Concrete Crossties and Fastening Systems: Previous Experiences, Current Research, and Future Advances

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Concrete Crossties and Fastening Systems: Previous Experiences, Current Research, and Future Advances

William W. Hay Railroad Engineering Seminar
Urbana, IL, USA
1 March 2013

J. Riley Edwards and the entire UIUC Concrete Crosstie Research Team
Outline

• Background and Research Justification
• RailTEC Concrete Crosstie Research
• Mechanistic Design Introduction
• Key Research Thrust Areas and Summary of Results
  – Materials Research
  – Laboratory Instrumentation
  – Field Instrumentation
  – Analytical Methods (FEA)
• Future Work
• Acknowledgements
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• **Background and Research Justification**

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Concrete Crossties – Overview of Use

• Typical Usage:
  – Freight → Heavy tonnage lines, steep grades, and high degrees of curvature
  – Passenger → High density corridors (e.g. Amtrak’s Northeast Corridor [NEC])
  – Transit applications

• Number of concrete ties in North America*:
  – Freight → 25,000,000
  – Passenger → 2,000,000
  – Transit → Significant quantities (millions)

*Approximate
Concrete Crosstie and Fastening System Components

Concrete Crossties

Clips

Rail Pads

Fastening Insulators

Shoulder
Fastening System Components

- Shoulder
- Clip
- Insulator
- Rail Pad Assembly
- Concrete Crosstie
Concrete Crossties and Fastening Systems – Hay Seminar

Complete System

8-9 ft
56.5 in
8-13 in
6-10 in

Prestress wire or strand
Shoulder insert
Tie pad between rail base and rail seat
Insulator Clip
## 2012 International Survey Results – Criticality of Problems

<table>
<thead>
<tr>
<th>Problem (higher ranking is more critical)</th>
<th>Average Rank</th>
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<tbody>
<tr>
<td><strong>International Responses</strong></td>
<td></td>
</tr>
<tr>
<td>Tamping damage</td>
<td>6.14</td>
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<tr>
<td>Shoulder/fastening system wear or fatigue</td>
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<tr>
<td>Cracking from center binding</td>
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<tr>
<td>Cracking from dynamic loads</td>
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<td>Derailment damage</td>
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<tr>
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## 2012 International Survey Results – Research Needs

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<tr>
<th>Research topic (higher ranking is more important)</th>
<th>Average Rank</th>
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<td><strong>North American Responses</strong></td>
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<td>Prevention or repair of rail seat deterioration (RSD)</td>
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<td>Track system design</td>
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Concrete Crosstie and Fastener Research Levels (and Examples)

**Materials**
- Concrete Mix Design
- Rail Seat Surface Treatments
- Pad / Insulator Materials

**Components**
- Fastener Yield Stress
- Insulator Post Compression
- Concrete Prestress Design

**System**
- Finite Element Modeling
- Full-Scale Laboratory Experimentation
- Field Experimentation
Current Research Sponsors

- Federal Railroad Administration (FRA) (Fastening System Design, Performance, Wear, Fatigue, Cracking, Environmental, etc.)
- Amsted RPS / Amsted Rail, Inc. (Fastening System Wear and Fatigue)
- Association of American Railroads (AAR) Technology Scanning Program (RSD and Fastening System Wear and Fatigue)
- Kansas City Southern (KCS) (Crosstie Design)
- NEXTRANS Region 5 Transportation Center (RSD)
- National University Rail (NURail) (Fastening System Wear and Fatigue)
- CN Fellowship in Rail Engineering (RSD)
Large Scale Abrasion Test:
Used to investigate abrasion as a mechanism leading to rail seat deterioration (RSD) while varying load magnitude, displacement, pad material, etc.

Small Scale Abrasion Resistance Test (SSART):
Evaluate various approaches to increasing the abrasion resistance of concrete and determine wear rates
Component Experimentation

Static Tie Tester:
Used to study the rail seat compression and bending moment behavior of the concrete crosstie under static loading conditions

Rail Bending Test:
Used to prove the concept of using the rail as a built-up load cell using strain gauges
Concrete Crossties and Fastening Systems – Hay Seminar

**System Experimentation - Laboratory**

**Pulsating Load Testing Machine (PLTM):**
Conduct full-scale concrete tie and fastening system testing by simulating various L/V ratios under repeated loads.

