Investigation of Feasible Methods to Mitigate Rail End Bolt-Hole Cracks Using Finite Element Analysis

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Presentation Outline

• Background and Problem Statement
• Purpose and Scope of Work
• Literature Review Summary
• Static Finite Element (FE) Modeling
• Preliminary Static FE Results
• Future Work and Path Forward
Background and Problem Statement

- Rail joints classification:
  - Insulated Joints
    - Bonded
    - Nonbonded
  - Bolted Joints
    - Compromise
    - Standard

- Common defects:
  - End Batter
  - Head-Web Separation
  - Joint Bar Center Crack
  - Bolt-Hole Crack

(The pictures are from CEE 409 Railroad Track Engineering, Learning Module 4. University of Illinois.)
Investigation of Methods to Mitigate Rail End Bolt-Hole Cracks Using FEA

Background and Problem Statement

- The primary cause of rail joint defects is the **discontinuity of both geometry and mechanical properties**, and the resulting impact loads.

- Bolt-hole cracks at rail joint propagating in the rail longitudinal direction is a major hazard, causing rail break or even loss of rail running surface.

- Most cracks are found to propagate from the first bolt-hole at the end of the rail toward the end of the rail section.

(The picture is from Wen et al. (2005), *Contact-impact stress analysis of rail joint region using the dynamic finite element method*)
Purpose and Scope of Work

• A large number of bolted rail joints still exist in North America rail infrastructure for a variety of reasons, especially in some early-built rail transit systems.

• Scope → to find feasible method(s) to solve or mitigate the bolt-hole crack problem.

• **Phase I** – Literature Review and Finite Element Modeling

• **Phase II** – Laboratory Experimentation
Literature Review Summary – Key Findings

- Bolt-hole cracks typically initiate at receiving rail end of the joint, at approximately $45^\circ$ to the neutral axis of rail;
- For the standard joints between continuously welded rail (CWR) strings, thermal-induced longitudinal stresses play a significant role causing the crack;
- For the standard joints among bolted-joint rail (BJR) track, the crack driving force could be represented by the positive shear stress at the bolt-hole.
Possible Causes

Joint Anomaly
- Gap
- Height Mismatch

Wheel Impact Load
- Dynamic Load

Possible Failure Modes
- Bolt Hole Cracks
- Bent or Broken Bolts
- Cracked or Broken Bars

Increased Deflection/Geometry Defect

Rail End Batter

Deteriorated Support

Loosened Bolts

(The picture is from Carolan et al. (2014), Engineering studies on joint bar integrity, part II: finite element analyses)
Existing Remedial Methods – Cold Expansion

- Apply cold expansion to the bolt-hole, by pulling an oversize tapered mandrel through it.
- The residual compressive stress could help lower the cyclic tensile stress around the hole.
- The reduced net stress help increase the fatigue life.

(Schematic of the Cold Expansion Process using Hydraulic Puller)

(Increase in Fatigue Life for Cold vs. Non-Cold Expanded Holes)

(The picture is from Reid (1993), Beneficial residual stresses at bolt holes by cold expansion)
Existing Remedial Methods – Saddled Joints

- Install “saddle” to protect and support joint bar.
- Saddled joint has better mechanical properties.

A Newer Joint Design with Web-Hugging Bars and Saddle

Stresses in Standard and Newer Joints

(The picture is from Igwemezie, J. and Nguyen, A.T. (2010), Anatomy of joint bar failures III)
Static FE Model Steps

**Step 1** – Develop models for nominal and worst scenario cases;

**Step 2** – Develop models of standard joints to study the influences of possible bolt-hole crack causes;

**Step 3** – Develop models of remedial joint designs, compare the results with models of standard joints to see the effectiveness.
# Static FE Model Variables

<table>
<thead>
<tr>
<th>Variable</th>
<th>Inputs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rail Section</td>
<td>100-lb / 115-lb</td>
</tr>
<tr>
<td>Plate Type (Track Stiffness)</td>
<td>Resilient Plates (4,000 psi) / Pandrol Plates (Old) (11,000 psi) / Pandrol Plates (New) (22,000 psi)</td>
</tr>
<tr>
<td>Joint Support Type</td>
<td>Suspended / Supported</td>
</tr>
<tr>
<td>Support Condition</td>
<td>Well (100%) / Poorly (≈0%)</td>
</tr>
<tr>
<td>Bolt Condition</td>
<td>Tight (22,000 psi) / Loose (6,000 psi)</td>
</tr>
<tr>
<td>Static Wheel Load</td>
<td>16,500 lb / wheel</td>
</tr>
<tr>
<td>Impact Wheel Load Factor</td>
<td>$I_m \geq 1.33$</td>
</tr>
<tr>
<td>Loading Position</td>
<td>a (on top of rail end) / b (between a and c) / c (on top of first bolt-hole)</td>
</tr>
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<tr>
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<td>a (on top of rail end)</td>
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</tbody>
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![Diagram with labels](image)
Investigation of Methods to Mitigate Rail End Bolt-Hole Cracks Using FEA

