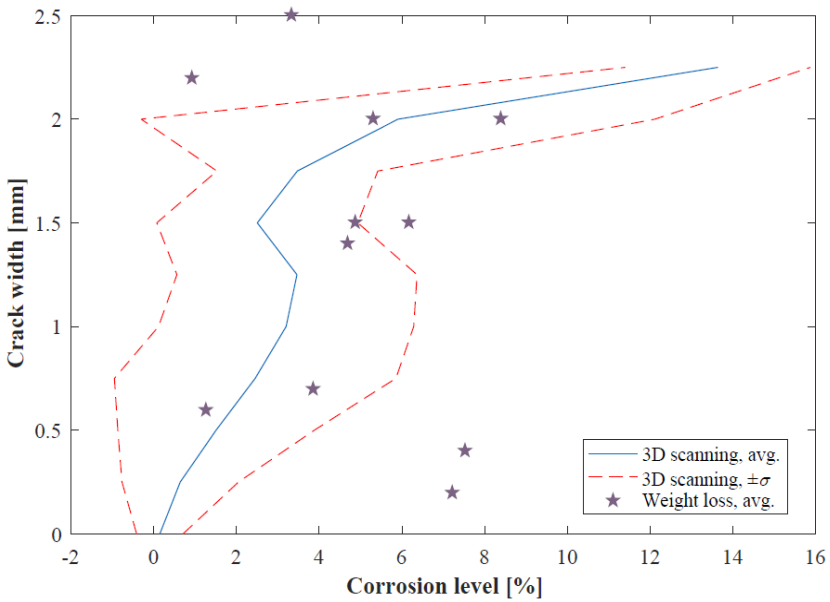
Investigations of correlations

Correlations between corrosion level and crack width

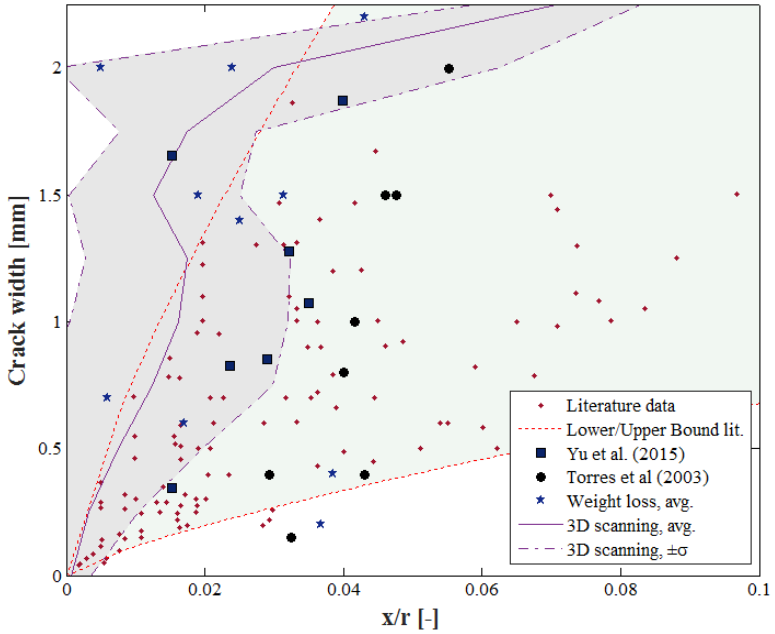
specimen M11



Crack width vs. corrosion level

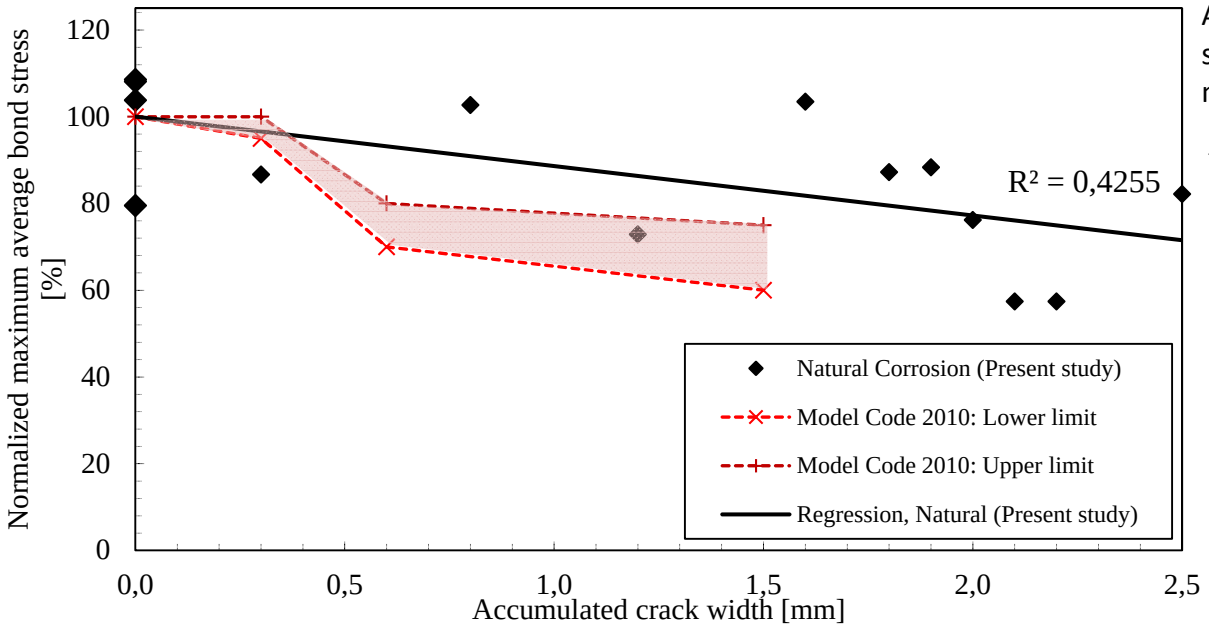


Natural corrosion vs. artificial corrosion



- Corrosion penetration/bar radius ratio:
  Comparing different bar diameters
- Literature data of accelerated corrosion tests
- Naturally corroded specimens showed larger crack widths for lower corrosion levels

