Mechanistic Investigation of Timber Crosstie Spike Failures

Preliminary Findings from the Laboratory and Field

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U.S. Department of Transportation
Federal Railroad Administration

RAILTEC
UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

Acknowledgements

- Project Sponsor

U.S. Department of Transportation
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- Industry Partnership

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Presentation Outline

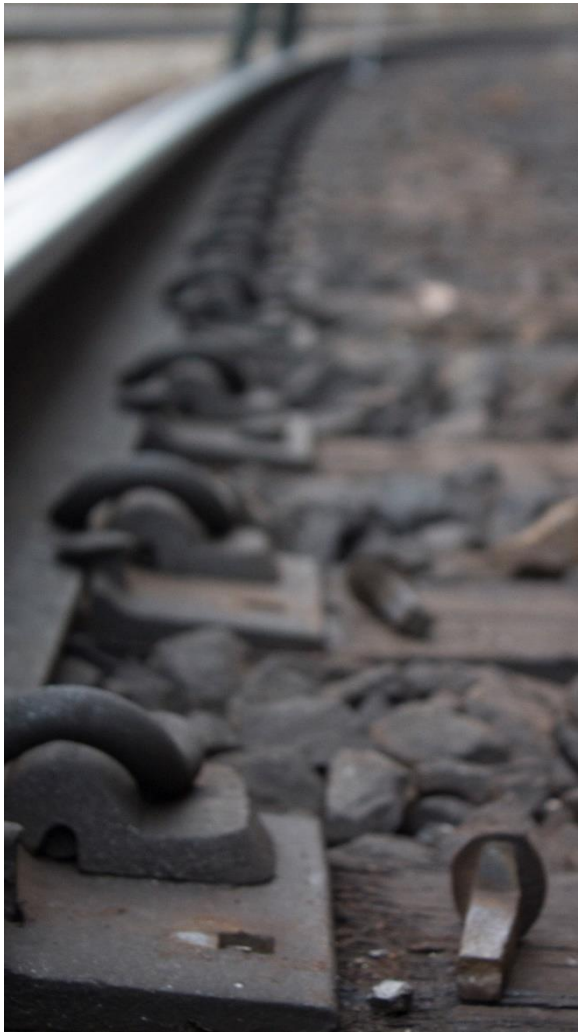
- Project Overview
- Phase I Review
- Phase II
  - Laboratory Experimentations
    - Single Spike Testing
    - Single Fastener Plan
  - Field Experimentation
    - Instrumentation
    - Hypotheses
  - Field Data Examples and Comparisons
    - Vertical Forces
    - Lateral Forces
    - Longitudinal Forces
    - Longitudinal Displacements
- Future Work

Project Overview

- **PHASE I:** How large is the problem?
  - Industry Survey
  - Interviews and Site Visits
  - Document scope of the problem
  - Hypotheses about spike breakage

- **PHASE II:** What is causing spike failures?
  - Execute laboratory experimentation plan developed in PHASE I
  - Attempt to replicate failures in the laboratory
  - Develop and perform parametric analyses with FE models of fastening systems
  - Validate models with laboratory work

- **PHASE III:** How do we prevent the failures?
  - Perform additional lab tests/FEA as needed
  - Investigate design improvements
  - Recommend improvements



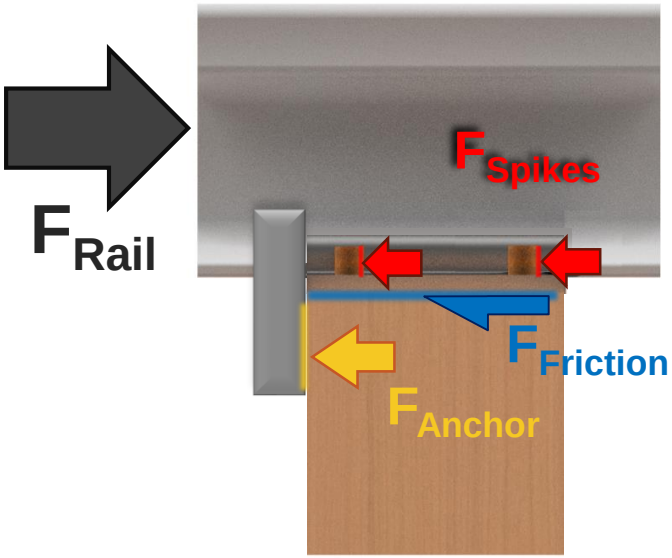
Phase I Review

- Spikes have been failing due to fatigue
  - Primarily on *premium fastening system*
  - Often *new ties*
  - Mainly on *curves*
  - Also in *special trackwork*
- Most likely a mechanism problem
- Leads to rapid gauge deterioration and have caused at least 11 derailments since 2000

Potential Factors

- *Lack of anchor increases* longitudinal loads

Traditional System with Anchor



$$F_{Spikes} = F_{Rail} - F_{friction} - F_{Anchor}$$

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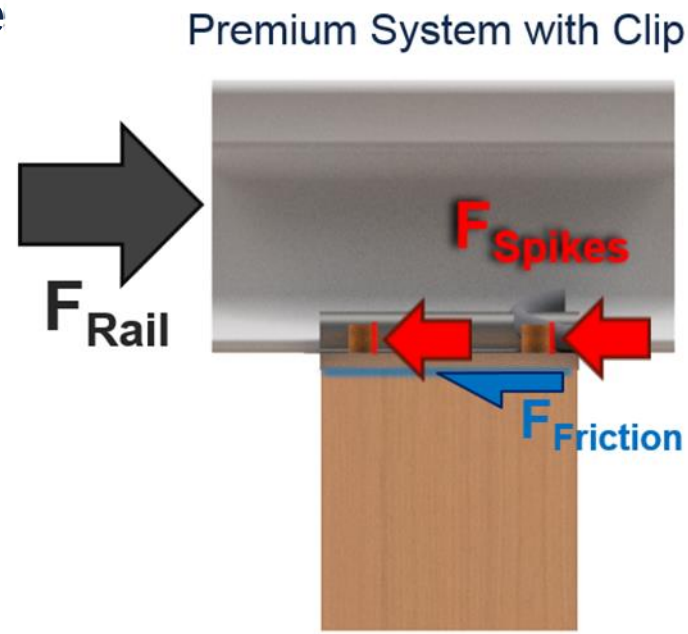

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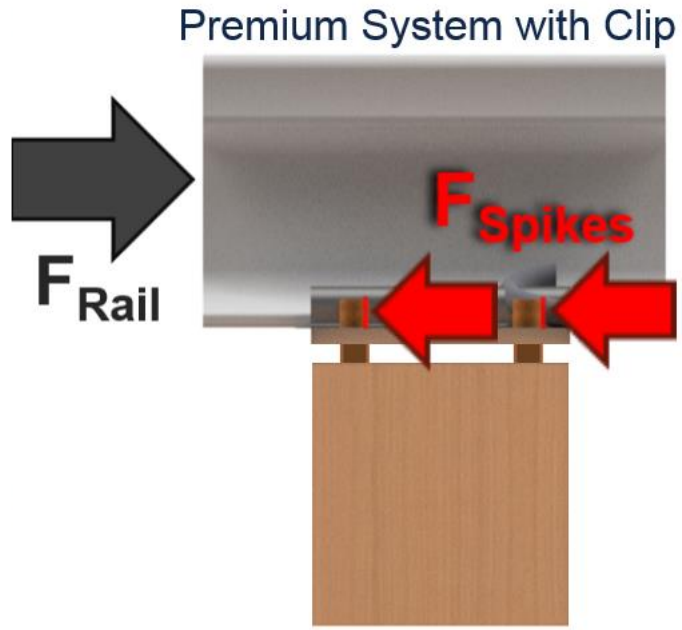
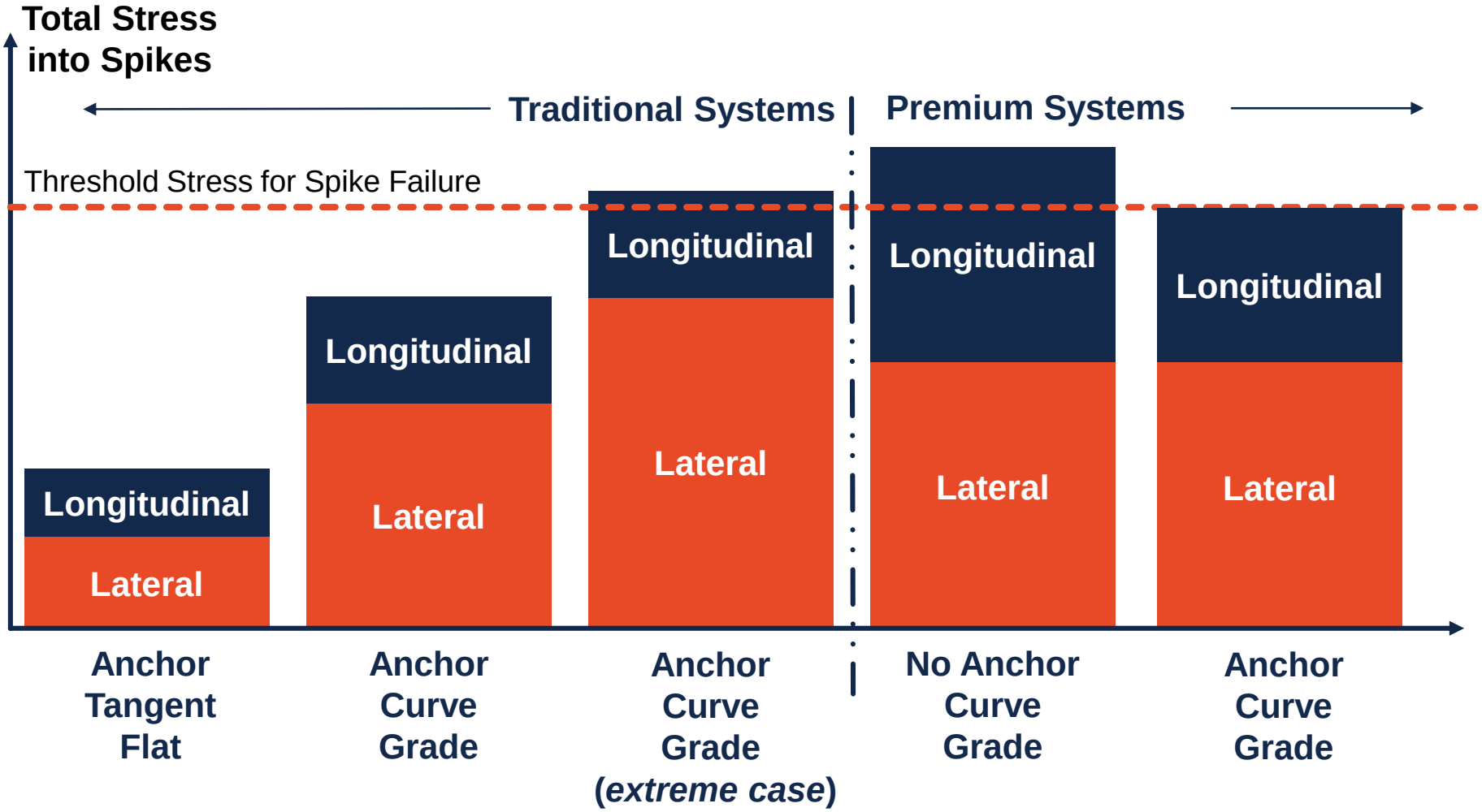
Potential Factors

