Outline

- Three main concrete tie failure modes studied at Volpe Center
  - Prestress cracks
  - Flexural cracks
  - Rail seat deterioration
- Approach
- Results
- Future work/research needs
- Acknowledgements
Cracking Related to Prestresses


(Source: NDT Corporation.)
Flexural Cracks

Rail seat cracking

Center bound cracking

(Source: Zeman, J. C., Hydraulic Mechanisms of Concrete-Tie Rail Seat Deterioration, M.S. Thesis, University of Illinois at Urbana-Champaign, 2010.)
Finite Element Model of Concrete Tie Components

- Steel reinforcement
- Concrete
- Steel-concrete interface
Concrete Damaged Plasticity

- Uniaxial tension: linear elasticity followed by tension stiffening
- Uniaxial compression: linear elasticity followed by strain hardening and strain softening
- Multi-axial yield function
- $d_t$ – tensile damage variable
- $d_c$ – compressive damage variable
Interface Micromechanics
Homogenized Interface Model

\[ \sigma, u_n \]

\[ \tau, u_t \]

Concrete

Reinforcement

\[ |\tau| = \sqrt{\tau_s^2 + \tau_t^2} \]
Elastoplastic Bond Model

- Interface stresses
  \[ \sigma = \sigma n + \tau_1 s + \tau_2 t \quad |\tau| = \sqrt{\tau_1^2 + \tau_2^2} \]

- Interface displacements
  \[ u = u_n n + u_{t1} s + u_{t2} t \quad u = u^{el} + u^{pl} \]

- Elasticity
  \[ \sigma = D^e u^{el} = D^e \left( u - u^{pl} \right) \]

- Yield surface
  \[ F(\sigma, \tau) = 0 \]

- Plastic flow
  \[ du^{pl} = d\lambda \frac{\partial Q}{\partial \sigma} \]
Adhesive-Frictional Bond Model for Smooth Wire
Bond Model Calibration

- Untensioned pullout tests
- Pretensioned prism tests
Bond Model Validation with Concrete Ties Made in Plant
Transfer Length in Concrete Ties with Smooth Wire: Test vs. FEA

![Graph showing transfer length in concrete ties with smooth wire: test data compared to simulation results for different concrete strengths. The graph includes data for 95% AMS and ZL conditions.]
Stresses upon Pretension Release and under Rail Seat Loading (Well Supported)

Deformation scale factor = 100
AREMA Center Negative Moment Test

\[ P = \frac{2M}{27'' \text{ (or } 686 \text{ mm)}} \]

THE FOLLOWING FORMULA SHALL BE USED TO DETERMINE THE VALUE OF \( P \)

1" x 1/2" (25.4 x 12.7 mm) WIDTH OF TIE RUBBER SUPPORT (50 DUROMETER A SCALE)

2" x 1" (50.8 x 25.4 mm) WIDTH OF TIE RUBBER SUPPORT (50 DUROMETER A SCALE)
Center Binding Condition with Assumed Deteriorated Ballast Support

- **Stiff**
  - $E=60,000$ psi
  - $\sigma_y=120$ psi

- **Weak**
  - $E=10,000$ psi
  - $\sigma_y=20$ psi

- **Medium**
  - $E=30,168$ psi
  - $\sigma_y=58$ psi

$\Delta h$
Static Analysis

- Two-step simulation
  - Pretension release
  - Center binding

- Simulated center binding scenarios
  - AREMA test
  - Deteriorated ballast support with $\Delta h=0.5$ in.

- Eight-strand concrete tie
  - Concrete compressive strength: 7,000 psi
  - Homogenized, frictional steel-concrete interface

- Calculation of equivalent wheel load assumes that a rail seat carries 50% of wheel load

- Average rail seat displacement calculated relative to tie center displacement
Center Bound Cracks: AREMA Test vs. Deteriorated Ballast Support
Force-Relative Displacement: AREMA Test vs. Deteriorated Ballast Support

Equivalent wheel load (kip) vs. Relative rail seat displacement (in.)

- AREMA test
- Deteriorated ballast (\(\Delta h=0.5\) in.)

AREMA specified pass/fail load
Dynamic Analysis

- Import damaged initial state of tie from the static analysis

- Increase max tie-ballast gap ($\Delta h$) to 2.5 in.; the gap under the rail seat is around 1 in.

- Apply dynamic rail seat load according to graph on the right
Concrete Damage Under Dynamic Load

\[ \Delta h = 2.5 \text{ in.} \]
Force-Relative Displacement Relation

Static analysis

\( \Delta h = 0.5 \text{ in.} \)

Dynamic analysis

\( \Delta h = 2.5 \text{ in.} \)

Frame #67, 68 kips

Equivalent wheel load (kip)

Relative rail seat displacement (in.)

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Static analysis \( (\Delta h = 0.5 \text{ in.}) \)
Dynamic Analysis

- Import damaged initial state of tie from the static analysis
- Apply dynamic rail seat load according to graph on the right
- Vary the max tie-ballast gap ($\Delta h$): 1.25, 2, and 2.5 in.
Concrete Damage Under Dynamic Load

\[ \Delta h = 2 \text{ in.} \]
Force-Relative Displacement Relation

Dynamic analysis

\( \Delta h = 2.5 \text{ in.} \)

\( \Delta h = 1.25 \text{ in.} \)

\( \Delta h = 2 \text{ in.} \)

\( \Delta h = 2.5 \text{ in.} \)

Static analysis (\( \Delta h = 0.5 \text{ in.} \))
Future Work/Research Needs

- Develop elastoplastic bond models for indented wires/strands
  - Apply in analysis of prestress cracks
- Design tests to characterize the interface normal stress-dilation relations
- Detailed (smaller-scale) interface modeling
Future Work/Research Needs

- Simulate asymmetric, center binding ballast support conditions
- Correlate simulated cracking pattern with field observation and wheel load level
- Verify analysis results with experiments
- Characterize mechanical properties and geometric profile of fouled ballast
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Questions?