UIUC FRA Crosstie and Fastening System BAA 2014-2: Investigation of Deteriorated Crossties and Support Conditions

Experimental Results

FRA and FTA Crosstie and Fastening System Research Program
Industry Partners (IP) Meeting
Tucson, AZ
4 November 2015
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Outline

- Motivation for Research
- Expected Industry Impact
- Laboratory Experimentation
- Preliminary Results
  - ANOVA
  - Effect of Support Conditions
  - Effect of Crosstie Cracking
- Conclusions
- Future Work
Motivation for Research

- The recent Industry Survey conducted by UIUC reported that North American Class I Railroads and other railway infrastructure experts would like to see laboratory experiments on concrete crosstie support conditions.

- Previous analysis of FRA accident database indicated that deteriorated concrete crossties and support conditions are among major track related accident causes in the US.

Expected Industry Impact

<table>
<thead>
<tr>
<th>Expected Impacts</th>
<th>Railroads</th>
<th>AREMA Chapter 30</th>
<th>Crossie Manufacturers</th>
<th>FRA - CFR 213</th>
</tr>
</thead>
<tbody>
<tr>
<td>Consensus on definition of failed concrete crossties</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Input on expected crosstie bending moments</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Input on expected concrete crosstie deflections and gage widening effect based on crosstie shape</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Estimation of crosstie support conditions based on bending moment measurements and cracking observation</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Experimental Matrix

- Matrix was executed five times to account for variability
- 12 combinations of support conditions and crosstie health variation

<table>
<thead>
<tr>
<th>Run Number</th>
<th>Support Condition</th>
<th>Crosstie Condition</th>
<th>Purpose</th>
<th>Vertical Load Applied to Each Rail Seat Simultaneously</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>Healthy Crosstie</td>
<td>Baseline - Healthy Crosstie, Full Support</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>Healthy Crosstie</td>
<td>Healthy Crosstie, Light Center Binding</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>Healthy Crosstie</td>
<td>Healthy Crosstie, Moderate Center Binding</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>Healthy Crosstie</td>
<td>Healthy Crosstie, Severe Center Binding</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>5</td>
<td>Healthy Crosstie</td>
<td>Healthy Crosstie, High Impact Loads (Rail Seat Positive)</td>
<td>0-20 kips, 0-89 kN</td>
</tr>
<tr>
<td>6</td>
<td>6</td>
<td>Healthy Crosstie</td>
<td>Healthy Crosstie, Newly Tamped</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>1</td>
<td>Deep Cracks, Full Support</td>
<td>Deep Cracks, Full Support</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>2</td>
<td>Deep Cracks, Light Center Binding</td>
<td>Deep Cracks, Light Center Binding</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>3</td>
<td>Deep Cracks, Moderate Center Binding</td>
<td>Deep Cracks, Moderate Center Binding</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>4</td>
<td>Deep Cracks, Severe Center Binding</td>
<td>Deep Cracks, Severe Center Binding</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>6</td>
<td>Deep Cracks, Newly Tamped</td>
<td>Deep Cracks, Newly Tamped</td>
<td></td>
</tr>
</tbody>
</table>

Measurement Devices

- **Surface Strain Gauges**
  - Calculation of bending moments

- **Linear Potentiometers**
  - Measurement of vertical displacements
  - Estimation of crosstie shape
Laboratory Experimentation Equipment

- Loading frame
- Supporting rubber pads

Analysis of Variance (ANOVA) Background

- Null hypothesis: $\mu_1 = \mu_2 = \mu_3$ (same population mean)
- If the null hypothesis is true, then the sample means should be similar, but not necessarily identical
- What level of variability of the sample means makes the null hypothesis wrong?
ANOVA Application - Bending Moments

- Conducted ANOVA with two factors
  - Support conditions (5 levels)
  - Crosstie health (2 levels)

- 300 total data points representing bending moments
  - 3 Locations: rail seat, center, and intermediate
  - 10 Factor combinations (5 support conditions x 2 crosstie health variations)
  - 10 Replicates for each factor combination

- One of the key values produced by ANOVA is the probability under the null hypothesis (p-value)
  - The higher the p-value, the less significant the factor

<table>
<thead>
<tr>
<th>Source</th>
<th>Degrees of Freedom</th>
<th>Sum of Squares</th>
<th>Mean Square</th>
<th>F value</th>
<th>Pr &gt; F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Support Conditions</td>
<td>4</td>
<td>663452</td>
<td>165863</td>
<td>38.92</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td>Cracking</td>
<td>1.0</td>
<td>3567</td>
<td>3567</td>
<td>0.8</td>
<td>0.4</td>
</tr>
<tr>
<td>Interaction</td>
<td>4.0</td>
<td>5177</td>
<td>1294</td>
<td>0.3</td>
<td>0.9</td>
</tr>
<tr>
<td>Error</td>
<td>80.0</td>
<td>340901</td>
<td>4261</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TOTAL</td>
<td>89.0</td>
<td>1013096</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

ANOVA Results - Bending Moments

*Rail Seat Load: 20 kips (89 kN)*

- Support conditions have a significant impact on bending moments
- The particular experimental cracking pattern (AREMA recommended practice for flexural performance) does not have a significant impact on bending moments

<table>
<thead>
<tr>
<th>ANOVA Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>P-value</td>
</tr>
<tr>
<td>--------------</td>
</tr>
<tr>
<td>Rail Seat</td>
</tr>
<tr>
<td>Support Conditions</td>
</tr>
<tr>
<td>Crosstie Health</td>
</tr>
</tbody>
</table>
Box Plot Background

