Mechanistic Investigation of Timber Crosstie Spike Failures
Preliminary Findings from the Laboratory and Field

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Acknowledgements

► Project Sponsor

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► Industry Partnership

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PANDROL
Presentation Outline

► Project Overview
► Phase I Review
► Phase II
  • Laboratory Experimentations
    - Single Spike Testing
    - Single Fastener Plan
  • Field Experimentation
    - Instrumentation
    - Hypotheses
  • Field Data Examples and Comparisons
    - Vertical Forces
    - Lateral Forces
    - Longitudinal Forces
    - Longitudinal Displacements
► Future Work
Project Overview

► PHASE I: How large is the problem?
  • Industry Survey
  • Interviews and Site Visits
  • Document scope of the problem
  • Hypotheses about spike breakage

► PHASE II: What is causing spike failures?
  • Execute laboratory experimentation plan developed in PHASE I
  • Attempt to replicate failures in the laboratory
  • Develop and perform parametric analyses with FE models of fastening systems
  • Validate models with laboratory work

► PHASE III: How do we prevent the failures?
  • Perform additional lab tests/FEA as needed
  • Investigate design improvements
  • Recommend improvements
Phase I Review

- Spikes have been failing due to fatigue
  - Primarily on *premium fastening system*
  - Often *new ties*
  - Mainly on *curves*
  - Also in *special trackwork*
- Most likely a mechanism problem
- Leads to rapid gauge deterioration and have caused at least 11 derailments since 2000

Potential Factors
- *Lack of anchor increases* longitudinal loads

\[
F_{\text{Spikes}} = F_{\text{Rail}} - F_{\text{friction}} - F_{\text{Anchor}}
\]
Phase I Review

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Potential Factors

► *Lack of anchor increases* longitudinal loads
  • *Plate uplift* further increases loads
  • Wood is weaker on that direction

► Stiffer fasteners reduces distribution of loads

► Crosstie age

\[ F_{\text{Spikes}} = F_{\text{Rail}} \]
Stress in Spikes – Hypothetical Graph

- **Total Stress into Spikes**
- **Threshold Stress for Spike Failure**

**Traditional Systems**
- Anchor Tangent Flat
- Anchor Curve Grade
- Anchor Curve Grade (extreme case)

**Premium Systems**
- No Anchor Curve Grade
- Anchor Curve Grade

**Types of Stress**
- Longitudinal
- Lateral

**Stress into Spikes**
- Premium Systems
- Traditional Systems

(RailTEC at Illinois | 8)
Phase II | Laboratory Experimentation

Understanding Fastener Mechanics

► Three stages of component testing under longitudinal loads

Single Spike  Single Fastener  Track Assembly
Single Spike Experimentation

Two Types of Experimentation
► Fatigue testing of cut spikes
► Static and cyclic longitudinal loading of cut spikes

Findings
► Fatigue failures recreated in the laboratory
► AREMA (Ch. 5) yield stress can be reached with less than 2,000 lb. longitudinal force
► Maximum stress along spike occurs at ~1.5” as would be expected based on field observations (*Shown in following slide*)
  • Provided data for FEM calibration
Cyclic Testing – Shakedown

Timber block with splits

- It appears the “splitting” allows for increased spike rotation and decreased bending
Cyclic Testing – Shakedown

Timber block with no split

► No “splitting” leads to increased spike bending and decreased rotation
Cyclic Testing – Shakedown

Varying Load Magnitude

► Load: Longitudinal only
  • ~2.40 M cycles between 200 and 1,500 lb.
  • ~3.60 M cycles between 200 and 1,900 lb.
  • ~0.25 M cycles between 200 and 2,300 lb.

► Failure information:
  • Approximate depth to failure: 1.56” from top of crosstie
  • Approximate cycle count 6.25 M
Cyclic Testing – Shakedown

Constant load magnitude

► Load:
  • 200 to 2,300 lb.

