Hydraulic Mechanisms of Concrete-Tie Rail-Seat Deterioration

William W. Hay Seminar

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Outline

- Concrete ties
- Rail seat deterioration (RSD)
- Hydraulic mechanisms of RSD
  - Hydraulic pressure cracking
  - Hydro-abrasive erosion
  - Cavitation erosion
- Laboratory experiments
  - Load tests
  - Uplift tests
- Conclusions and tie pad design
- Future concrete tie research at Illinois
Concrete Ties

- Prestressed concrete crossties, part of ballasted track structure
- Basic functions:
  - Support train loads and distribute loads to ballast
  - Stabilize the rails to maintain safe track geometry
  - Electrically isolate the rails for the track circuit
Concrete Ties for Heavy Haul Railroads

- Freight lines with high annual traffic, curvature, and axle loads use concrete ties
- Promising alternative to traditional timber ties
  - Concrete ties have higher initial cost in North America
  - Concrete ties should have longer service life and require less maintenance – lower life-cycle cost
Concrete Tie Failures

Rail Seat Positive Cracking

Center Negative Cracking (Center Binding)

Derailment Damage
Concrete Tie Failures

- Yielded (Sprung) Clip
- Tie Pad Degradation
- Rail Seat Deterioration
## 2008 Survey of Class I Railroads

<table>
<thead>
<tr>
<th>Most Critical Concrete Tie Problems</th>
<th>Average Rank</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rail seat deterioration (RSD)</td>
<td>6.83</td>
</tr>
<tr>
<td>Shoulder/fastener wear or fatigue</td>
<td>6.67</td>
</tr>
<tr>
<td>Derailment damage</td>
<td>4.83</td>
</tr>
<tr>
<td>Cracking from center binding</td>
<td>4.58</td>
</tr>
<tr>
<td>Cracking from dynamic loads</td>
<td>1.83</td>
</tr>
<tr>
<td>Tamping damage</td>
<td>1.83</td>
</tr>
<tr>
<td>Other (ex: manufactured defect)</td>
<td>1.33</td>
</tr>
<tr>
<td>Cracking from environmental or chemical degradation</td>
<td>1.25</td>
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Rail Seat Deterioration (RSD)

- Degradation under the rail on a concrete tie
- Also “rail seat abrasion”
- Leads to track geometry problems and damage of fastening components
- Difficult to detect without lifting the rail
- Increases maintenance costs and shortens service life of the tie
## Causes of RSD

<table>
<thead>
<tr>
<th>Causes</th>
<th>High Stresses at Rail Seat</th>
<th>Relative Motion at Rail Seat</th>
<th>Presence of Moisture</th>
<th>Presence of Abrasive Fines</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Internal Factors</strong></td>
<td>Loss of proper rail cant</td>
<td>Looseness of fastening system (loss of toe load)</td>
<td>Tie pad seal</td>
<td>Tie pad seal</td>
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<tr>
<td></td>
<td>Scrubbing action</td>
<td></td>
<td>Concrete saturation</td>
<td>Fines from wear of rail seat components</td>
</tr>
<tr>
<td><strong>External Factors</strong></td>
<td>High vertical loads</td>
<td>Uplift action</td>
<td>Climate</td>
<td>Environment</td>
</tr>
<tr>
<td></td>
<td>High L/V ratio</td>
<td>Lateral action</td>
<td></td>
<td>Track maintenance</td>
</tr>
<tr>
<td></td>
<td>High longitudinal loads</td>
<td>Longitudinal action</td>
<td></td>
<td>Train operations</td>
</tr>
<tr>
<td></td>
<td>Poor load distribution</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>among adjacent ties</td>
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</table>
## Concrete Deterioration Mechanisms

<table>
<thead>
<tr>
<th>Potential Mechanisms</th>
<th>High Stresses at Rail Seat</th>
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<td>✓</td>
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<tr>
<td>Crushing</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
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<tr>
<td>Freeze-Thaw</td>
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<td>✓</td>
<td></td>
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<tr>
<td>Hydraulic Pressure</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Hydro-Abrasive Erosion</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Cavitation Erosion</td>
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<td></td>
<td>✓</td>
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Hydraulic Mechanisms = Theories

- The hydraulic mechanisms require the presence of moisture between the tie pad and the rail seat
  - Are these mechanisms feasible?
  - If so, how to mitigate these mechanisms?

