


SHRP2 SOLUTIONS
STRATEGIC HIGHWAY RESEARCH PROGRAM

Implications of Cracks in Concrete on Service Life

PennDOT Workshop Training

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Discussion Topics

- Introduction
- Types of Cracking
- Theories on Durability Behavior of Cracked Concrete
- *fib* Bulletin 34 Development
- Past Research
- Summary

Introduction

- Deterioration methodology in *fib* Bulletin 34 for both Chloride and Carbonation-Induced Corrosion is based on “uncracked” concrete
- The definition of “uncracked” is vague
- Industry professionals have different opinions on what is considered “uncracked”, e.g.,
  - Fully prestressed members
  - Gravity loads causing full compression
  - Cracks under a specified size

Introduction

- Prestressed concrete components
  - Generally considered uncracked under service loads and thus fully conforms to the *fib* Bulletin 34 chloride ingress model
  - Are still subjected to potential deterioration and need a concrete quality and depth of cover sufficient to withstand chloride loading
- Reinforced concrete components
  - Undergo some degree of cracking with load
  - Cracks may lead to early corrosion initiation

Types of Cracking

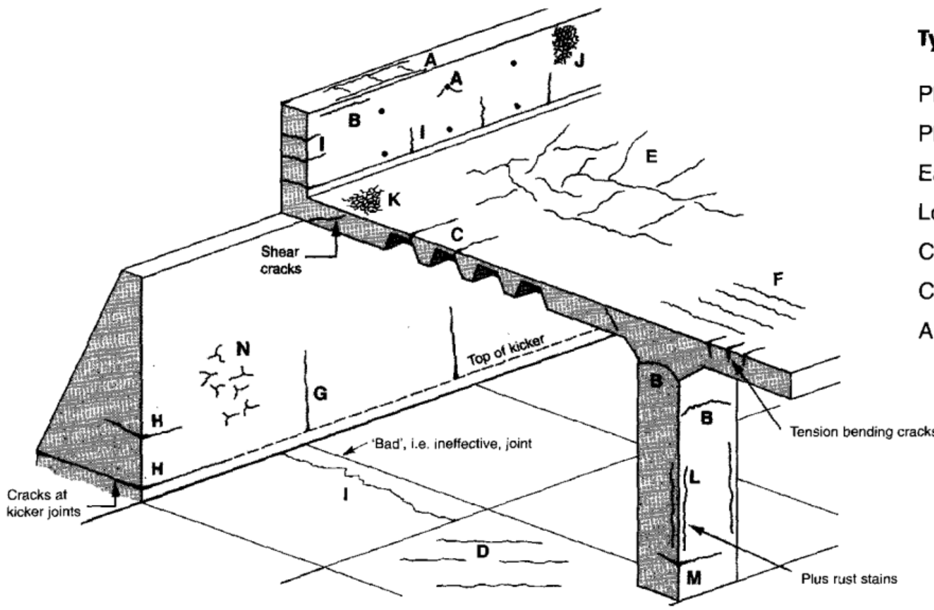
- Cracks developed from loads and restraints that may contribute to premature corrosion

- Other: cracks due to poor construction process, shrinkage, temperature differential, deterioration mechanisms (AAR, DEF, etc.)

- Cracking as a consequence of corrosion propagation

Load / Restraint Cracking

- Load-induced cracks
- Early-age cracks from shrinkage, thermal, etc.