- *Lack of anchor increases* longitudinal loads
  - *Plate uplift* further increases loads
  - Wood is weaker on that direction
- Stiffer fasteners reduces distribution of loads
- Crosstie age



$$F_{Spikes} = F_{Rail}$$

Stress in Spikes – Hypothetical Graph



Phase II | Laboratory Experimentation

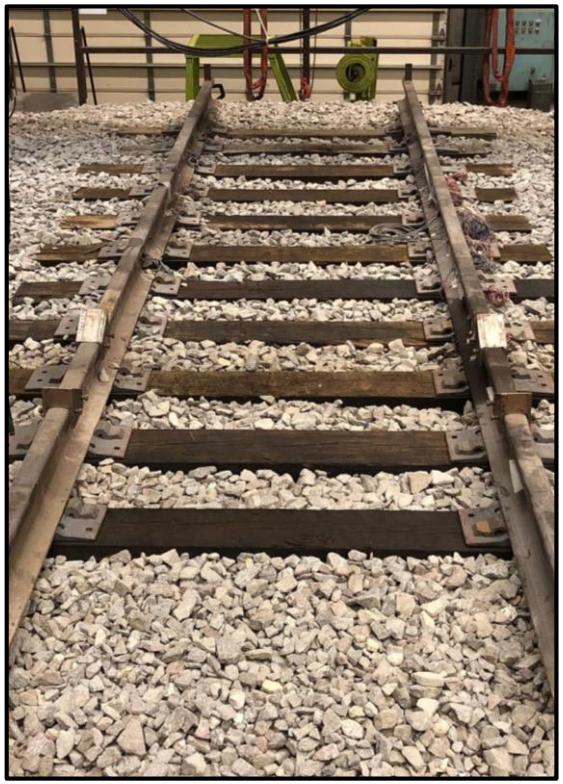
Understanding Fastener Mechanics

- Three stages of component testing under longitudinal loads

Single Spike

Single Fastener

Track Assembly



Single Spike Experimentation

Two Types of Experimentation

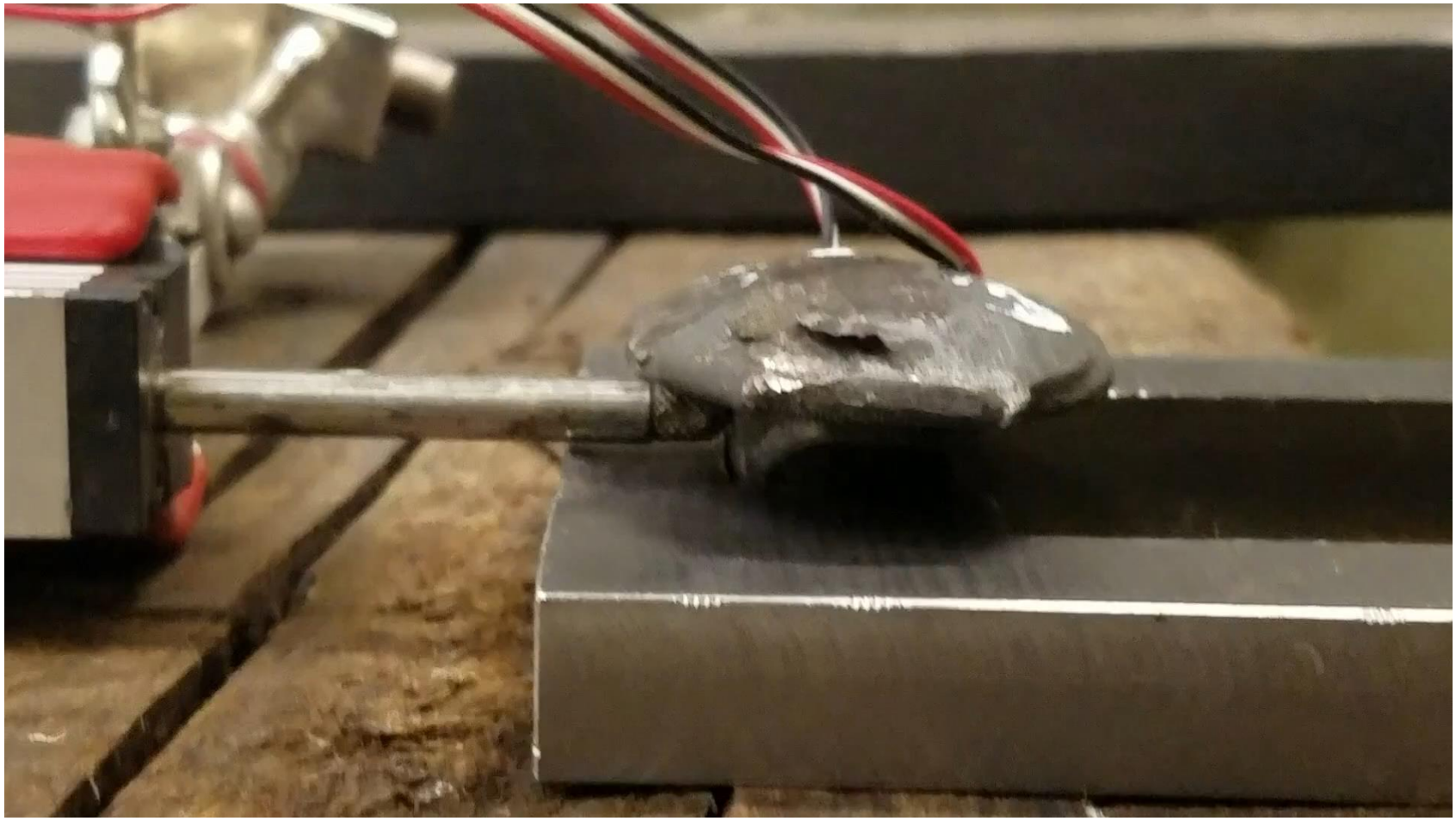
- Fatigue testing of cut spikes
- Static and cyclic longitudinal loading of cut spikes

Findings

- Fatigue failures recreated in the laboratory
- AREMA (Ch. 5) yield stress can be reached with less than 2,000 lb. longitudinal force
- Maximum stress along spike occurs at ~1.5” as would be expected based on field observations*(Shown in following slide)*
  - Provided data for FEM calibration

Cyclic Testing – Shakedown

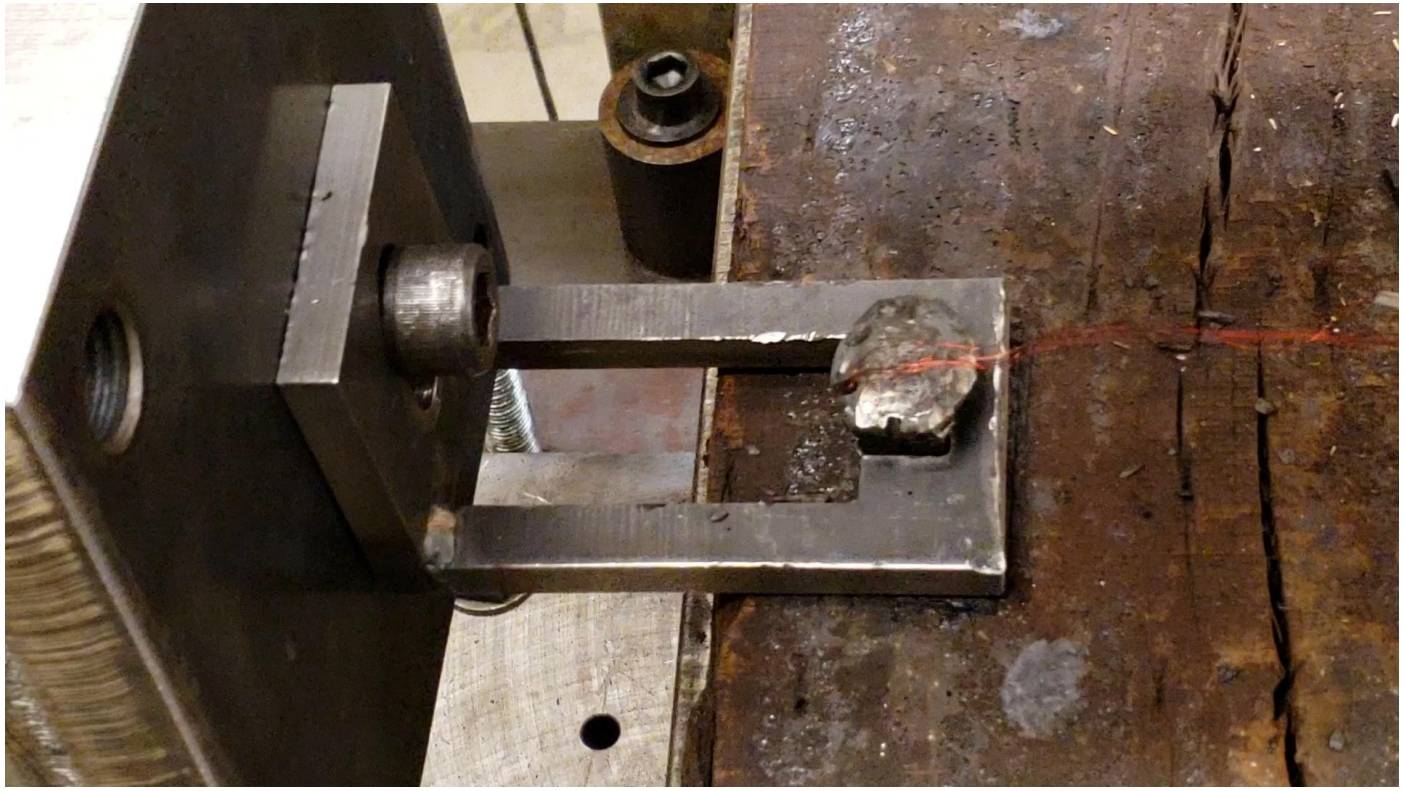
Timber block with splits



- It appears the “splitting” allows for increased spike rotation and decreased bending

Cyclic Testing – Shakedown

Timber block with no split

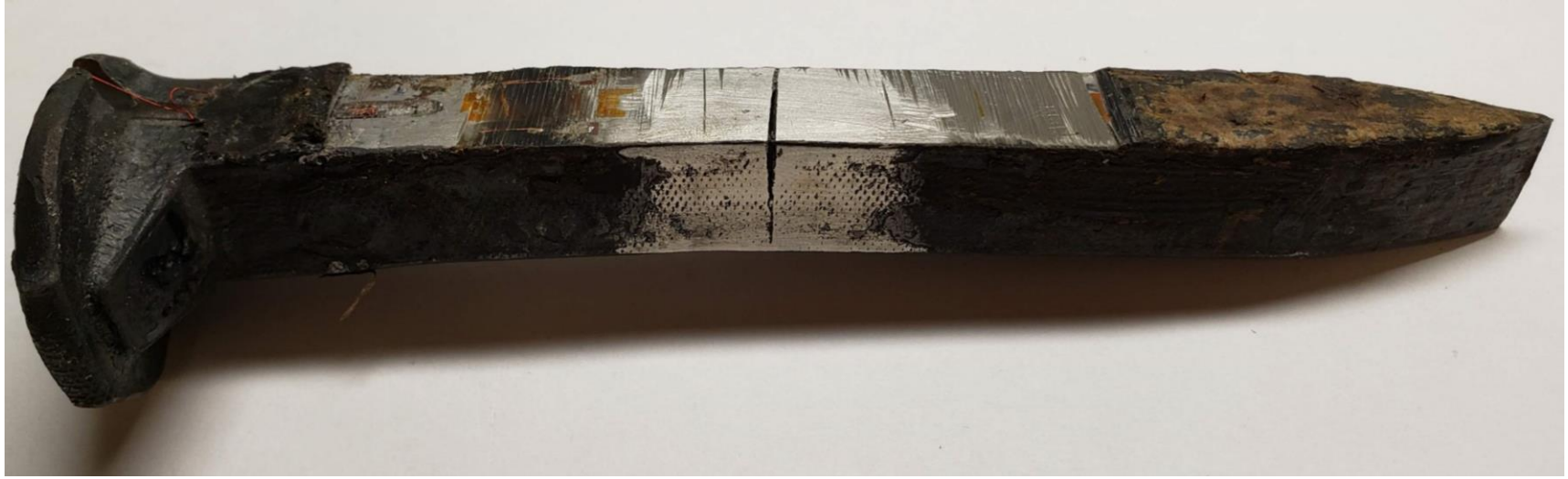


- No “splitting” leads to increased spike bending and decreased rotation

Cyclic Testing – Shakedown

Varying Load Magnitude

- Load: Longitudinal only
  - ~2.40 M cycles between 200 and 1,500 lb.
  - ~3.60 M cycles between 200 and 1,900 lb.
  - ~0.25 M cycles between 200 and 2,300 lb.
- Failure information:
  - Approximate depth to failure: 1.56” from top of crosstie
  - Approximate cycle count 6.25 M