► Failure information:
  • Approximate depth to failure: 1.63” from top of crosstie
  • Approximate cycle count 0.74 M
Longitudinally Loaded Spike Stress Profile

Stress Along Spikes at 2000 lb

-1
0
1
1.5" - Typical Spike Breakage

Distance From Top of Tie (in.)

Stress (ksi)

0 5 10 15 20 25 30 35 40 45 50 55 60 65

Specimen X
Specimen Y

AREMA (Ch. 5) Standard for Spike Yield

Bottom of spike head Load Application Zone

Top of crosstie (ToFC)

Tested Yield Strength of Samples
Single Fastener Experimentation

Testing procedure
► Single fastener loaded with static and cyclic longitudinal loads
► Instrumentation will provide insight on load distribution to spikes and the effect of key variables

Current variables to consider
► Fastener
  • Traditional
  • Typical e-clip
  • Reduced toe-load e-clip
► Plate uplift vs. No uplift
► Anchor vs. No anchor
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
Field Experimentation

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
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
Evaluation of Fastener Response

- Rail and plate displacements measured with specially designed DMDs (Displacement Measurement Devices)
  - Rail displacements relative to plate
  - Plate displacements relative to the tie

Plate movement was recreated in computer animation
Field Site Overview

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

Thermocouple
Two ties and one crib instrumented in each track.
Data Acquisition and Collection

On-site computer
► Always reading data from the instrumentation
► Keeps most recent data on memory
► Records data:
  • When a wheel is detected
  • 6 seconds prior to wheel detection
# Field Instrumentation

<table>
<thead>
<tr>
<th></th>
<th>Our hypotheses</th>
<th>What we see</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Vertical Loads</strong></td>
<td>![Track 1] ➔ ![Track 3]</td>
<td>?</td>
</tr>
<tr>
<td><strong>Lateral Loads</strong></td>
<td>![Track 1] ➔ ![Track 3]</td>
<td>?</td>
</tr>
<tr>
<td><strong>Longitudinal Rail Loads</strong></td>
<td>![Track 1] ➔ ![Track 3]</td>
<td>?</td>
</tr>
<tr>
<td><strong>Longitudinal Plate Displacements</strong></td>
<td>![Track 1] ➔ ![Track 3]</td>
<td>?</td>
</tr>
</tbody>
</table>

Grade: 1.76%  
Curvature: 9.2°  
Lubricated (TOR and GF)  
Airbrake grade
Vertical and Lateral Forces Example

Lead Locomotives

- Vertical and lateral load traces are clean and reasonable.
Vertical and Lateral Forces Example

Helper Locomotives

- Evidence of high lateral forces on helper locomotives
Vertical Forces and Plate Disp. Example

For this train

- Vertical displacements follow expected trends
- Clear uplift in Plate 2 but less often in Plate 1
**Track Loading Comparison**

**Vertical Axle Loads**

- **Track 1**
  - N = 30 Trains
  - (7877 Axles)

- **Track 3**
  - N = 17 Trains
  - (5472 Axles)
Track Loading Comparison

Lateral Axle Loads

Track 1
N = 30 Trains
(7877 Axles)

Track 3
N = 17 Trains
(5472 Axles)
Longitudinal Forces Example

For this train

► Rail axial tension build up can be seen before train appears
Longitudinal Forces Example

For this train:
- Rail axial tension build up can be seen before train appears
- Evidence of longitudinal loads on the rail with plate uplift
Track Loading Comparison

Longitudinal Rail Loads Before Train

Longitudinal Rail Load (kips)

Compression

Tension

<table>
<thead>
<tr>
<th>Track 1</th>
<th>Track 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>High Rail</td>
<td>N = 6 Trains</td>
</tr>
<tr>
<td>Low Rail</td>
<td>N = 6 Trains</td>
</tr>
</tbody>
</table>

① ③
Track Loading Comparison

Longitudinal Plate Displacement Relative to the Tie

Track 1
N = 30 Locomotives
(180 Axles)