**Static Load Testing Machine (SLTM):**
Provides a means to study the behavior of the crosstie and fastening system under static load.
System Experimentation - Field

Field installation at Monticello Railway Museum (MRM):
Full-scale concrete tie and fastening system field preparation testing site

Field Installation at the Transportation Technology Center (TTC):
Conduct full-scale concrete tie and fastening system testing in field while varying track geometry, train type, and speed
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Current Design Process

- Found in AREMA Manual on Railway Engineering
- Based largely on practical experience:
  - Lacks complete understanding of failure mechanisms and their causes
  - Empirically derives loading conditions (or extrapolates existing relationships)
- Can be driven by production and installation practices
- Improvements are difficult to implement without understanding complex loading environment
Principles of Mechanistic Design

1. Quantify track system input loads (wheel loads)

2. Qualitatively establish load path (free body diagrams, basic modeling, etc.)
   - Establish the locations for load transfer

3. Quantify loading conditions at each interface / component (including displacements)
   a. Laboratory experimentation
   b. Field experimentation
   c. Analytical modeling (basic $\rightarrow$ complex/system)

4. Link quantitative data to component geometry and materials properties (materials decision)
Principles of Mechanistic Design (cont.)

5. Relate loading to failure modes (e.g., how does lateral loading relate to post insulator wear?)

6. Investigate interdependencies through modeling

7. Run parametric analyses
   – Materials, geometry, load location

8. Development and testing of innovative designs
   – Novel rail pad, sleeper, insulator designs
   – Geometry and materials improvements

9. Establish mechanistic design practices

10. Adoption into AREMA Recommended Practices
Determining System Input Loads

• Quantitative methods of data collection (Step 1):
  – Wheel Impact Load Detectors (WILD)
  – Instrumented Wheel Sets (IWS)
  – Truck Performance Detectors (TPD)
  – UIUC Instrumentation Plan (FRA Tie BAA)

• Most methods above are used to monitor rolling stock performance and assess vehicle health

• Can provide insight into the magnitude and distribution of loads entering track structure
  – Limitations to WILD: tangent track (still need lateral curve data), good substructure (not necessarily representative of the broader rail network)
Vertical Wheel Loads – Shared Infrastructure

Source: Amtrak, Edgewood, MD – November 2010
Effect of Traffic Type on Peak Wheel Load

Source: Amtrak – Edgewood, MD (November 2010)
Impact Loads and Percent Exceedance

\[ \text{Impact Factor (IF)} = \frac{\text{Peak Load}}{\text{Static Load}} \]

Amtrak, Edgewood, MD – November 2010
So What is Our Design Threshold?

*Need curves for each component / interface and failure mode*
Development of Quantitative Loading Model

- Peak Vertical Wheel Load vs. Speed
- Confidence interval
- Car Type 1
- Car Type 2
- Car Type 3
Development of Quantitative Loading Model

Conceptual Sketch

- Nominal Wheel Load
- Peak Vertical Wheel Load

- Locomotives
- 286k Freight Car (Load)
- 315k Freight Car (Load)
- 286k Freight Car (Empty)
- 315k Freight Car (Empty)
- Pass. Coach 1
- Pass. Coach 2

Freight Car (Load)
Freight Car (Empty)
Establishment of the Qualitative Load Path

Subscripts
b = rail base
p = pad
i = insulator clip bearing area
c = clip
s = shoulder
o = insulator post
t = sleeper

Legend
Reaction
Input Load
F = Field
G = Gauge
B = Base
Rail Seat Load Calculation Methodologies

![Graph showing rail seat load calculation methodologies with load versus load curves for AREMA, USACE, Average, Kerr, and Talbot.](image)

Analysis courtesy of Christopher Rapp
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Large Scale Abrasion Test – Deterioration Test Results

- Consistently able to cause deterioration of concrete due to abrasion
- Concrete deterioration initiated near pad edges and propagates inward
- Heat build up in pad materials at local contact points lead to softening
- Difficult to correlate severity of abrasion to input variables
  - Heterogeneity of concrete surface
  - Contact angle and pressure distribution
Mean Coefficient of Friction (COF) – Nylon 6/6

![Graph showing the mean coefficient of friction (COF) for Nylon 6/6 under different loading conditions. The graph plots the frictional coefficient (μ) against loading cycles. The data points for 3 kips, 5 kips, and 10 kips are represented with different markers and error bars indicating variability.]
Mean Coefficient of Friction (COF) – Nylon 6/6 and Polyurethane

(5 kip load)

Frictional Coefficient, $\mu$

Loading Cycles
Small-Scale Test for Abrasion Resistance (SSTAR): Test Setup Overview

