Cyclic life of cracked crossties exposed to water

An investigation of post-tensioned crossties and leaching in concrete

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NURail Center

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Outline

- Introduction
  - Motivation
  - Previous results
- Laboratory investigation
  - Material damage hypotheses
    - Leaching experiments
  - Crosstie failure hypotheses
    - Bond loss experiments
- Conclusion
  - Summary
  - Next steps

Motivation

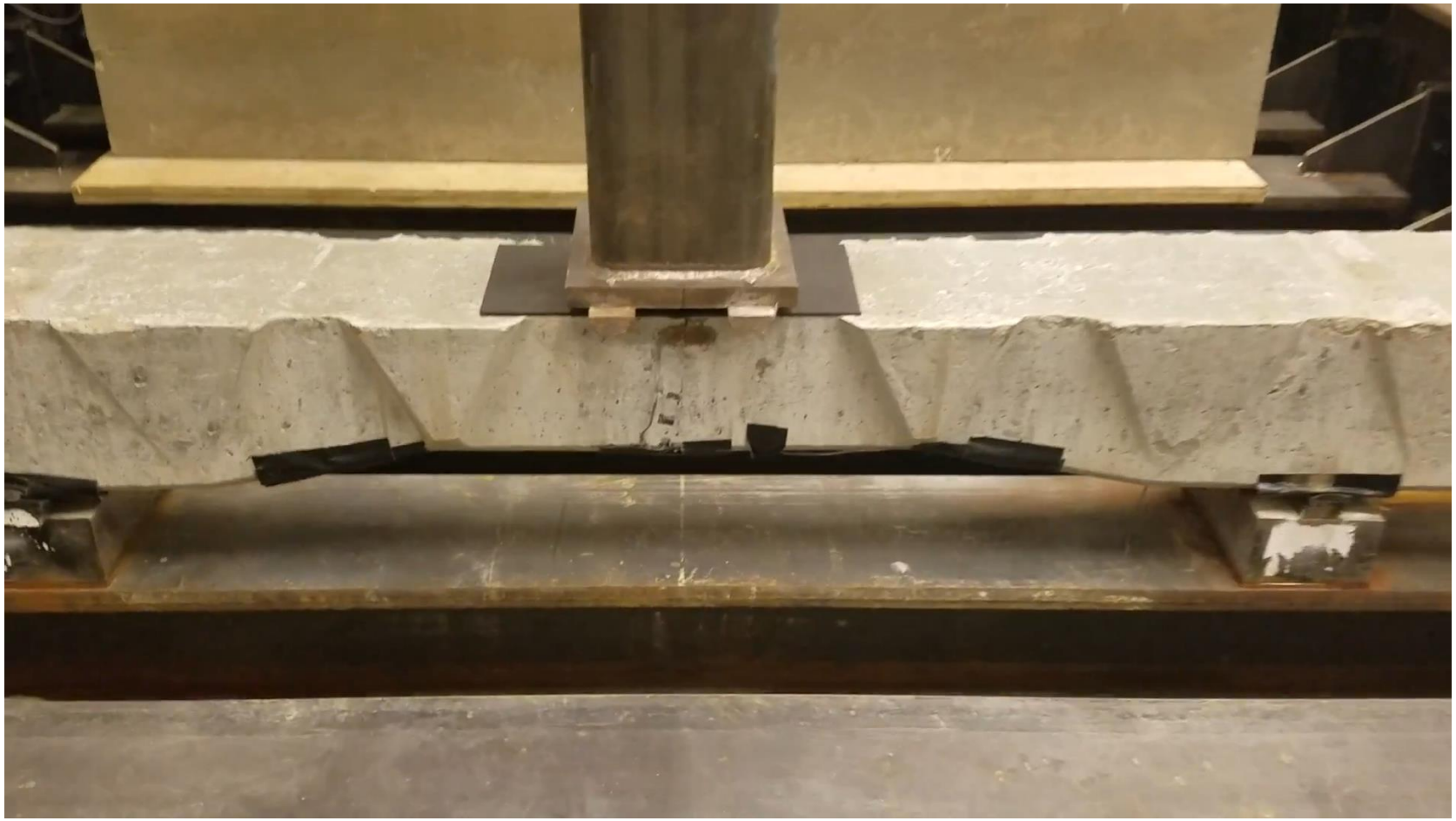
Is water detrimental to concrete crosstie service life?




- Is water accelerating concrete damage?
- Is material damage reducing the crosstie structural capacity?

Review – Dry sleeper at 70% of capacity

No failure after 11 million cycles (infinite life)



Note: 70% of ultimate capacity corresponds to 1.3 times the cracking load

Review – Wet crosstie at 70% of capacity

Test with periodic water spray (1h *on*, 5h *off*)

Note: 70% of ultimate capacity corresponds to 1.3 times the cracking load

Review - Pretensioned crosstie results

- 6 crossties of same design cyclically loaded to 70% of capacity
  - 2 Dry: 11 million cycles with no failure *(infinite life)*
  - 2 Constant water spray: 1.01 and 1.68 million cycles
  - 2 Periodic spray: 0.57 and 1.56 million cycles

Constant water spray test

Periodic water spray test

- 2 other crosstie designs showed similar trends (shakedown tests)

Material damage hypotheses

Does in-crack water cause material damage?

no

End of investigation

yes

Why?