- **Hydraulic Pressure Cracking** – load creates high pressure that causes tensile cracking in the concrete

- **Hydro-Abrasive Erosion** – load accelerates water and suspended-particles to high velocity, causing wear on the surface

- **Cavitation Erosion** – rail uplift lowers pressure until water cavitates, and the resulting vapor bubbles collapse and damage the surface
Hydraulic Pressure Cracking

- Modeled state of stress:
  - Elastic stress distribution
  - Beam on an elastic foundation
- Modeled pore water pressure as a function of the surface water pressure
- Compare effective stress with tensile strength of concrete (700 psi)

Effective Stress = σ – u
Hydro-Abrasive Erosion

- Erosion rate depends on
  - Velocity of water and suspended particles
  - Angle of impact with the surface
  - Concentration of suspended particles
  - Particle size, shape, and hardness

- Erosion due to high-velocity water or particles
  - Critical water velocity ~ 400 ft/s
  - Critical particle velocity ~ 165 ft/s
  - Particle velocity could be 60-72% of the water velocity
Cavitation Erosion

1. Drop in pressure to vapor pressure (-14.3 psig)
2. Air bubbles form (0.5-10 mm diameter)
   - Internal pressure ~ -14.3 psig
     • Unstable
3. Bubbles collapse rapidly
   - Collapse pressure depends on:
     • Initial size of bubble
     • Surrounding water pressure
   - Pressure up to millions of psi
Sealing: Pressure vs. Velocity

• Consider ideal situations in order to frame the problem
  – Water inside a rigid piston chamber
• The applied load transfers energy to the water
  – Water energy is in the form of pressure or velocity
• Bernoulli’s equation for pipe flow:

\[ p + \frac{1}{2} \rho v^2 = \frac{P}{A} \]
Concept behind Laboratory Tests

- Measure water pressure at the rail seat surface in the laboratory
  - Test on blocks of concrete instead of full ties, but maintain full-scale tie pads and loads
  - Measure the potential for wear, not the actual wear
- Treat the load (down-stroke) and uplift (up-stroke) separately
  - **Load Tests:**
    - Hydraulic pressure cracking
    - Hydro-abrasive erosion
  - **Uplift Tests:**
    - Cavitation erosion
Instrumented Concrete Block

Cross-section of the design

Finished block
Tie Pads and Pad Assemblies

- Thermoplastic pads: polyurethane, santoprene rubber, EVA
- Surface geometries: flat, grooved, dimpled, studded
- 2-part or 3-part assemblies contain steel or plastic layer
- Varying compressibility, flexural rigidity, and hardness
Test Setup

Steel-based, plexiglass water tank

100-kip MTS servo-hydraulic actuator,
10 gpm servovalve
Measured force, displacement, acceleration
Load Test Procedure

- Load-control mode
- Variables:
  - Tie pad
  - Max load
    - 20-60 kips
    - 20-kip static rail seat load
  - Waveform
    - Loading rate
Pressure vs. Load, All Trials

- Flexible Pads
- Semi-rigid Pads
- Pad Assemblies, Rigid Layer

Applied Load (kips) vs. Maximum Surface Pressure (psig)
Pressure vs. Cycles, Flexible Pads, 40 kips

![Graph showing peak water pressure vs. load cycle for different types of pads: Grooved Polyurethane Pad, Flat Polyurethane Pad, and Dimpled Santoprene Pad.](image-url)
Concrete Damage Limits, 40 kips

Pore Pressure, $u$ (psig)

Strength limit, surface pressure

Strength limit, pore pressure

Family of pore pressure curves, based on surface pressure

Fatigue Limit

Strength Limit
Damage Limits and Mean Regression Lines

Maximum Surface Pressure (psig)

Applied Load (kips)

$P = \frac{P}{A}$

Flexible

Semi-Rigid

Fatigue Limit

Strength Limit

Pad Assemblies
Damage Limits and Load Cycle Envelopes, 40 kips

- Strength Limit
- Mean load-pressure value
- Fatigue Limit
- Fatigue cycles per train