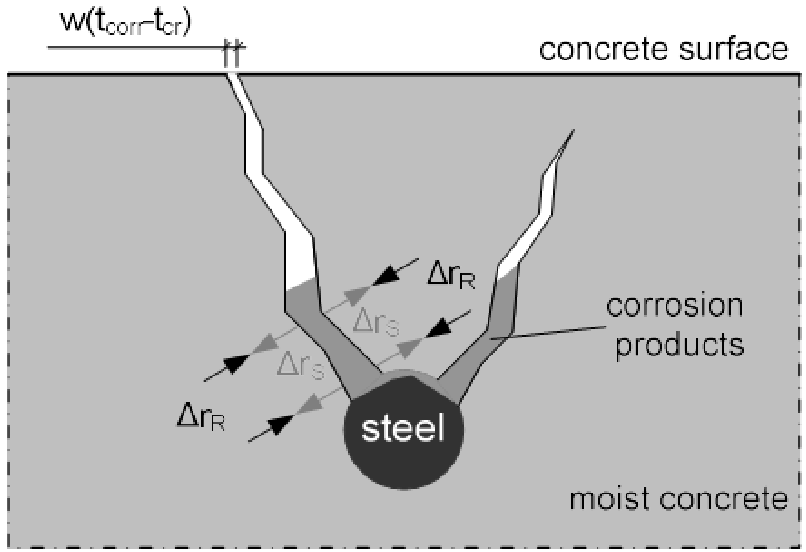
Type of cracking

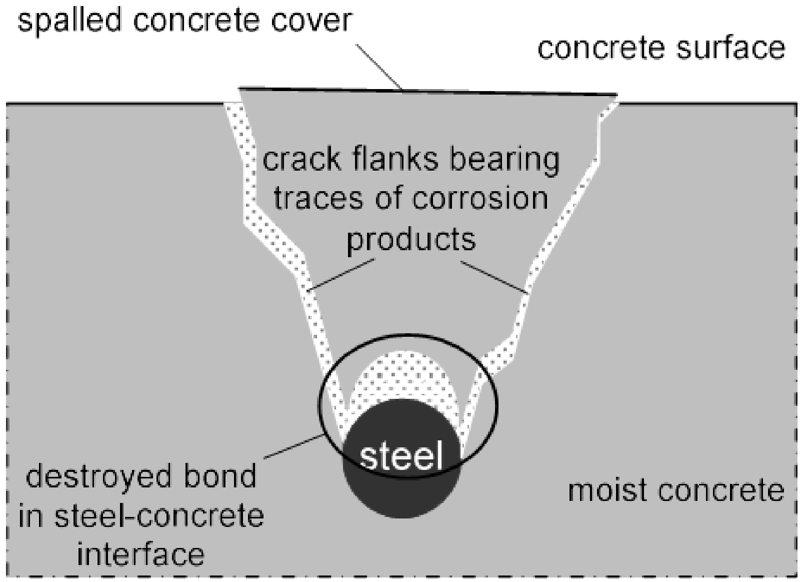
Plastic settlement	A, B, C
Plastic shrinkage	D, E, F
Early thermal contraction	G, H
Long-term drying shrinkage	I
Crazing	J, K
Corrosion of reinforcement	L, M
Alkali–silica reaction	N

- Accelerates the diffusion process and shortens time to initiate corrosion

Corrosion Propagation Cracks

- Signals end of initiation phase / start of propagation phase
- Formation of Iron Oxide is an expansive process





Load & Constraint Cracking

- Creates the most concern to adopting **Service Life Design**

- Role of cracking on corrosion is controversial
  - Prestressing industries believe their products perform better because they are uncracked
  - Long-term performance of reinforced concrete with small cracks has been used to calibrate the methodology in *fib* Bulletin 34

Theories on Durability Behavior of Cracked Concrete

- Currently Two Theories
  - A: Cracks provide access for chlorides to reach the reinforcing, accelerating time to initiation and corrosion propagation
  - B: Cracks provide access for chlorides, but corrosion is localized and limited. Eventually chlorides reach reinforcing in uncracked areas and initiate widespread corrosion. Over the long term, little difference exists between cracked and uncracked concrete behavior provided the cracks are within a certain limit (within what is normally expected for reinforced concrete)

Theories on Durability Behavior of Cracked Concrete

- Similar Theories Reported In:
  - Poston, R.W., Carrasquillo, R.L. & Breen, J.E., *Durability of Prestressed Bridge Decks*, Research Report 316-1, Texas Department of State Highways & Public Transportation, July 1985, p 15-17.
  - Salas, R.M, Schokker, A.J., West, J.S., Breen, J.E. & Kreger, M.E., *Conclusions, Recommendations and Design Guidelines for Corrosion Protection of Post-Tensioned Bridges*, Research Report 0-1405-9, Texas Department of Transportation, Austin, TX, February 2004, p 26-27.
  - Matthews, S., Design of Durable Concrete Structures, IHS BRE Press, Berkshire, 2014, p 129-136

- Similar controversy discussed 30 years apart

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- Deterioration models for “uncracked” concrete
- Commentary to Section 3.3 – Influence of cracks upon reinforcement corrosion
  - Identifies most severe conditions as horizontal surfaces and both cracks and chloride attack from top (e.g. parking decks), needing extra protection measures
  - Suggests 0.3mm (0.012”) crack width limits without extra protection for other locations