Working hypotheses

Bursting due to high in-crack water pressure

Measure pressure

Leaching of concrete (chemical reaction)

Eliminate leaching

Today's focus

Abrasion from water flow and fines

Eliminate water flow

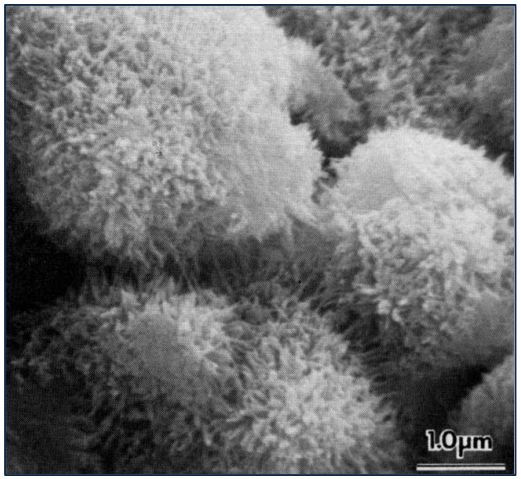
Cavitation due to pressure drop

Assess frequency effect

Concrete composition review

- Cement Chemist Notation (CCN)

CCN	Actual formula	Name
C	CaO	Lime
S	SiO_2	Silica
A	Al_2O_3	Alumina
F	Fe_2O_3	"Rust"
H	H_2O	Water



C-S-H as "fuzzy tennis balls"

- Mature cement paste by volume (%)
  - **60** C-S-H*, calcium silicate hydrate → strength builder
  - **20** CH, calcium hydroxide→ pH riser; **soluble, can leach out**
  - **15** C_x(A,F)-H** group
  - **5** unhydrated cement

**dashes mean not stoichiometric*
***(A,F) means either A or F*

Leaching chemistry and kinetics

- Pure or soft water attack
  - CH is dissolved and carried out with flow, increasing porosity

$$\mathrm{Ca(O}H)_2 \rightarrow Ca^{2+} + 2OH^-$$

- Acidic water attack
  - Acid will form salts (efflorescence)
  - Rainwater carries carbonic acid (formed naturally from CO_2)

$$\mathrm{Ca(O}H)_2 + H_2CO_3 \rightarrow CaCO_3(calcium\ carbonate) + 2H_2O$$

- Leaching kinetics
  - Fick's Law (diffusivity)

$$J = D\left(\frac{dC}{dx}\right)$$

$J = mass\ transport\ rate$
$D = diffusion\ coefficient$
$\left(\frac{dC}{dx}\right) = concentration\ gradient$

Leaching consequences

- Consequences of CH leaching
  - Porosity increases
    - Possible reduction of abrasion resistance[1]
    - More ingress of moisture and particles

- Hypothesis for cracked concrete ties under cyclic loading
  - Rainwater quickly initiates CH leaching inside an open crack
  - When crack closes, abrasive flush may remove leached surface
    - Diffusion coefficient remains low
  - More rainwater comes in the next cycle
    - Concentration gradient remains high
  - Thus, leaching may not reduce over time as it would in other structures

[1] C. D. Atiş, "Abrasion-Porosity-Strength Model for Fly Ash Concrete," *J. Mater. Civ. Eng.*, vol. 15, no. 4, pp. 408–410, Aug. 2003.

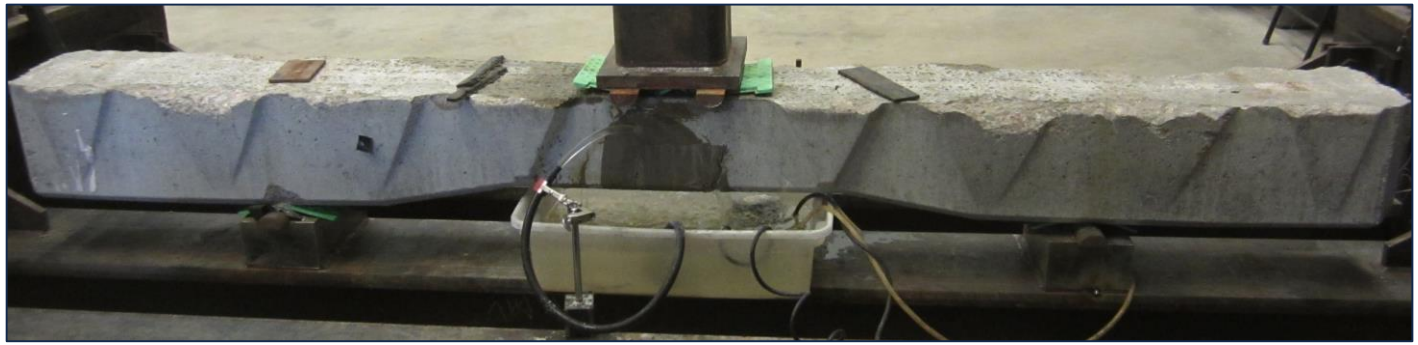
Investigating leaching in the laboratory

- Null hypothesis (H_o)
  - Leaching is a governing degradation mechanism
- Compare cyclic life of specimens in two conditions:
  - Potable water → *leaching*
  - Solution like concrete pore water → *negligible leaching*
    - Water solution with Ca^{2+} at 3 mol/L and pH 12
- If cycles to failure are similar
  - Reject H_o
    (else, fail to reject H_o)

Leaching Investigation results

- Prism cycles to failure
  - Plain water: **18,192** (mean of three results)
  - Pore water solution: **9,557** (one result)
  - Setup: prisms submerged, 4-point bending

- Crosstie cycles to failure
  - Regular water: **1,205,039** (mean of four results)
  - Pore water solution: **892,500** (one result)
  - Setup: constant spray, 4-point bending



- Takeaway: leaching is not a leading degradation mechanism

Component failure hypotheses

Do cracked crossties fail sooner when moisture is present?

no

End of investigation

yes

Why?