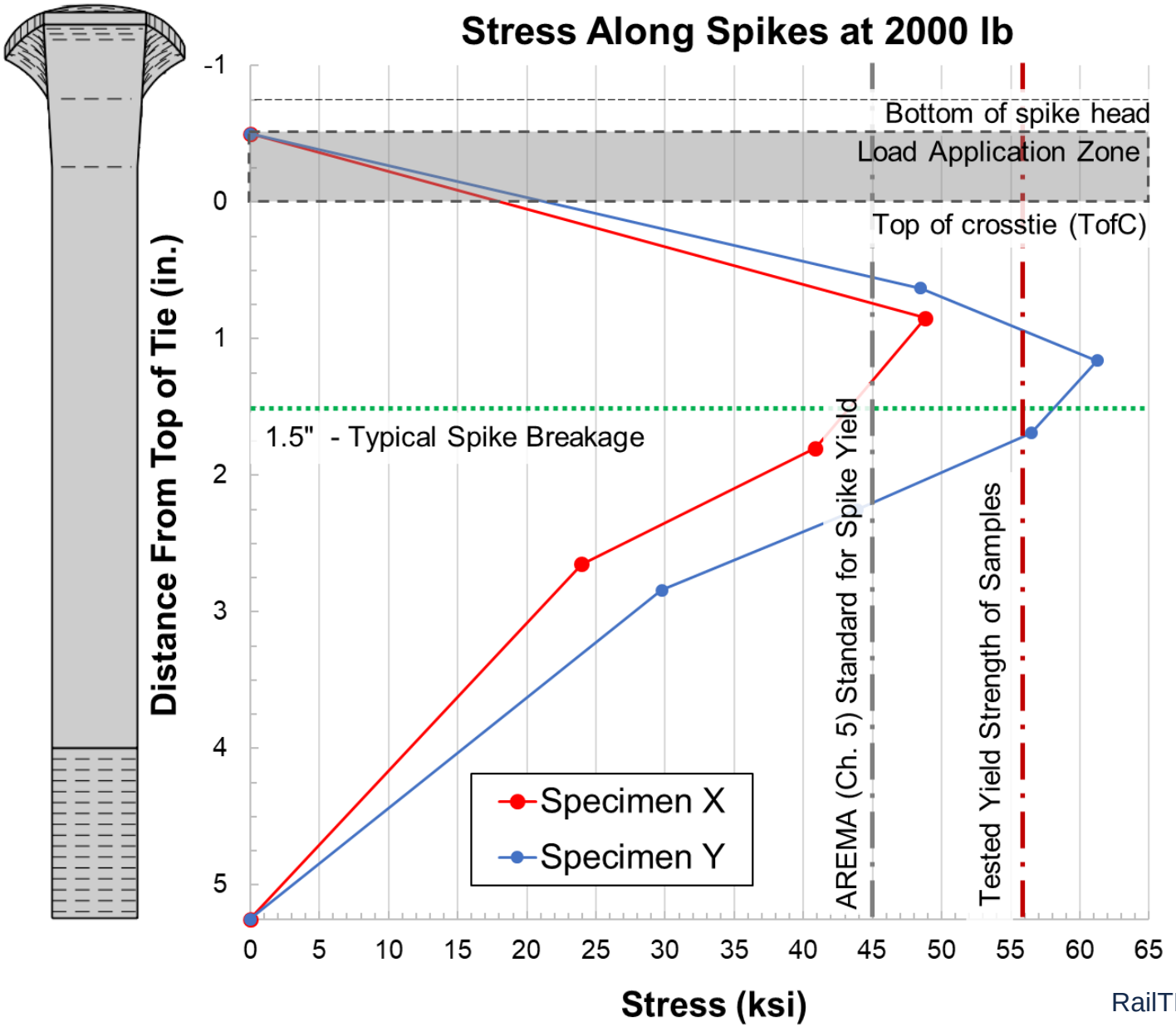


Cyclic Testing – Shakedown

Constant load magnitude

- Load:
  - 200 to 2,300 lb.
- Failure information:
  - Approximate depth to failure: 1.63” from top of crosstie
  - Approximate cycle count 0.74 M

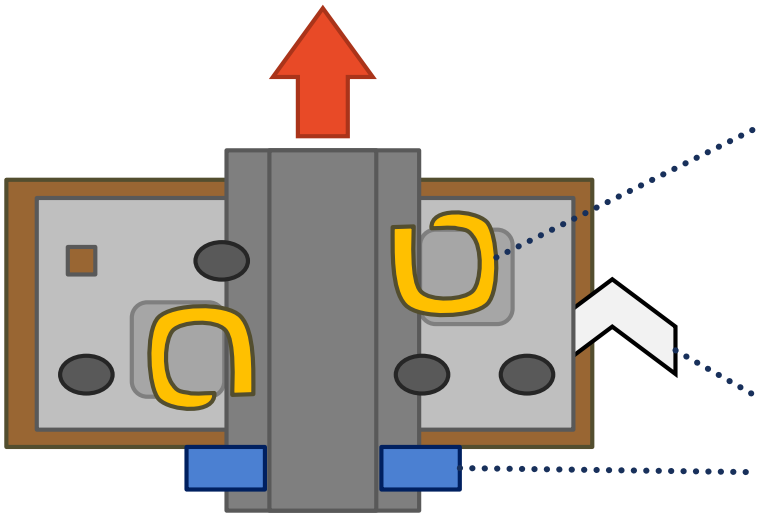
Longitudinally Loaded Spike Stress Profile



Single Fastener Experimentation

Testing procedure

- Single fastener loaded with static and cyclic longitudinal loads
- Instrumentation will provide insight on load distribution to spikes and the effect of key variables



Top view

Current variables to consider

- Fastener
  - Traditional
  - Typical e-clip
  - Reduced toe-load e-clip
- Plate uplift vs. No uplift
- Anchor vs. No anchor

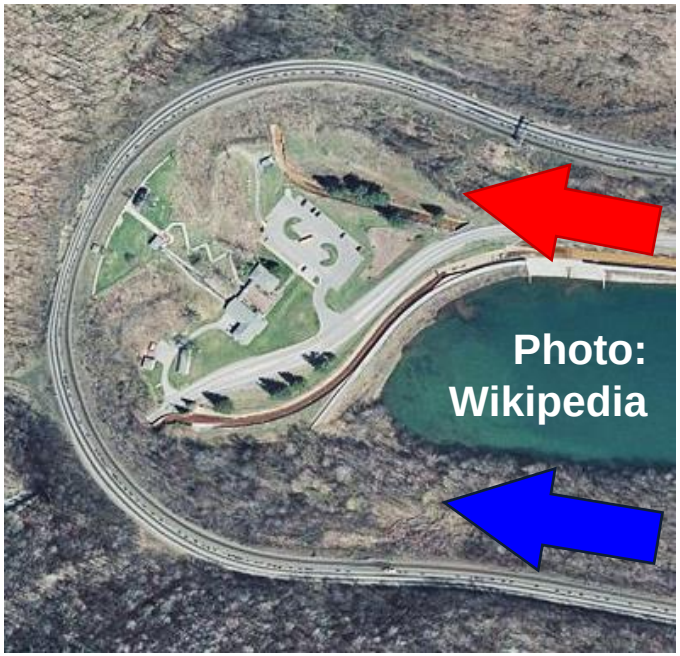
Field Experimentation Overview

Horseshoe Curve

- 3-track curve in Norfolk Southern's Pittsburgh line
- Westbound track has primarily **uphill empty** trains (45.6 MGT)
  - Tractive effort is distributed throughout *the locomotives*
- Eastbound track has primarily **downhill loaded** trains (50 MGT)
  - (Air)break forces are distributed throughout *the entire train*

Key feature: Tracks have the *same curvature, grade and climate*, allowing the comparison of the effects of the following on loading demand and fastener response

- Anchor
- Temperature
- Load
- Speed
- Direction of traffic
- Braking vs. traction forces
- High vs. low rail



Field Experimentation

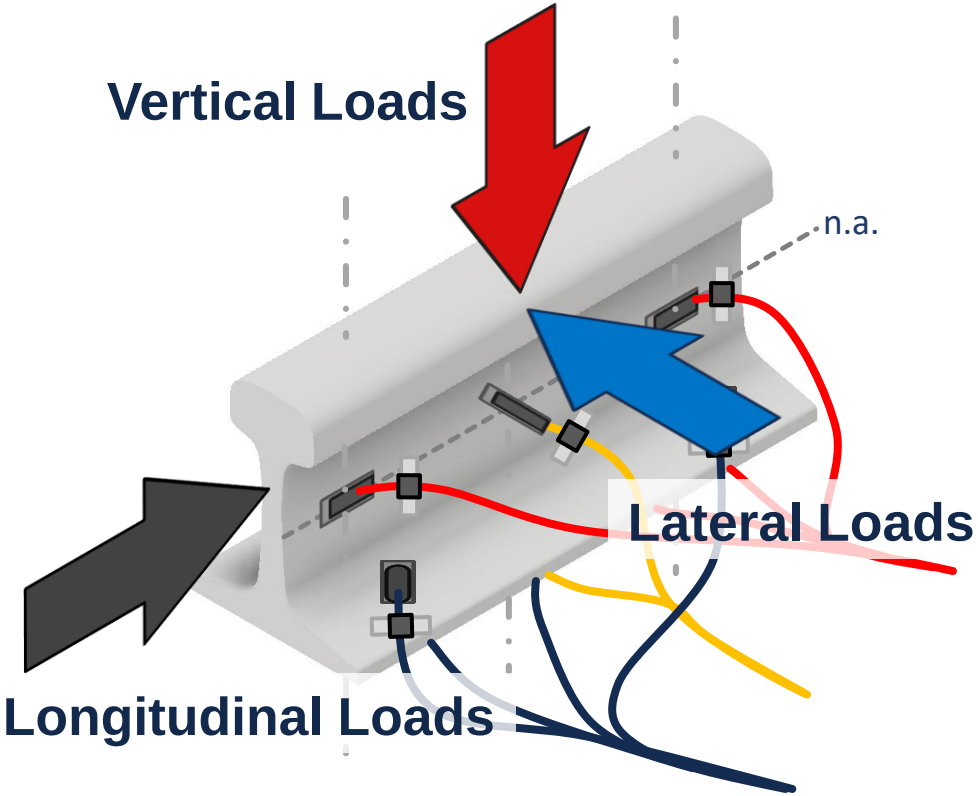
High Level Outcomes

Data acquisition through field experimentation allows for

- **Quantification of Loading Environment**
  - Improve our understanding of the load demands placed on the fastening systems as a result of passing trains
- **Evaluation of Fastening System Response**
  - Improve our understanding of the characteristic stiffnesses, deformations, and displacements as demands/conditions (loading, weather, etc.)
- **Development of Analytical Model**
  - Validate a three dimensional (3D) finite element (FE) model
  - Compare data with laboratory results

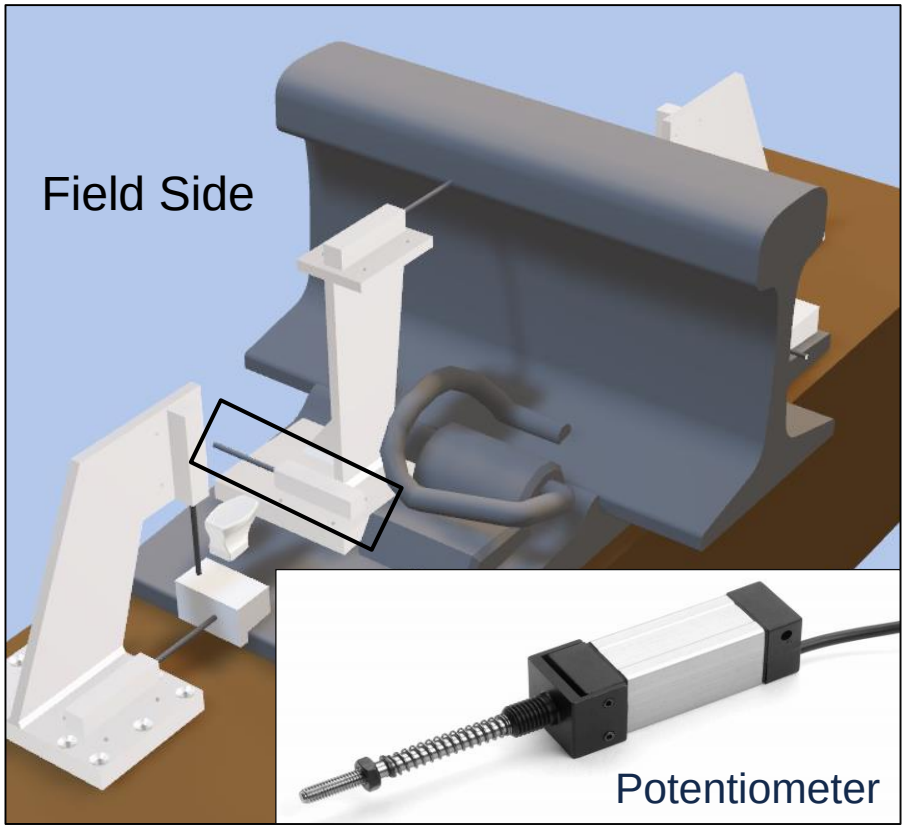
Quantification of Loading Environment

- Vertical, lateral and longitudinal loads collected with industry standard load circuits installed in the center of the crib on both high and low rails



Evaluation of Fastener Response

- Rail and plate displacements measured with specially designed DMDs (Displacement Measurement Devices)
  - Rail displacements relative to plate
  - Plate displacements relative to the tie



