VANCOUVER
2017 IABSE
SYMPOSIUM

Durability assessment of reinforced concrete structures due to chloride ingress up and beyond induction period

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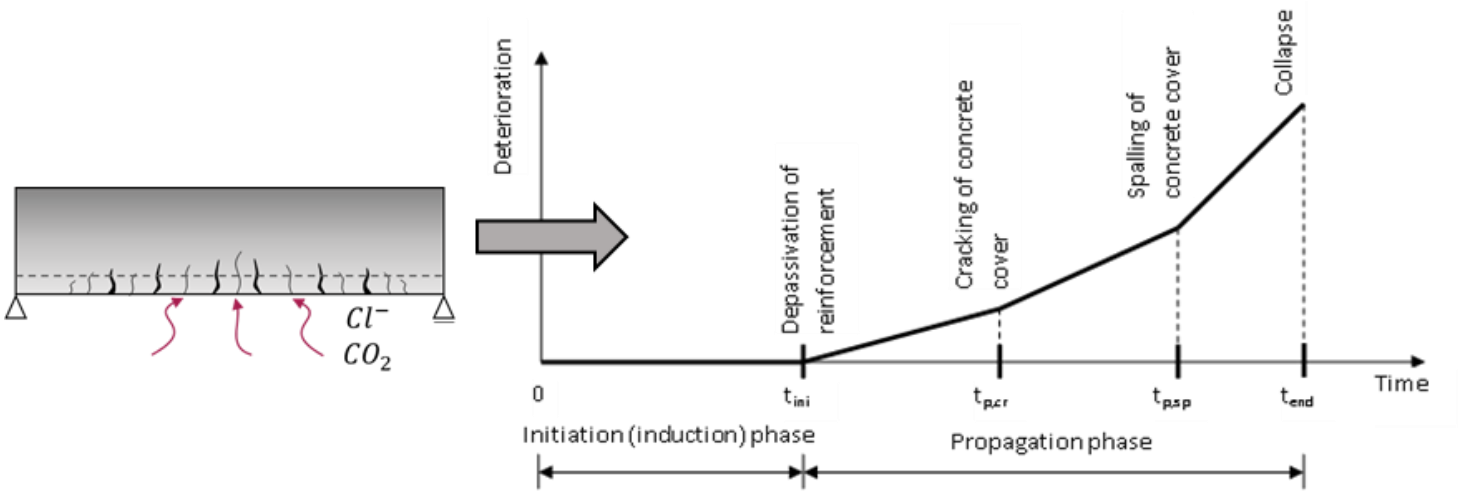
Outline

- Corrosion of reinforcing steel due to Cl^-
- Models for induction and propagation phases
- Chemo-mechanical linking
- Examples
  - Bridge strut
  - RC beam from Nougawa bridge

Reinforcing steel corrosion in chloride environment



- Initiation (induction) phase ends when Cl exceeds critical concentration
- Cracks accelerate penetration (0.3 mm crack decreases induction time approximately 5 times)
- Propagation phase forms expanding corrosion products

Model for propagation phase (1)

- 1D chloride concentration (Kwon et al., 2009)

$$C(x,t) = C_S\left[1 - erf\left(\frac{x}{2\sqrt{D_m(t)f(w)t}}\right)\right] \qquad f(w) = 31.61w^2 + 4.73w + 1$$

- Corrosion current density (Liu and Weyers, 1998)

$$i_{corr} = 0.926 \cdot \exp\left[7.98 + 0.7771\ln(1.69C_t) - \frac{3006}{T} - 0.000116R_C + 2.24t^{-0.215}\right]$$

- 1D model for corrosion depth (R_{corr}~3 for pitting)

$$x_{corr}(t) = \int_{t_{ini}}^{t} 0.0116 i_{corr}(t) R_{corr}\, \mathrm{d}t$$

- Effective bar diameter

$$d(t) = d_{ini} - \psi 2x_{corr}(t)$$

Model for propagation phase (2)

