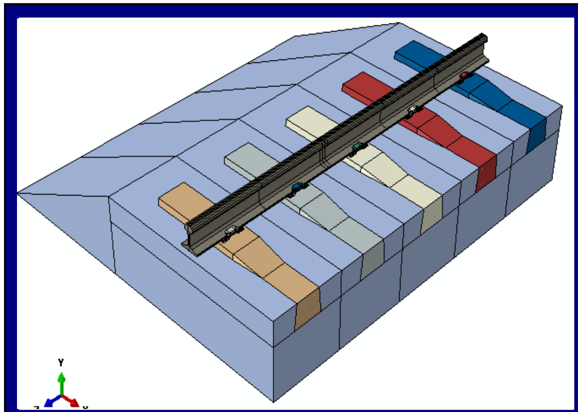
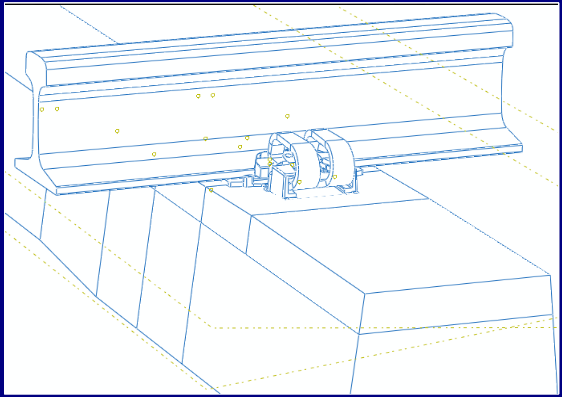
Finite Element Models of Concrete Sleepers and Fastening Systems in North America





World Congress on Railway Research (WCRR) 2013

Sydney, NSW, Australia

27 November 2013

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Marcus S. Dersch, and J. Riley Edwards

U.S. Department of Transportation
Federal Railroad Administration

RAILTEC
UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

WCRR 2013
Sydney Australia

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/

NURail Center

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

ILLINOIS
UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

Partner Institutions

UIC UNIVERSITY OF ILLINOIS AT CHICAGO

MIT Massachusetts Institute of Technology

Michigan Tech

UK UNIVERSITY OF KENTUCKY

THE UNIVERSITY of TENNESSEE UT KNOXVILLE

ROSE-HULMAN INSTITUTE OF TECHNOLOGY · 1874 ·

Concrete sleepers – Overview of Use

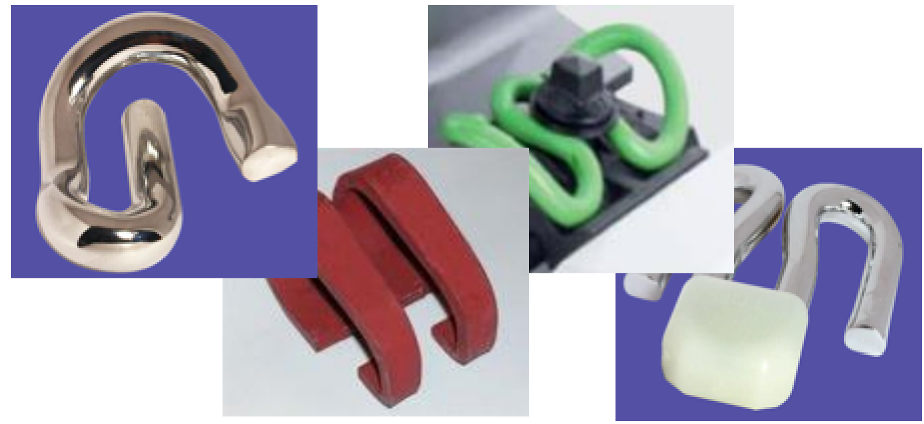
- Typical Usage:
  - Freight → Heavy tonnage lines, steep grades, and high degrees of curvature
  - Passenger → High density corridors (e.g. Amtrak's Northeast Corridor [NEC])
  - Transit applications
- Number of concrete sleepers in North America*:
  - Freight → 25,000,000
  - Passenger → 2,000,000
  - Transit → Significant quantities (millions)

**Approximate*

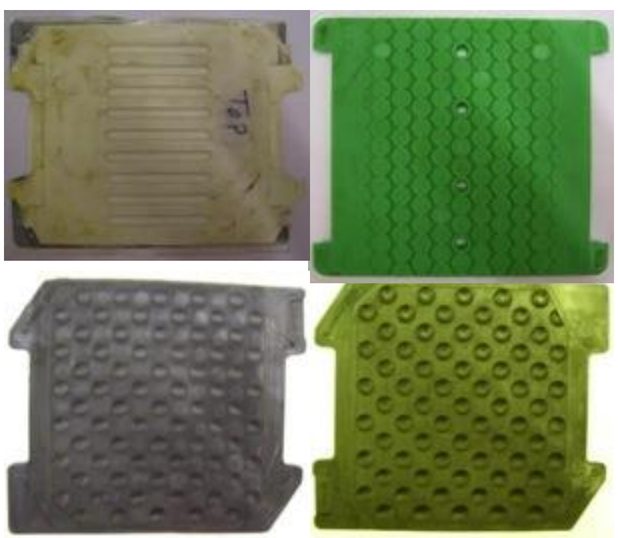
Concrete Sleeper and Fastening System Components

Concrete Sleepers

Clips

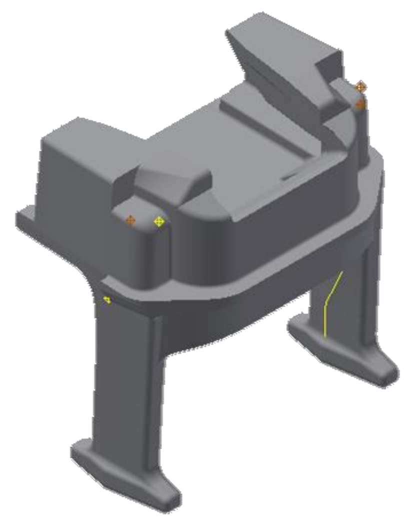


Rail Pads



Fastening Insulators

Shoulder



RailTEC Concrete Sleeper and Fastener Research Program Levels

Materials

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

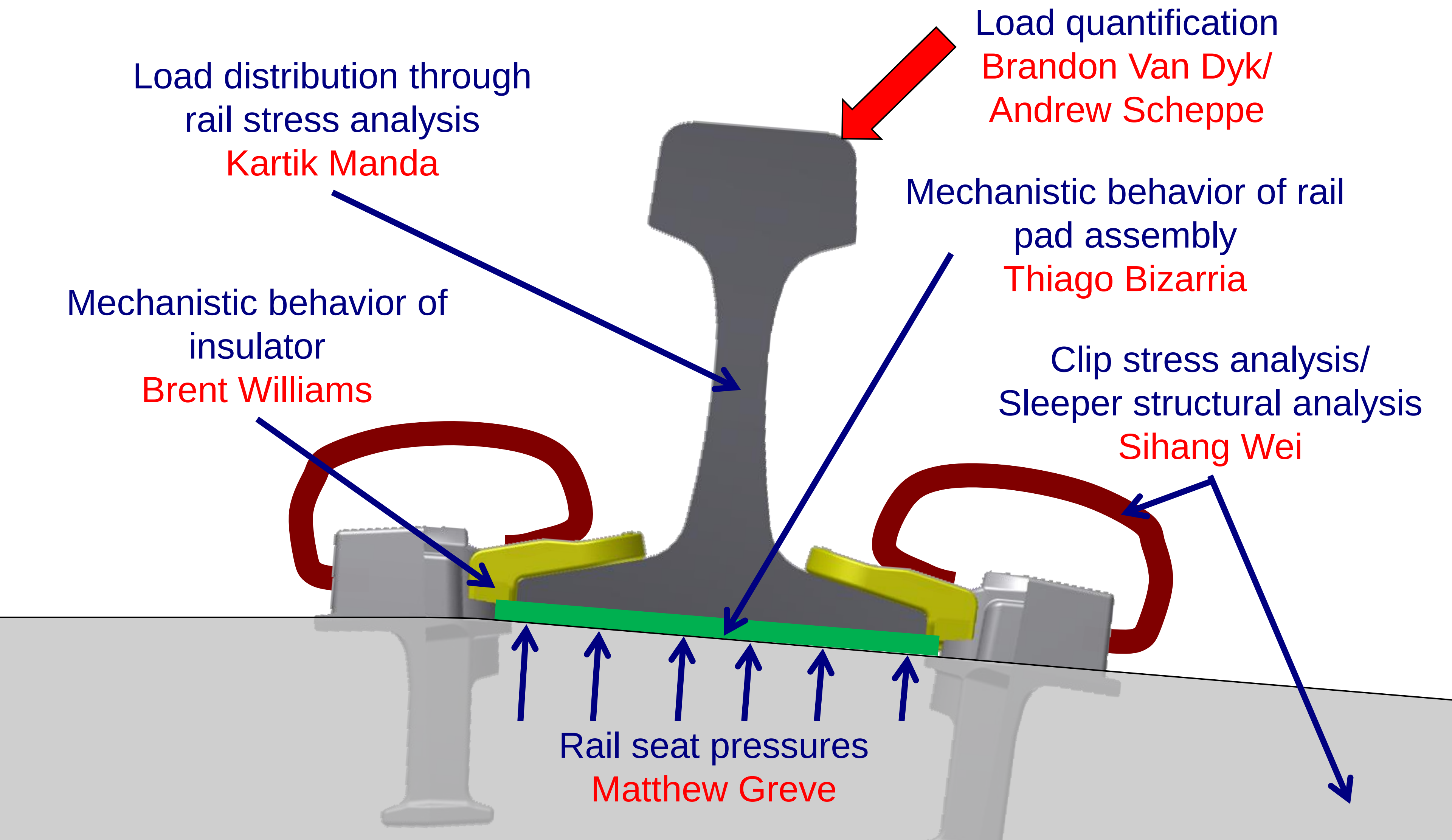
Components

- 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



Other research: Concrete materials (Emily Van Dam),
FE modeling (George Chen and Austin Zhang)

FRA Tie and Fastening System BAA Objectives and Deliverables

U.S. Department of Transportation
Federal Railroad Administration

- **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 BAA Industry Partners:

UNION PACIFIC BUILDING AMERICA®
BNSF RAILWAY
AMTRAK®
Amsted RPS
Amsted Rail
GIC INGENIERÍA Y CONSTRUCCIÓN S.A. DE C.V.
HANSON
LBFoster 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

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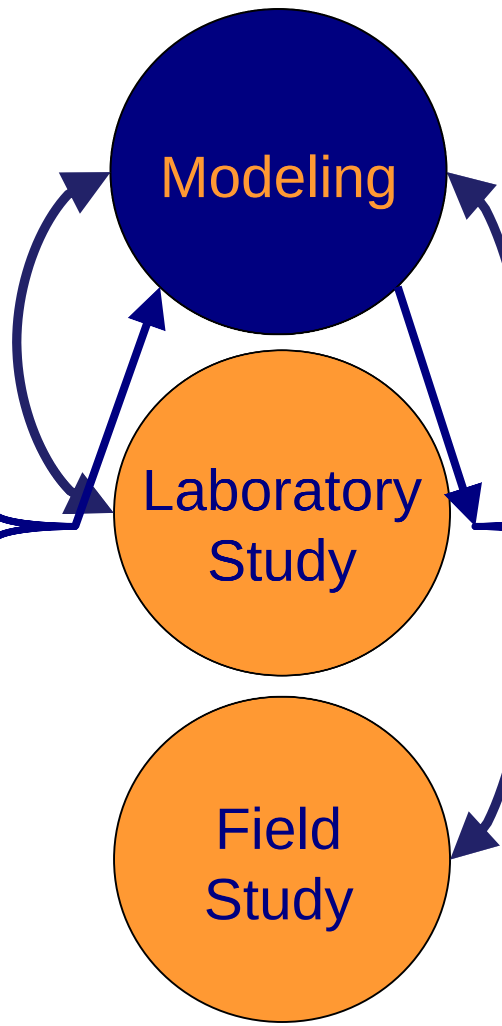


Outputs/Deliverables

Data Collection

Document Depository

Groundwork for Mechanistic Design

International Survey Report

Load Path Map

Parametric Analysis

State of Practice Report

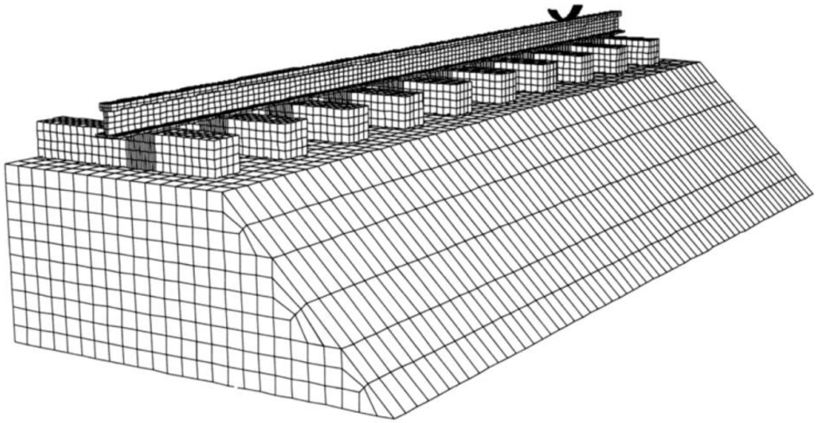
Validated Tie and Fastening System Model

Improved Recommended Practices

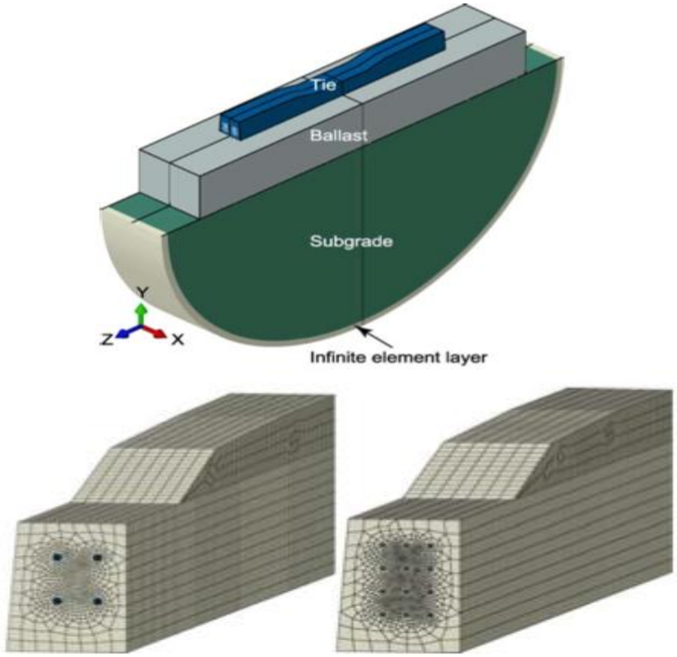
Track Superstructure Modeling – Prior Work

Track System Modeling

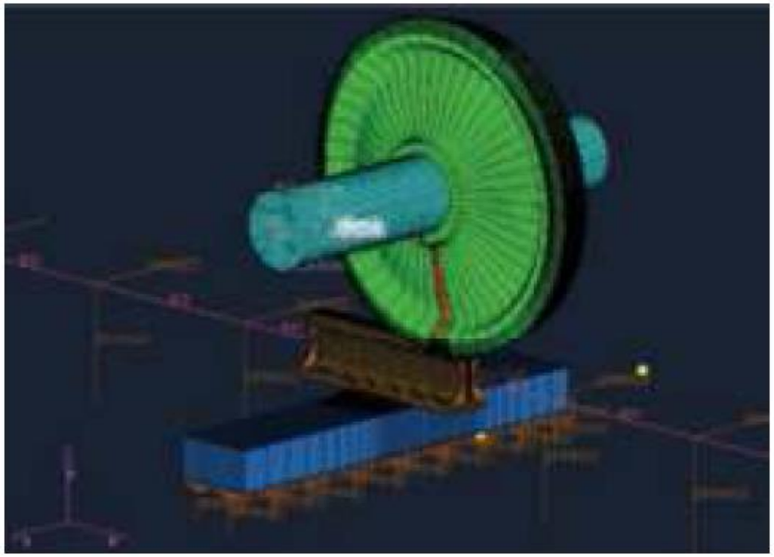
- Simplified fastening systems
- Focused on vertical loading
- Simplified support conditions



(Lundqvist and Dahlberg, 2005 - Sweden)



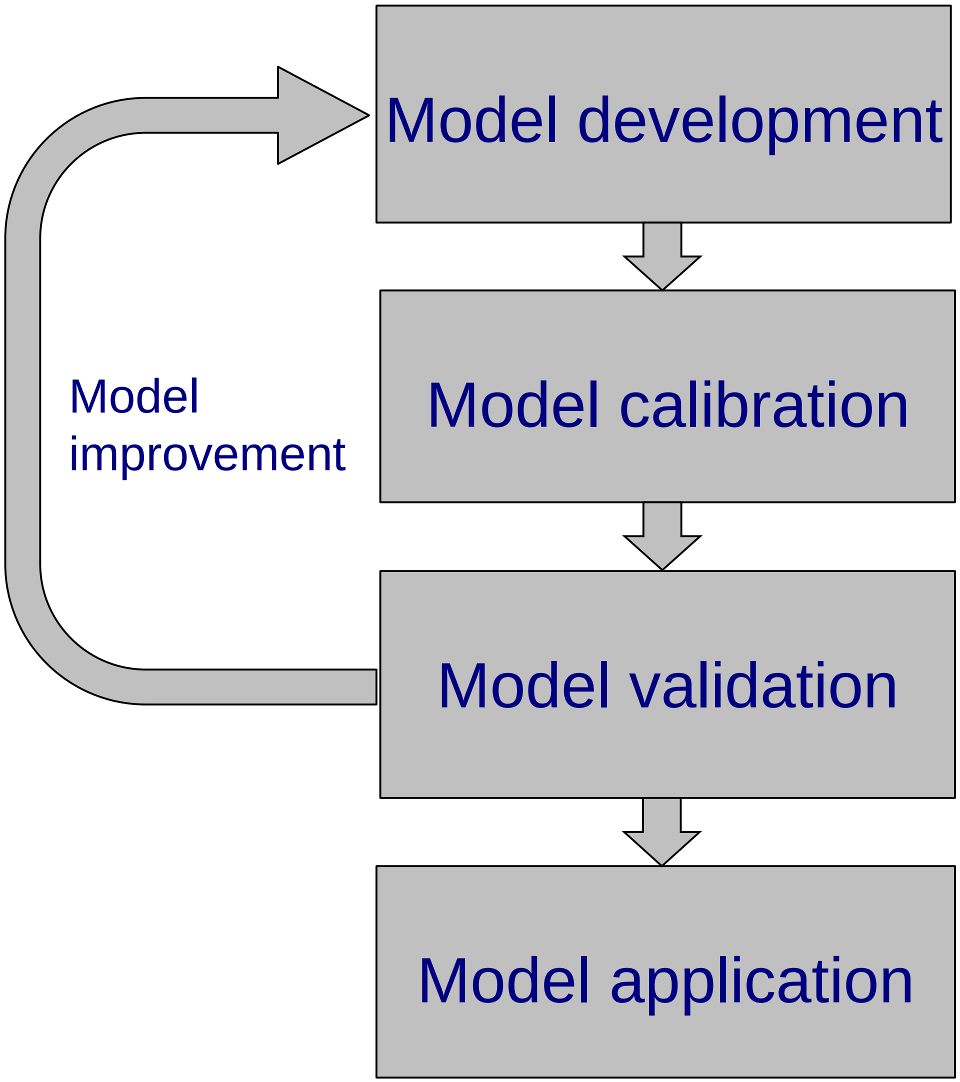
(Yu and Jeong, 2011)