Track 3
N = 17 Locomotives
(102 Axles)
# Field Instrumentation Initial Findings

## Our hypotheses vs What we see

<table>
<thead>
<tr>
<th>Field</th>
<th>Our hypotheses</th>
<th>What we see</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Vertical Loads</strong></td>
<td><img src="image1" alt="Track 1" /> ➔ <img src="image2" alt="Track 3" /></td>
<td><img src="image1" alt="Track 1" /> ➔ <img src="image2" alt="Track 3" /></td>
</tr>
<tr>
<td><strong>Lateral Loads</strong></td>
<td><img src="image3" alt="Track 1" /> ➔ <img src="image4" alt="Track 3" /></td>
<td><img src="image3" alt="Track 1" /> ➔ <img src="image4" alt="Track 3" /></td>
</tr>
<tr>
<td><strong>Longitudinal Rail Loads</strong></td>
<td><img src="image5" alt="Track 1" /> ➔ <img src="image6" alt="Track 3" /></td>
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</tr>
<tr>
<td><strong>Longitudinal Plate Displacements</strong></td>
<td><img src="image7" alt="Track 1" /> ➔ <img src="image8" alt="Track 3" /></td>
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- **Grade:** 1.76%
- **Curvature:** 9.2°
- **Lubricated (TOR and GF)**
- **Airbrake grade**
Field Data Analysis – Future Work

► Model (Kerr) and quantify loads being transferred to the fasteners

► Further investigate plate displacement behavior

► Investigate/quantify difference in longitudinal stiffness for fasteners with and without anchors – Track 3 vs Track 1

► Quantify the effect of speed, weight, direction, length, etc. in longitudinal / lateral loading
Phase I Single Spike FEM Summary

- Longitudinal load is more detrimental than an equivalent lateral load
  - This is due to the timber being less resistant on 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
Final Calibrated Single Spike Results

- A longitudinal load of 2,000 lb. or a lateral load of 2,750 lb. can lead to the fatigue strength of the spike being exceeded.
Current Focus:
• Spike hole tolerances do not ensure all spikes are engaged and
• Given there are multiple spike arrangements for a given fastener

Investigate effect of the following on spike stress state:
• Spike engagement
• Spike arrangement
• Loading direction/magnitude
FEM Update | Model Overview

► From previous validated model
  • Interactions: spike – crosstie
  • Materials: spike and timber
  • Mesh: spike and timber (near plate/spikes)

► Loads applied in-line with field data (longitudinal only shown below)
  • Simplified as a traction distributed over the rail seat
  • No e-clips modeled for simplification
**FEM Update | Preliminary Results**

- Effect of spike engagement
  - Loading (P): 7,000 lb. longitudinal

  ![Diagram](image1)

  ![Diagram](image2)

  - Spike stress is effected by spike engagement
    - There is a ~100% increase in maximum spike stress from plate on left (~20 ksi) to plate on right (~40 ksi)

  *Fatigue Limit is ~33ksi*
FEM Update | Preliminary Results

▸ Effect of spike engagement
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▸ Spike stress is effected by spike engagement
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*Fatigue Limit is ~33ksi
Effect of spike arrangement

- Loading (P): 7,000 lb. longitudinal

Spike stress is effected by arrangement

- There is a ~30% increase in maximum spike stress from plate on left (~20 ksi) to plate on right (~26 ksi)

*Fatigue Limit is ~33ksi
Effect of spike arrangement

- Loading (P): 7,000 lb. longitudinal

Spike stress is effected by arrangement

- There is a ~30% increase in maximum spike stress from plate on left (~20 ksi) to plate on right (~26 ksi)

*Fatigue Limit is ~33ksi
Current tolerances do not ensure all spikes are engaged at one time.

There can be different spiking patterns for a given premium fastening systems.

The effect of spike engagement can significantly affect spike stress:
- In the example provided, by up to 100%.
- This led to a stress that exceeded the fatigue limit.

The effect of spike arrangement can affect spike stress:
- In the example provided, by up to 30%.

Therefore, additional work will investigate if there might be any reasonable recommendations that can be made to reduce risk of increasing spike stress.
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