Finite Element Models of Concrete Sleepers and Fastening Systems in North America

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Outline

• RailTEC Overview

• Concrete Sleeper Research Program Overview

• Methodology for Finite Element (FE) Analysis

• FE Models of Field Experiments
  • Displacement calibration
  • Load distribution validation

• Applications for Calibrated FE Models

• Conclusions

• Future Work
Rail Transportation and Engineering Center (RailTEC) at the University of Illinois at Urbana-Champaign (UIUC)

• **Strongest academic curriculum in rail in North America**
  – Nine rail and public transport courses supported by one of the strongest engineering colleges in North America
  – Educating B.S., M.S. and Ph.D. students with specialization in rail
  – Leading national efforts to expand rail educational opportunities in the U.S.

• **Breadth and depth in rail research**
  – Seven faculty and Senior Research Engineers specializing in rail
  – Dozen other affiliated faculty with substantial rail research knowledge and experience

• **World-class expertise in engineering & technology**
  – All branches of engineering, materials sciences, information technology and computer science

[http://ict.uiuc.edu/railroad/](http://ict.uiuc.edu/railroad/)
National University Rail (NURail) Center

• The first rail-focused University Transportation Center (UTC) under the US Department of Transportation (DOT) Research and Innovative Technology Administration (RITA) program

• The primary objective of the NURail Center is to improve and expand rail education, research, workforce development, and technology transfer in the US

Lead Institution

Partner Institutions
Concrete sleepers – Overview of Use

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

• Number of concrete sleepers in North America*:
  – Freight $\rightarrow$ 25,000,000
  – Passenger $\rightarrow$ 2,000,000
  – Transit $\rightarrow$ Significant quantities (millions)

*Approximate
Concrete Sleeper and Fastening System Components

Concrete Sleepers

Clips

Rail Pads

Fastening Insulators

Shoulder
RailTEC Concrete Sleeper and Fastener Research Program Levels

**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 Tie and Fastener Research Coverage

Load distribution through rail stress analysis
Kartik Manda

Mechanistic behavior of insulator
Brent Williams

Mechanistic behavior of rail pad assembly
Thiago Bizarria

Load quantification
Brandon Van Dyk/Andrew Scheppe

Clip stress analysis/
Sleeper structural analysis
Sihang Wei

Rail seat pressures
Matthew Greve

Other research: Concrete materials (Emily Van Dam),
FE modeling (George Chen and Austin Zhang)
FRA Tie and Fastening System
BAA Objectives and Deliverables

• Program Objectives
  – Conduct experimental laboratory testing, field testing, and analytical modeling to quantify loads
  – Provide mechanistic design recommendations for concrete sleepers and fastening system design in the US, focusing on shared use infrastructure

• Program Deliverables
  – Mechanistic design practices for concrete sleepers and fastening systems
  – Validated Finite Element (FE) model of concrete sleeper and fastening system
  – Centralized knowledge and document depository for concrete sleepers and fastening systems
  – Ultimate objectives → decreased life cycle costs and Improved safety due to improved performance of critical infrastructure components
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**

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Modeling

Laboratory Study

Field Study
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**Modeling**

**Laboratory Study**

**Field Study**

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**Improved Recommended Practices**
Track Superstructure Modeling – Prior Work

**Track System Modeling**

- Simplified fastening systems
- Focused on vertical loading
- Simplified support conditions

(Lundqvist and Dahlberg, 2005 - Sweden)

(Yu and Jeong, 2011)

(Tangtragulwong 2009)
Methodology for FE Analysis

- Model development
  - Component model
  - Single-sleeper model
  - Multiple-sleeper model
- Model calibration
  - Displacement measurement
  - Strain measurement
- Model validation
  - Vertical load distribution
  - Lateral load distribution
- Model application
  - Parametric studies
  - Simplified tool
UIUC Sleeper and Fastener FE Modeling Approach

• Modeling was conducted using ABAQUS

• All elements, except the prestress strand, were modeled using eight-node brick elements

• Each node had three translational degrees of freedom (DOF)

• Prestress strands were modeled as 1-D truss element with stiffness along length of sleeper

• Concrete material property was modeled using damage plasticity model

• Mesh density was varied for each component per demand
Review of Model Development: Component Model

Component Validation

Stress concentration due to support

Mises stress contour
( Clamping force = 11.6 kN)

Clamping force-displacement curves
FE Models for Field Experiment

- Two symmetric models with identical loads are used to simulate the behavior of track in the field:
  - Global model includes five sleepers and fastening systems along with substructure support
  - Detailed model includes a single sleeper and fastening system with substructure support

![Detailed model](image1)

![Global model](image2)
FE Models for Field Experiment

• Detailed Model:
  • Component geometry is very detailed
  • Fine mesh defined
  • Clamping force applied with clips

• Global Model:
  • Component geometry is simplified
  • Coarse mesh is defined
  • Clamping force represented with pressure

Detailed model

Global model
FE Models for Field Experiment

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FE Models for Field Experiment

• Global model simulates the system-level track behavior
• Displacements at the end of the detailed model rail segment are outputs of the global model (submodel technique)
• The combination of the two models capture the global behavior of the track system, and provide accurate prediction close to the loading point within a reasonable calculation time
Field Experimentation for Model Calibration

• Initial calibration was based on laboratory data

• Next step → acquire field data to further refine the FE model

• Data acquired for model calibration:
  – Vertical sleeper displacement
  – Lateral force at iron shoulder
  – Lateral rail base and web displacement
  – Vertical force at rail seat
Field Experimentation: Primary Areas of Investigation