(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

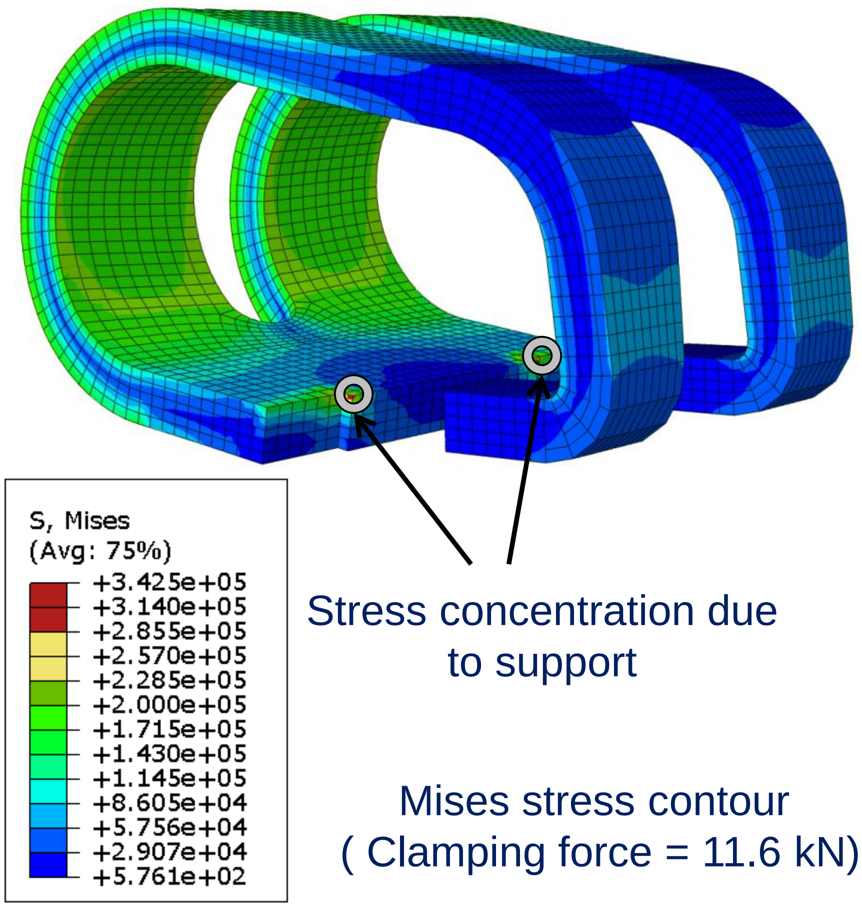


UIUC Sleeper and Fastener FE Modeling Approach

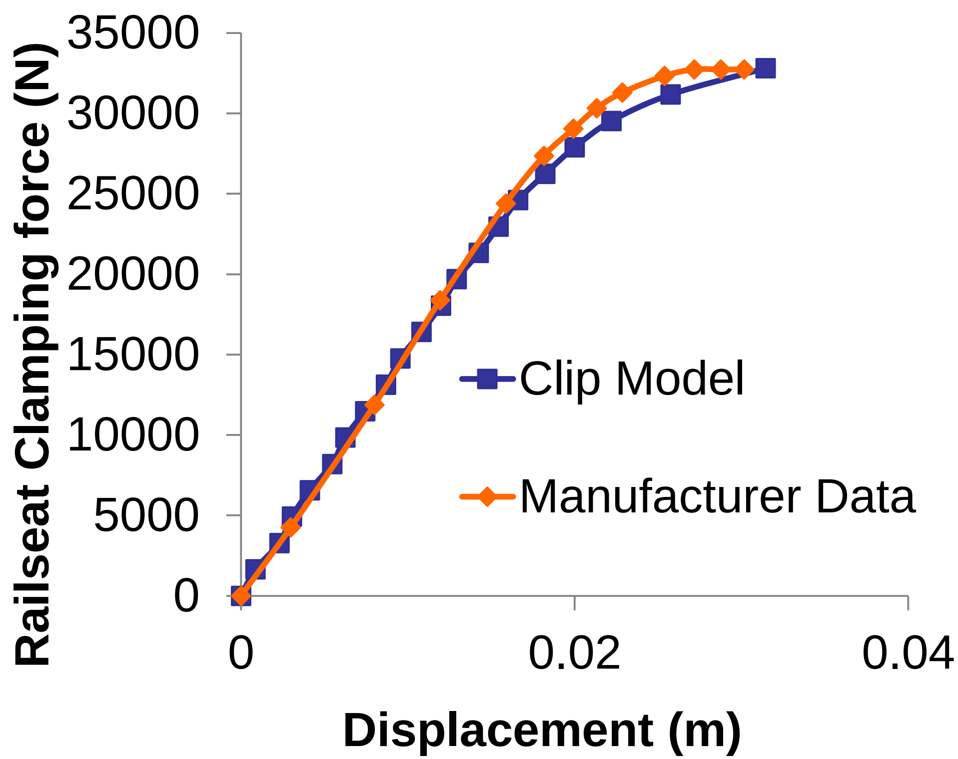
- Modeling was conducted using ABAQUS
- All elements, except the prestress strand, were modeled using eight-node brick elements
- Each node had three translational degrees of freedom (DOF)
- Prestress strands were modeled as 1-D truss element with stiffness along length of sleeper
- Concrete material property was modeled using damage plasticity model
- Mesh density was varied for each component per demand

Review of Model Development: Component Model

Component Validation



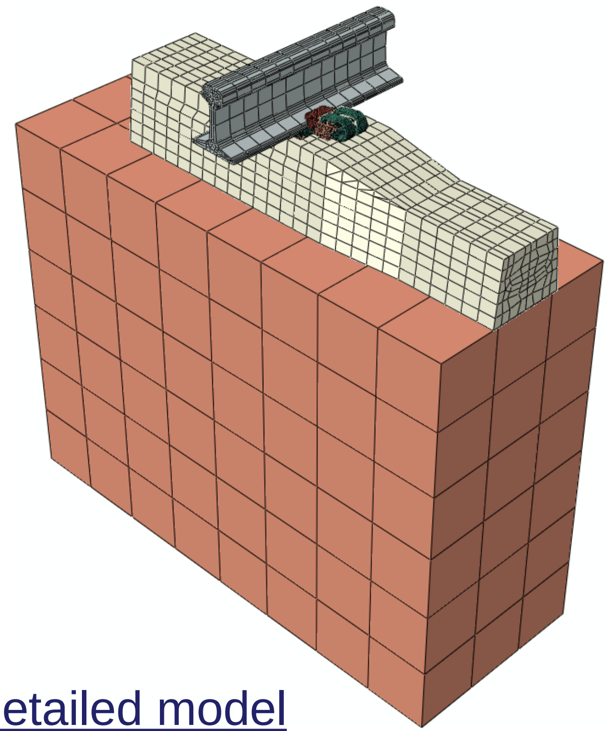
Mises stress contour
(Clamping force = 11.6 kN)



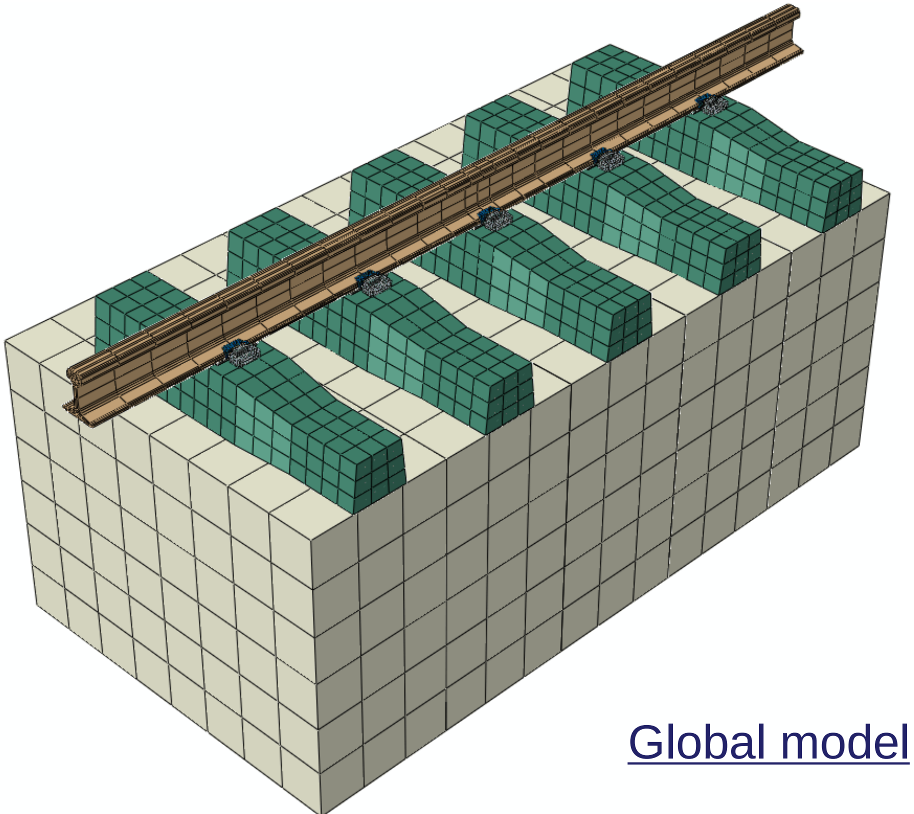
Clamping force-displacement curves

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



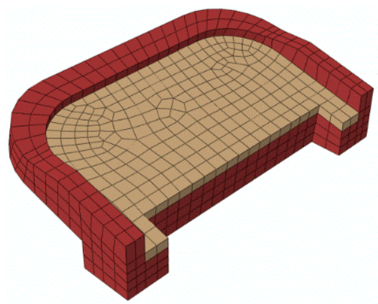
Detailed model

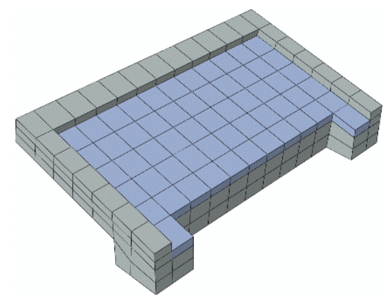


Global model

FE Models for Field Experiment

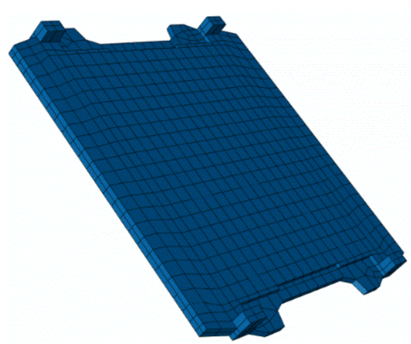
- Detailed Model:
  - Component geometry is very detailed
  - Fine mesh defined
  - Clamping force applied with clips
- Global Model:
  - Component geometry is simplified
  - Coarse mesh is defined
  - Clamping force represented with pressure