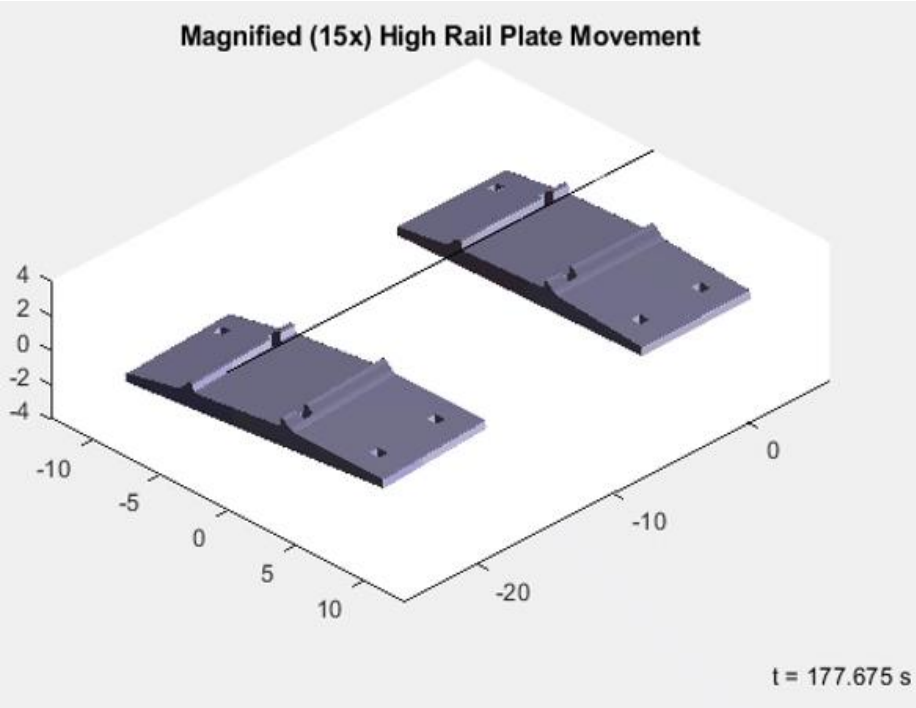
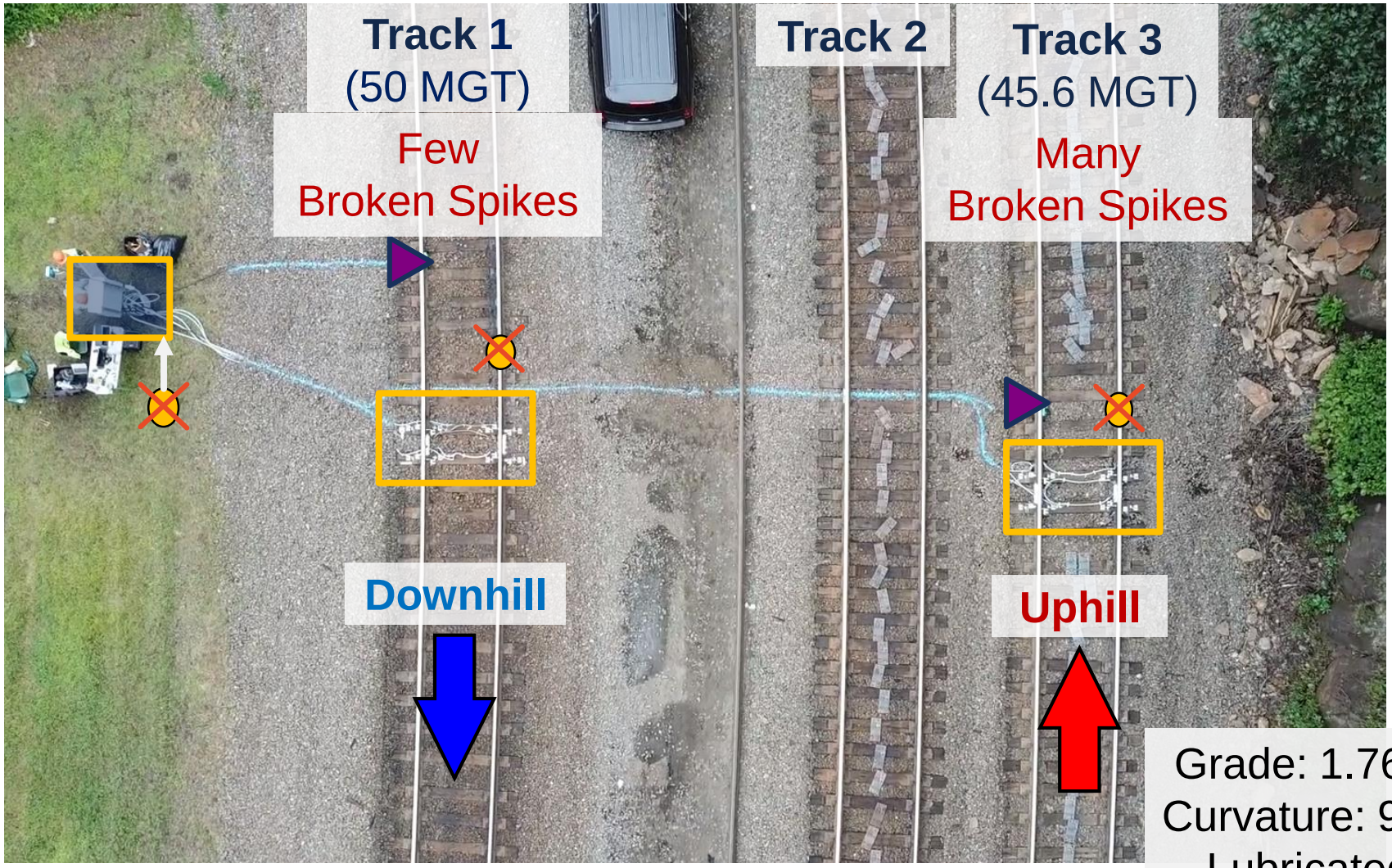


Plate movement was recreated in computer animation

Field Site Overview



Grade: 1.76%
Curvature: 9.2°
Lubricated
Airbrake grade

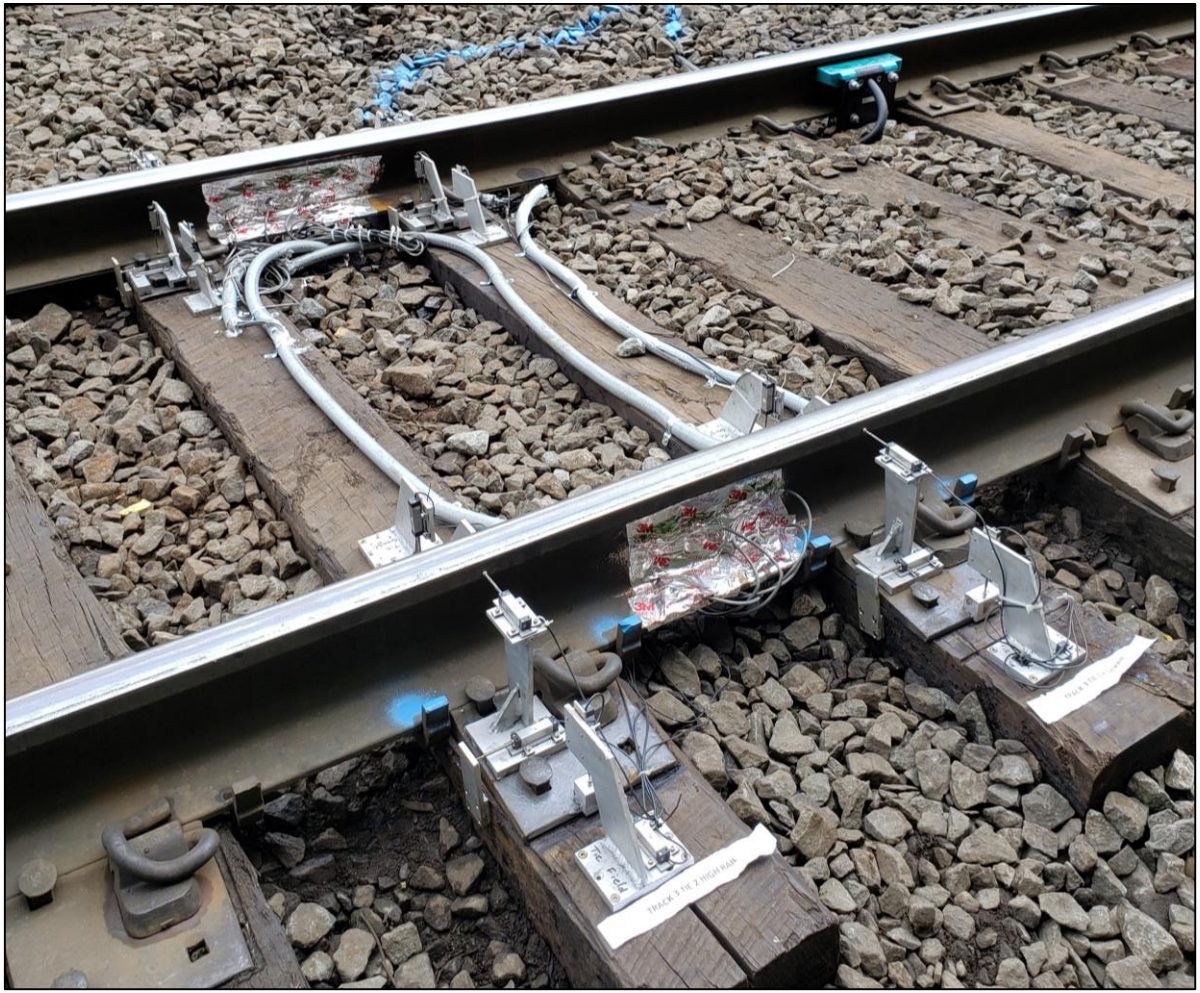
Instrumentation Area

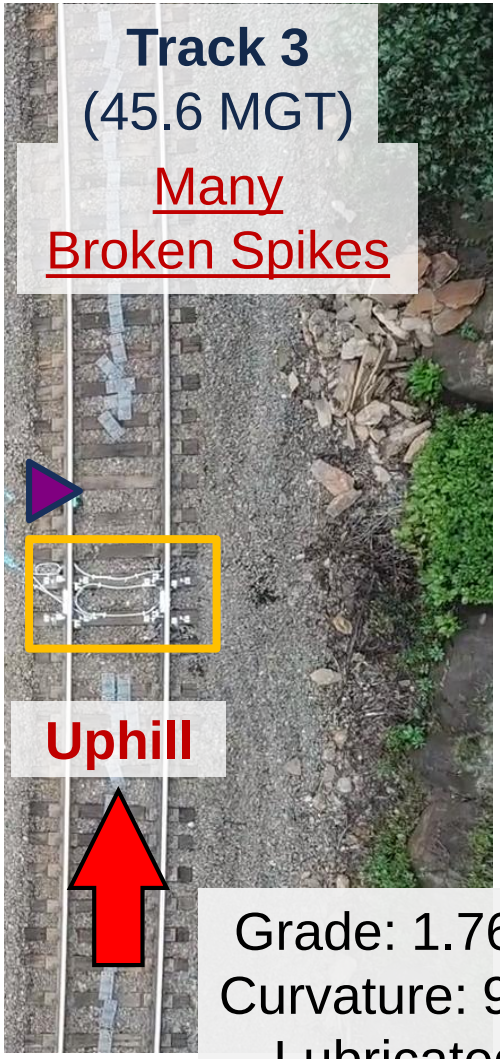
Data Collection Box

Wheel Counter

Thermocouple

Track Overview





Grade: 1.76%
Curvature: 9.2°
Lubricated
Airbrake grade

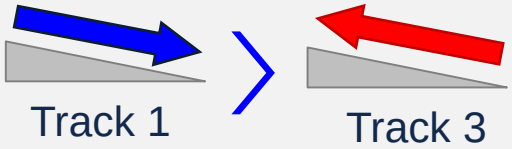
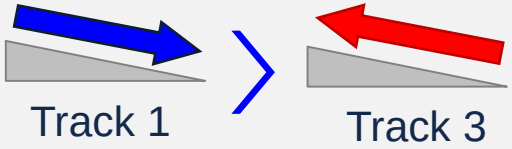
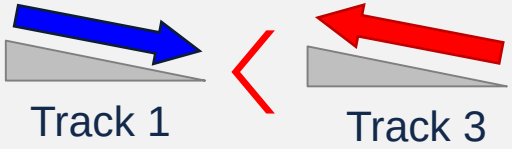
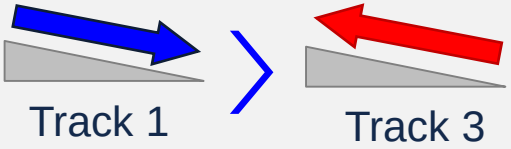
- Two ties and one crib instrumented in each track