Working hypotheses

Loss of bond increases compressive stresses

Monitor strain/ Use post-tensioned ties

Today's focus

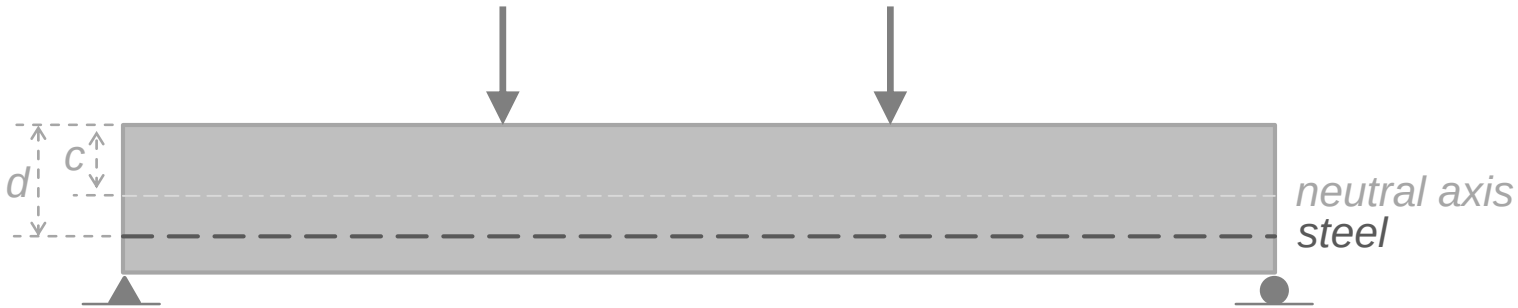
Collapse due to corrosion volume change

Look for evidence of rust

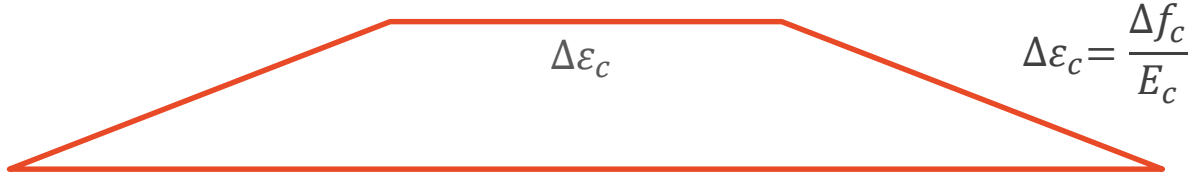
Reduced fatigue endurance limit underwater