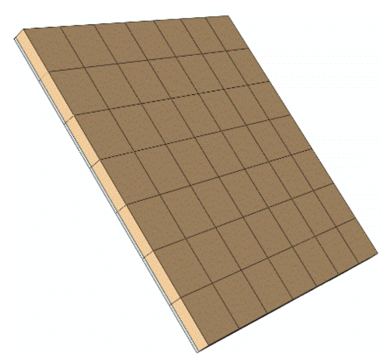




Detailed model

Global model





FE Models for Field Experiment

- Detailed Model:
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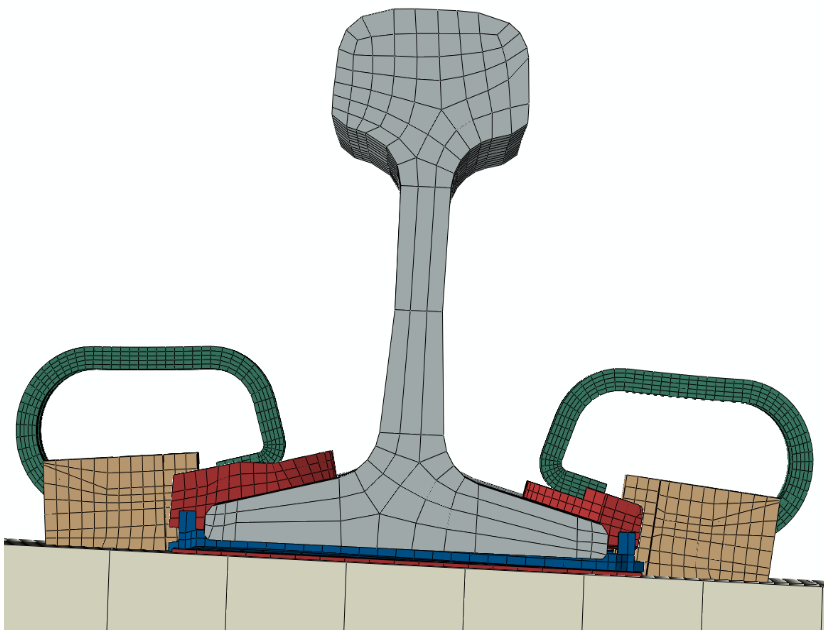
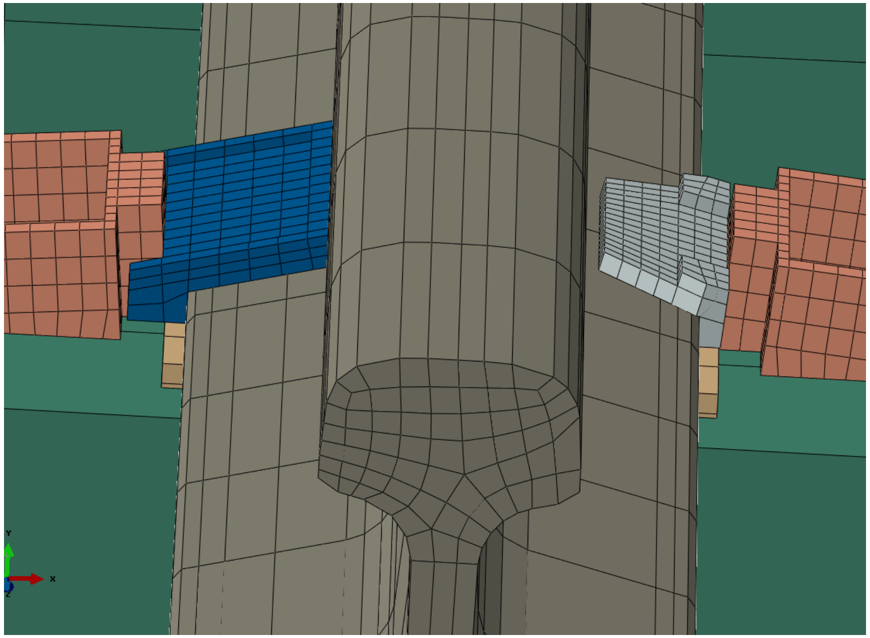
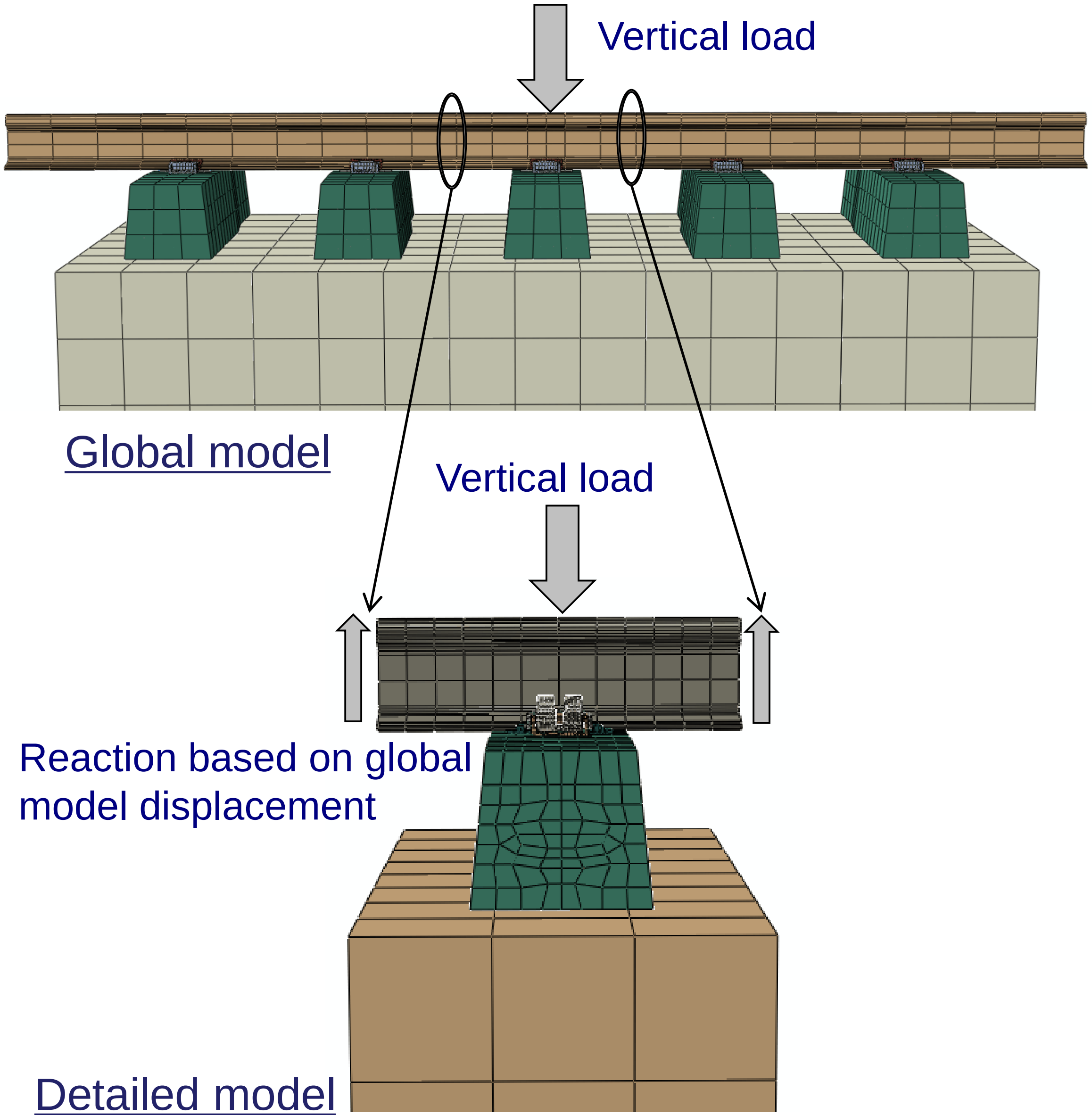