- Consists of a powered rotating steel wheel with 3 lapping rings
  - Lapping rings permitted to rotate about their own axis
  - Vertical load applied using the dead weights (4.5 pounds)
  - Abrasive sand and water dispensed during testing
Effect of Mineral Admixtures

- 30% Fly ash
- Control
- 10% Silica fume
- 5% Silica fume
- 15% Fly ash

Wear Depth (millimeters)
Test Duration (minutes)
Effect of Other Variations in Mix Design
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FRA Tie and Fastening System BAA Objectives and Deliverables

• Program Objectives
  – Conduct comprehensive international literature review and state-of-the-art assessment for design and performance
  – Conduct experimental laboratory and field testing, leading to improved recommended practices for design
  – Provide mechanistic design recommendations for concrete sleepers and fastening system design in the US

• Program Deliverables
  – Improved mechanistic design recommendations for concrete sleepers and fastening systems in the US
  – Improved safety due to increased strength of critical infrastructure components
  – Centralized knowledge and document depository for concrete sleepers and fastening systems

FRA Tie and Fastener BAA Industry Partners:

- Union Pacific
- BNSF Railway
- Amtrak
- Amsted RPS
- Amsted Rail
- GIC
- Hanson
- LB Foster
- CXT Concrete Ties
FRA Tie and Fastener Project Structure

**Inputs**
- Comprehensive Literature Review
- International Tie and Fastening System Survey
- Loading Regime (Input) Study
- Rail Seat Load Calculation Methodologies
- Involvement of Industry Experts

**Outputs/Deliverables**
- Data Collection
- Document Depository
- Groundwork for Mechanistic Design
- International Survey Report
- Load Path Map
- Parametric Analysis
- State of Practice Report
- Validated Tie and Fastening System Model

**Improved Recommended Practices**
FRA Tie and Fastener Project Structure

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**Outputs/Deliverables**
- Data Collection
- Groundwork for Mechanistic Design
- Laboratory Study
- Field Study
- Modeling

- Document Depository
- International Survey Report
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**Improved Recommended Practices**
Quantification of Lateral Loads Entering the Shoulder Face (Insert)

- Instrumented shoulder face insert
  - Original shoulder face is removed
  - Small beam insert replaces removed section
  - 4-point bending beam experiment

- Beam strategy is a well-established, successful technology
Transfer of Lateral Load to Shoulder Face

32.5 kip vertical load, 0.5 L/V ratio
Percent of Lateral Load Transferred to Shoulder
Preliminary Data

% Transferred

L/V Ratio

0% 0.1 0.2 0.3 0.4 0.5
Railseat Pressures Under Different Rail Pads

- Load Applied: 32.5 kip vertical, 16.9 kip lateral (0.52 L/V)

<table>
<thead>
<tr>
<th>Contact Area (in²)</th>
<th>Max Pressure (psi)</th>
</tr>
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<tbody>
<tr>
<td>TPV</td>
<td>25.8</td>
</tr>
<tr>
<td>MDPE</td>
<td>19.0</td>
</tr>
<tr>
<td>Two-Part Pad Assembly</td>
<td>23.9</td>
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</tbody>
</table>

![Images of rail seat pressures under different rail pads]
Laboratory Instrumentation

- Development and refinement of field instrumentation
- Research with controlled variables to investigate
  - Displacement of rail and fastening system components
  - Pressure distribution under different L/V ratios, support conditions, and fastening system components

- Make recommendations to refine future laboratory tests
Full Scale Track Response Experimental System
Full Scale Track Response Experimental System
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**Improved Recommended Practices**

**Modeling**

**Laboratory Study**

**Field Study**
Goals of Field Instrumentation

• Lay groundwork for mechanistic design of concrete sleepers and elastic fasteners
• Quantify the demands placed on each component within the system
• Develop an understanding into field loading conditions
• Provide insight for future field testing
• Collect data to validate the UIUC concrete sleeper and fastening system FE model
Areas of Investigation

**Rail**
- Stresses at rail seat
- Strains in the web
- Displacements of web/base

**Fasteners/ Insulator**
- Strain of fasteners
- Stresses on insulator

**Concrete Sleepers**
- Moments at the rail seat
- Stresses at rail seat
- Vertical displacements of sleepers
Field Instrumentation Map (July 2012)

- **Full Instrumentation**
  - Lateral, vertical, and chevron strain gauges on rail
  - Embedment and external concrete strain gauges on crosstie
  - Matrix based tactile surface sensors at rail seat (at rail seat W)
  - Linear potentiometers on rail and crosstie

