Timber Crosstie Spike Failures:

Overview, Loading Demands, and Mitigation Considerations

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Acknowledgements

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► Wheel and Rail Seat Loads – Field Results
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  • Lateral
  • Longitudinal
► TTC Results
  • Test vs Control
► Spike Stress Mitigation Methods - Modeling
  • Screw vs Cut
  • Plate Clamping Force
  • Spike Engagement
► Preliminary Recommendations for Mitigating Spike Failures
Background on Spike Failures

► Spikes have been failing due to fatigue
  • Primarily on *premium fastening system*
  • Often *new ties*
  • Mainly on *curves*
  • Also in *special trackwork*

► Driven by overloading mechanism

Traditional System with Anchor

- Longitudinal Rail Seat Load
  - Rail-Plate Friction
    - Plate
    - Plate-Tie Friction
    - Spikes
    - Rail Anchor
      - Crosstie
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  • Also in *special trackwork*

► Driven by overloading mechanism

► Leads to rapid gauge deterioration causing at least 10 derailments since 2000

Likely Driving Factors

► *Lack of anchor increases longitudinal loads*
  • Wood is weaker in this direction
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Likely Driving Factors

- *Lack of anchor increases* longitudinal loads
  - Wood is weaker in this direction

- *Plate uplift* further increases loads

- Stiffer fasteners reduce distribution of loads

- Crosstie age
Stress in Spikes – Hypothetical Graph

Total Stress into Spikes

Threshold Stress for Spike Failure

Traditional Systems | Premium Systems

- Longitudinal
- Lateral

Anchor Tangent Flat | Anchor Curve Grade | Anchor Curve Grade | No Anchor Curve Grade | Anchor Curve Grade (extreme case)

- Longitudinal
- Lateral

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Project Thrust Areas

**Laboratory**
Controlled experiments to better characterize load transfer and rail displacement/slip of various fasteners

**Analytical Modeling**
Quantification of load distribution and spike stress while investigating key factors affecting load transfer

**Field**
Quantification of loading demands (vert., lateral, long.) and fastener response to service loading
Thrust Area Interaction

A. Lab ↔ Field:
   • Field data can inform lab loading magnitude
   • Controlled experiments can challenge/replicate field data and inform future field work

B. Field → Model:
   • Field provides load input for model

C. Lab ↔ Model:
   • Lab provides data for calibration of models
   • Model helps to focus lab experiments

D. Provides opportunity to make comprehensive recommendations
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Field Experimentation Motivation

High Level Outcomes

Data acquisition through field experimentation allows for

► Quantification of Loading Environment
  • Improve our understanding of the load demands placed on the fastening systems as a result of passing trains

► Evaluation of Fastening System Response
  • Improve our understanding of the characteristic stiffnesses, deformations, and displacements as demands/conditions (loading, weather, etc.)

► Development of Analytical Model
  • Validate a three dimensional (3D) finite element (FE) model
  • Compare data with laboratory results
Field Experimentation Overview

Horseshoe Curve

► 3-track curve in Norfolk Southern’s Pittsburgh line
► Westbound track has primarily **uphill empty** trains (45.6 MGT)
  • Tractive effort is distributed throughout *the locomotives*
► Eastbound track has primarily **downhill loaded** trains (50 MGT)
  • (Air)break forces are distributed throughout *the entire train*

Key feature: Tracks have the same curvature, grade and climate, allowing the comparison of the effects of the following on loading demand and fastener response

- Anchor
- Temperature
- Load
- Speed
- Direction of traffic
- Braking vs. traction forces
- High vs. low rail
Quantification of Loading Environment

- Vertical, lateral and longitudinal loads collected with industry standard load circuits installed in the center of the crib on both high and low rails
Field Experimentation Review

Track 1 (50 MGT)
Few Broken Spikes
Downhill

Track 2

Track 3 (45.6 MGT)
Many Broken Spikes
Uphill

Grade: 1.76%
Curvature: 9.2°
Lubricated Airbrake grade

Instrumentation Area
Data Collection Box
Wheel Counter
Track Overview

- Two ties and one crib instrumented in each track

Track 3 (45.6 MGT)
- Many Broken Spikes

Uphill
- Grade: 1.76%
- Curvature: 9.2°
- Lubricated
- Airbrake grade
Percent Exceeding Vertical Wheel Loads