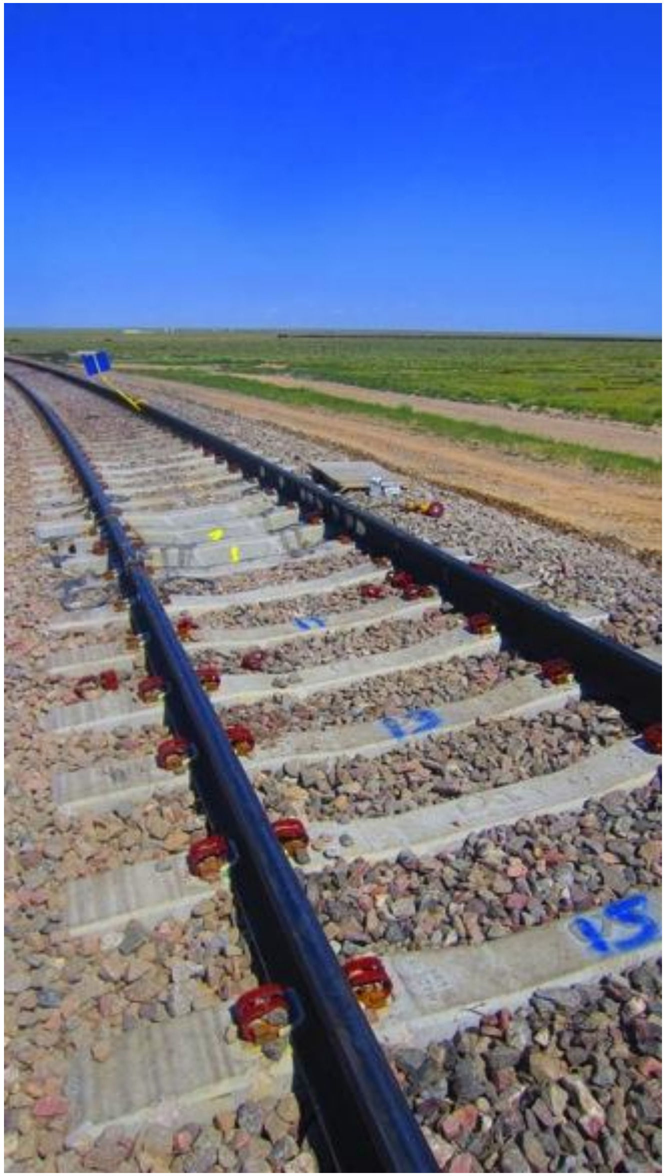
FE Models for Field Experiment

- 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

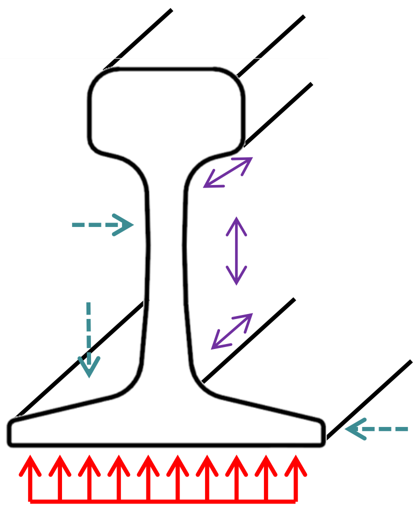
- Initial calibration was based on laboratory data
- Next step → acquire field data to further refine the FE model
- Data acquired for model calibration:
  - Vertical sleeper displacement
  - Lateral force at iron shoulder
  - Lateral rail base and web displacement
  - Vertical force at rail seat



Field Experimentation: Primary Areas of Investigation

Rail

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

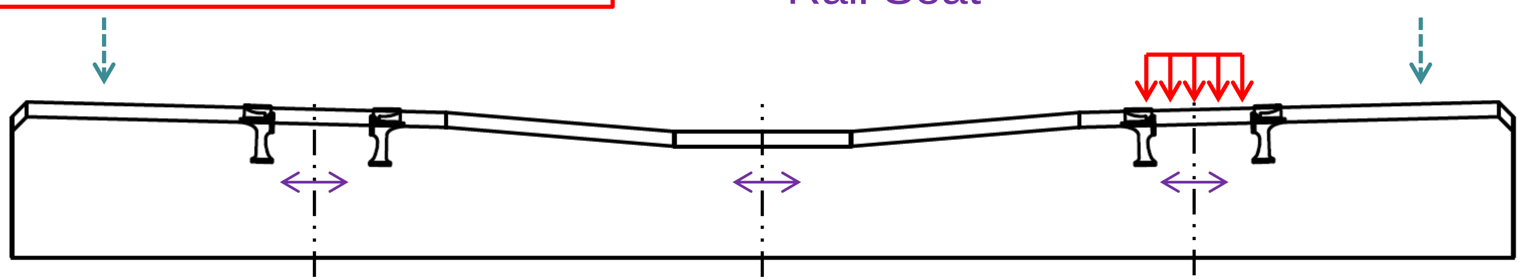


Fasteners/ Insulator

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

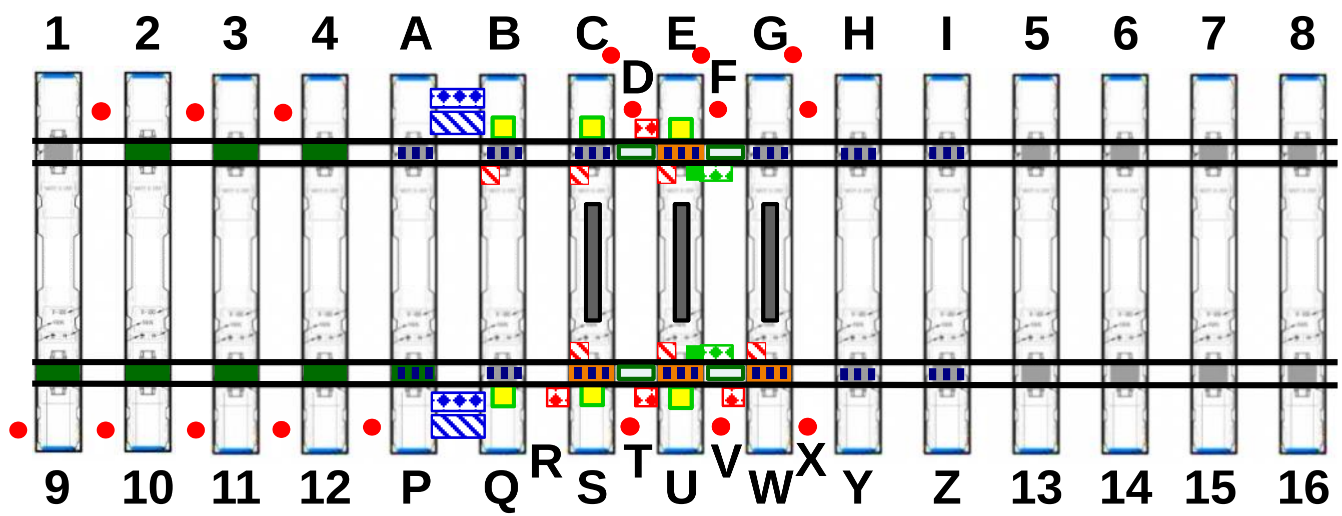
Concrete Sleepers

- Moments along sleeper
  - Midspan
  - Rail Seat
- Stresses at rail seat
- Vertical displacements of sleeper



May 2013 Field Instrumentation

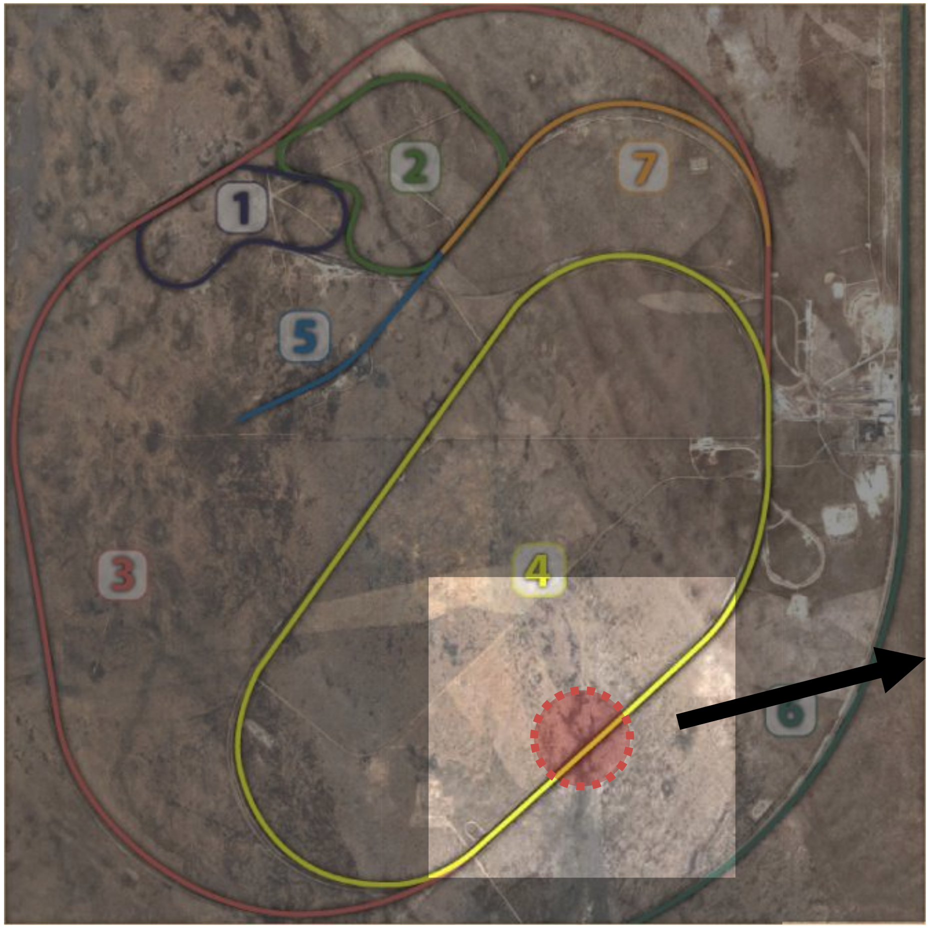
- Acquired data from ~200 channels of instrumentation simultaneously
- All instrumentation was deployed to achieve a specific objective
- A sub-set of the data was acquired for model calibration and validation



Rail Displacement Fixture
Rail Longitudinal Displacement/Strains
Pad Assembly Longitudinal Displacement
Pad Assembly Lateral Displacement
Insulator Longitudinal Displacement
Insulator Vertical Displacement
Steel Rods

Vertical Web Strains
Vertical and Lateral Circuits
Shoulder Beam Insert (Lateral Force)
Embedment Gages, Vertical Circuit, Clip Strains
Sleeper Surface Strains
MBTSS