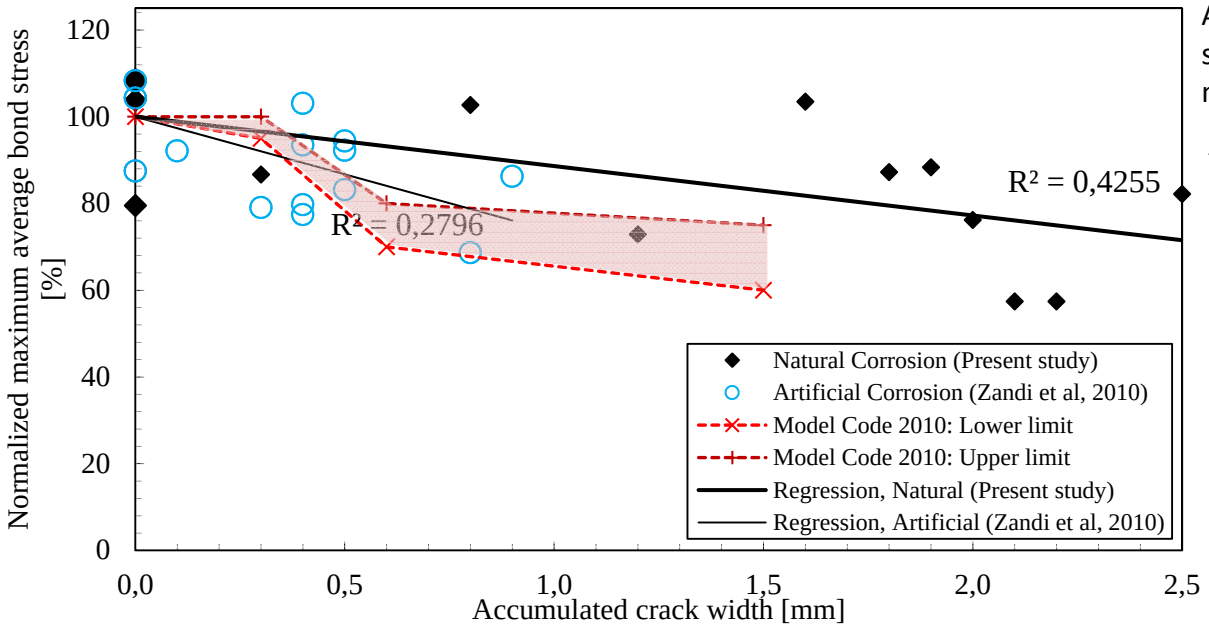
Normalized bond stress vs. crack width



Average bond stresses were normalized

$\hat{\tau}/\tau_{Ref.avg}$

Normalized bond stress vs. crack width



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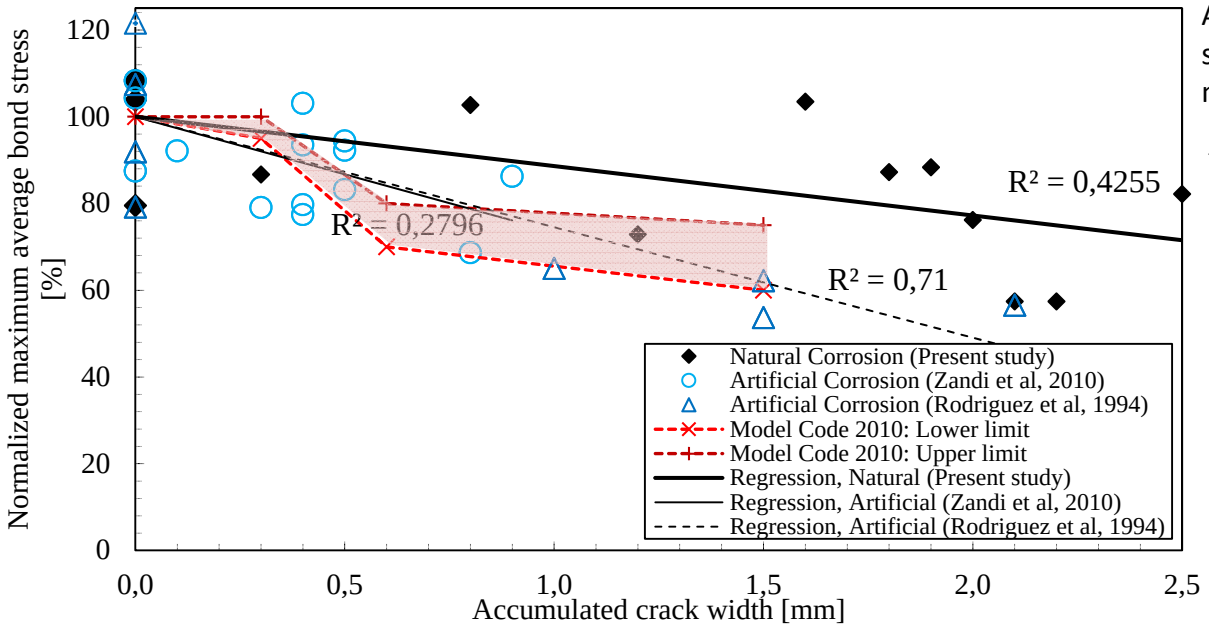
Normalized bond stress vs. crack width