(July 2019)

Vertical wheel loading is generally greater in Track 1
  • Expected, since operations of loaded trains are biased on that track

Track 3 operations are seen to be underbalanced
  • On average, low rail vertical loads are more than 30% greater than high rail

(26% of Wheel Load)
Percent Exceeding Vertical Wheel Loads

(July 2019)

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Track 1 field-facing lateral wheel loads are larger in magnitude than in Track 3

10% of lateral loads are gauge-facing in Track 1 and 30% in Track 3
Track 1 field-facing lateral wheel loads are larger in magnitude than in Track 3
10% of lateral loads are gauge-facing in Track 1 and 30% in Track 3
Longitudinal Loading

Wheel, rail axial, and fastener

Following elastic track model by Kerr(2003)
Longitudinal Loading
Wheel, rail axial, and fastener

Following elastic track model by Kerr(2003)
Superposition of Axial Loads

Distribution of vertical and lateral forces

Distribution of longitudinal forces

Cancellation of rail axial forces occur between locomotives
Superposition of Fastener Loads

- Fastener loading is greatest **between** locomotives
- Plate uplift can occur during application of longitudinal loading
- Load superposition studied:
  - Draft paper: “Analytical Elastic Modelling of Railroad Track Response”
Effect of Distributed Power on Fastener Loads

- Increased distance between trucks reduce superposition effects
- This example shows a 40% reduction of fastener demand by having two locomotives just 1 car apart
The measured rail axial forces are 50-70% higher on Track 3 (on average)
Estimated Longitudinal Fastener Forces

(July 2019)

- Longitudinal rail seat loads are more than an order of magnitude lower than rail axial forces.
- Longitudinal fastener loads on Track 3 are greater than Track 1 (on average).
## Summary: Lat and Long Fastener Forces

### Lateral Rail Seat Load* - kips (kN)

<table>
<thead>
<tr>
<th>%</th>
<th>Low Rail</th>
<th>High Rail</th>
<th>Low Rail</th>
<th>High Rail</th>
</tr>
</thead>
<tbody>
<tr>
<td>99</td>
<td>6.71 (29.9)</td>
<td>7.02 (31.2)</td>
<td>4.14 (18.4)</td>
<td>5.14 (22.9)</td>
</tr>
<tr>
<td>95</td>
<td>5.97 (26.6)</td>
<td>5.77 (25.7)</td>
<td>2.88 (12.8)</td>
<td>3.24 (14.4)</td>
</tr>
<tr>
<td>90</td>
<td>5.47 (24.3)</td>
<td>5.18 (23.0)</td>
<td>2.19 (9.7)</td>
<td>2.27 (10.1)</td>
</tr>
<tr>
<td>50</td>
<td>1.98 (8.8)</td>
<td>1.61 (7.2)</td>
<td>0.53 (2.3)</td>
<td>0.11 (0.5)</td>
</tr>
</tbody>
</table>

### Estimated Longitudinal Rail Seat Load - kips (kN)

<table>
<thead>
<tr>
<th>%</th>
<th>Low Rail</th>
<th>High Rail</th>
<th>Low Rail</th>
<th>High Rail</th>
</tr>
</thead>
<tbody>
<tr>
<td>99</td>
<td>1.65 (7.3)</td>
<td>1.92 (8.5)</td>
<td>2.82 (12.6)</td>
<td>2.36 (10.5)</td>
</tr>
<tr>
<td>95</td>
<td>1.51 (6.7)</td>
<td>1.64 (7.3)</td>
<td>2.40 (10.7)</td>
<td>1.96 (8.7)</td>
</tr>
<tr>
<td>90</td>
<td>1.25 (5.5)</td>
<td>1.55 (6.9)</td>
<td>2.09 (9.3)</td>
<td>1.73 (7.7)</td>
</tr>
<tr>
<td>50</td>
<td>0.84 (3.8)</td>
<td>0.97 (4.3)</td>
<td>1.39 (6.2)</td>
<td>1.29 (5.7)</td>
</tr>
</tbody>
</table>

- 90<sup>th</sup> percentile lateral loads are ~3k greater on Track 1 compared to Track 3.
- 90<sup>th</sup> percentile longitudinal loads are 0.5k greater on Track 3 compared to Track 1.
- If entire load was transferred to spikes, fatigue failures would occur in all rails.