Field Instrumentation Locations



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

Loading Environment

- Track Loading Vehicle (TLV)
  - Static
  - Dynamic

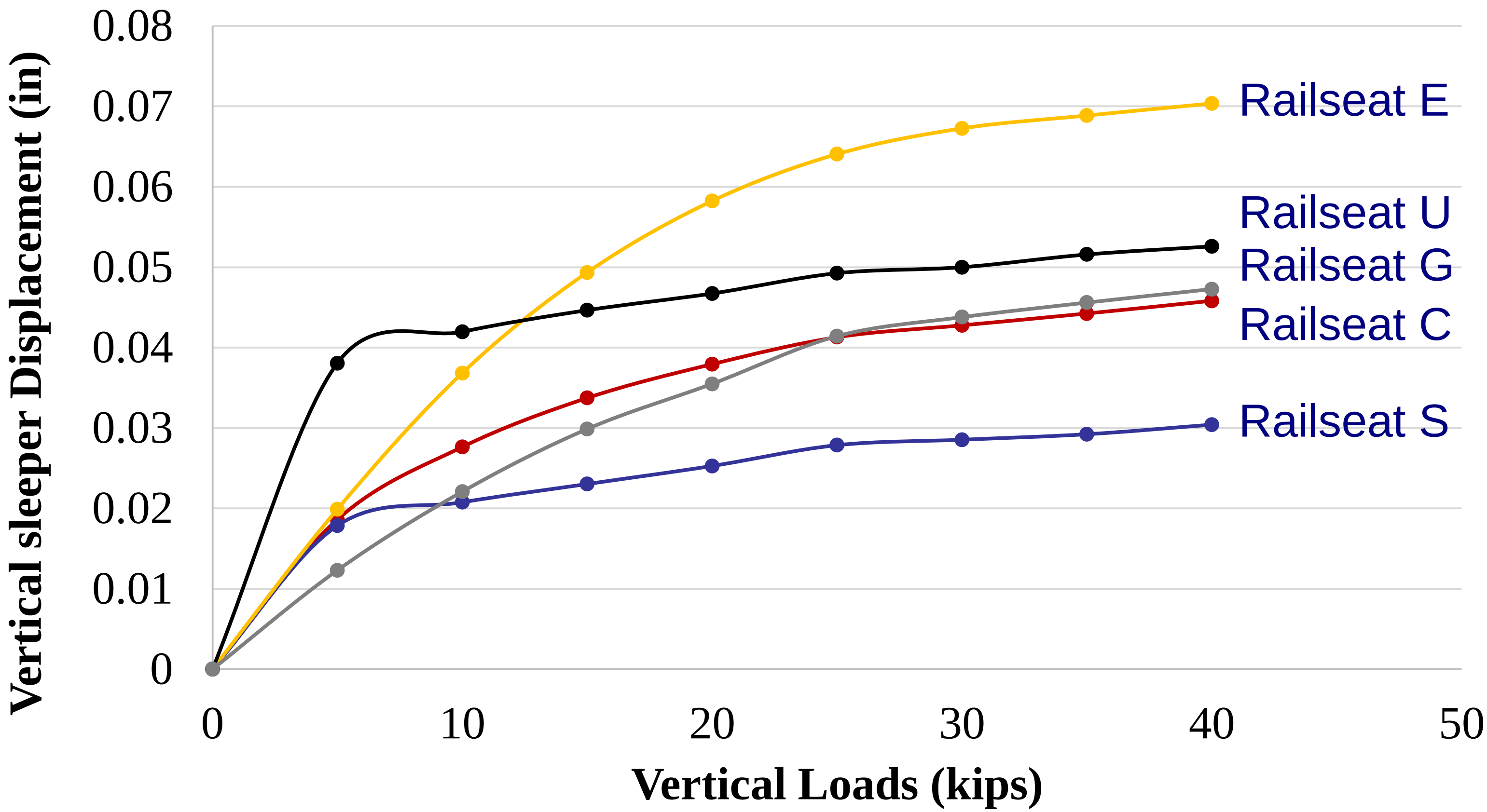
- Freight Consist
  - 3, 6-axle locomotives on HTL
  - 4-axle locomotives on RTT
  - 9 loaded and one empty freight cars
- Passenger Consist
  - 6-axle locomotive on HTL
  - 4-axle locomotive on RTT
  - 10 coaches
- FAST Train

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

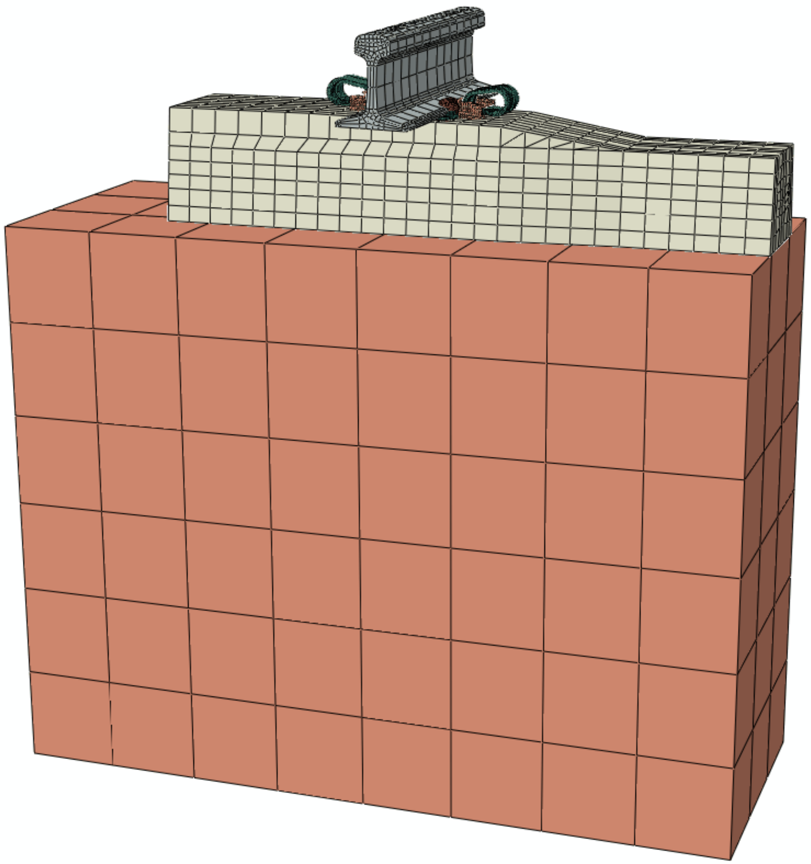
Vertical Sleeper Displacement: Acquired Data

- 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)



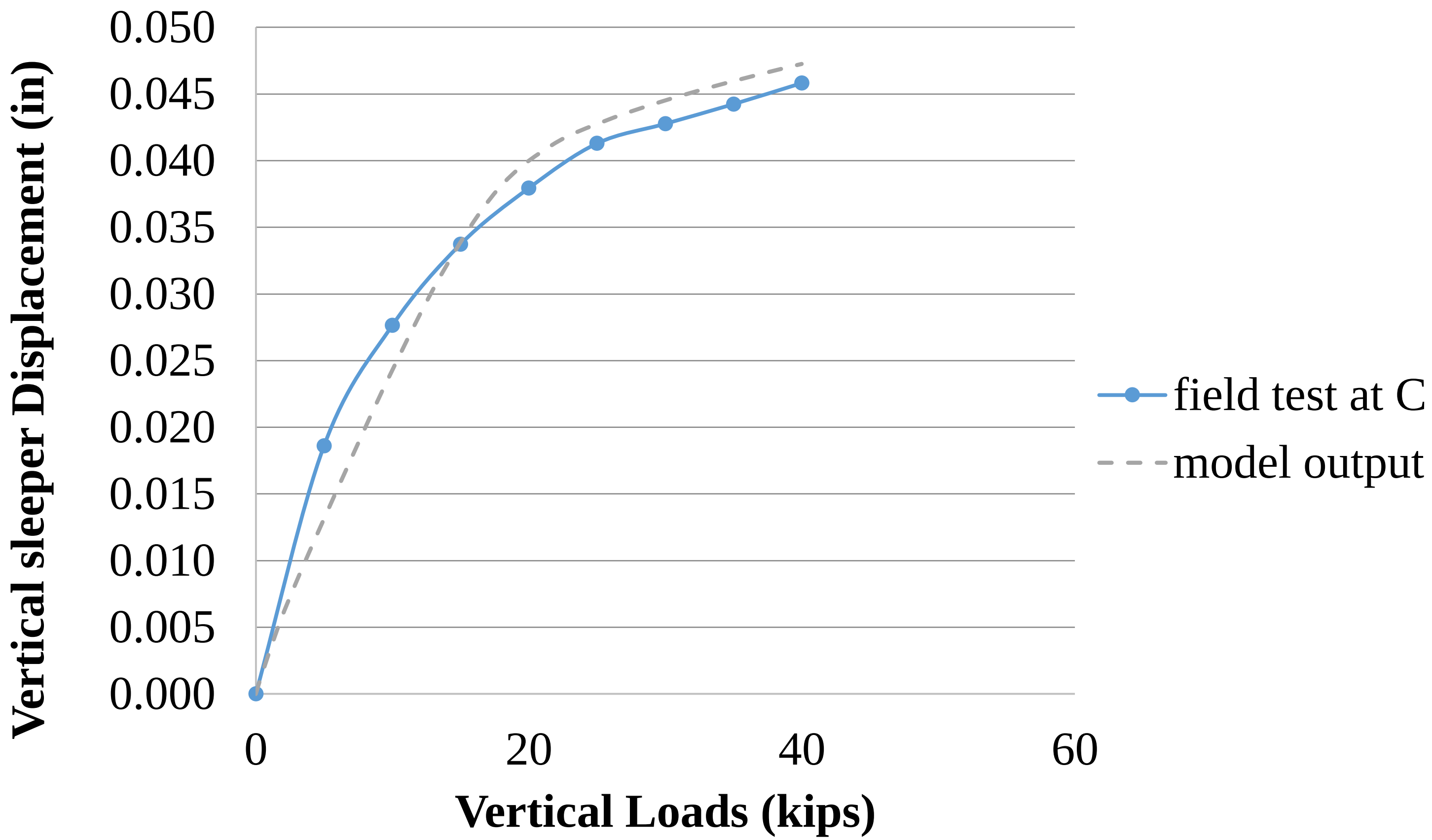
Vertical Sleeper Displacement: Calibration Approach