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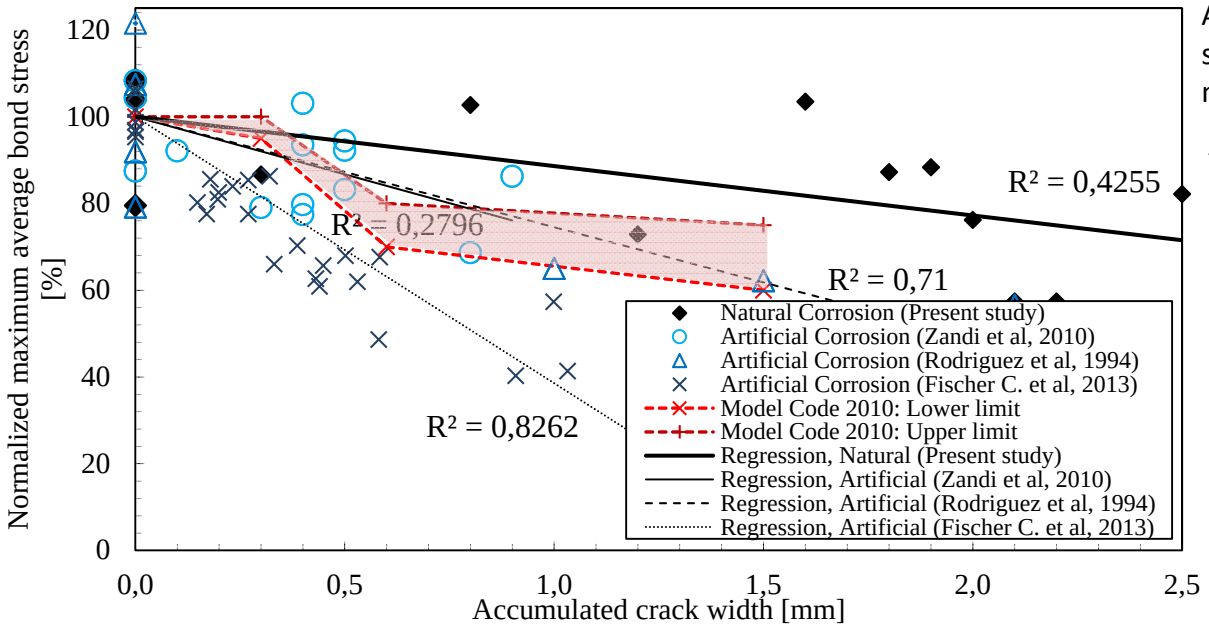


Average bond stresses were normalized

$\hat{\tau}/\tau_{Ref.avg}$

Conclusions

Experiments

Investigations of correlations

- Test set-up worked properly, expected failure mode obtained
- Damaged specimens had less capacity
- Corrosion levels by weight loss were twice as large as 3D scanning
- 3D scanning showed corrosion patterns and longitudinal variations

Conclusions

Experiments

Investigations of correlations

Compared to test results from the literature:

For same crack width:

- Larger bond capacity
- Smaller corrosion levels

For same corrosion level:

- Smaller bond capacity
- Larger crack widths

Using the existing knowledge in the literature should be in the safe side

Tool for Assessment and Service-life Evaluation of Corroded Reinforced Concrete Bridges

ARC

Mattias Bomfors (RISE-CBI), Kamyab Zandi (Chalmers);
Karin Lundgren (Chalmers); Oskar Larsson (LTH) ; Daniel Honfi (RISE); Per Kettil (Skanska)

Project partners

Swedish Cement and Concrete Research Institute

RISE

LUNDS UNIVERSITET
Lunds Tekniska Högskola

SKANSKA

Financiers

TRAFIKVERKET

Swedish Cement and Concrete Research Institute

SBUF
SVENSKA BYGGBRANSCHENS UTVECKLINGSFOND
The development fund of the Swedish construction industry

Aim and Objectives

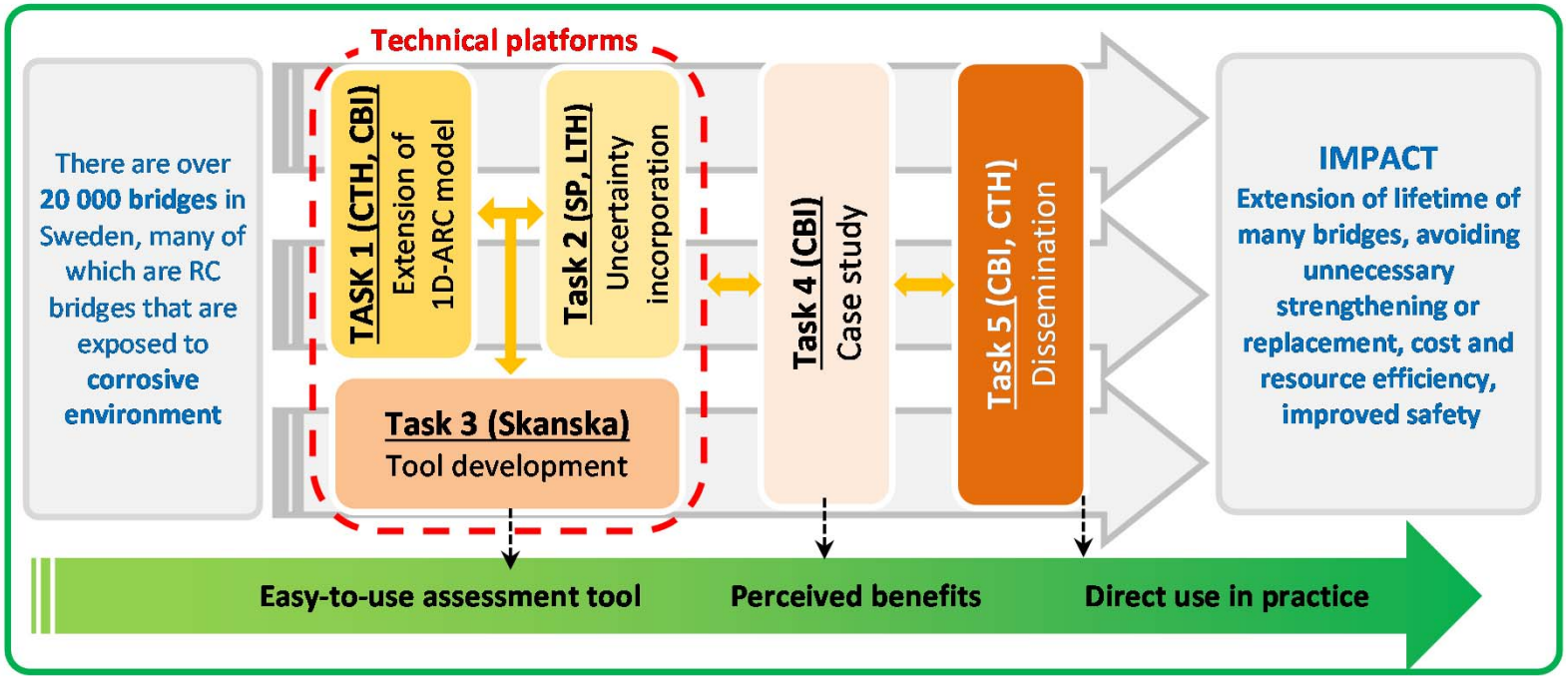
Aim

- To establish a reliable model and a simple tool for use in practical application to assess the structural effects of reinforcement corrosion and to evaluate the remaining service-life of bridges.