Data Acquisition and Collection

On-site computer

- Always reading data from the instrumentation
- Keeps most recent data on memory
- Records data:
  - When a wheel is detected
  - 6 seconds prior to wheel detection

Field Instrumentation

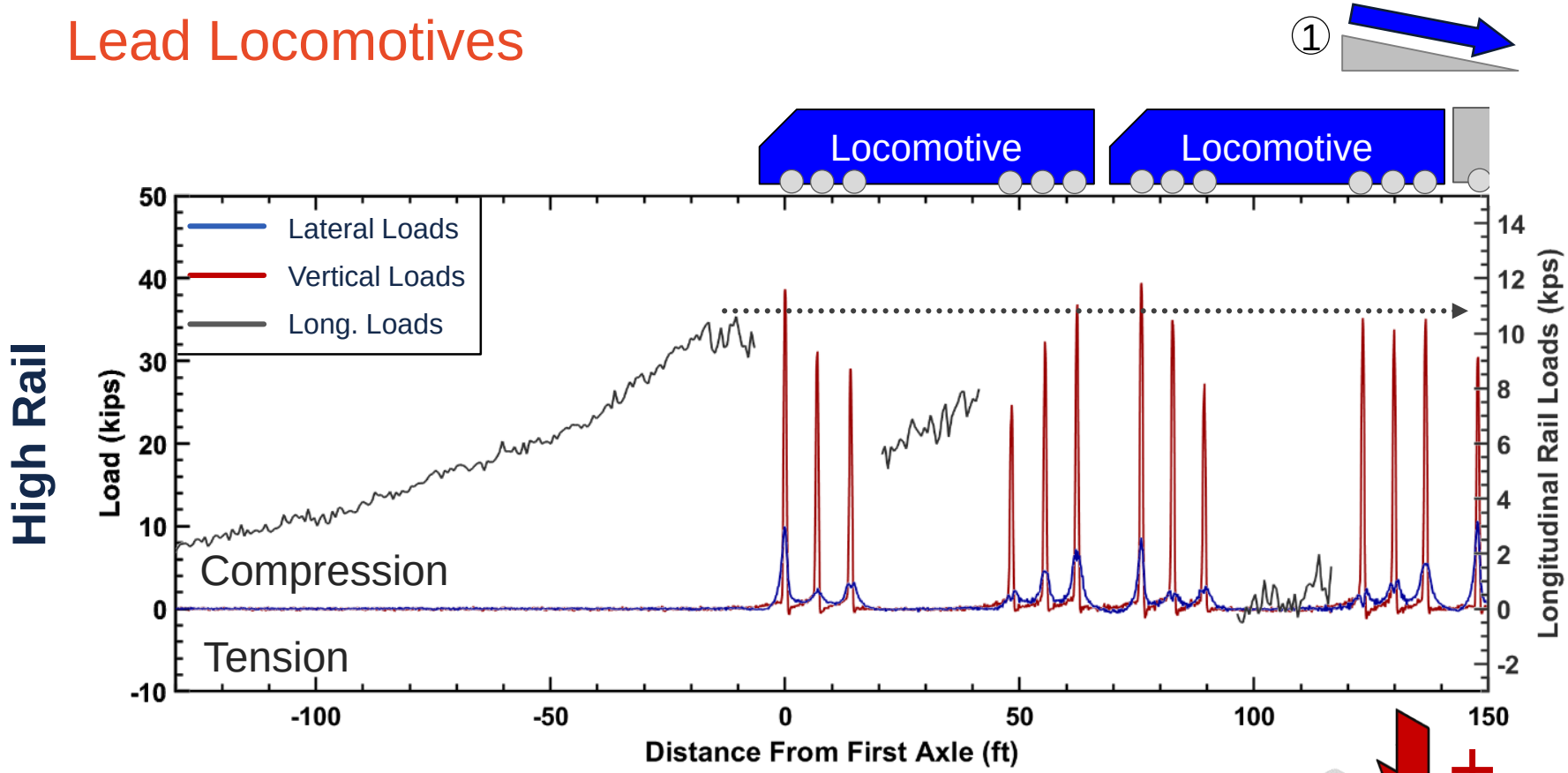
	Our hypotheses	What we see
Vertical Loads		?
Lateral Loads		?
Longitudinal Rail Loads		?
Longitudinal Plate Displacements		?

Grade: 1.76% Lubricated (TOR and GF)

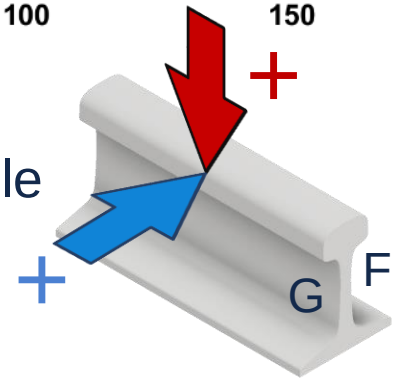
Curvature: 9.2° Airbrake grade

Vertical and Lateral Forces Example

Lead Locomotives

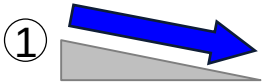


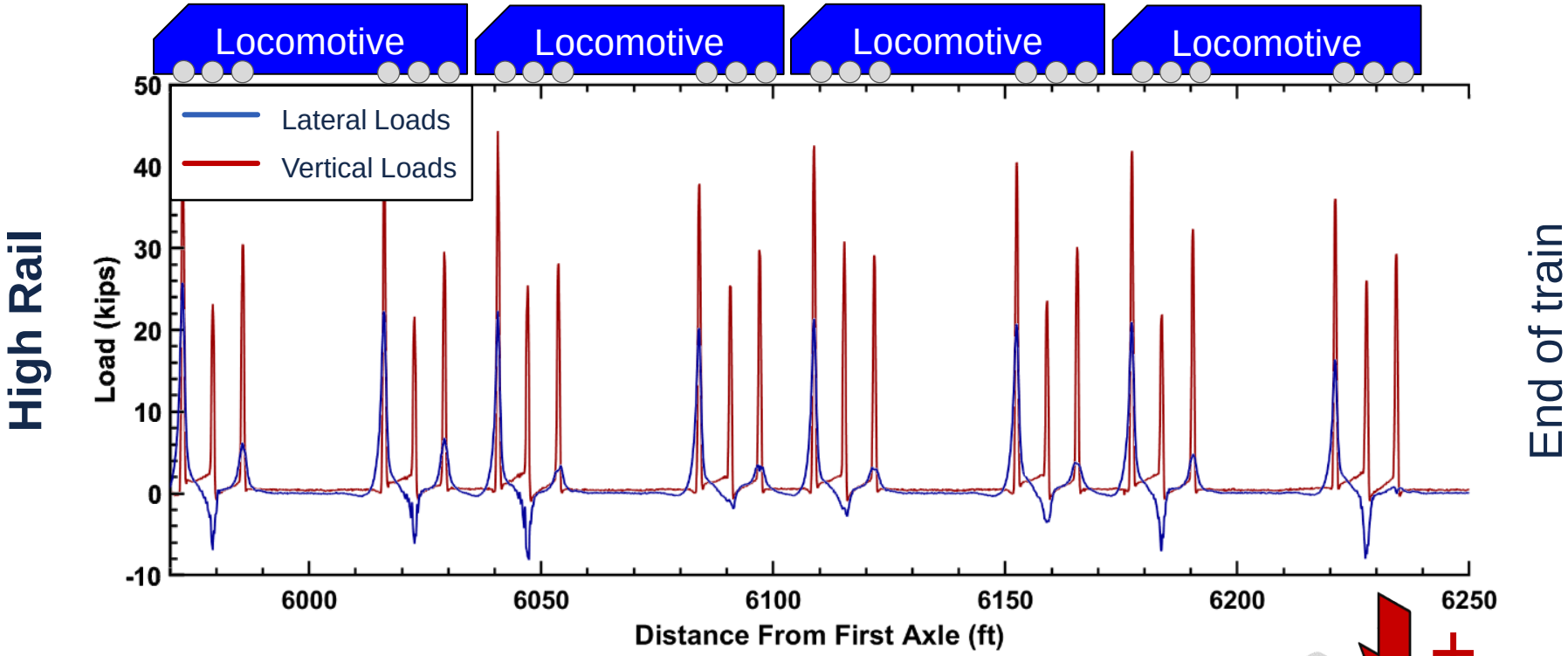
- Vertical and lateral load traces are clean and reasonable