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- Chloride Ingress model based on diffusion property of concrete, $D_{app,C}$

$$C_{crit} \geq C(x=a,t) = C_o + (C_{s,\Delta x} - C_o) \cdot \left[1 - \text{erf}\left(\frac{a - \Delta x}{2\sqrt{D_{app,C} \cdot t}}\right)\right]$$

$$D_{app,C} = k_e \cdot D_{RCM,0} \cdot k_t \cdot A(t)$$

$$k_e = \exp\left(b_e\left(\frac{1}{T_{ref}} + \frac{1}{T_{real}}\right)\right)$$

$$A(t) = \left(\frac{t_o}{t}\right)^{\alpha}$$

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- Usually developed from chloride profile tests on existing structures or test samples stored in similar conditions to those expected in service
- Profiles taken at several ages because $D_{app,C}$ varies significantly with time
- For new designs, it's impractical to obtain chloride profiles in a timely manner, so another method was adopted

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- In development of procedure, hundreds of profile samples collected from existing reinforced concrete structures with some degree of cracking
- Data collated by cement type, supplemental cementitious material (fly ash, slag, silica fume), water/cement ratio, and chloride exposure zones
- $D_{app,C}$ back calculated for all these types of mix proportions

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- Comparable concrete mixes were made and tested using the Nordtest NT Build 492 rapid chloride migration test to compute $D_{RCM,0}$

- Same NT Build 492 tests that Lehigh University performed on typical PennDOT concrete mix designs

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- Performed regression analyses using both sets of data to best fit $D_{app,C}$ obtained from existing structures (with some cracking) to $D_{RCM,0}$ obtained from similar proportioned uncracked concrete test specimens

$$\mathbf{D_{app,C}} = k_e \cdot \mathbf{D_{RCM,0}} \cdot k_t \cdot A(t)$$

$$k_e = \exp\left(b_e\left(\frac{1}{T_{ref}} + \frac{1}{\mathbf{T_{real}}}\right)\right)$$

$$A(t) = \left(\frac{t_o}{t}\right)^{\boldsymbol{\alpha}}$$

- *fib* method assumed to be calibrated to account for cracking

Past Research

- The 1985 Texas Research Report
  - Accelerated Testing (196 days) supports:
    - Local corrosion initiates rapidly in reinforced concrete with 0.015” cracks
    - Local corrosion does not initiate in prestressed concrete with 0.002” cracks
  - Longer duration testing to verify or refute either Theories A or B not undertaken
  - Does not provide guidelines for determining service life

Past Research

- The 2014 Textbook, *Design of Durable Concrete Structures*, gives the following references on cracking and concrete durability:
  - 12 research reports/projects (1972 to 2010)
  - 2 documents (1997 & 2009) summarizing findings of research reports
  - "Although body of research is quite extensive, there are significant differences in the findings, some of which are potentially conflicting."

Past Research – Otieno (2009)

- Crack width (at surface or level of reinforcing)
- Crack spacing / frequency
- Depth of crack (does it reach reinforcing)
- Shape of crack (wedge-shaped or parallel sides)
- Orientation of crack (parallel or perpendicular to reinforcing)
- Self healing (maximum width crack that can undergo self healing)
- Whether crack is active (changing width) or dormant (constant width) over time

Past Research – Cape Town, South Africa (2007-2010)

- Corrosion initiation almost instantaneous in presence of cracks
- Available models may overestimate service life
- For constant cover, corrosion rate increases with width of crack
- For constant surface crack width, corrosion increases with decreasing cover

Past Research – Cape Town, South Africa (2007-2010)

- Corrosion can be reduced by higher quality concrete – lower water/cement ratio, use of fly ash and slag
- Concretes made with fly ash and slag less sensitive to effects of cracking than for ordinary Portland cement
- Blended cement concretes have high resistivity which reduces the corrosion rate

Summary

- Effects of cracking on durability has been debated for many years
- Currently no universally accepted scientific methods to address cracked concrete durability
- We could:
  - – Require prestressing to eliminate cracks in all concrete components, **or**
  - – Design all concrete by the Avoidance of Deterioration Method (using Stainless Steel)
- These solutions not fully practical or economical

Summary

- Another possible path is:
  - Delaying implementation of **Service Life Design** until sufficient research is completed to address cracking
  - With no in-place design process, this approach would not likely promote research
  - **Service Life Design** may not be implemented in a timely manner (if at all)
- This solution is not desirable

Summary

- A better approach is to:
  - Continue adopting **Service Life Design**
  - Monitor and collect data on durability performance behavior of cracked concrete
  - Promote research to develop potential modifications to the current chloride ingress deterioration model
    - e.g., higher chloride migration coefficients to account for cracked sections

Questions?

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