Objectives

- To further develop and validate ARC model
- To incorporate the effect of uncertainties into ARC model
- To integrate the models into a simple-to-use tool
- To demonstrate the use of the model and the tool
- To dissemination project outcomes

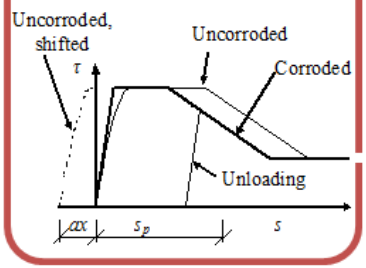
ARC overview



Major milestones in ARC model development

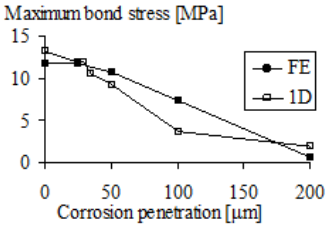
2006-2007

- Formulation of 1D-ARC model



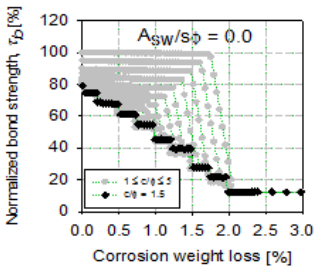
2008-2010

- Validation with 3D NLFE analyses and experiments



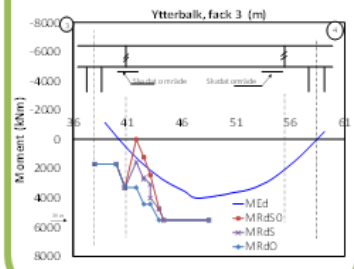
2011-2014

- Validation for natural corrosion and cover spalling



2014

- Pilot study for two bridges



2014-...

Adopted by *fib* SAG7

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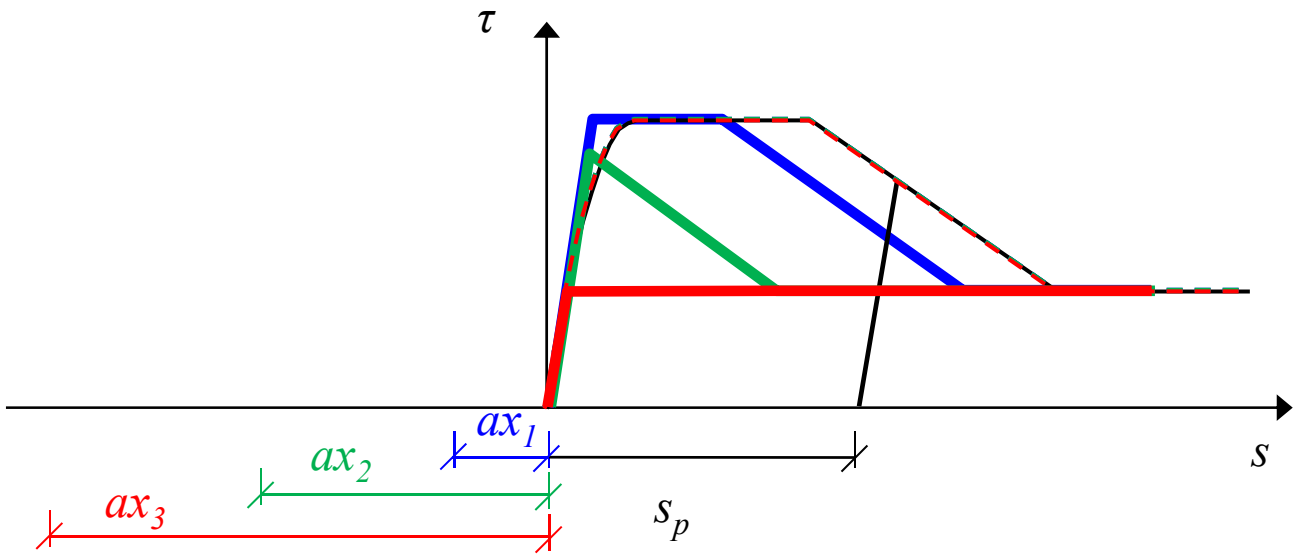

$$\tau = D(s - s_p)$$

$$|\tau| \leq \tau_b(\kappa)$$

$$\kappa = s_p + ax$$

a = 8.1

Major milestones in ARC model development

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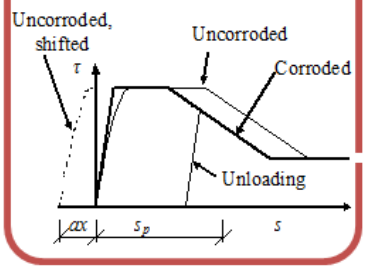

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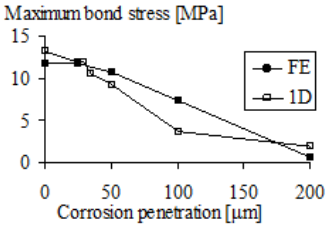

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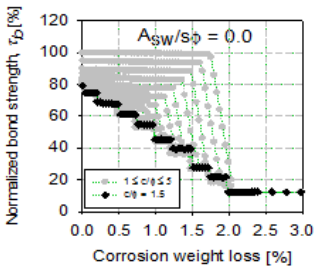

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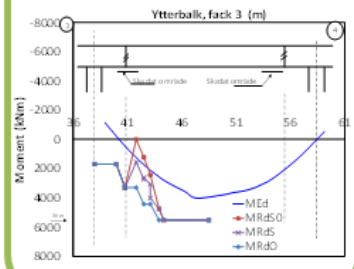

2014-...