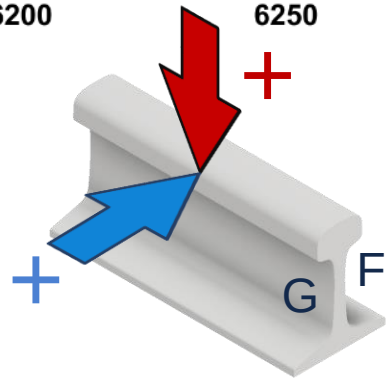
Vertical and Lateral Forces Example

Helper Locomotives

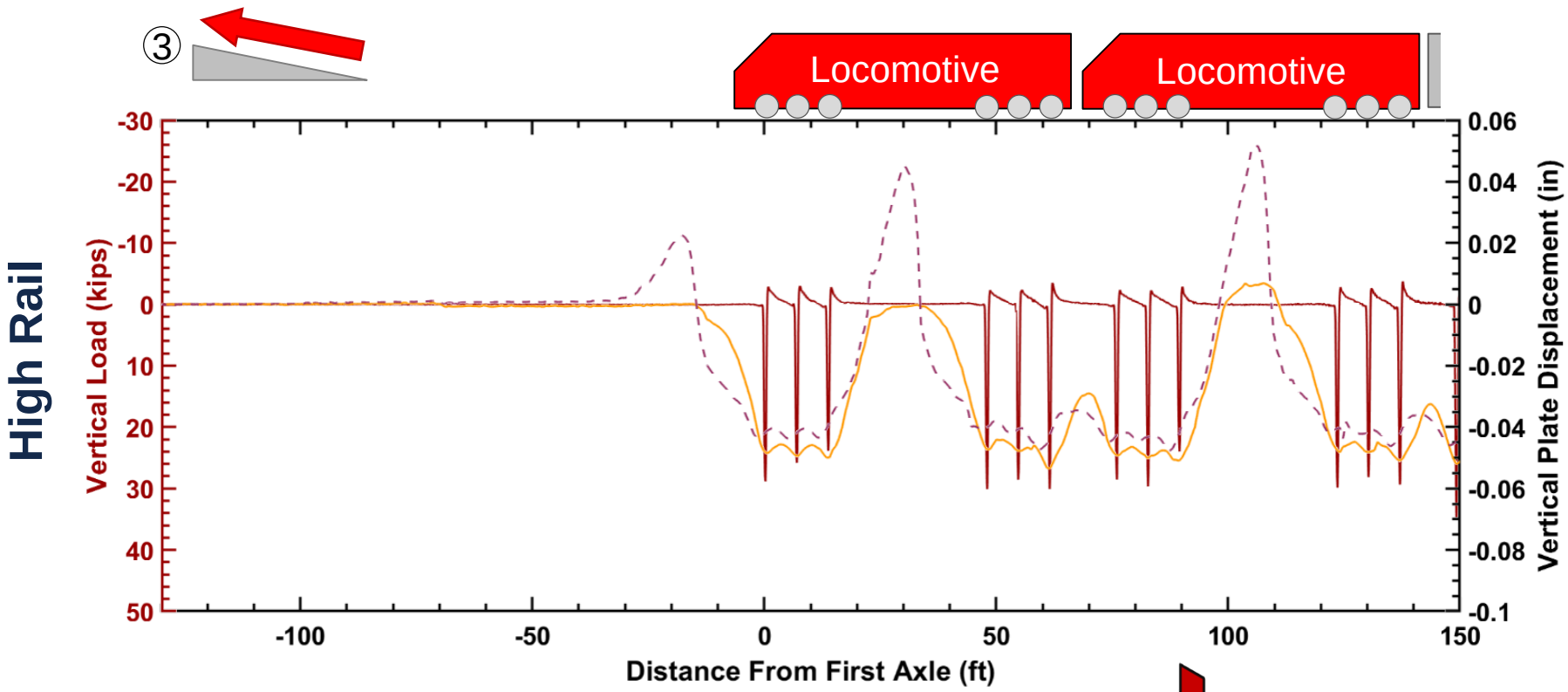




- Evidence of high lateral forces on helper locomotives

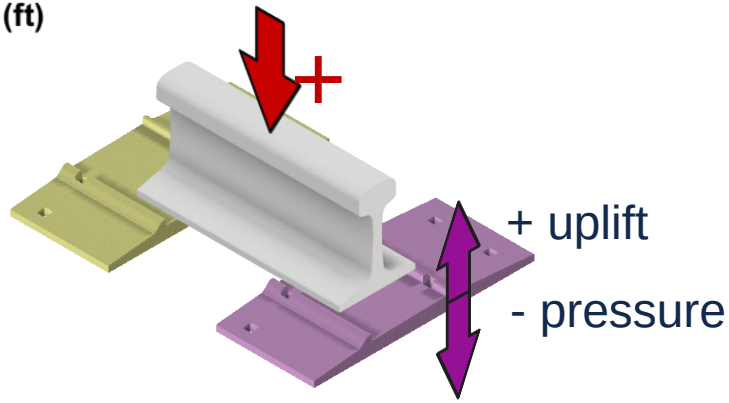


Vertical Forces and Plate Disp. Example



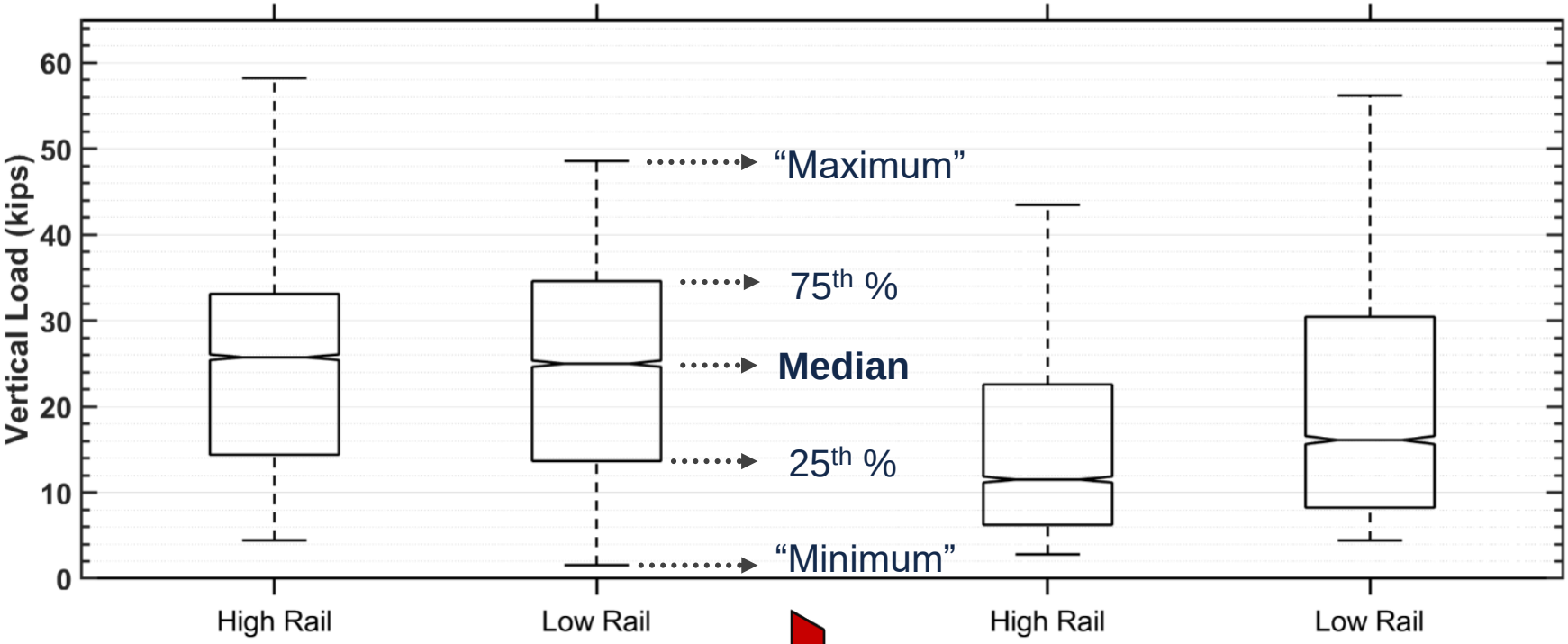
For this train

- Vertical displacements follow expected trends
- Clear uplift in Plate 2 but less often in Plate 1



Track Loading Comparison

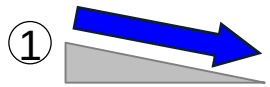
Vertical Axle Loads

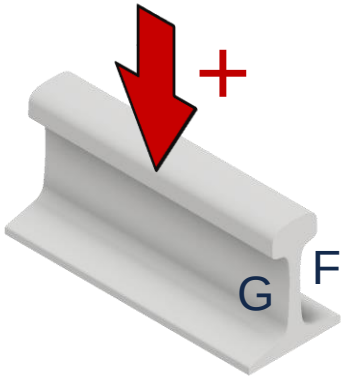


Track 1

N = 30 Trains

(7877 Axles)

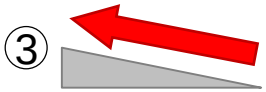




Track 3

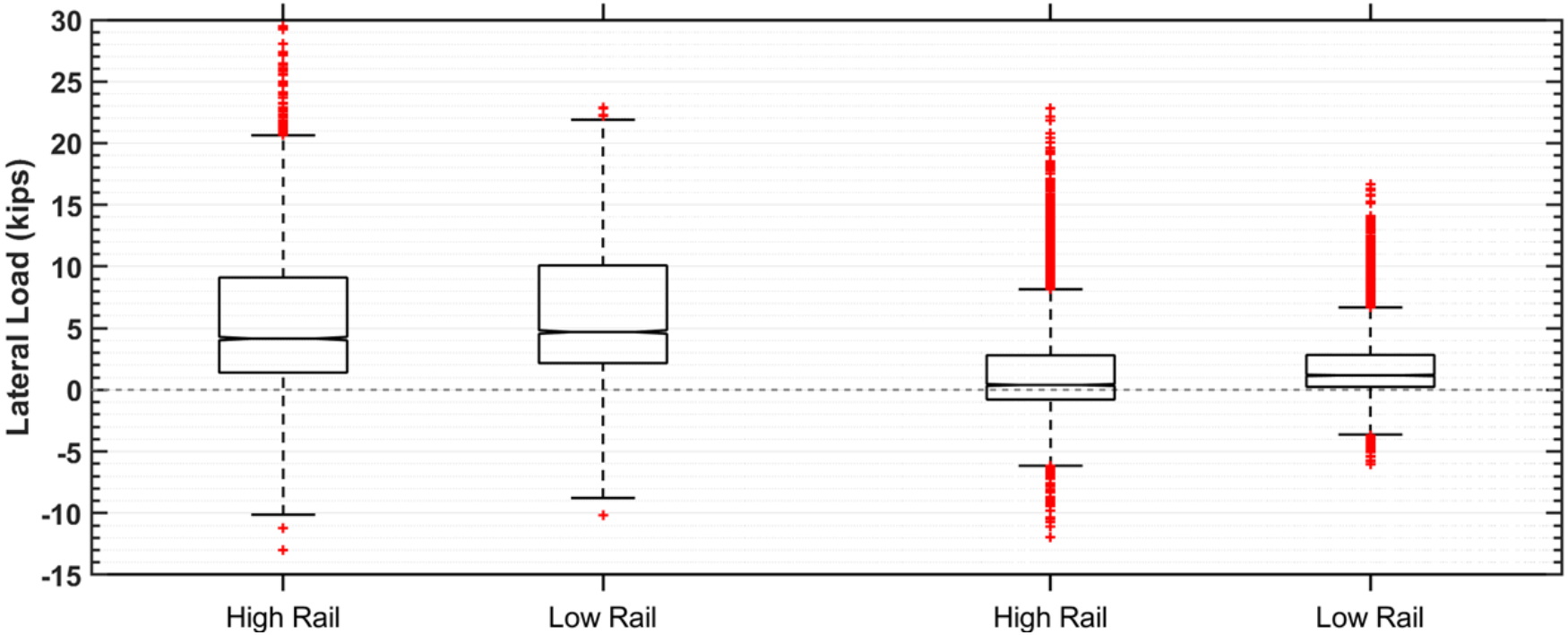
N = 17 Trains

(5472 Axles)



Track Loading Comparison

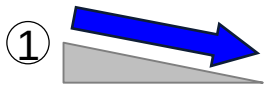
Lateral Axle Loads

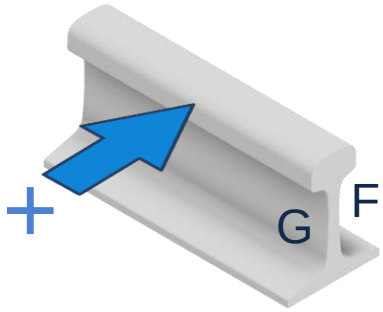


Track 1

N = 30 Trains

(7877 Axles)

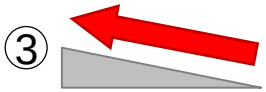




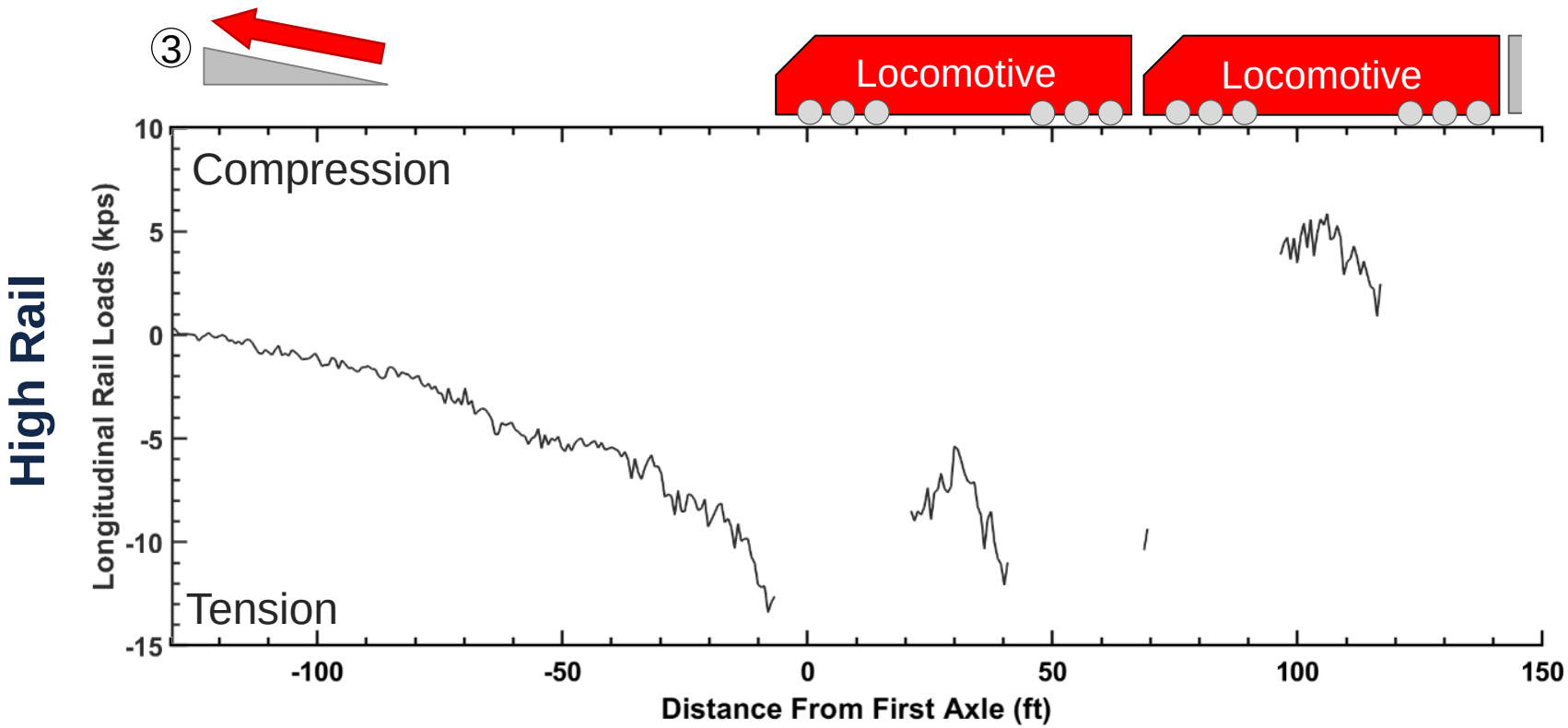
Track 3

N = 17 Trains

(5472 Axles)