- Cracking of concrete cover (DuraCrete, 2000)

$$x_{corr,cr} = a_1 + a_2 \frac{cover}{d_{ini}} + a_3 f_{t,ch}$$

- Spalling of concrete cover (DuraCrete, 2000)

$$x_{corr,sp} = \frac{w^d - w_0}{b} + x_{corr,cr}$$

- Direct steel exposure

Corrosivity zone (ISO 9223)		**Typical environment**	**Corrosion rate for first year (µm/y)**	
Category	Description		Mild steel	Zinc
C1	Very low	Dry indoors	≤1,3	≤0,1
C2	Low	Arid/Urban inland	>1,3 a ≤25	>0,1 a ≤0,7
C3	Medium	Coastal and industrial	>25 a ≤50	>0,7 a ≤2,1
C4	High	Calm sea-shore	>50 a ≤80	>2,1 a ≤4,2
C5	Very High	Surf sea-shore	>80 a ≤200	>4,2 a ≤8,4
CX	Extreme	Ocean/Off-shore	>200 a ≤700	>8,4 a ≤25

Simulation workflow

Geometry
Dimensions
Reinforcement
Cover thickness

Material properties
Concrete (w/c)
Steel

Boundary conditions
Supports
Mechanical loads
Thermal loads
Prescribed displacements
Surface concentration