- **Partial Instrumentation**
  - Vertical strain gauges on rail
  - Matrix based tactile surface sensors (at rail seats G and Y)
  - Linear potentiometers on crosstie (at rail seats C and G)
Instrumented Crosstie Construction

Embedment gauge installed between shoulders on prestress wire
Instrumented Crosstie Construction

Placement and protection of surface strain gauges
TTCl Field Testing Locations

5 degree curve spiral
Balance Speed = 33 mph

Tangent
Speeds up to 105 mph

Railroad Test Track (RTT)

High-Tonnage Loop (HTL)
Objectives of Field Experimental Program
Loading Environment

- Track Loading Vehicle (TLV)
  - Static
  - Dynamic
    - Track modulus

- Freight Consist
  - 6-axle locomotive (393k)
  - Instrumented car
  - Nine cars
    - 263, 286, 315 GRL Cars

- Passenger Consist
  - 4-axle locomotive (255k)
  - Nine coaches
    - 87 GRL
Installation of Clip by Professors ("experts")
Fully Instrumented Rail Seats
Instrumented Low Rail
Field-side Instrumentation

- Vertical Sleeper Displacement
- Clip Strain
- Vertical Web Strain
- Base Displacement
Gauge-side Instrumentation

Lateral Rail Displacement
Data Acquisition System
Tangent Track (RTT) – Passenger Train
Tangent Track (RTT) – Freight Train
Lateral Loads on Tangent Track (Freight)

Leading axles of a 10-car freight train (30, 33, and 36t axle loads).
Lateral Loads on Tangent Track (Freight)

- No correlation between lateral loads and train speed on tangent track.

Leading axles of a 10-car freight train (30, 33, and 36t axle loads).
RTT Curved Instrumentation – Train Pass
Lateral Loads Acting on a Curve Track

- Median load is ~5.5 times larger than what was recorded in tangent track.

Leading axles of a 10-car freight train (30, 33, and 36t axle loads).
Global Track Deflections Under Passage of Freight Train
Vertical Displacements of Crossties (HTL)

- Vertical Displacement (in)
- Vertical Load (kips)

Graph showing the relationship between vertical displacement and vertical load for different load levels (HIGH, LOW) and tie configurations (U, S, W, E, C, G). The graph illustrates how the displacement increases with the load, with different patterns for each load level and tie configuration.
Deflections from train passes do not exceed static response: typically 60% (passenger) and 75% (freight).
No significant relationship between train speed and sleeper deflection
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**Modeling**

**Laboratory Study**

**Field Study**

**Improved Recommended Practices**
Concrete Sleeper and Fastening System

- Rail
- Pad & Abrasion frame
- Clip
- Insulator
- Shoulder
- Concrete Sleeper
Component Modeling

Rail Clip

Rail Clip model
Component Modeling: Validation

- Clip Model

Mises stress contour (Clamping force = 11.6 kN)

Stress concentration due to support

Clamping force-displacement curves

- Clip Model

Manufacturer Data
Component Modeling: Concrete Sleeper and Ballast

Static loading of the model

Deformation contour
System Modeling - COF Estimation

- Clip & Insulator: 0.25
- Shoulder & Insulator: 0.25
- Rail & Pad: 0.50
- Plate and Tie: 0.25
- Pin Support
System Modeling: Single-Sleeper Modeling

Laboratory Test Validation

Symmetric BC in the middle

Fixed at bottom
System Model: Multiple-Sleeper Modeling

- Track loading vehicle (TLV) applying vertical and lateral loads to the track structure in field
- The symmetric model including 5 Sleepers

Simplified model: Fastening system were replaced by BCs and pressure

Detailed model with the fastening system
System Modeling: Lateral Load Path

36 Kip Vertical Load

Lateral Load

Friction + Insulator Post +Shoulder to Pad

Friction (F1)

Insulator Post (F2)

Shoulder to Pad (F3)

Lateral Load Path

Force (lb) vs L/V Ratio

0 0.05 0.1 0.15 0.2 0.25 0.3 0.35 0.4

0 2000 4000 6000 8000 10000 12000 14000
Future System-Level Modeling Work

- **Additional comparisons:** More measurements on the lab testing set-ups will be deployed and compared with the models.

- **Large-scale modeling:** More Models will be built to look into the distribution of loading among multiple ties and the discrete support condition of rail.

- **Realistic loading:** More load types (vertical, lateral, and longitudinal loads) and load forms (static and dynamic load) will be applied to the track system to better simulate the actual loading environment.