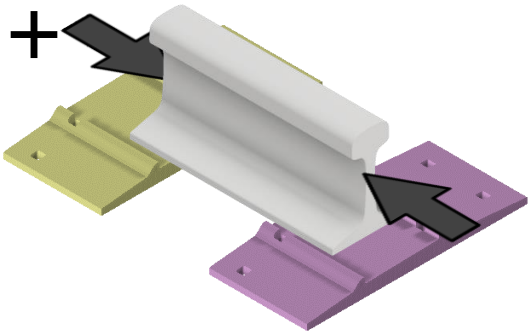


Longitudinal Forces Example

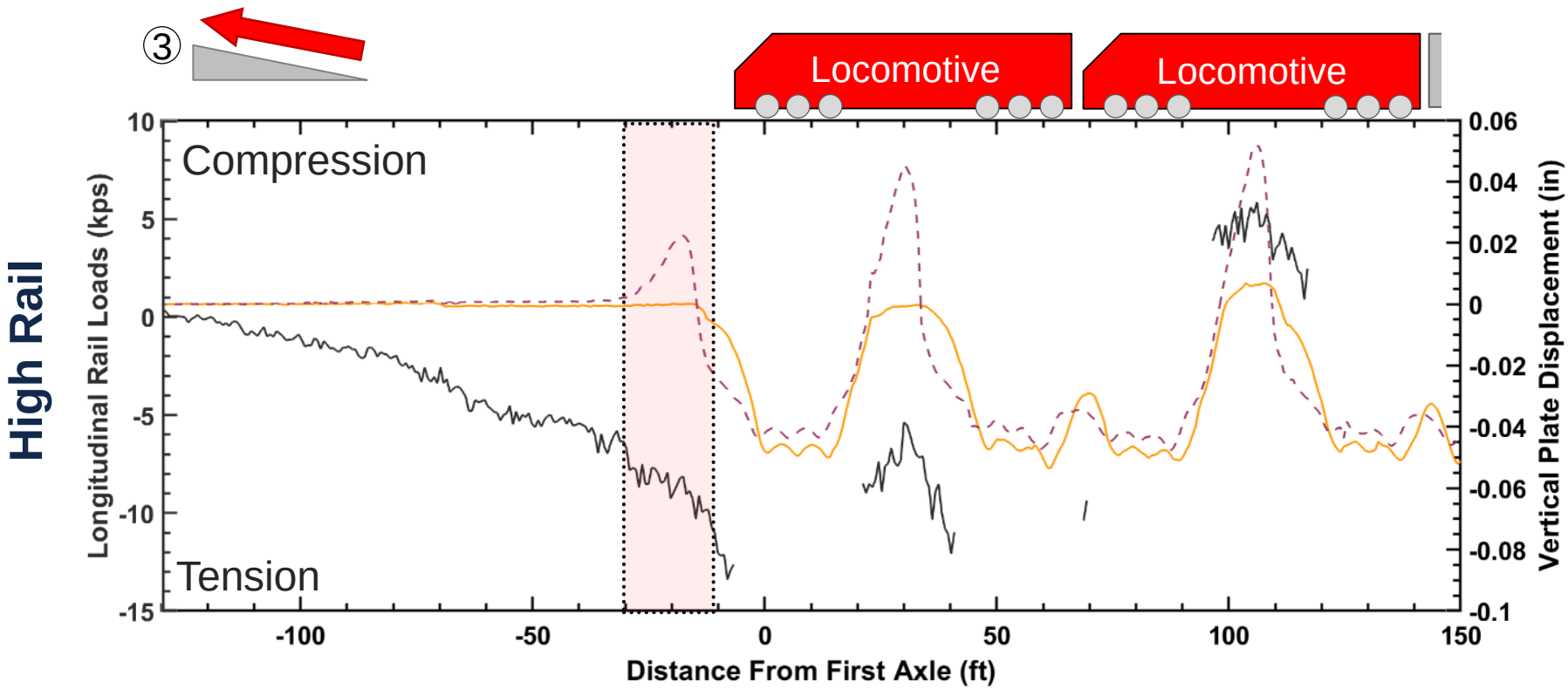


For this train

- Rail axial tension build up can be seen before train appears

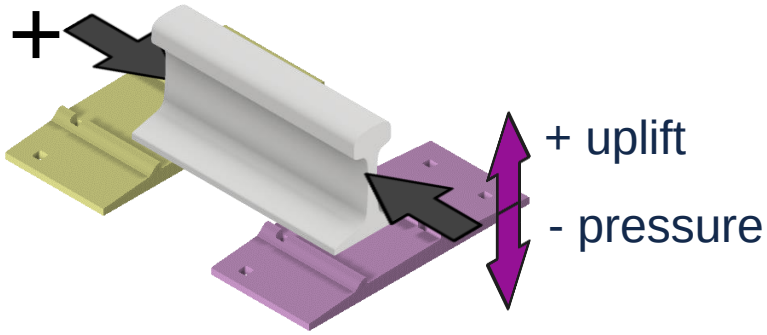


Longitudinal Forces Example



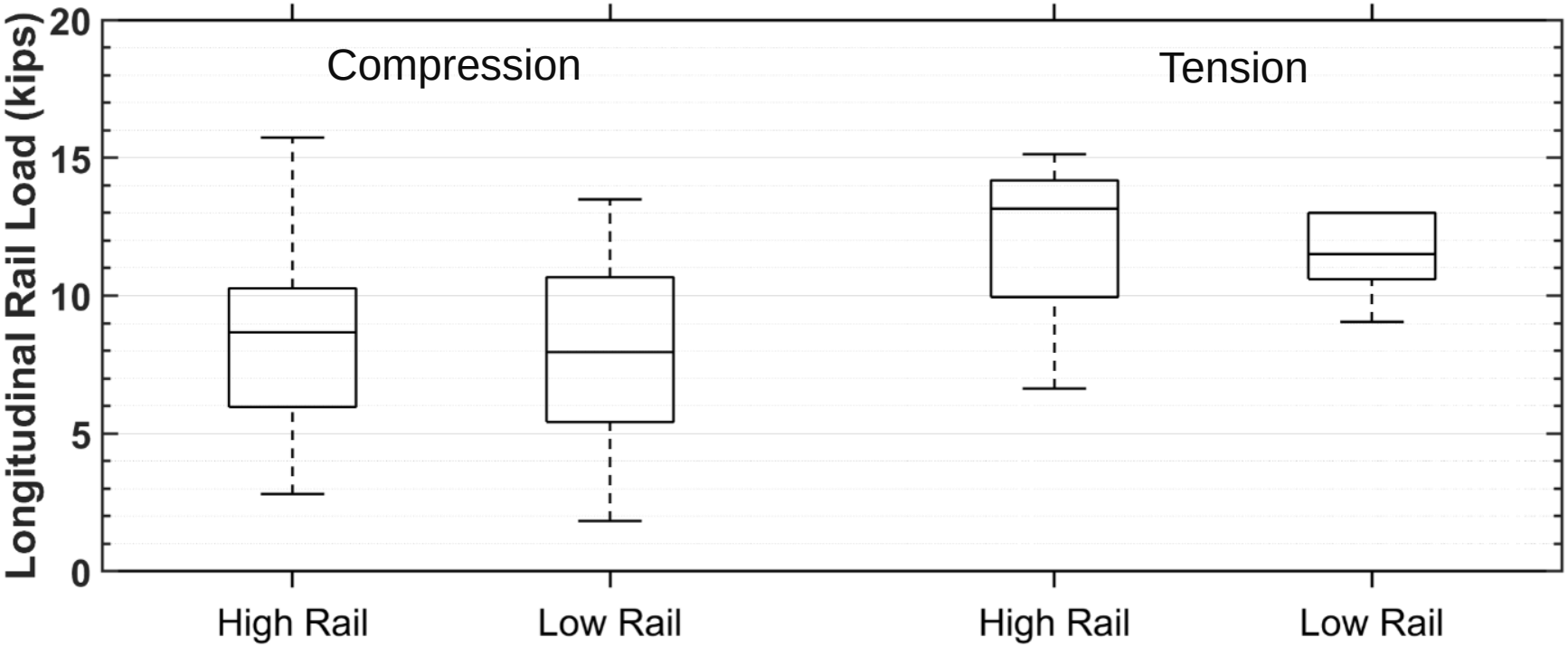
For this train

- Rail axial tension build up can be seen before train appears
- Evidence of longitudinal loads on the rail with plate uplift



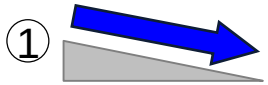
Track Loading Comparison

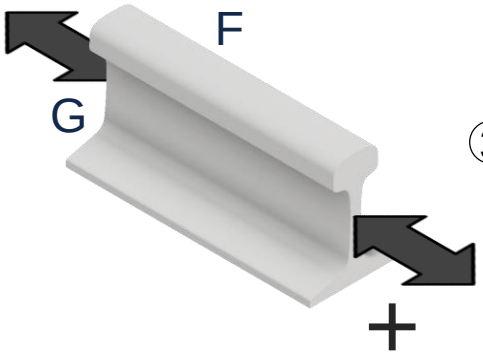
Longitudinal Rail Loads Before Train



Track 1

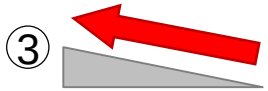
N = 6 Trains





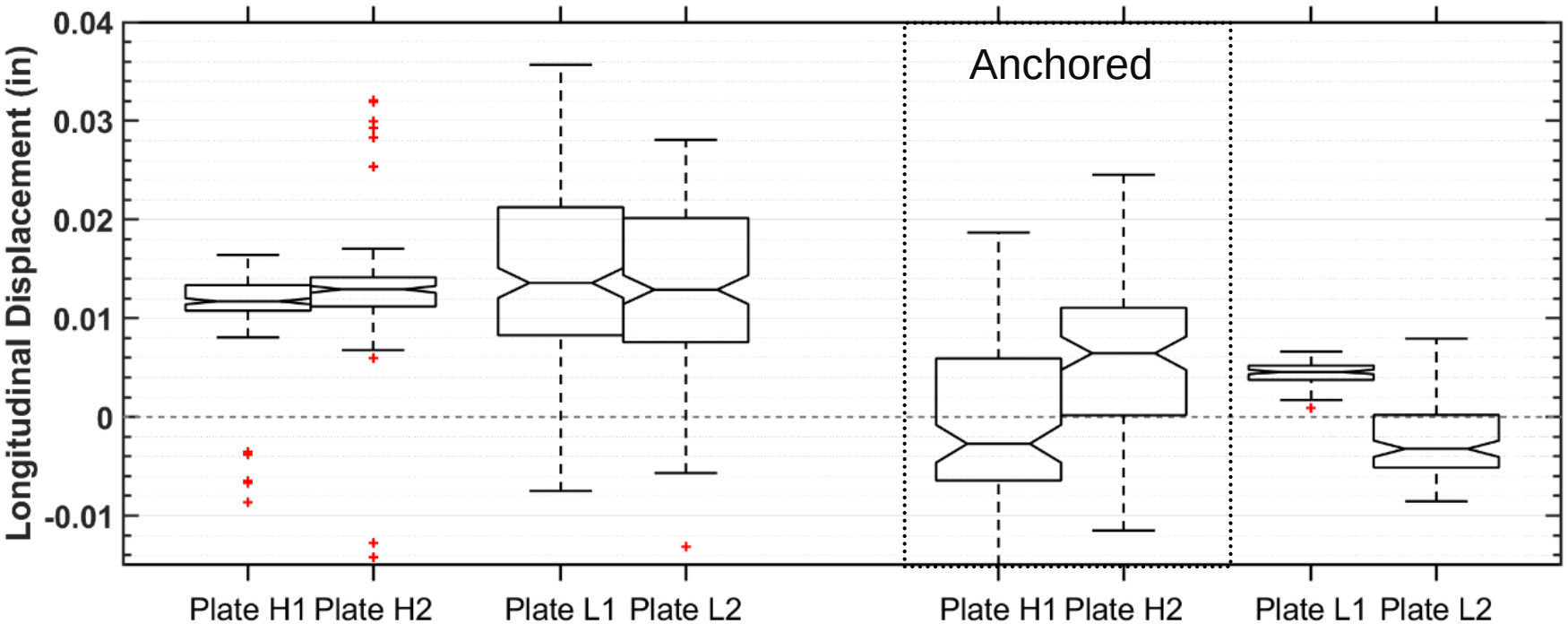
Track 3

N = 6 Trains



Track Loading Comparison

Longitudinal Plate Displacement Relative to the Tie



Track 1

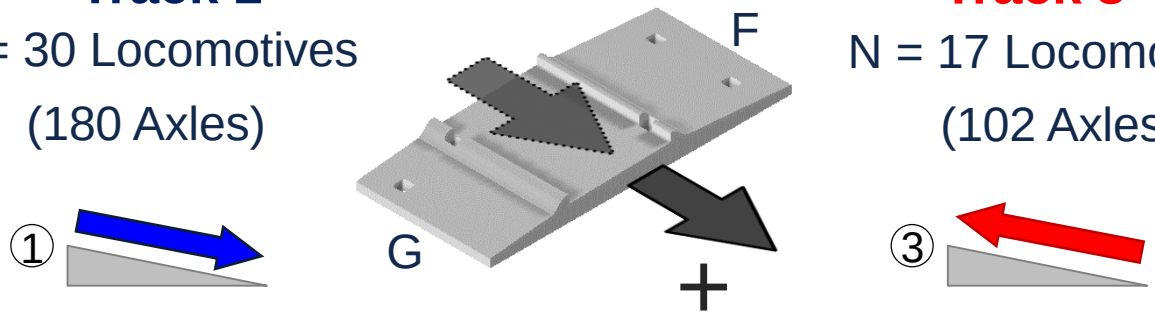
N = 30 Locomotives

(180 Axles)