Initial conditions
Temperature
Concentration

Mechanical model

Stress, strain, damage

Load bearing capacity

Crack width

Chemo-mechanical model

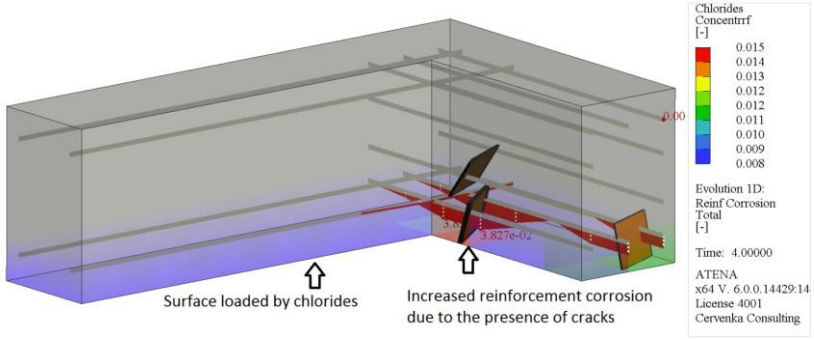
Cl transport for induction stage

Propagation stage

Induction time, cracking, spalling

Remaining reinforcement

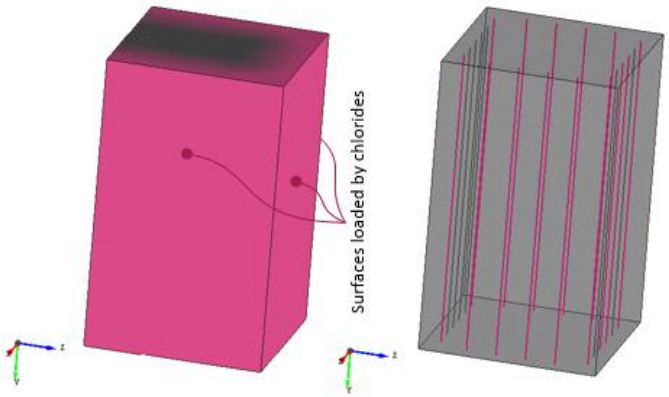
Mechanical model



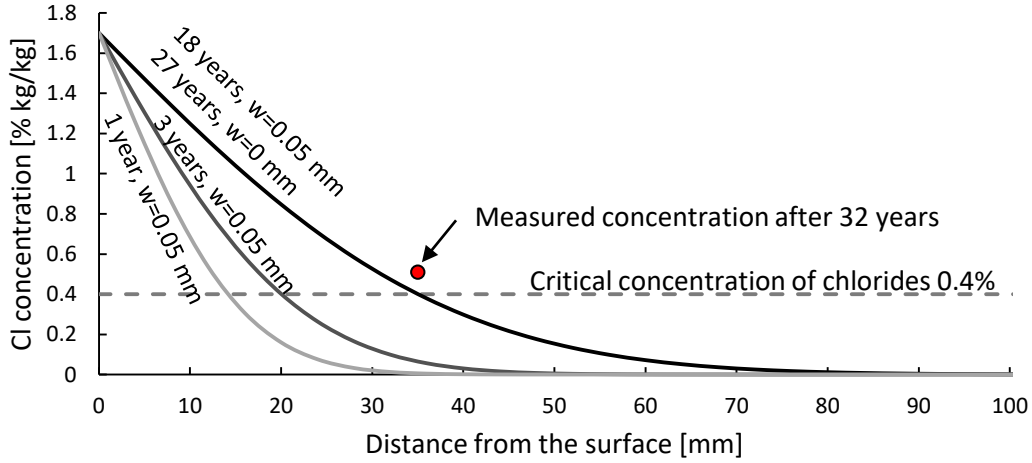
Example 1 – concrete strut

- Prestressed bridge in Prague, 14+36+14 m
- Built 1984, diagnostics 2016
- Struts C35/45 (CEM I 350 kg/m^3)
- Bars ø32 mm with stirrups
- Bars' cover 35 mm

[Ing. Junek, Pontex]