- **Parametric studies:** Parametric studies about material properties and geometric dimensions will be conducted using the model.
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Current Research Thrust Areas

- Continued **data analysis** to understand the governing mechanics of the system by investigating the:
  - elastic fastener (clamp) strain response
  - number of ties effected simultaneously
  - bending modes of the sleepers
  - pressure magnitude and distribution at the rail seat
- Continued **comparison and validation** of the UIUC tie and fastening system finite element model (Chen, Shin)
- Preparation for **instrumentation trip** (May 2013)
  - Focus on lateral load path by gathering
    - relative lateral sleeper displacements
    - global lateral sleeper displacements
    - load transferred to the clamp, insulator-post, and shoulder
- Small-scale, **evaluative tests** on Class I Railroads
The Future of Concrete Crossties and Fastening Systems…

• Mechanistic design and materials choices
  – Concrete materials (e.g. mineral and chemical admixtures, coatings, etc.)
  – Improved plastics (e.g. Nylon abrasion frame, polyurethane rail pad, etc.)
  – Other advanced materials (e.g. tie armor)

• Considerations of friction at **all** system interfaces, and how it relates to overall system design
  – Improved understanding of component interaction

• **Lowering the stress state** of the tie and fastening system:
  – Larger rail seats
  – Under Sleeper Pads (USP)

• Improved design validation tests (AREMA C-30 Modifications)
• System level design, once components are better optimized
RailTEC Concrete Tie Research Team

- Previous Personnel
  - 3 Graduate Research Assistants
  - 6 Undergraduate Research Assistants

- Current Personnel
  - 9 Graduate Research Assistants
  - 1 Post Doctoral Researcher
  - 1 Visiting Scholar
  - 6 Undergraduate Research Assistants
  - 2 Research Engineers
  - 4 Professors
Acknowledgements

Research Sponsors:

U.S. Department of Transportation
Federal Railroad Administration

Amsted Rail

Mextrans

ASSOCIATION OF AMERICAN RAILROADS

KANSAS CITY SOUTHERN Lines

CN

FRA Tie and Fastener BAA Industry Partners:

UNION PACIFIC

BUILDING AMERICA®

BNSF RAILWAY

AMTRAK®

GIC

LB Foster

CXT Concrete Ties

HANSON
Other Supporting Organizations

- BNSF
- UNION PACIFIC
- AMTRAN
- NORFOLK SOUTHERN
- CSX
- CN
- CANADIAN PACIFIC RAILWAY
- U.S. Department of Transportation
- Federal Railroad Administration
- Amsted RPS
- Amsted Rail
- GIC
- LB Foster
- HANSON
- NORTRAK
- PANZER
- Vossloh
- TCI
Key Industry Experts and Individuals

- Amsted RPS / Amsted Rail, Inc.: Jose Mediavilla, Dave Bowman, Brent Wilson, Thai Nguyen, Chase Nielsen, Brent Wilson
- BNSF Railway: John Bosshart, Tom Brueske, Hank Lees, Seth Ogan, Hal Lewandoski,
- Union Pacific Railroad: Kevin Hicks, Eric Gehringer, Dwight Clark, Steve Ashmore
- Vossloh: Winfred Boesterling, Michael Steidl, Rigi Chackanad, Chris Kenyon
- Pandrol Track Systems: Bob Coats, Scott Tripple, Dave Kangas, Frank Brady
- CXT Concrete Ties: Pelle Duong, Jim Parsley, Mark Hammons, Vince Petersen
- VAE Nortrak: Steve Mattson
- Rocla Concrete Tie: Al Smith (retired), Rusty Crowley, Pedro Lemmertz
- GIC: Mauricio Gutierrez, Carlos Gutierrez
- TTCI: Dave Davis, Richard Reiff, Michael Brown, Ken Laine
- Engis Corporation: Peter Kuo, Steven Griffin
- Others: Jerry Rose, Tim Johns, Bill Riehl, Brandon Hunter, Al Smith, Fabian Weber, John Clark, Jim Gauntt, Michael Land, Rob Loomis, Jeff DeGross
- UIUC: Tim Prunkard, Don Marrow, Darold Marrow, Marc Killion, Ernie Barenberg, Greg Banas, Jim Meister, Dauren Kumarbekov, Josh Brickman, Steven Jastrzebski, Michael Wnek, Andrew Kimmle, Calvin Nutt, Alex Ng, Kris Gustafson, Chris Naranjo, Matthew Greve, Brad Jones, Dan Rivi, Alex Schwarz, Matthew Jarrett, Scott Schmidt, Andrew Stirk