*35% of Wheel Loads
Field Conclusions and Path Forward

► Longitudinal rail seat loads (up to ~2,800 lbs.) are one order of magnitude lower than rail axial load (up to ~28,000 lbs.)
► Underbalanced speed operations on Track 3 lead to 30% greater vertical loads on low rail compared to high rail
► Load demand itself does not explain why failure is predominant on the high rail of Track 3

Future Work:
► Investigate the effect of operational characteristics and friction on rail seat load transfer to crossties
  • Longitudinal
    - Loads are applied during rail uplift
    - Uplift mitigates the effect of friction on longitudinal load transfer
  • Lateral
    - Loads applied roughly with vertical loads
    - Friction should help transfer lateral loads
Hypothetical: Rail Seat Load Components

Lateral (Spike), Lateral Friction, and Longitudinal (Spike)

Coefficient of friction assumed to be 0.20 between plate and crosstie.
Project Thrust Areas

Laboratory
Controlled experiments to better characterize load transfer and rail displacement/slip of various fasteners

Analytical Modeling
Quantification of load distribution and spike stress while investigating key factors affecting load transfer

Field
Quantification of loading demands (vert., lateral, long.) and fastener response to service loading
TTC Field Work Overview

► Control zone:
  • e-clips and cut spikes
  • 20 crossties

► Test zone:
  • Tension clamps with screw spike and spiral washer
  • 30 crossties

► Duration: Fall 2019 – Summer 2020

► Tonnage Accumulated: 170 MGT

► Visual Inspections:
  • performed every few months

► Track Geometry and Loaded Gage:
  • measured after fall and spring seasons
Details of “loose screw spikes” within Test zone (after 60 MGT)
- 3 of 240 exhibited 30 – 45 degrees of rotation (1 – 1.5 mm of uplift)
- Spring washers estimated to still apply between 2 – 3 kips of clamping force

Indications of additional “loose screw spikes” after 170 MGT on 5 rail seats
TTC Field Gage Results and Discussion

Potential factors leading to improved performance of Test Zone

- Spring washers encourage plate to crosstie contact
  - Increases friction between plate and crosstie
  - Indicated in reduced/less variable base gage widening

- Tension clamps provide improved/consistent clamping force compared to e-clip
  - More consistent toe-load
  - Increased lateral/rotational strength/stiffness
  - Indicated in reduced head gage widening
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**Analytical Modeling**
Quantification of load distribution and spike stress while investigating key factors affecting load transfer

**Field**
Quantification of loading demands (vert., lateral, long.) and fastener response to service loading
Single Spike FEM Summary

- Longitudinal load is more detrimental than an equivalent lateral load
  - This is due to the timber being less resistant in that direction
  - This finding supports the theory that spike failures in premium fastening systems are primarily related to longitudinal loads

- Stress can exceed the fatigue limit of spike steel at regular service loads
- Max. stress depth varies with the magnitude and direction of applied load
- Species of timber significantly effects the depth/load of failure
Recent FEA Investigation Focus: Spike Stress Mitigation Methods

- Spike cross-sectional area
- Spike type (cut vs screw)
- Spike loading location
- Plate engagement with tie (vertical clamping force)
- Spike engagement with plate
- Quantity of spikes within a given fastening system
Modeling Overview

Three basic models were developed for this study:

- Single cut spike-timber block model
  - Quantify effect of cross-sectional area and loading location
- Single screw spike-timber block model
  - Quantify effect of spike type
- Single rail seat model with multiple spikes, plate, and timber block
  - Quantify effect of spike/plate/tie engagement and quantity of spikes used
Multiple railroads are moving from cut spikes to screw spikes for premium fasteners
- At least one railroad has moved from screw spikes to cut spikes

Perceived advantages of screw spikes (relative to cut spikes):
- Increased bending strength
- Increased plate hold-down strength

Expectations based on geometry (relative to cut spikes):
- Increased bending strength at the upper shaft
- Decreased bending strength at threads
- Increased stresses in the threads at equivalent loads