- 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



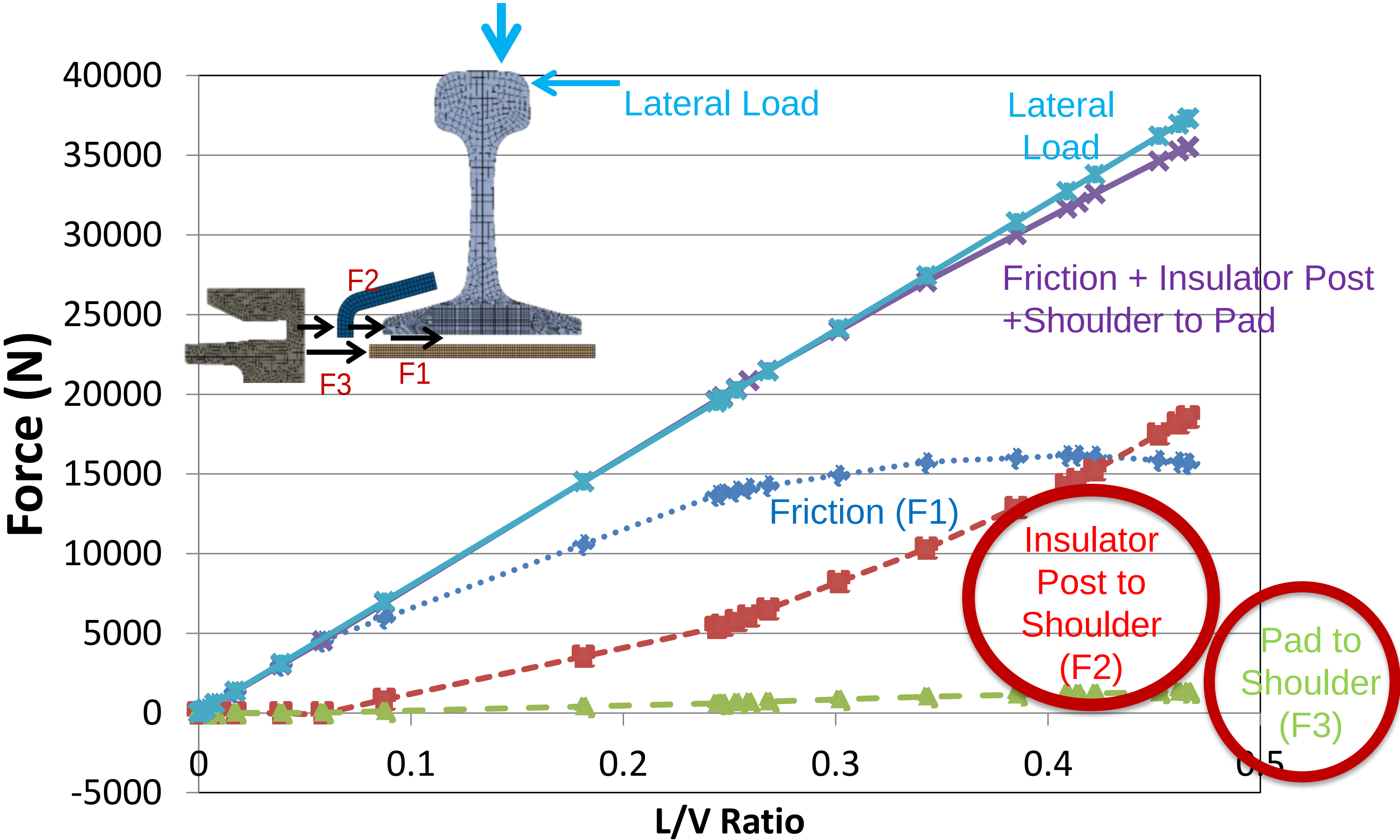
Vertical Sleeper Displacement: Calibration Results

- 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



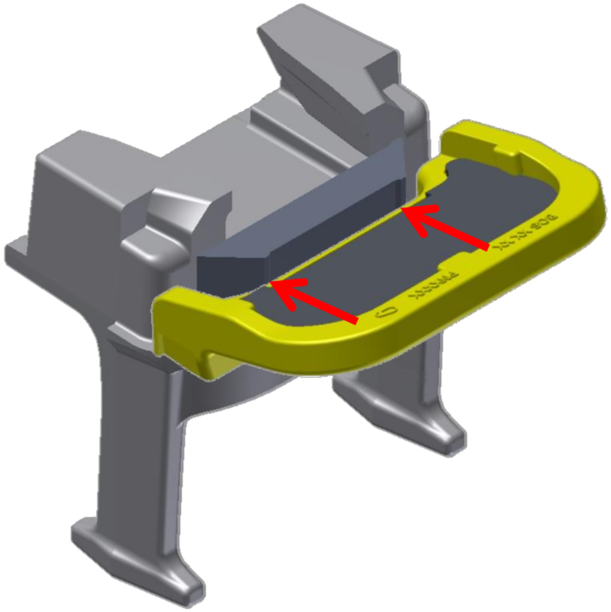
Lateral Rail Seat Load Model Calibration

- 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



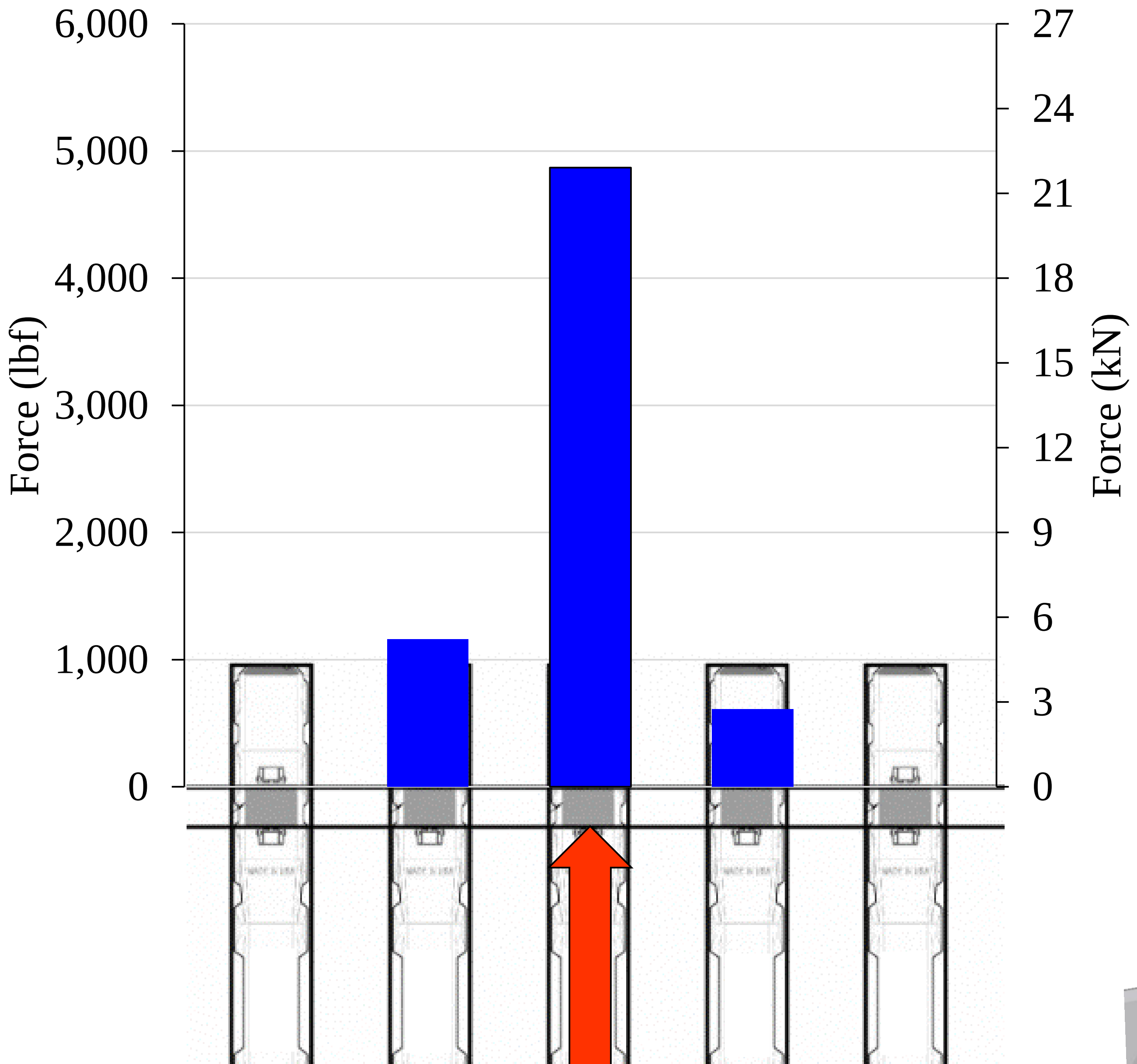
Lateral Shoulder Force: Instrumentation Deployed

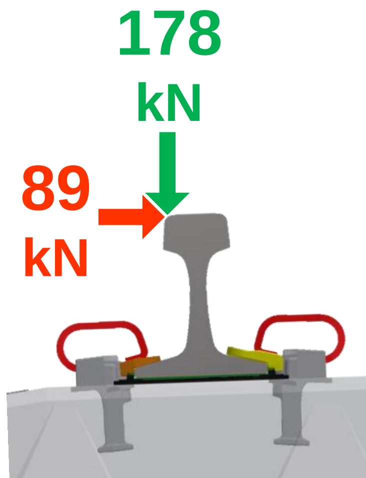
- Lateral Load Evaluation Device (LLED)
  - Original shoulder face is removed
  - Insert designed as a beam and optimized to replace removed section and maintains original geometry
  - Measures bending strain of beam under 4-point bending
    - Measuring bending strain is a proven technique