- Box plots are great to:
  - Visualize outliers
  - Compare variability of different cases
  - Check for symmetry
  - Check for normality

<table>
<thead>
<tr>
<th>Bending Moment</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Rail Seat Bending Moments

- Rail Seat Load: 20 kips
- Healthy crosstie
- 10 replicates

Typical design limit for rail seat positive bending moment (AREMA) 158 kip-in

-2 kip-in
**Intermediate Bending Moments**

- Rail Seat Load: 20 kips
- Healthy crosstie
- 10 replicates

**Center Bending Moments**

- Rail Seat Load: 20 kips
- Healthy crosstie
- 10 replicates

Typical design limit for center negative bending moment (AREMA)
Mean Separation Procedure

- **Objective:** Confirm that the results from different support conditions are significantly different due to many overlapping data

- **Method:** Use mean separation procedure
  - Used Fisher’s *Least Significant Difference* (LSD) Method
  - Confidence level of 90% (i.e. alpha = 0.1)

<table>
<thead>
<tr>
<th>Location</th>
<th>Rail Seat Load</th>
<th>Intermediate</th>
<th>Center</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean t-Grouping</td>
<td>Mean t-Grouping</td>
<td>Mean t-Grouping</td>
</tr>
<tr>
<td>Full Support</td>
<td>130.1</td>
<td>33.2</td>
<td>-7.3</td>
</tr>
<tr>
<td>Light Center Binding</td>
<td>57.5</td>
<td>-35.1</td>
<td>-57.8</td>
</tr>
<tr>
<td>High Center Binding</td>
<td>-2.5</td>
<td>-172.8</td>
<td>-227.5</td>
</tr>
<tr>
<td>Lack of Rail Seat Support</td>
<td>157.5</td>
<td>26.5</td>
<td>-52.1</td>
</tr>
<tr>
<td>Lack of Center Support</td>
<td>124.0</td>
<td>52.3</td>
<td>20.8</td>
</tr>
</tbody>
</table>

*All values are in kip/in and correspond to a rail seat load of 20 kips (89 kN). Note: 1 kip/in = 8.851 kN/m.

- “Full Support” and “Lack of Center Support” were never found to be significantly different

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**Flexural Performance under Different Support Conditions**

*Rail Seat Load: 20 kips (89 kN), Healthy Crosstie*
Crosstie Shape under Different Support Conditions

**Rail Seat Load: 20 kips (89 kN), Healthy Crosstie**

![Graph showing displacement under different support conditions](image)

Crosstie Displacement under Different Support Conditions

**Rail Seat Load: 20 kips (89 kN), Healthy Crosstie**

![Bar graph showing displacement](image)

- Results are comparable to field data obtained at TTC in 2012-2013 as part of prior FRA-funded crosstie research at UIUC
Derivation of Gage Widening Equation due to Crosstie Bending

\[
\frac{1}{2} \Delta g = \sqrt{2 \left( \frac{l^2 + r^2}{4} \right) (1 - \cos \theta) \times \sin \left[ \tan^{-1} \left( \frac{l}{r} \right) + \phi - \frac{\theta}{2} \right] - \frac{w}{2} \cos \phi + \frac{w}{2} \cos (\phi - \theta)}
\]

\[\theta = \sin^{-1} \left[ \frac{\Delta dcot \phi \times \sin \phi}{\sqrt{(\Delta dcot \phi)^2 + (r - \Delta dsc \phi)^2 + 2(\Delta dcot \phi)(r - \Delta dsc \phi)(\cos \phi)}} \right] \]

\[\Delta g: \text{ Change of gage} \]
\[r: \text{ Distance between potentiometers close to rail seat} \]
\[\phi: \text{ Rail cant angle (1:40)} \]
\[w: \text{ Width of rail head} \]
\[l: \text{ Rail height} \]
\[\Delta d: \text{ The difference of vertical displacements between potentiometers close to rail seat} \]

ANOVA* for gage widening has the same conclusions as for bending moments

- Support conditions have a significant impact on gage widening
- Cracking does not have a significant impact on gage widening (for particular cracking pattern and crosstie model used in this study)

<table>
<thead>
<tr>
<th>Factor</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Support Conditions</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td>Crosstie Health</td>
<td>0.25</td>
</tr>
</tbody>
</table>

*Gage widening data was transformed to meet ANOVA assumptions
Conclusions

- Small amounts of center binding can result in large differences in center bending moment. In comparison with the lack of center support case:
  - 241.2 kip-in change for high center binding (at center)
  - 78.6 kip-in change for light center binding (at center)
- Rail seat bending moments are less sensitive to changes in support. In comparison with the lack of center support case:
  - 33.4 kip-in change for lack of rail seat support (at rail seat)
- The results above indicate that tamping (removing center support) can drastically reduce center bending moments
- Typical design recommended practices might underestimate center negative bending moments (-227 kip-in experimental vs. -201 kip-in design)
- The center cracks generated at the laboratory seem to have no effect on crosstie bending moments or displacements (p-values of 0.19 and 0.68)
- Gage widening effect due to pure concrete crosstie bending is very small, even with worst experimental support condition case (0.1 inch)

Path Forward

- Refine analysis of experimental data
- Plan future finite element modeling (FEM) on system level
- Plan future experiments using the Track Loading System (TLS)
- Study ways to positively impact AREMA Chapter 30 and CFR 213
Acknowledgements

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  - TTX Company
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- RailTEC Team

Questions or Comments?

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