Adopted by *fib* SAG7

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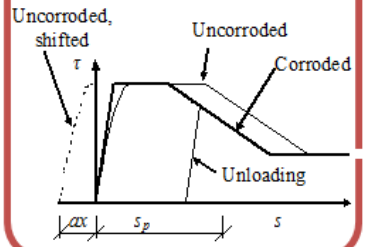

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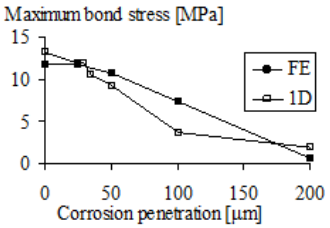
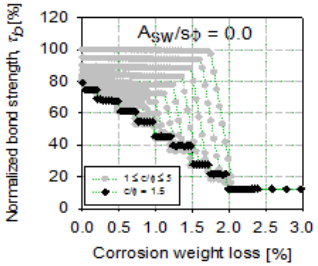


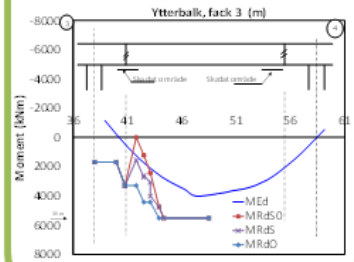
2011-2014

- Validation for natural corrosion and cover spalling



2014

- Pilot study for two bridges



2014-...

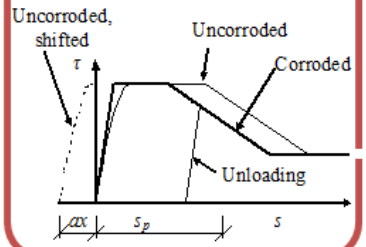
Adopted by *fib* SAG7

Pilot study for two bridges: Blommenbergsviadukten and Gröndalsviadukten

Major milestones in ARC model development

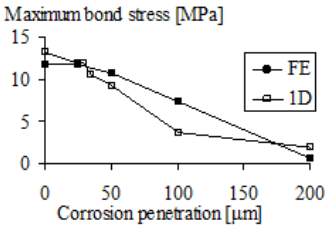
2006-2007

- Formulation of 1D-ARC model



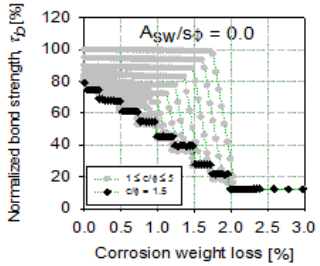
2008-2010

- Validation with 3D NLFE analyses and experiments



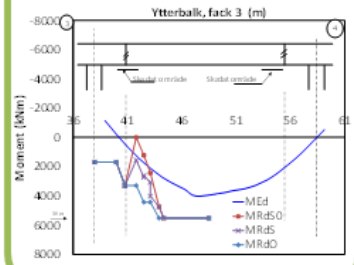
2011-2014

- Validation for natural corrosion and cover spalling



2014

- Pilot study for two bridges



2014-...

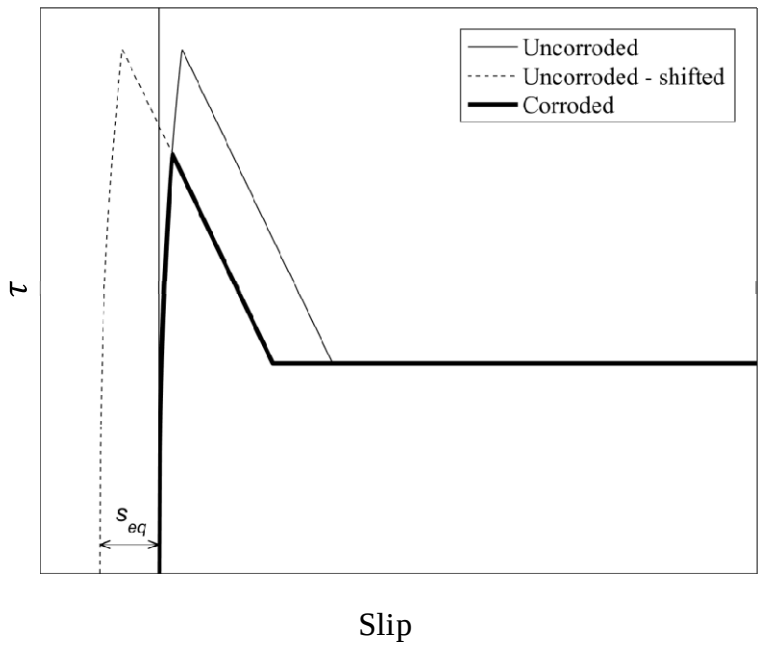
Adopted by *fib* SAG7

Conclusions from assessment of Blommenberg- and Gröndal viaducts

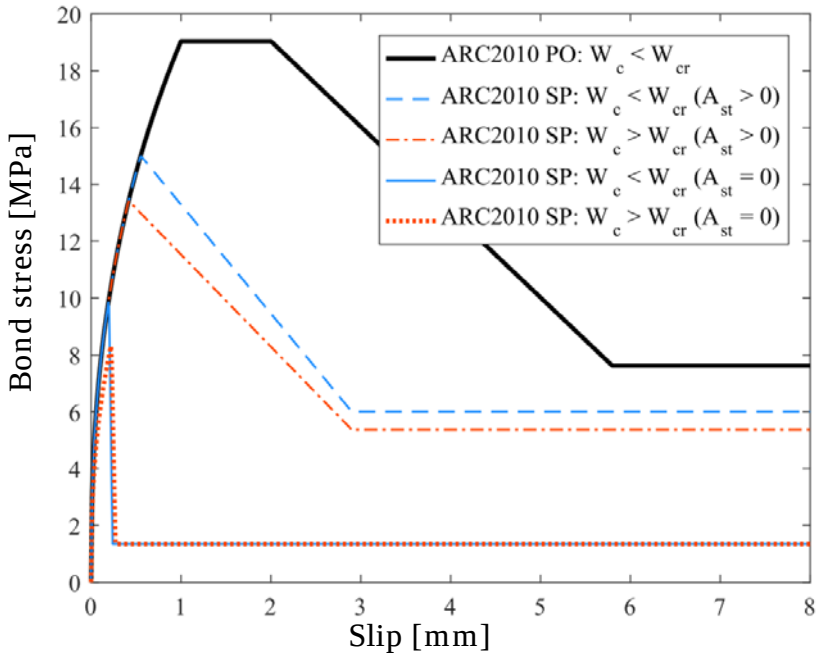
- Sufficient capacity was shown in all beams, in all spans, except for a small violation in one span.
- Detailed inspection will be made to judge if the damage is as large as assumed.
- Earlier: planned strengthening ~46 mkr
- Now: planned maintenance ~19 mkr.
- Assessment cost ~0,2 mkr
  => Saved 27 mkr