Consider cyclic life as a function of load level

Concrete strain in 4-point bending

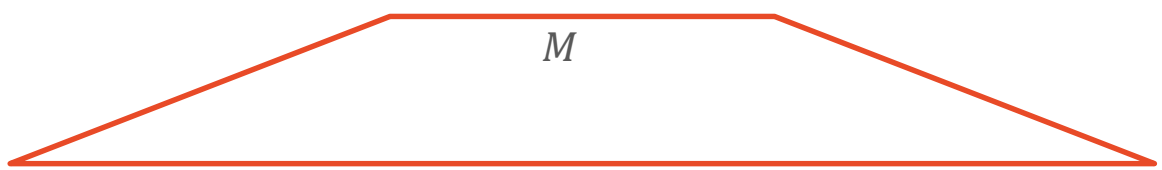


concrete strain at steel level

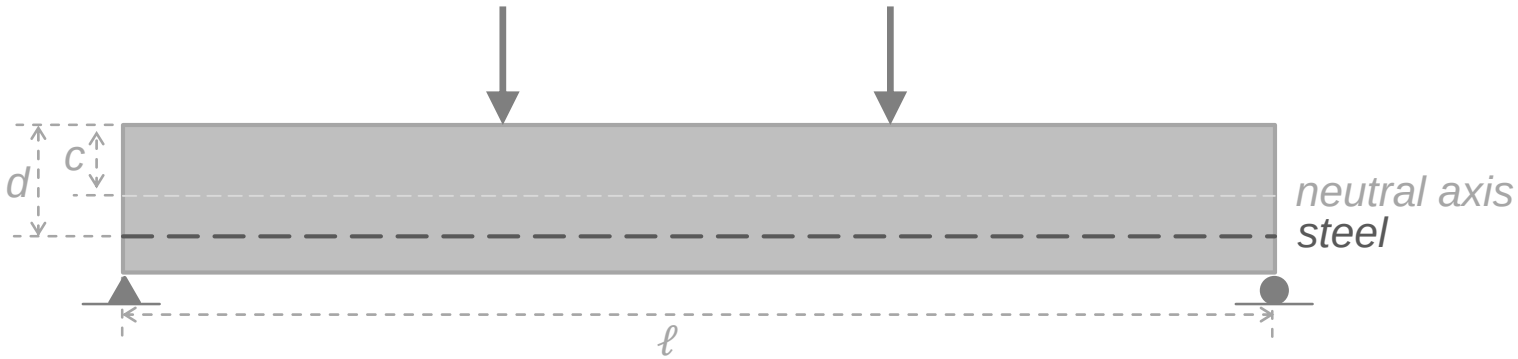


$$\Delta\varepsilon_c = \frac{\Delta f_c}{E_c} = \frac{M(d-c)}{E_c I}$$

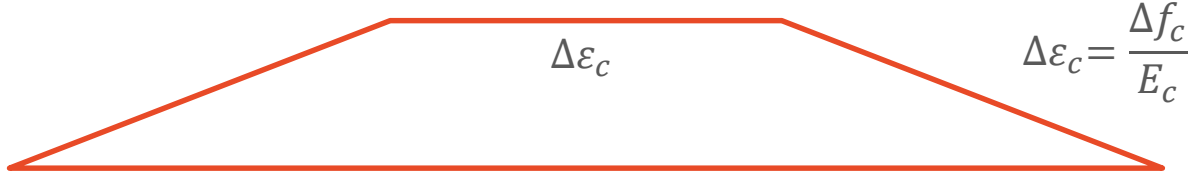
external moment



Steel strain in 4-point bending



concrete strain at steel level



$$\Delta\varepsilon_c = \frac{\Delta f_c}{E_c} = \frac{M(d-c)}{E_c I}$$

relationship concrete-steel

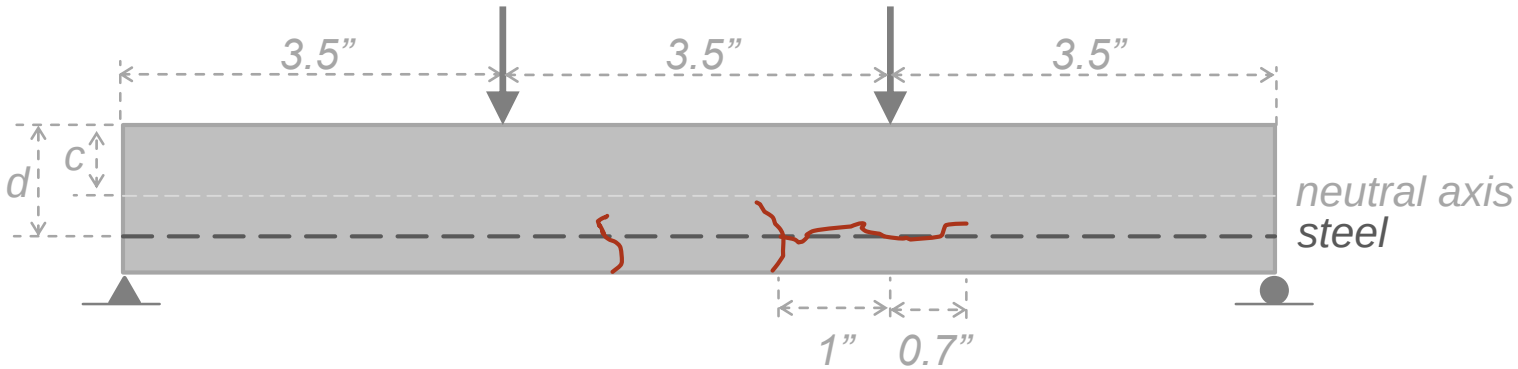
$$\text{Bond exists?} \begin{cases} \text{Yes} \rightarrow \Delta\varepsilon_s = \Delta\varepsilon_c \\ \text{No} \rightarrow \Delta\ell_s = \Delta\ell_c \end{cases}$$

(same total elongation)

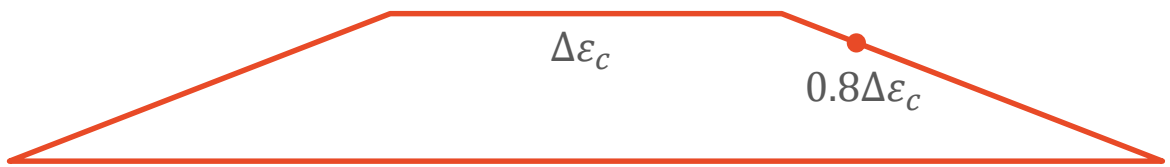
steel strain without bond

$$\Delta\varepsilon_s = \frac{\Delta\ell}{\ell}$$

Steel strain with longitudinal crack



concrete strain at steel level



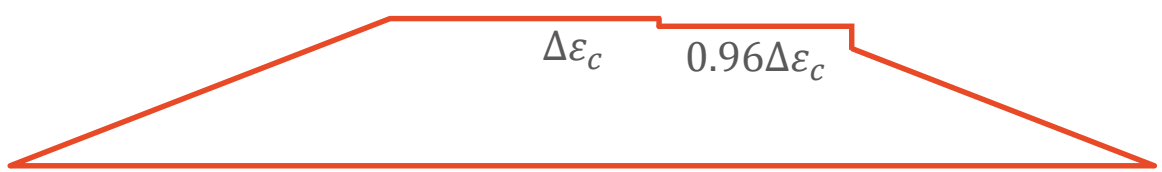
elongation at crack

$$\Delta\ell = \Delta\varepsilon_c \times 1" + 0.9\Delta\varepsilon_c \times 0.7" = \Delta\varepsilon_c \times 1.63"$$