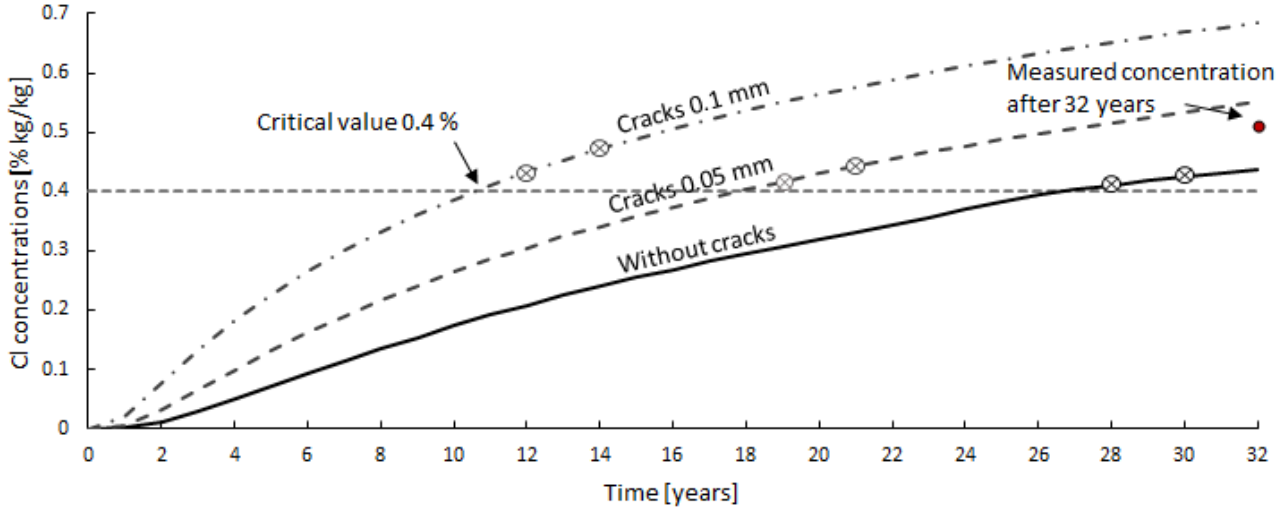


Geometry (0.6 x 0.6 m) of the bridge strut and chloride profile

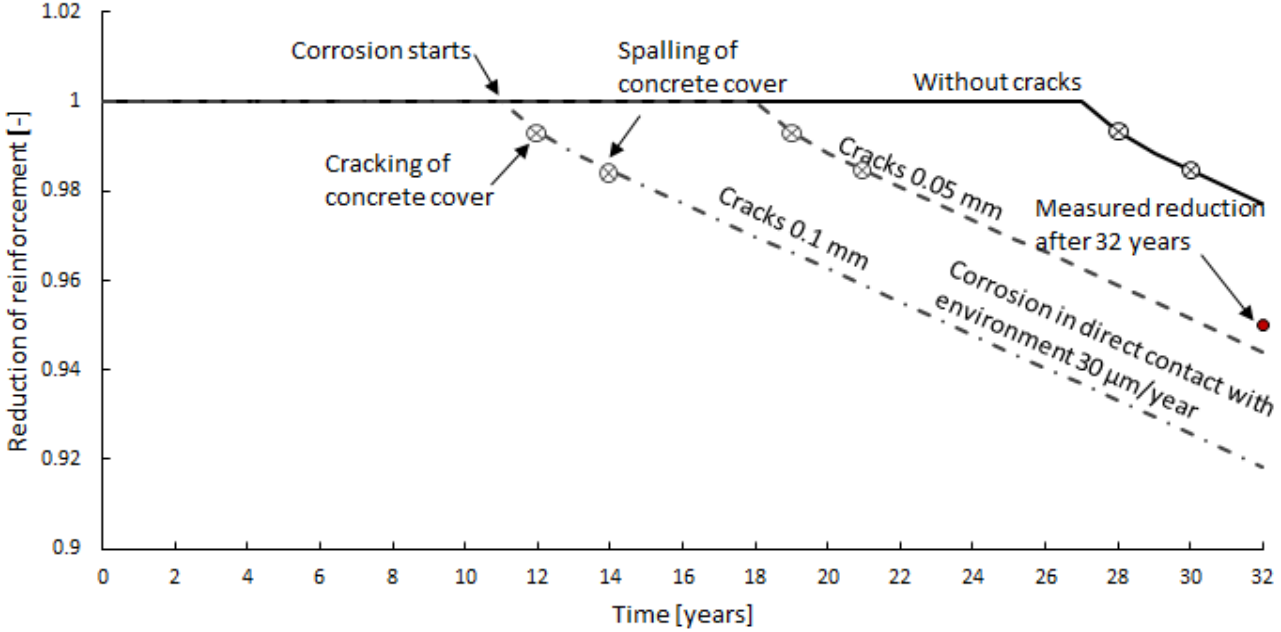


Chloride distribution in the depth of the bridge strut for the surface concentration of 1.7 % kg/kg, induction phase.

Example 1 – concrete strut



Chloride concentrations at the reinforcement depth, concrete cover = 35 mm for three scenarios of crack width.

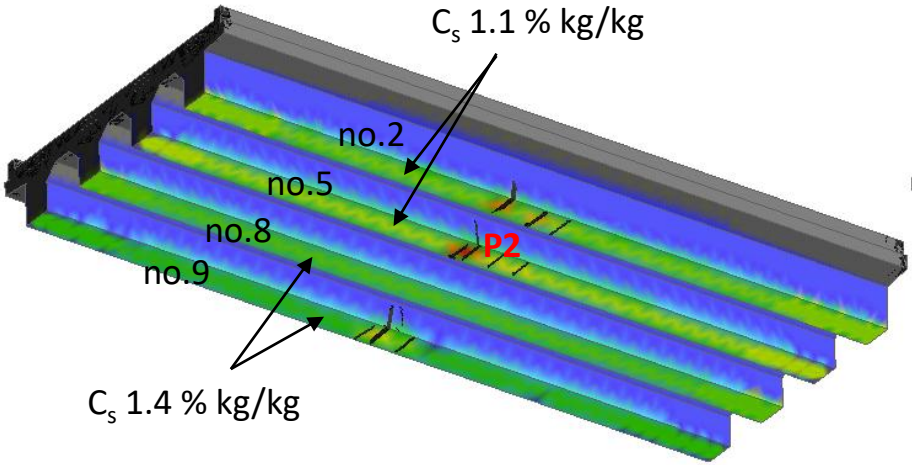


Reduction of the reinforcement area during service life.