Field Installation

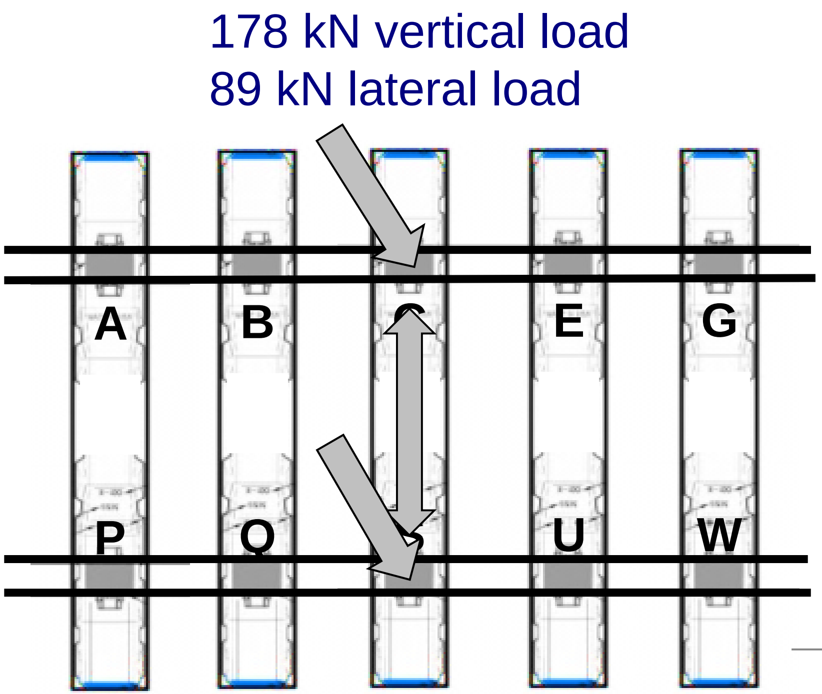
Lateral Shoulder Force: Acquired Data

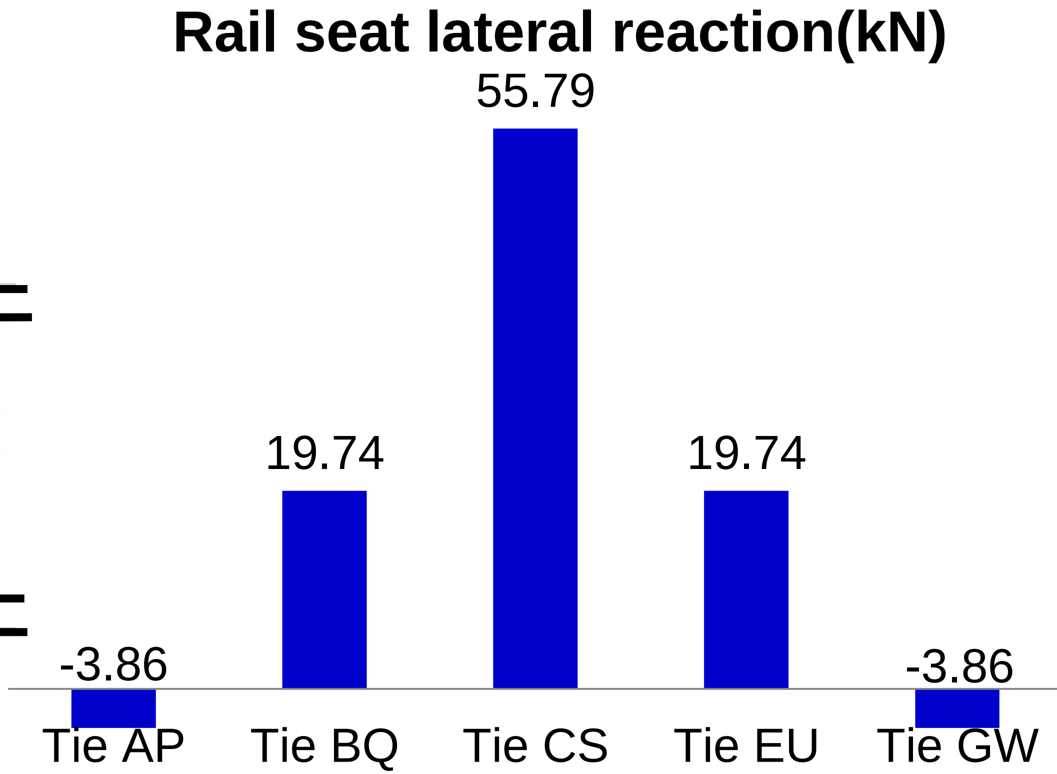




Lateral Rail Seat Load: Model Output

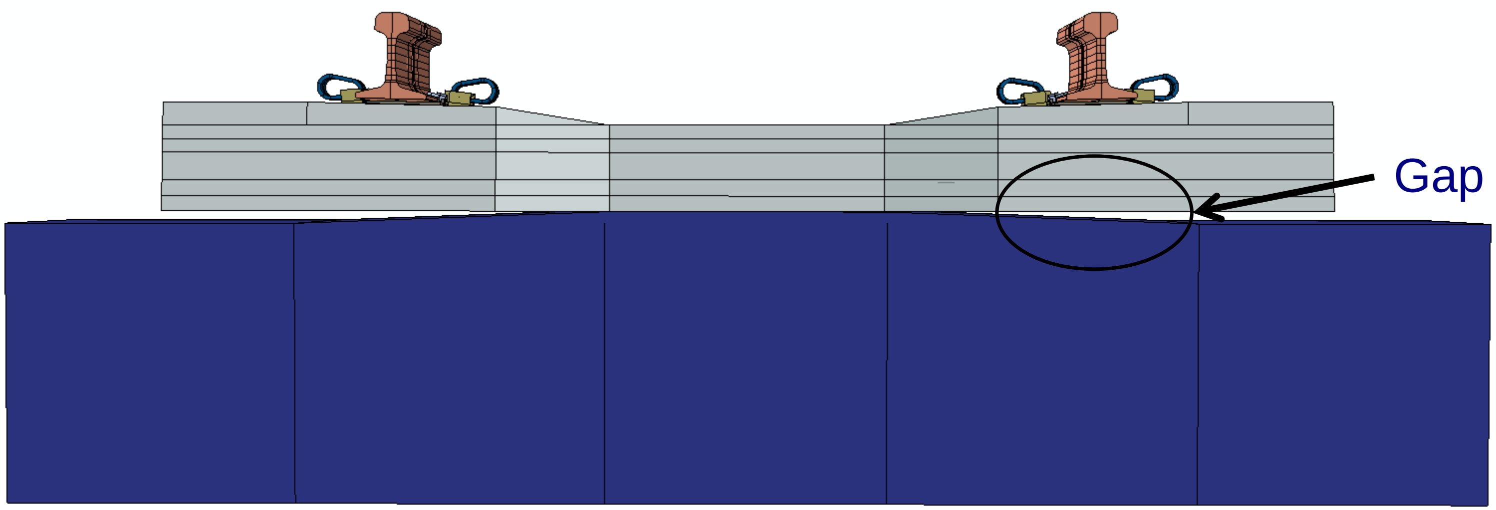
- Literature states lateral load distribution is similar to vertical load
- Results show that the lateral load distribution is over fewer sleepers





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

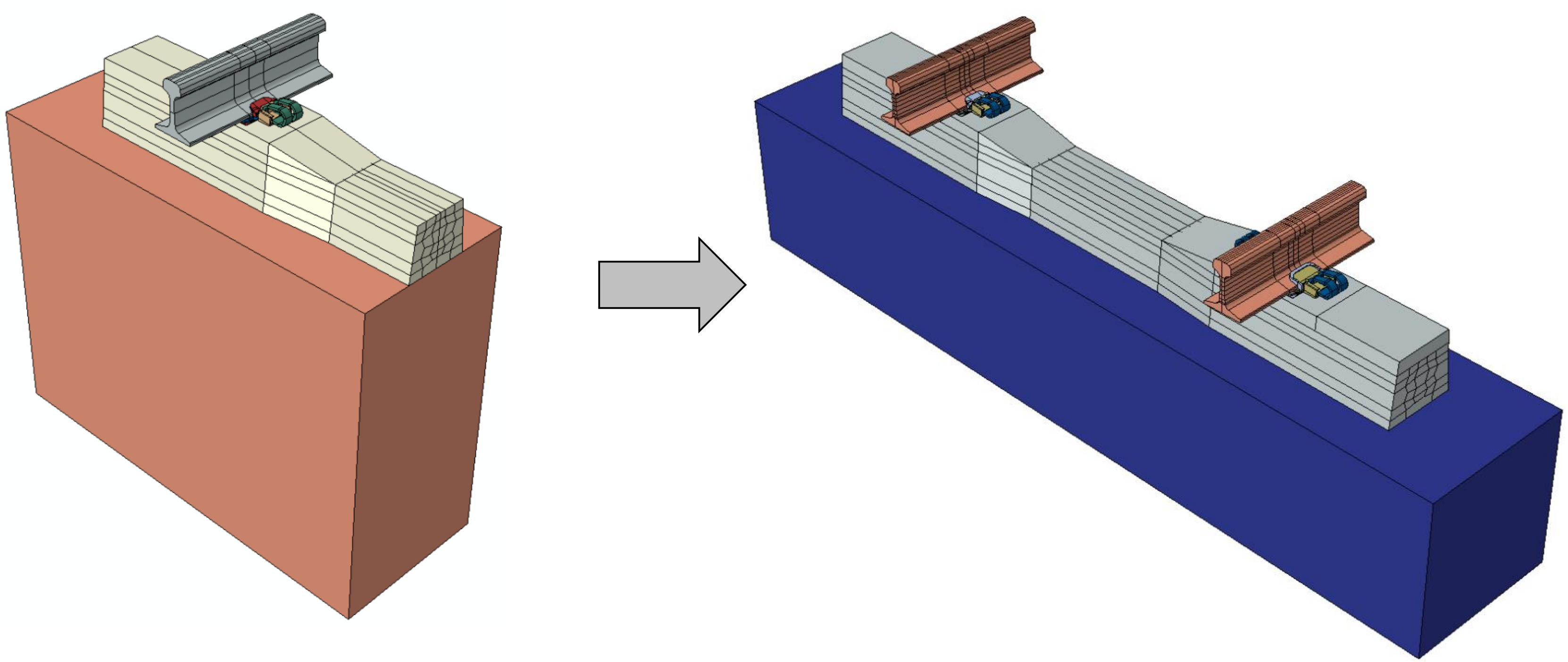


Conclusions

- 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

I – TRACK

Statistical Analysis from FEM

Free Body Diagram Analysis

Probabilistic Loading

Finite Element Model

Laboratory Experimentation

Field Experimentation

Parametric Analyses

2014 International Crosstie and Fastening System Symposium

http://ict.uiuc.edu/railroad/Crosstie/2014/crossties.php

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.

Acknowledgements

U.S. Department of Transportation

Federal Railroad Administration

- Funding for this research has been provided by the Federal Railroad Administration (FRA)
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  - Union Pacific Railroad
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  - Hanson Professional Services, Inc.
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  - TTX Company
- Professor Erol Tutumluer for assisting with ballast modeling (UIUC)
- Entire Concrete Crosstie and Fastening System Research Team at UIUC

FRA Tie and Fastener BAA Industry Partners:

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http://ict.uiuc.edu/railroad/CEE/crossties/downloads.php

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