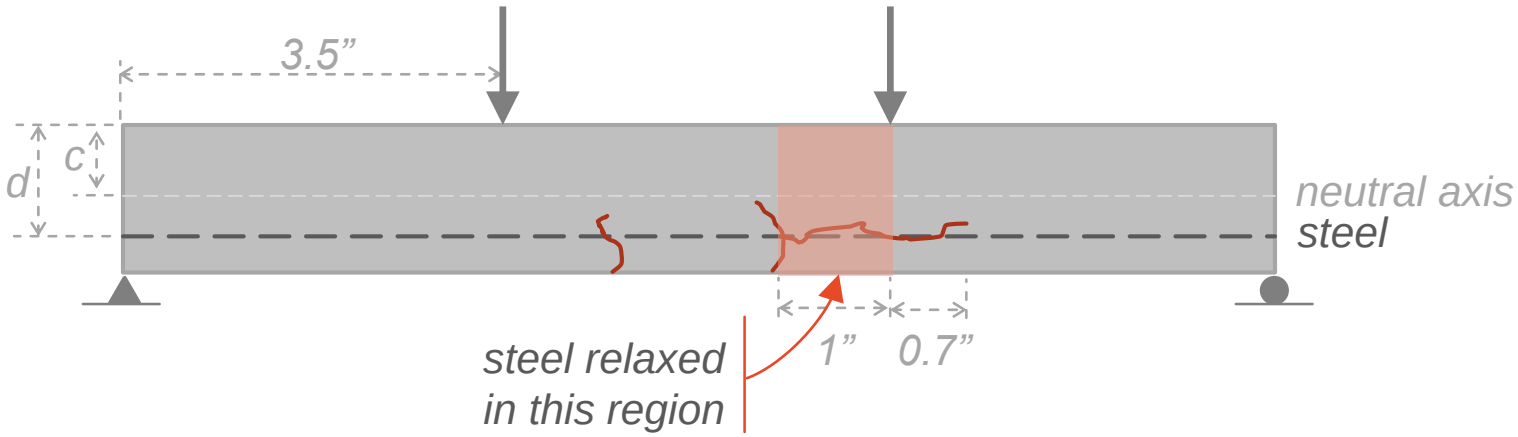
steel strain along crack

$$\Delta\varepsilon_s = \frac{\Delta\ell}{\ell} = \frac{\Delta\varepsilon_c \times 1.63"}{1.7"} = 0.96\Delta\varepsilon_c$$

steel strain (hypothesized)



Longitudinal crack consequences



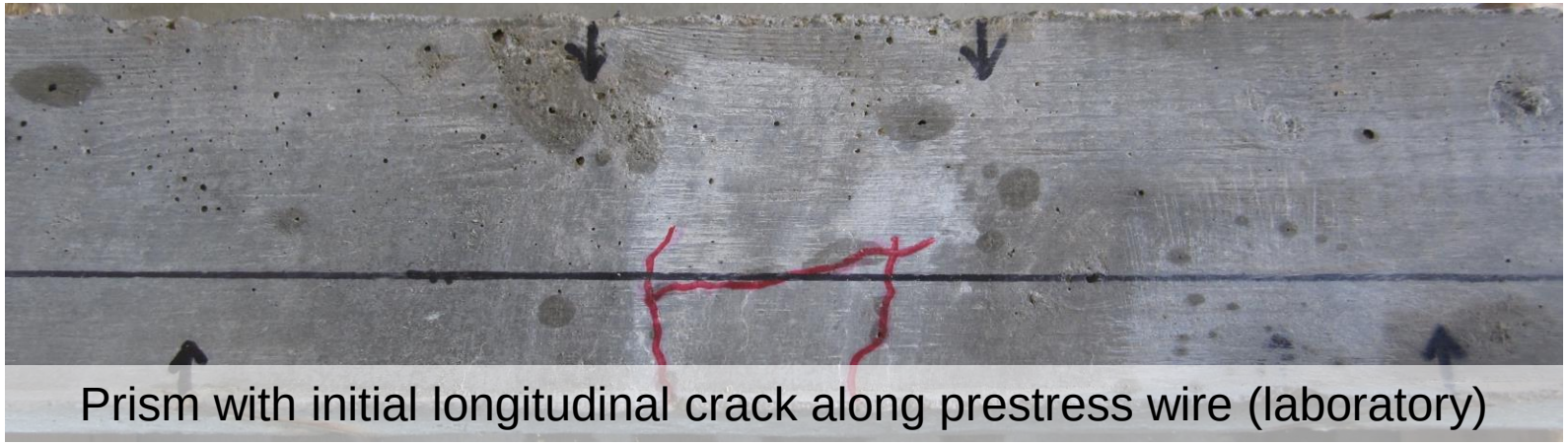
- Cracking raises concrete stress due to steel relaxation (hypothesis)
  - Tension forces may drop where bond is lost
  - But the external load must be resisted
  - More deformation will be necessary to stress steel again
  - This will increase concrete stresses
  - Ultimately, fatigue life will be reduced

Do longitudinal cracks really happen?

Prism with initial longitudinal crack along prestress wire (laboratory)

Video of longitudinal crack in crosstie under load (field)

Do longitudinal cracks really happen?



Prism with initial longitudinal crack along prestress wire (laboratory)

Video of longitudinal crack in crosstie under load (field)

Investigating bond loss in the laboratory

- Null hypothesis (H_o)
  - Loss of bond reduces flexural capacity, even if only in tensile region

- Compare cyclic life two crosstie types:
  - Pretensioned → *bond loss possible*
  - Post-tensioned, unbonded → *bond loss not possible*

- If cycles to failure are similar
  - Reject H_o
    (else, fail to reject H_o)

Bond investigation results

- 6 **pretensioned** crossties loaded to 70% of capacity (review)
  - 2 Dry: 11 million cycles with no failure *(infinite life)*
  - 4 Water spray: all less than 2 million cycles

- 2 **post-tensioned** crossties loaded to 70% of capacity
  - 1 Dry: 10 million cycles, no failure *(infinite life)*
  - 1 Constant water spray: 10 million cycles, no failure *(infinite life)*

longitudinal crack

Summary

- Presence of water in cracks appears to decrease cyclic life
- Leaching does not seem to be a governing degradation mechanism
- Loss of bond seem to reduce flexural capacity of crossties that rely on bond, even if only in tensile region
- Concrete ties that rely on bond will likely have a shorter service life in high precipitation areas when cracked

Acknowledgements

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BNSF RAILWAY

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LBFoster CXT Concrete Ties

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TTX

Thank you for your attention!