- Flexible Pad, Constant
- Flexible Pad, Full Loss
- Flexible Pad, Partial Loss

Peak Water Pressure (psig)

Load Cycle
Sensitivity of Fatigue Limit, Mean Pressure

Maximum Surface Pressure (psi) vs. Applied Load (kips)

- Unsaturated, 10,000-psi Concrete
- Unsaturated, 7,000-psi Concrete
- Saturated, 7,000-psi Concrete
- 20% Confinement Reduction

Flexible
Semi-Rigid
Fatigue Limits
Pad Assemblies
Sensitivity of Strength Limit, Upper 95% Pressure

- Unsaturated, 10,000-psi Concrete
- Unsaturated, 7,000-psi Concrete
- Saturated, 7,000-psi Concrete
- 20% Confinement Reduction

Strength Limit

- Flexible
- Semi-Rigid
- Pad Assemblies

Maximum Surface Pressure (psig) vs. Applied Load (kips)
Estimations of Fatigue Damage Potential

- Assumptions:
  - 100-MGT line
  - 120-car coal trains
  - 286-kip gross car load
  - 7,000-psi concrete
  - Saturated concrete 50 days of the year
  - Wet, unsaturated concrete 100 days of the year
- Worst-case pad: grooved polyurethane
  - Flexible pad = high pressure
  - No loss of pressure with load cycles
- 2003 WILD distribution: 14 years to 1 million fatigue cycles
- 2008 WILD distribution: 182 years to 1 million fatigue cycles
Theoretical Water Velocity from Mean Pressure

\[ v = \sqrt{\frac{2P}{\rho}} \left( \frac{1}{A} - p \right) \]

Water velocity from Bernoulli’s equation

Critical Water Velocity

\[ v = \sqrt{\frac{2P}{\rho A}} \]

Applied Load (kips)

Theoretical Water Velocity (ft/s)

Pad Assemblies

Semi-Rigid

Flexible
Potential for Hydro-Abrasive Erosion

Particle velocity scaled from water velocity

\[ v = 0.72 \sqrt{\frac{2P}{\rho A}} \]

\( P \) = Applied Load (kips)
\( A \) = Pad Assemblies
\( \rho \) = Density

Critical Particle Velocity

Theoretical Particle Velocity (ft/s)

Applied Load (kips)
Conclusions from the Load Tests

- Hydraulic pressure cracking is feasible; effectively mitigate with
  - Tie pad that does not seal water
  - Low frequency of high impact loads
  - High-strength, air-entrained, low permeability concrete
- Hydro-abrasive erosion appears to be feasible
  - Would mitigate with a sealing tie pad
    - Conflicts with mitigation of hydraulic pressure cracking
  - Needs further study before recommendations can be made
Uplift Test Procedure

- Position-control mode
- Variables:
  - Tie Pad
  - Uplift
    - 0.03” to 0.09”
  - Waveform
- Displacement rate

![Graphs showing position, acceleration, and pressure over time with rebound peaks indicated.]
Suction and Cavitation Potential

Peak Surface Pressure (psig)

-21 -18 -15 -12 -9 -6 -3 0

Tie Pads


Absolute Vacuum Error Range Error Range
Rebound Pressure and Collapse Pressure

Max Peak Rebound Pressure (psig)

Min. Peak Suction (psig)

Flexible Pads
Semi-Rigid Pads
Pad Assemblies, Rigid Layer
Cavitation Erosion Potential

Talbot equation predicts that uplift stroke lasts $1E-01$ s for 60-mph train

- All bubbles collapse before the wheel load
- Bubble radius limited by tight space

Rayleigh Time to Collapse (s)

Bulk Water Pressure (psia)
Cavitation Erosion Potential (cont.)