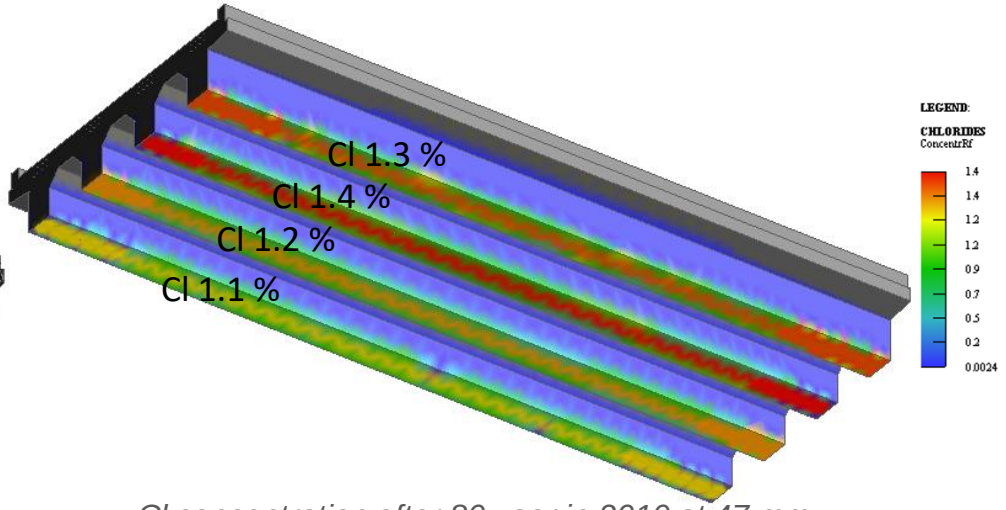
Example 2 – Nougawa bridge, Japan

- Built 1930 in coastal area, stirrup's concrete cover 47 mm
- Reinforced beams, 3x4 spans @ 10.8 m = 131 m
- Bars ø25.4 mm, stirrups ø9.5 mm
- Cover restored in 1960, C_{crit}=0.4%
- Two beams tested in 2009

Validated specimen, (Tanaka et al.)



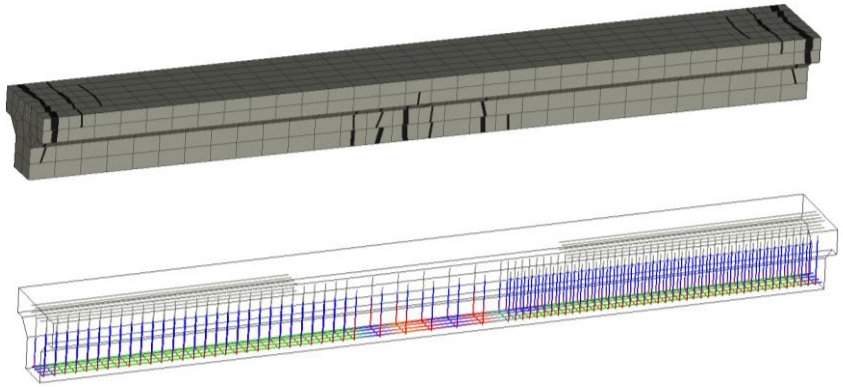
Cl concentration after 30 year in 1960 at 47 mm



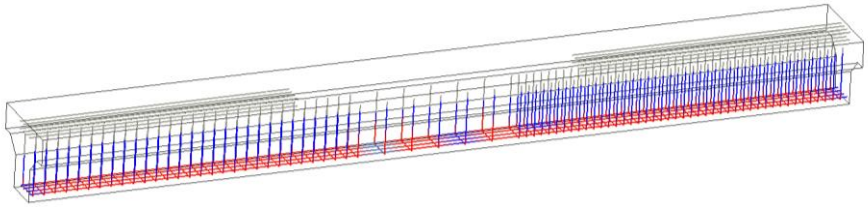
Cl concentration after 80 year in 2010 at 47 mm