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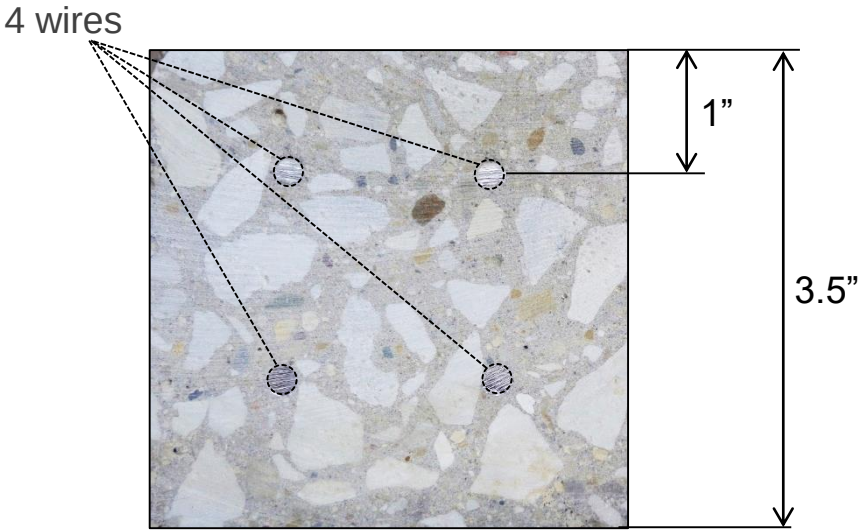
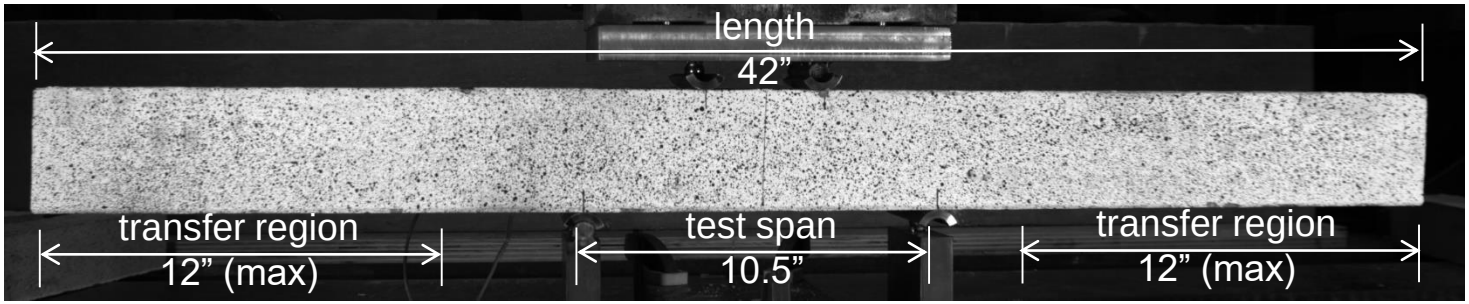
APPENDIX

More on cyclic loading and water interaction

Lab experimentation – prism review

- Scaled specimens timeline
  - 14 Sep 2017 - casting
  - 19 Sep 2017 - wires release
  - 18 Oct 2017 - first test
- Similar design used at KSU [2]
  - 3.5” x 3.5” with 4 wires
  - Volumetric ratio of crosstie
- Testing out of transfer region
  - Length 42”, Test span 10.5”
  - Transfer length < 12” [1]