Task 1 - Extension of ARC model

Equivalent slip

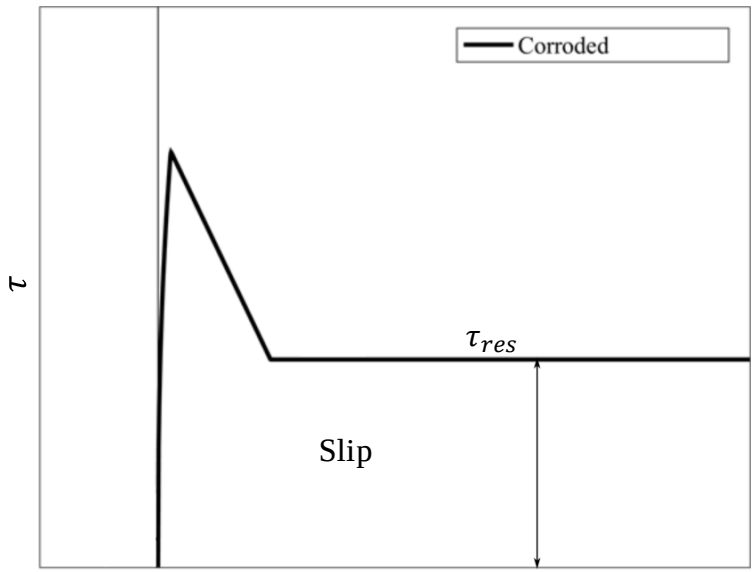


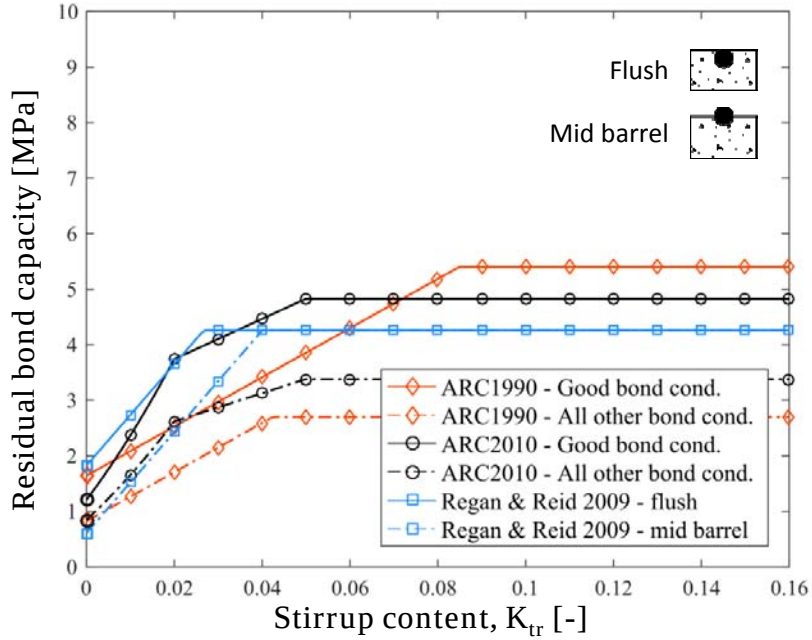
Corrosion-induced cracking



Task 1 - Extension of ARC model

Residual capacity

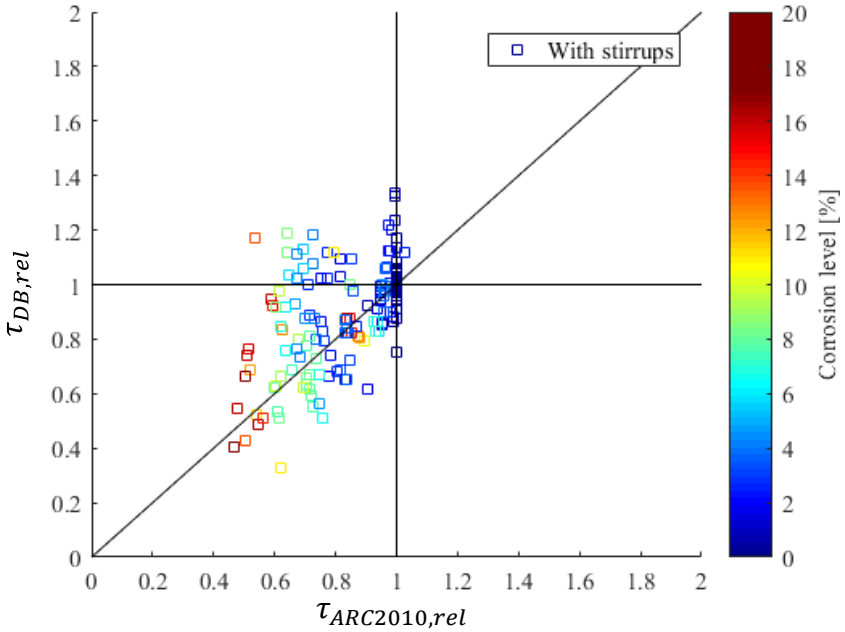




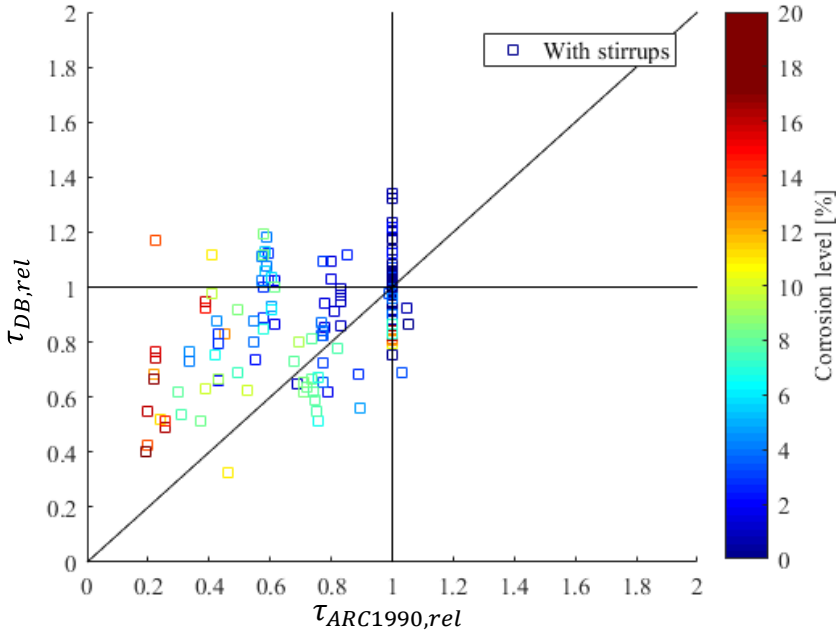
Task 1 - Extension of ARC model

Comparison between ARC2010 and ARC1990

ARC2010

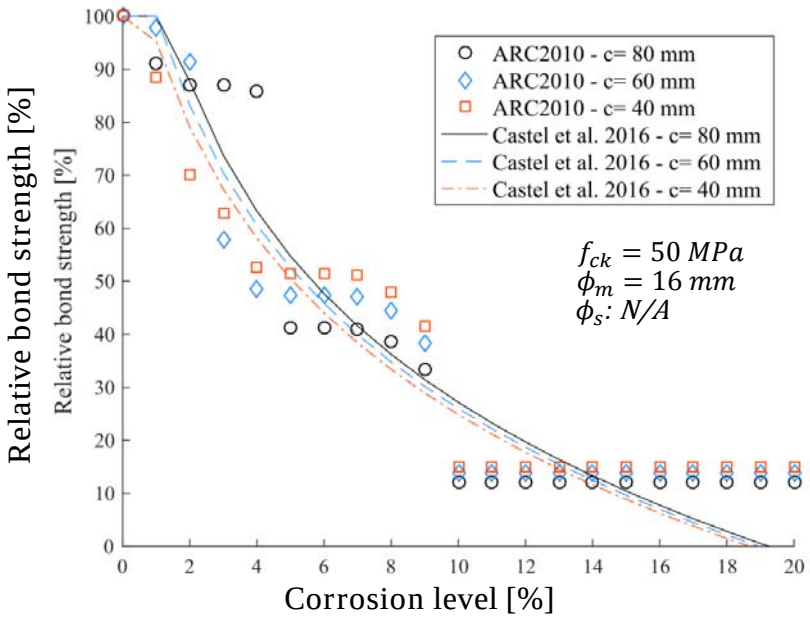


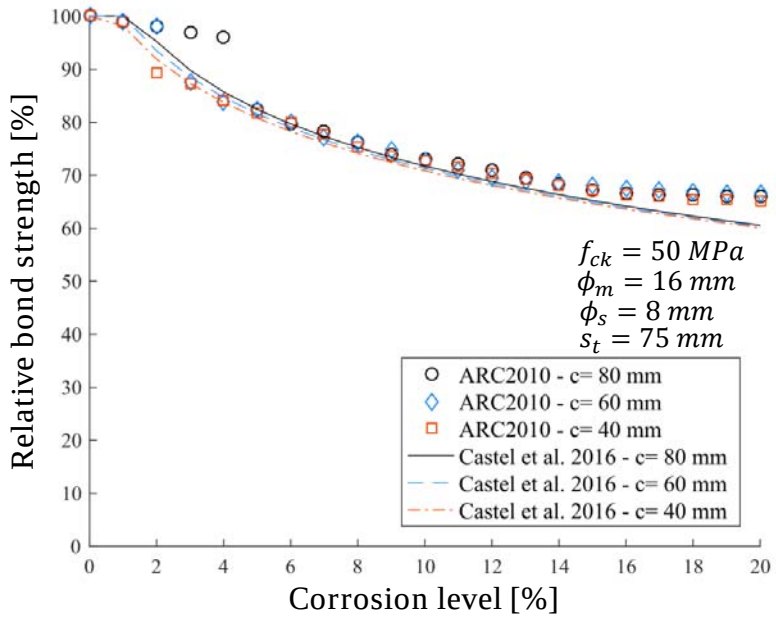
ARC1990



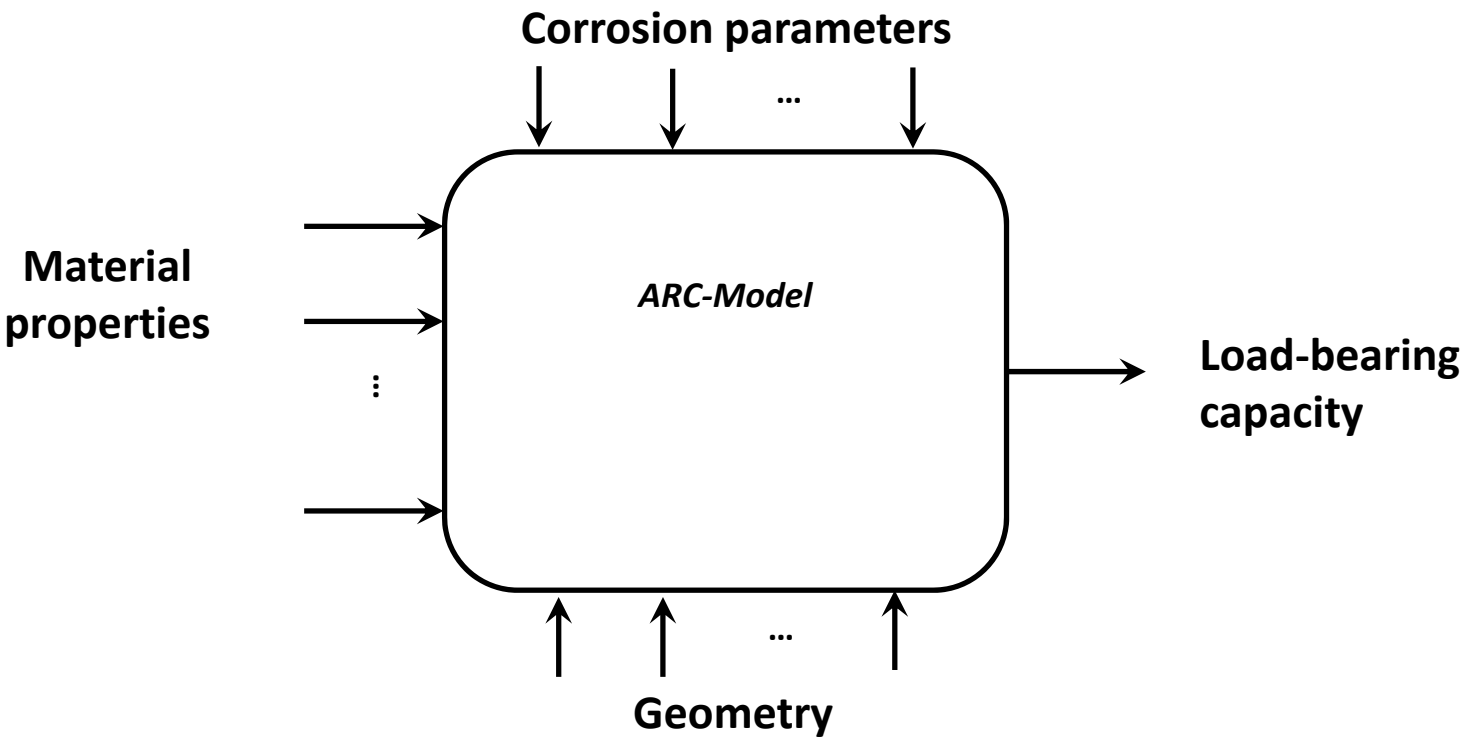
Task 1 - Extension of ARC model