I – Well-supported ties, Tight bolts, $l_m=1.33$

$P_w = 22,000$ lb

$P_w = Impact\ Wheel\ Load = 1.33 \times 16500 = 22,000$ lb

$P_b = Bolt\ Preload = 22,000$ lb / bolt

$K = Track\ Modulus \times Tie\ Spacing = 4,000$ psi $\times 22.5$ in $= 90,000$ lb/in

$K = 90,000$ lb/in

$K = 90,000$ lb/in

$K = 90,000$ lb/in

$K = 90,000$ lb/in

Max. Principal Stress around Rail End Bolt-Hole

<table>
<thead>
<tr>
<th></th>
<th>Magnitude (psi)</th>
</tr>
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<tbody>
<tr>
<td>Tension (T)</td>
<td>177,000</td>
</tr>
<tr>
<td>Compression (C)</td>
<td>115,000</td>
</tr>
<tr>
<td></td>
<td>52,000~69,000</td>
</tr>
</tbody>
</table>

Note:
1. Tensile and Yield Strengths are provided by sponsor;
2. Fatigue Strength is estimated by 45~60% of Yield Strength

$\approx 12,000$ psi (23% Fatigue Strength)
Static FE Models and Results

II – Poorly-supported tie, Loose bolts, $I_m = 3.0$

$P_w = 50,000$ lb

$P_b = 6,000$ lb

$K=90,000$ lb/in

$K=90,000$ lb/in

$K=1,000$ lb/in

$K=90,000$ lb/in

$P_w = \text{Impact Wheel Load} = 3.0 \times 16500 = 50,000$ lb

$P_b = \text{Bolt Preload} = 6,000$ lb / bolt

<table>
<thead>
<tr>
<th>Load Position</th>
<th>Max. Tensile Stress around 1st Rail End Bolt-Hole (psi)</th>
</tr>
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<tbody>
<tr>
<td>a</td>
<td>19,330</td>
</tr>
<tr>
<td>b</td>
<td>27,460</td>
</tr>
<tr>
<td>c</td>
<td>40,560</td>
</tr>
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Static FE Models and Results

II – Poorly-supported tie, Loose bolts, $l_m=3.0$, (case c)

S, Max. Principal (Abs)
(Avg: 75%)

-4.056e+04
-3.434e+04
-2.813e+04
-2.191e+04
-1.569e+04
+9.471e+03
+3.253e+03
-2.966e+03
-9.184e+03
-1.540e+04
-2.162e+04
-2.784e+04
-3.406e+04

≈ 41,000 psi
(79% Fatigue Strength)

(The picture is from Wen et al. (2005), Contact-impact stress analysis of rail joint region using the dynamic finite element method)
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Preliminary Static FE Model Results

- When the rail joint system is in good condition (i.e. well-supported ties, tight bolts, and low impact wheel loads), **the stresses around the rail end bolt-hole are well below the fatigue strength (23%)**;
- When the rail joint system is deteriorated (e.g. poorly-supported tie, loosened bolts, and high impact wheel loads), **the stresses around the rail end bolt-hole can approach the fatigue strength (79%)**;
- The critical case is when the wheel load is right above the rail end bolt-hole;
- As supported by other literature, the maximum tensile stress regions are at approximately **45°** around rail end bolt-hole.
Future Work and Path Forward

- **Refine the mesh** around the bolt-hole of interest, and **perform the mesh sensitivity analysis** to approach the convergence value of the stresses;

- **Extend the model in longitudinal direction** and import additional crossties along the rail base to reduce boundary effect in simulation, and better represent field conditions;

- **Compare the influences of poorly-supported crosstie**, loose bolts and high impact load, respectively, and find out the dominant one(s);

- **Develop dynamic model** for fatigue analysis via introducing moving wheel(s) into the model.
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