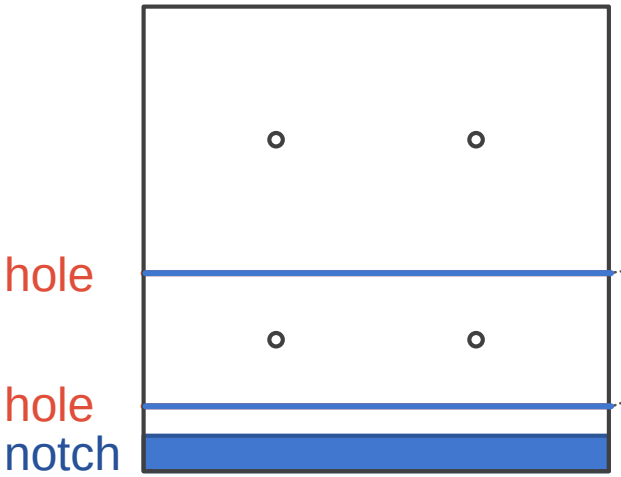


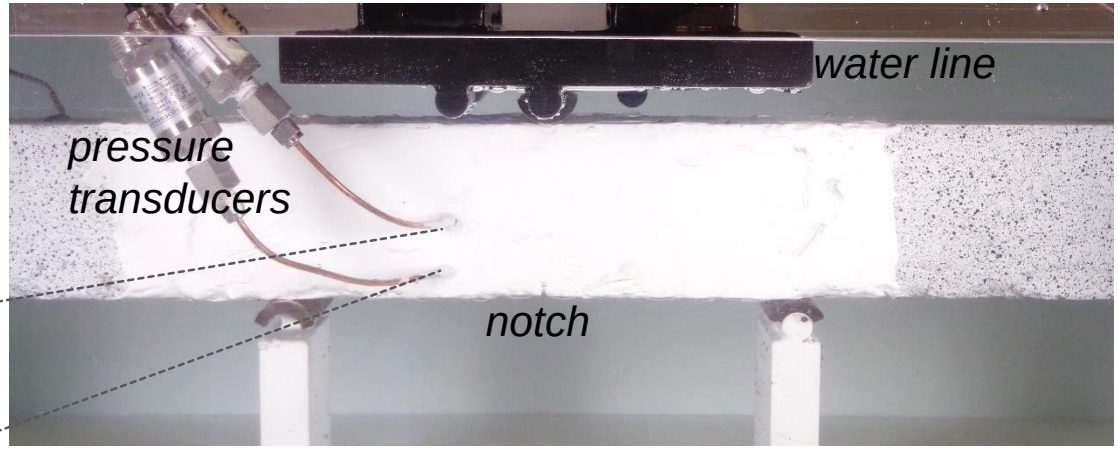
[2] Bodapati, N.N.B., W. Zhao, R.J. Peterman, C.-H.J. Wu, B.T. Beck, M. Haynes and J.R. Holste. 2013. Influence of Indented Wire Geometry and Concrete Parameters on The Transfer Length in Prestressed Concrete Crossties. In: *2013 Joint Rail Conference*, April 2013.

Prisms for water pressure analysis

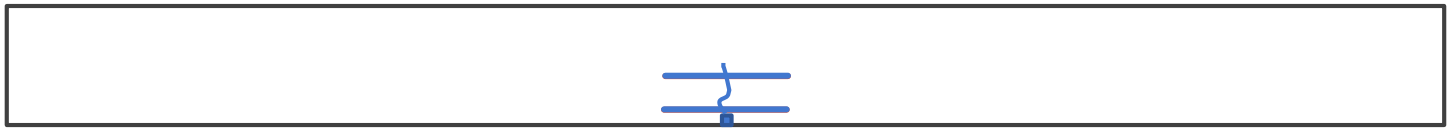
- **Precast holes:** provides means to measure induced hydraulic pressure
- **Precast notch:** attempt to force single crack to intersect with holes

Cross section

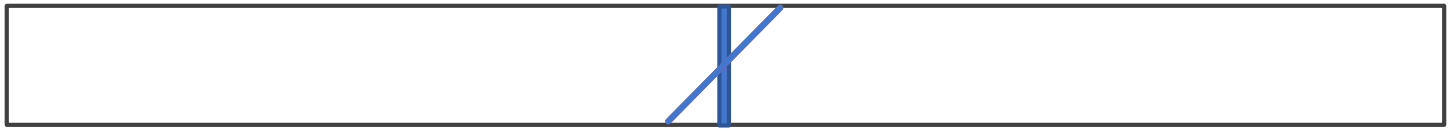




Profile view

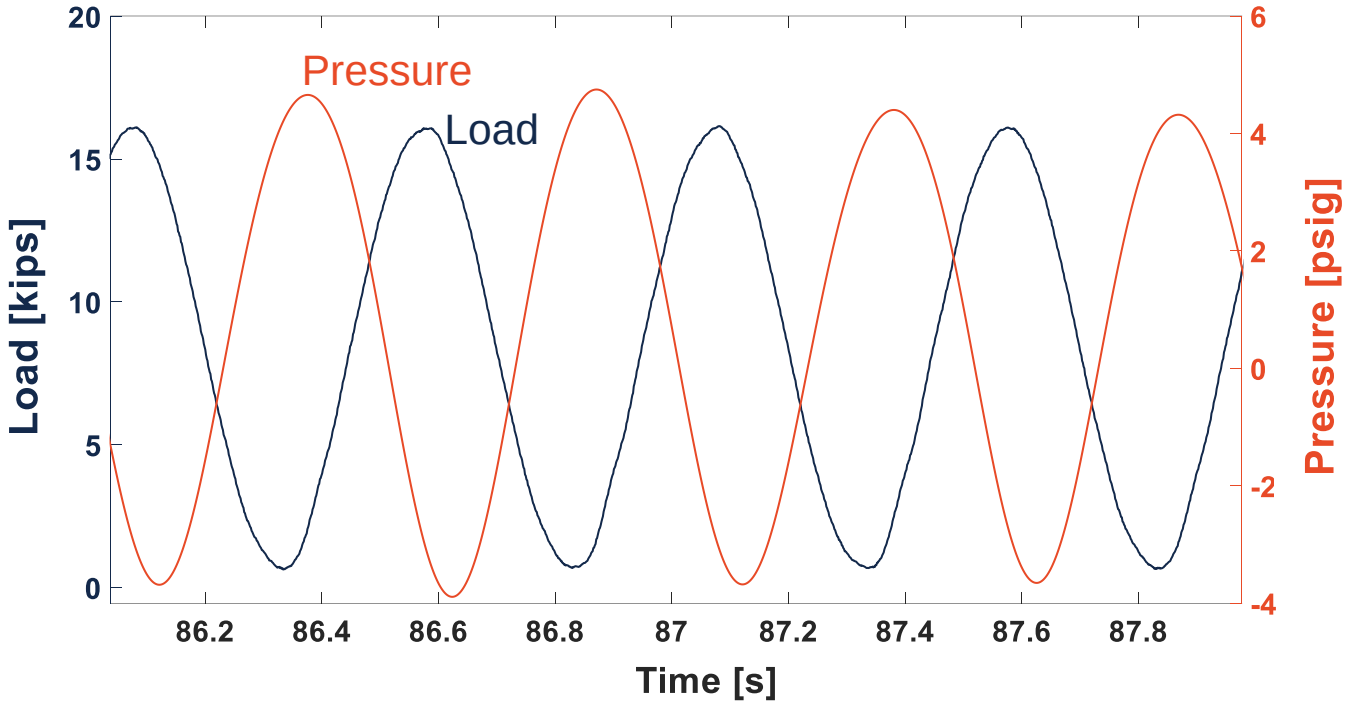


Plan view



Results: water pressure in crack (cont.)