Example 2 – Nougawa bridge, Japan

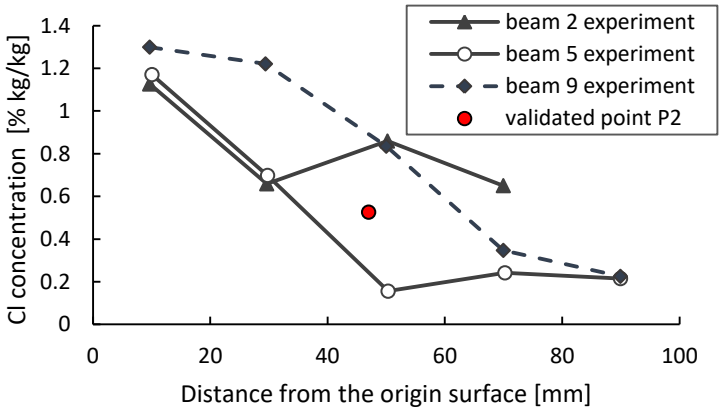
- Predicted reinforcement area of 64% agrees well with the measured value of 62.5%

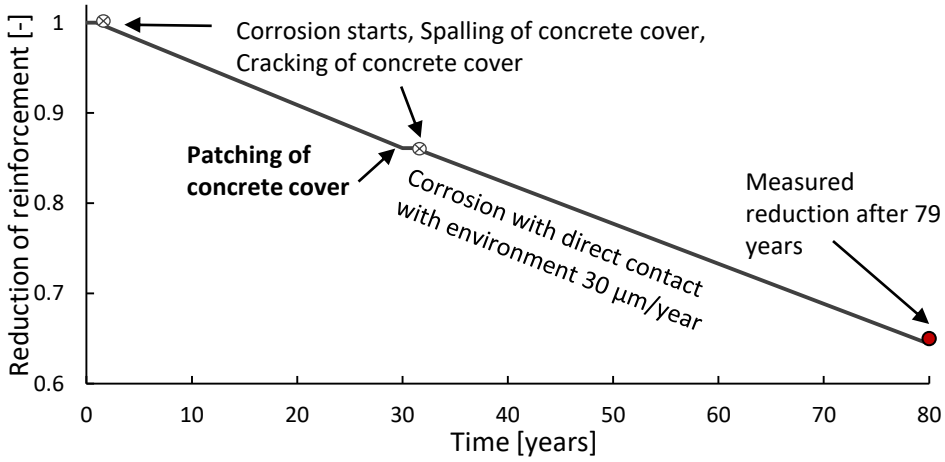


Reinforcement corrosion after 30 years in 1960



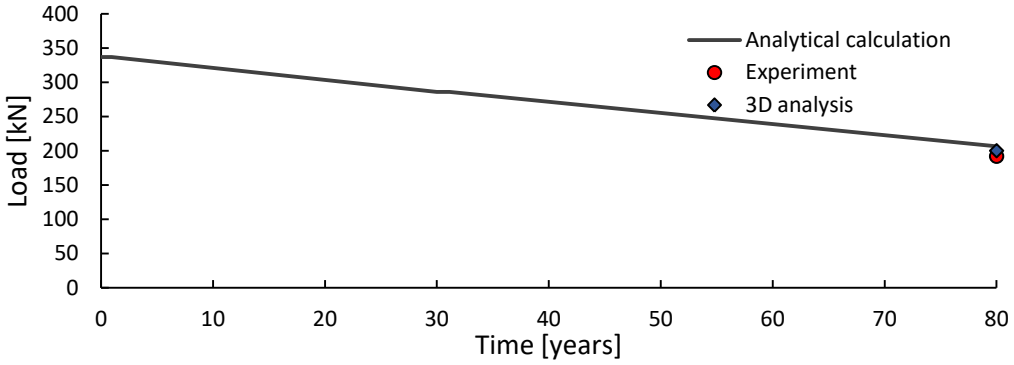
Reinforcement corrosion after 79 years in 2009