Due to rapid collapse, bulk water pressure \( \leq \) atmospheric pressure

- Bulk Water Pressure (psi)
- Transducer should fail at \( \geq 270 \) psia*
- Rebound peaks \(< 100 \) psia

*Transducer did not fail

\[ 1E-1, 1E, 1E+1, 1E+2, 1E+3, 1E+4, 1E+5, 1E+6, 1E+7, 1E+8, 1E+9 \]

\[ 0.1, 1.0, 10.0, 100.0, 1,000.0, 10,000.0 \]
Conclusions from the Uplift Tests

- Cavitation erosion appears to be an infeasible RSD mechanism
  - Cavitation may occur in the rail seat surface water
    - Can prevent with tie pads that do not seal water
      - Same conclusion for hydraulic pressure cracking
  - Analysis and results suggest that collapse pressure will not damage the concrete
    - Bubbles are too small and collapse too rapidly
Revised Understanding of RSD

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Conclusions Related to Pad Design

• The sealing potential of a tie pad or assembly depends on
  – Tie pad material properties and surface geometry
  – Clip toe load
  – Uniformity of rail seat surface
• To prevent sealing and the potential for hydraulic pressure use
  – Pad assembly with rigid layer, preferably hard plastic bottom
  – Thermoplastic pad in contact with rail seat should have escape channels for water
• Balance hydraulic considerations with abrasion/erosion mitigation
  – Intrusion of moisture and abrasive fines
    • Better to have flow in and out rather than risk trapping the moisture?
  – Pad durability and stiffness
Remaining Questions

• How much could hydro-abrasive erosion contribute to RSD?
  – Appears to be a feasible mechanism
  – Would have to measure velocity and wear in another setup

• How much of a seal do tie pads produce on a fully assembled concrete tie?
  – Different sealing potential than with the laboratory blocks?
  – Measure intrusion of moisture and fines under different conditions
Future Concrete Tie Research at Illinois

- Full-scale abrasion tests on concrete ties
- Fastening system design
  - Load path
  - Elasticity and damping
- Simple abrasion tests with polymers and abrasive slurry
- Characterize the demands on insulators
- Effects of curing techniques on global and local concrete properties
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- **Data Analysis:** Samantha Chadwick, Mark Dingler, Mauricio Gutierrez-Romero, Katie Lenzini
Questions?
Sample WILD Distributions

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<tr>
<td>0-25</td>
<td>80.932%</td>
<td>94.210%</td>
</tr>
<tr>
<td>25-35</td>
<td>12.383%</td>
<td>4.692%</td>
</tr>
<tr>
<td>35-45</td>
<td>4.500%</td>
<td>0.944%</td>
</tr>
<tr>
<td>45-55</td>
<td>1.586%</td>
<td>0.135%</td>
</tr>
<tr>
<td>&gt;55</td>
<td>0.599%</td>
<td>0.018%</td>
</tr>
</tbody>
</table>

Sample size: 0.03 million

59.6 million
Sample Calculations for Fatigue Damage Potential

\[
\text{Daily Traffic} = \frac{(100 \times 10^6 \text{ tons year}) (2 \text{ kips ton})}{(120 \text{ cars train})(286 \text{ kips car})(365 \text{ days year})} = 16 \text{ trains day}
\]

\[
\text{Annual Load Cycles} = (120 \text{ cars train})(4 \text{ axles car})(1 \text{ cycle axle})(16 \text{ trains day})(365 \text{ days year}) = 2.8 \times 10^6 \text{ cycles year}
\]

\[
\frac{\text{fatigue cycles}}{\text{year}} = \text{load cycles} \left[ \sum_{i=1}^{2} P(\text{moisture}_i) \sum_{j=1}^{5} P(\text{load}_j) \left( \frac{\text{fatigue cycles}}{\text{load cycle}} \right)_{ij} \right]
\]

2003 WILD:
Grooved Poly.: \[2.8 \times 10^6 \left[ 0.14(0.06 + 0.03 + 0.01) + 0.27(0.03 + 0.01) \right] = 69,400 \text{ fatigue cycles year}\]

\[
\text{Time to 1 million cycles} = \frac{1 \times 10^6}{69,400} = 14 \text{ years}
\]

2008 WILD:
Grooved Poly.: \[2.8 \times 10^6 \left[ 0.14(.94% + .14% + .02%) + 0.27(.14% + .02%) \right] = 5,500 \text{ fatigue cycles year}\]

\[
\text{Time to 1 million cycles} = \frac{1 \times 10^6}{5,500} = 182 \text{ years}
\]