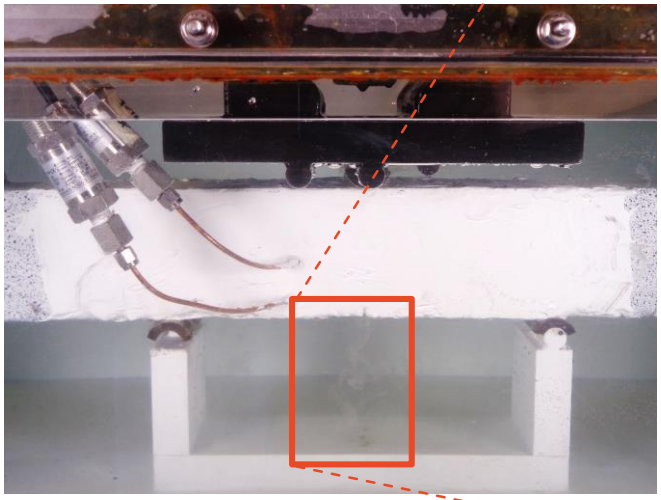
- Pressure and load out of phase
  - High load opens crack and causes pressure to drop
  - Low load closes crack and causes pressure to rise

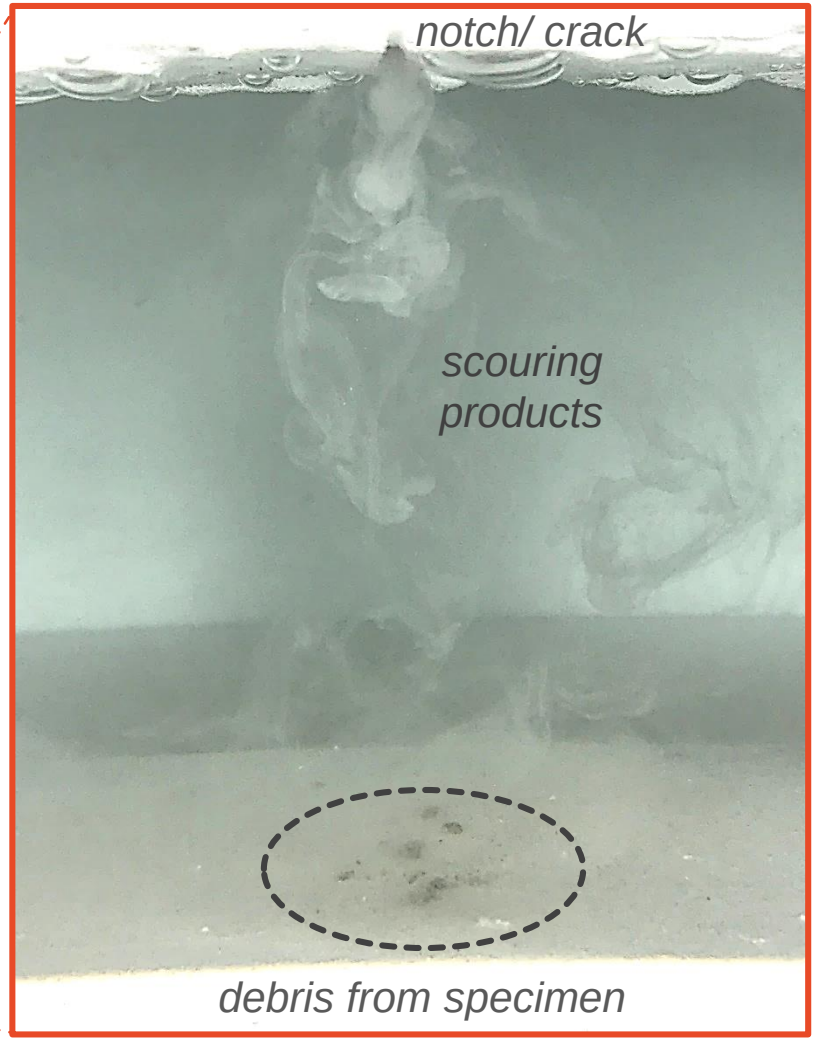


- Pressures are too low to cause tensile fracture
  - Concrete tensile strength concrete: **700 psi**
    (two orders of magnitude away from top pressures)

Why does water accelerate deterioration?

- How is water causing damage?
  - Water pressure too low
- Alternative hypotheses
  - Material properties changing [3,4]
  - Abrasion





[3] Bruhwiler, E. and V.E. Saouma. 1995a. Water Fracture Interaction in Concrete – Part I: Fracture Properties. *Materials Journal*, 92(3): 296–303.

[4] Bruhwiler, E. and V.E. Saouma. 1995b. Water Fracture Interaction in Concrete – Part II: Hydrostatic Pressure in Cracks. *Materials Journal*, 92(4): 383–390.

Static loading of prisms in water

Ultimate capacity results

- Prisms take lower load underwater
  - Air = 30.5 kips, Water = 25.1 kips