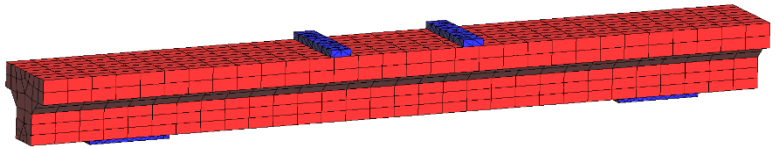




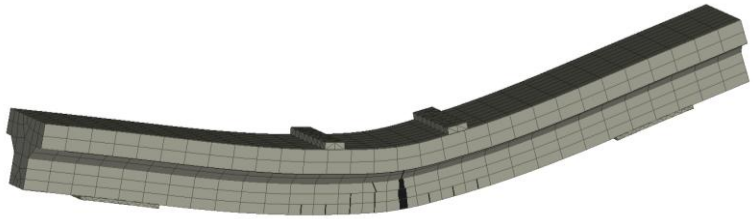
Example 2 – Nougawa bridge, Japan

- ULS analysis, 4 point bending @ 3+2+3 m

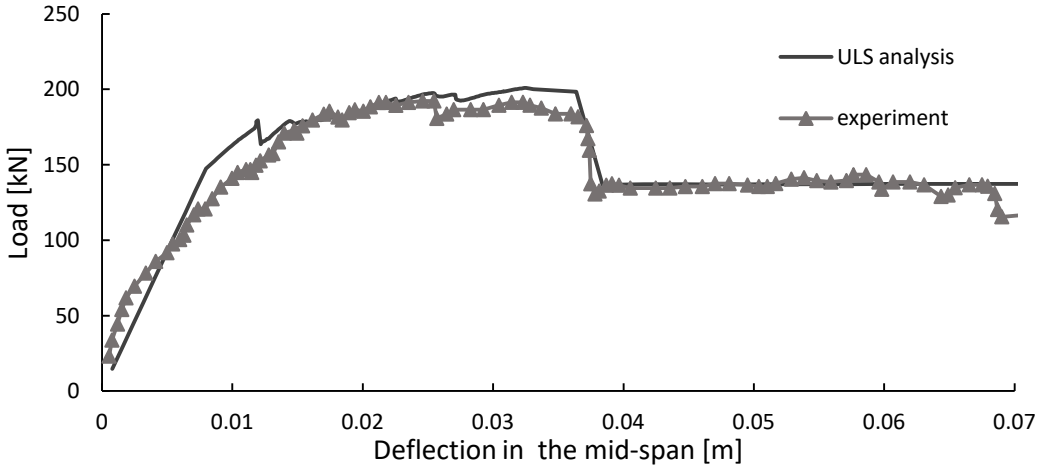


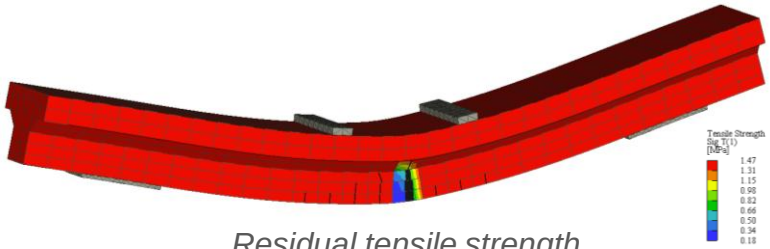


Loaded geometry of cut out beam specimen

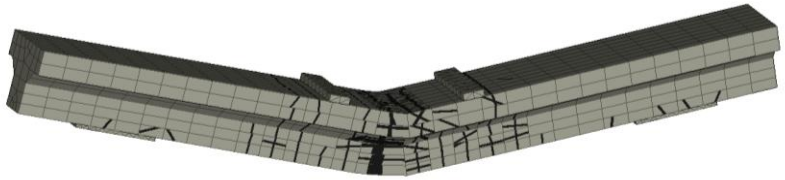


Start of ULS analysis





Residual tensile strength



End of ULS analysis

Conclusions

- Simplified simulation of chloride ingress for reinforced concrete
  - Induction and propagation periods
  - Cl acceleration by crack width
  - Effective reinforcing area
- Further linking with ULS analysis
- Possible linking with LCA

We gratefully acknowledge the financial support from the Technology Agency of the Czech Republic TAČR under the project TA04031458 and SGS12/116/OHK1/2T/11 granted by the Czech Technical University in Prague.