### Cut vs Screw Spikes: Background

<table>
<thead>
<tr>
<th>Spike (type/location)</th>
<th>Cut (Upper Shaft)</th>
<th>Screw (Upper Shaft)</th>
<th>Screw (Threads)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cross Section</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Area Moment of Intertia Formula</td>
<td>-</td>
<td>bh³/12</td>
<td>πr⁴/4</td>
</tr>
<tr>
<td></td>
<td>I (in⁴)</td>
<td>0.0127</td>
<td>0.0380</td>
</tr>
<tr>
<td></td>
<td>y (in.)</td>
<td>0.3125</td>
<td>0.4690</td>
</tr>
<tr>
<td>Stress (force/in²)</td>
<td>24.6 × M*</td>
<td>12.3 × M*</td>
<td>31.3 × M*</td>
</tr>
</tbody>
</table>

*where M represents the internal moment in force-in.
Cut vs Screw Spike: Visualization

Each spike subjected to 2,500 lb. longitudinal load

- Maximum spike stress depth:
  - Cut spike: 1.5”
  - Screw spike: 2.0”
Cut vs Screw Spike: Quantification

- Each spike subjected to 2,500 lb. longitudinal load
- Longitudinal loads < 2000 lb. there is < 10% difference in max stress
- Beyond 2000 lb. stress in screw spikes increase rapidly
Normal Clamping Force: Background

Goal:
► Ensure load is transferred through spike and friction when plate is engaged with tie

Challenge:
► Wave action of the rail leads to uplift of the plate, eliminating friction

Proposed Solution:
► Develop friction force through preloading of plate:
  • Screw spikes do this upon first installation, but can loosen over time
  • Spring washers could be utilized (and are utilized internationally)
► Spring washer applied load studied:
  • 3,400 lb. ea. after initial “settling”
  • 1,000 lb. ea. after minimal cutting/loosening

* Example of load vs disp. for this spring washer, not an indication of load at installation.
Effect of Normal Clamping Force

- Fastening system subjected to 2,500 lb. longitudinal load
- Normal clamping force of 1,000lb./spike and 3,400lb./spike investigated

- 3,370lb./spike resulted in an 80% reduction in spike stress (on average)
- 1,000lb./spike resulted in a 70% reduction in spike stress (on average)
- Thus, most of longitudinal force taken by friction
Spike Engagement: Background

- Plate hole tolerances are larger than potential displacement
  - Hold down and line spike holes are 0.065 in. and 0.125 in. larger than the 0.625 in. standard cut spike
  - Displacement of spike subjected to load not expected to exceed 0.04 in.
- Not all spikes will be in contact at one time
Effect of Spike Engagement with Plate

► Fastening system with 4 spikes subjected to 2,500 lb. longitudinal load with one spike moved to other side of spike hole (extreme tolerance)

► Disengaged spike acts as though it has been removed from system

► Load is not evenly redistributed among engaged spikes

► Disengagement of a single spike resulted in up to a 140% (2.4 times) increase in spike stress
Modelling Conclusions

1. The disengagement of a single can lead to a 140% (2.4 times) increase in a remaining spike’s stress

2. There is an inverse relationship between plate-sleeper normal clamping force and spikes stress
   - Clamping force of 1,000 lb./spike can reduce spike stress by 70%

3. There is little difference in cut and screw spike strength (capacity) at longitudinal loads below 2,000 lbs. (8.90 kN)

4. There is an inverse linear relationship between spike cross-section and resulting stress
   - For each 1% increase in spike width there is ~ 2% reduction in stress
   - Increasing spike width by 0.1” resulted in 29% reduction in stress

5. There is direct linear relationship between spike contact location and resulting stress
   - A +/- 0.245” change in load location can lead to +/- 20% change in maximum stress

► Draft journal paper submitted to JRRT
   - “Methods to Mitigate Railway Premium Fastening System Spike Fatigue Failures using Finite Element Analysis”
Preliminary Recommendations for Mitigating Spike Failures

Through Operations:
- Reduce longitudinal demands by:
  - Distributing power where possible/feasible
  - Evenly distributing tractive effort among multiple units
- Reduce lateral forces when possible by:
  - Proper gauging (wide gauge),
  - TOR lubrication,
  - etc.
- Operating near balanced speed to encourage equal vertical loading on high and low rail
- Building trains limiting unloading of vertical rail (string line condition, etc.)

Through Fastening System Design:
- Encourage engagement (clamping/contact) between plate and crosstie
- Encourage engagement of all spikes with plate
- Increase strength of spike(s) to account for additional loading
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