Comparison to Castel et al. 2016

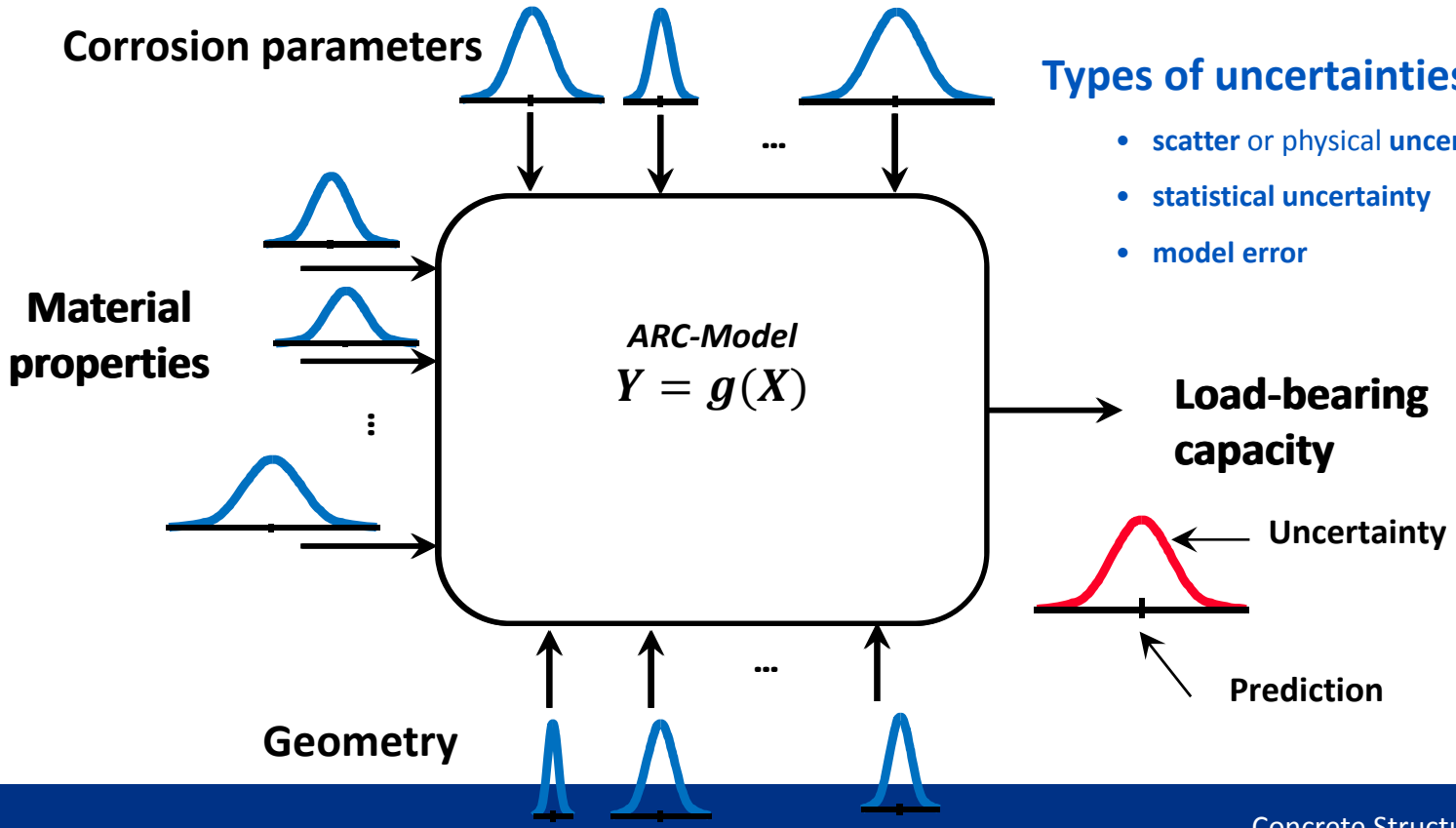




Task 2 – Incorporation of uncertainty



Task 2 – Incorporation of uncertainty



Types of uncertainties:

- **scatter** or physical **uncertainty**
- **statistical uncertainty**
- **model error**

Future work within ARC

Task 3 – ARC program/tool

- Current ARC-code developed in Matlab
- Easy to use platform with built-in functions
- Open source code, no need of compilation

=> PLAN:

- Improved structure of the code and self-explanatory input- and command file
- Supplemented with a brief program manual + ready-to-use example files
- Make it accessible for download
- Possibly translate to similar free open-source environment, e.g. SciLab, FreeMat

Task 4 – case study

Demand list

- Corroded RC structure with Ribbed bar
- Actual investigation case at Trafikverket together with a consultant company
- Time frame late 2017 – early 2018

Wish list

- Anchorage problem
- Varying corrosion levels
- Availability of documentation

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