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

Fasteners/Insulator
- Strain of fasteners
- Stresses and force on insulator/shoulder

Concrete Sleepers
- Moments along sleeper
  - Midspan
  - Rail Seat
- Stresses at rail seat
- Vertical displacements of sleeper
May 2013 Field Instrumentation

- Acquired data from ~200 channels of instrumentation simultaneously
- All instrumentation was deployed to achieve a specific objective
- A sub-set of the data was acquired for model calibration and validation
Field Instrumentation Locations

- TTC (Pueblo, CO, USA)
- Railroad Test Track (RTT)
  - Tangent
- 610 mm sleeper spacing
Loading Environment

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

- **Freight Consist**
  - 3, 6-axle locomotives on HTL
  - 4-axle locomotives on RTT
  - 9 loaded and one empty freight cars

- **Passenger Consist**
  - 6-axle locomotive on HTL
  - 4-axle locomotive on RTT
  - 10 coaches

- **FAST Train**
Vertical Sleeper Displacement: Instrumentation Deployed

- Linear potentiometers were mounted to rods driven into the substructure until refusal
- Data was acquired at both ends of three adjacent sleepers
Vertical Sleeper Displacement: Acquired Data

- Vertical behavior of the model is calibrated based on vertical sleeper displacement measurements from field experiment at TTC.
- The measurements are from static test using the Track Loading Vehicle (TLV) on the Railroad Test Track (RTT).

![Graph showing vertical sleeper displacement vs. vertical loads for different railseats C, U, G, E, and S.]
Vertical Sleeper Displacement: Calibration Approach

- A block is modeled as a general support for the track system to represent the ballast, subballast, and subgrade.
- Hyperelastic material model is defined for the block, and it is calibrated to match the displacement measurement.
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**Vertical Sleeper Displacement: Calibration Results**

- **Vertical Sleeper Displacement (in)**
  - Field test at C
  - Model output

- **Vertical Loads (kips)**
  - 0 to 60 kips
Lateral Rail Seat Load Model Calibration

- The lateral load input into a rail seat is supported by friction and the shoulder.
- The force imparted into the shoulder was acquired in the field to calibrate the model.

\[
\text{Lateral Load} = \text{Friction (F1)} + \text{Insulator Post to Shoulder (F2)} + \text{Shoulder to Pad (F3)}
\]
Lateral Shoulder Force: Instrumentation Deployed

• Lateral Load Evaluation Device (LLED)
  – Original shoulder face is removed
  – Insert designed as a beam and optimized to replace removed section and maintains original geometry
  – Measures bending strain of beam under 4-point bending
  • Measuring bending strain is a proven technique

Field Installation
Lateral Shoulder Force: Acquired Data

- Force (lbf): 1,000, 2,000, 3,000, 4,000, 5,000, 6,000
- Force (kN): 89, 178

Graph showing force in kN and lbf with data points at 89 kN and 178 kN.
Lateral Rail Seat Load: Model Output

- Literature states lateral load distribution is similar to vertical load
- Results show that the lateral load distribution is over fewer sleepers

178 kN vertical load
89 kN lateral load

Rail seat lateral reaction (kN)

<table>
<thead>
<tr>
<th>Tie</th>
<th>Reaction (kN)</th>
</tr>
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<tbody>
<tr>
<td>AP</td>
<td>-3.86</td>
</tr>
<tr>
<td>BQ</td>
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<td>CS</td>
<td>55.79</td>
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<tr>
<td>EU</td>
<td>19.74</td>
</tr>
<tr>
<td>GW</td>
<td>-3.86</td>
</tr>
</tbody>
</table>
Application of the Calibrated Model

- Parametric studies have been conducted:
  - Tensile cracking of concrete
  - Lateral load path of the fastening system
  - Bond-slip behavior between prestressing strand and concrete
- Based on design of experiments, results from preliminary parametric studies are used to build a simplified calculation tool (I-TRACK) on track response
Conclusions

• A 3D detailed and global finite element model of the sleeper and fastening system have been developed

• A submodel technique has successfully been deployed to quickly and accurately study the behavior of the sleeper and fastening system

• The models are calibrated with select data from field experiments and there is
  • Good agreement observed when comparing displacements
  • Reasonable agreement observed when comparing vertical and lateral reaction distributions
Future Work

- The submodel technique will be incorporated into the full-scale model to simulate the loading scenario in curved track.
- The multi-sleeper model will continue to be refined to reduce run-time.
- Further parametric studies will be conducted to evaluate:
  - Effect of surface interaction properties (i.e. friction)
  - Effect of vertical track modulus
  - Effect of component geometry on system behavior
Future Work:
Full-Scale Laboratory Validation
Overall Program Deliverables

**Mechanistic Design Framework**
- Literature Review
- Load Path Analysis
- International Standards
- Current Industry Practices
- AREMA Chapter 30

**Finite Element Model**
- Laboratory Experimentation
- Field Experimentation
- Parametric Analyses

**I – TRACK**
- Statistical Analysis from FEM
- Free Body Diagram Analysis
- Probabilistic Loading
2014

International Crosstie and Fastening System Symposium

Rail Transportation and Engineering Center (RailTEC)
University of Illinois at Urbana-Champaign, Newmark Lab, Champaign, IL 61801

3 – 5 June 2014

This three day conference will have presentations, discussions and a technical tour that focus on the state of the art in timber, concrete, steel and composite crosstie and fastening system design, performance, research, modeling, and inspection.
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  - Hanson Professional Services, Inc.
  - CXT Concrete Ties, Inc., LB Foster Company
  - TTX Company
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http://ict.uiuc.edu/railroad/CEE/crossties/downloads.php