Track 3

N = 17 Locomotives

(102 Axles)



Field Instrumentation Initial Findings

	Our hypotheses	What we see
Vertical Loads	Track 1 > Track 3	Track 1 > Track 3
Lateral Loads	Track 1 > Track 3	Track 1 > Track 3
Longitudinal Rail Loads	Track 1 < Track 3	Track 1 < Track 3
Longitudinal Plate Displacements	Track 1 > Track 3	Track 1 ? Track 3

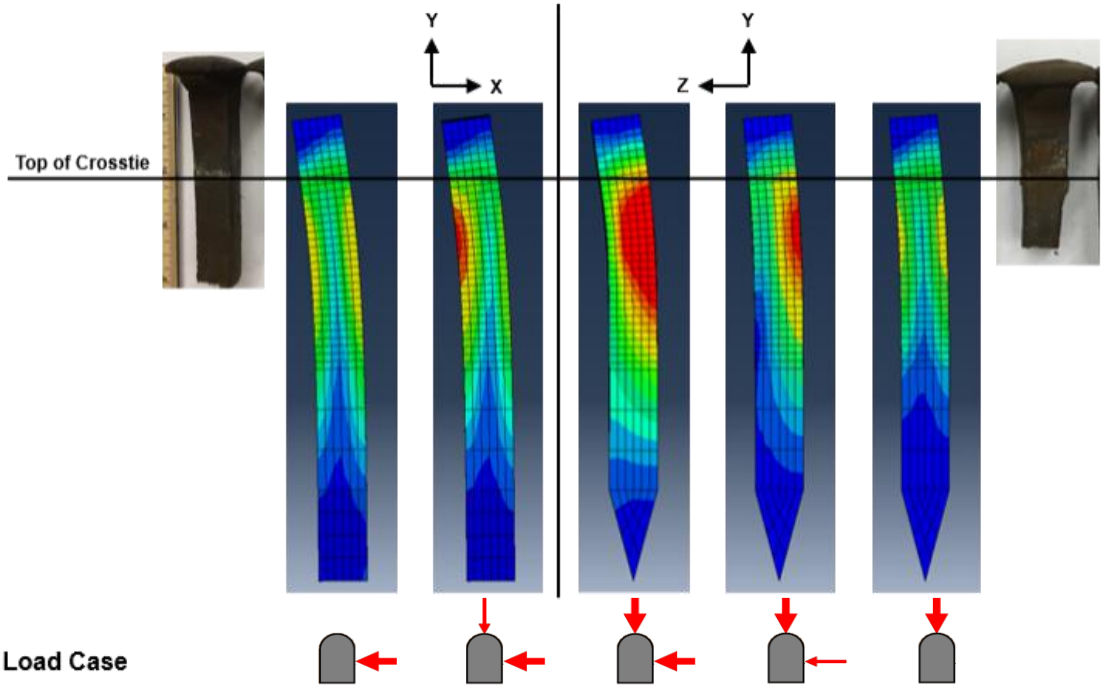
Grade: 1.76% Lubricated (TOR and GF)

Curvature: 9.2° Airbrake grade

Field Data Analysis – Future Work

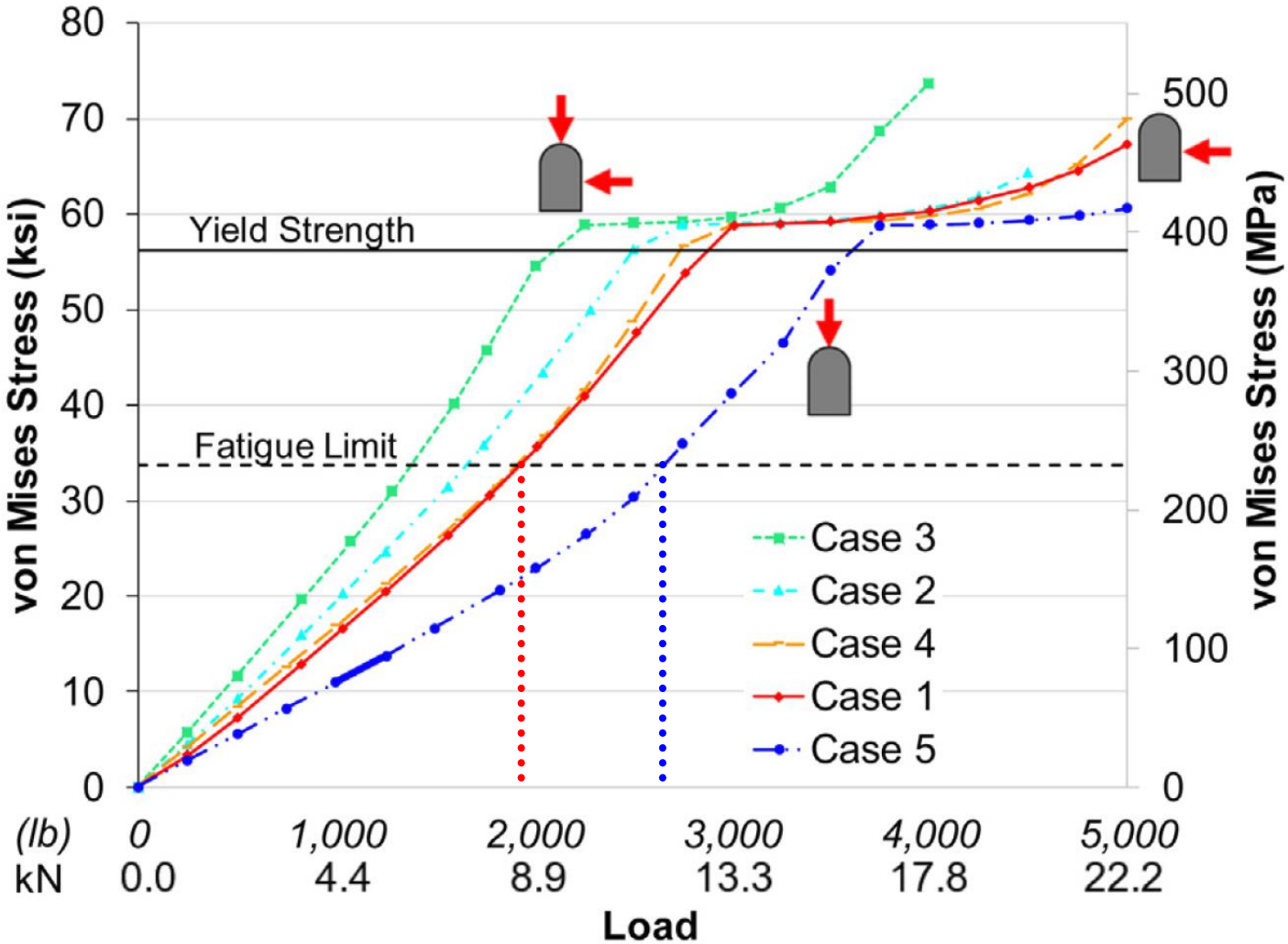
- Model (Kerr) and quantify loads being transferred to the fasteners
- Further investigate plate displacement behavior
- Investigate/quantify difference in longitudinal stiffness for fasteners with and without anchors – Track 3 vs Track 1
- Quantify the effect of speed, weight, direction, length, etc. in longitudinal / lateral loading

Phase I Single Spike FEM Summary



- Longitudinal load is more detrimental than an equivalent lateral load
  - This is due to the timber being less resistant on that direction
  - This finding supports the theory that spike failures in premium fastening systems are primarily related to longitudinal loads
- Stress can exceed the fatigue limit of spike steel at regular service loads
- Max. stress depth varies with the magnitude and direction of applied load
- Species of timber significantly effects the depth/load of failure

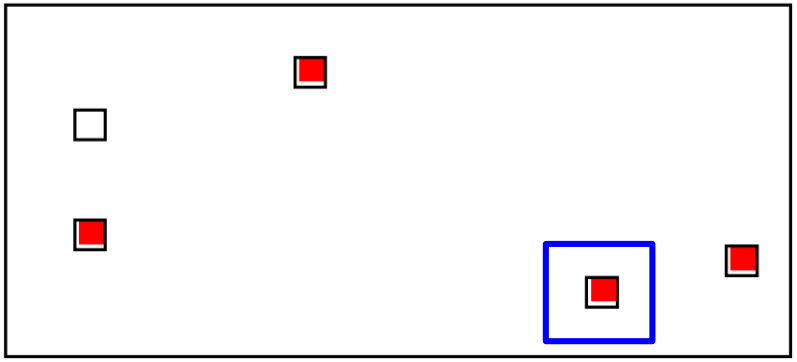
Final Calibrated Single Spike Results



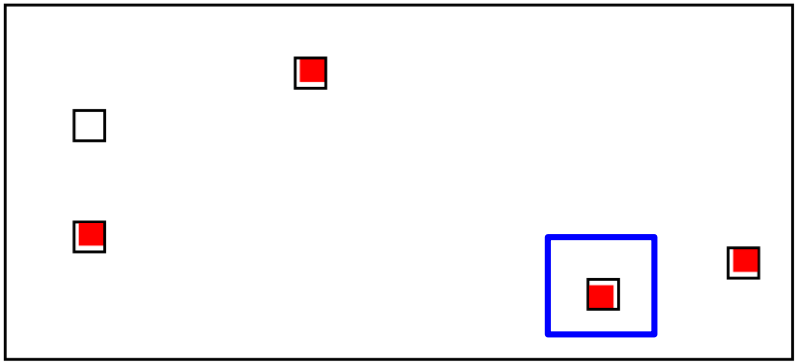
- A longitudinal load of 2,000 lb. or a lateral load of 2,750 lb. can lead to the fatigue strength of the spike being exceeded

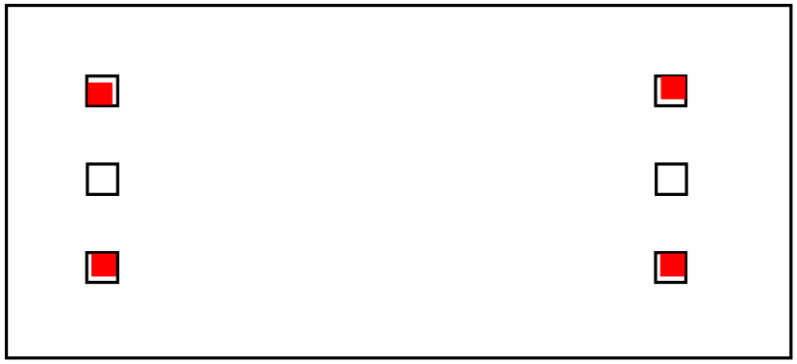
FEM Recent Progress | Study Outline

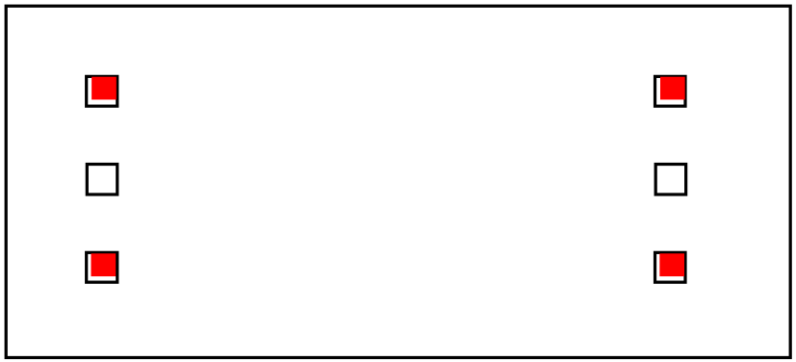
- Current Focus:
  - Spike hole tolerances do not ensure all spikes are engaged and
  - Given there are multiple spike arrangements for a given fastener



- Investigate effect of the following on spike stress state:
  - Spike engagement
  - Spike arrangement
  - Loading direction/magnitude

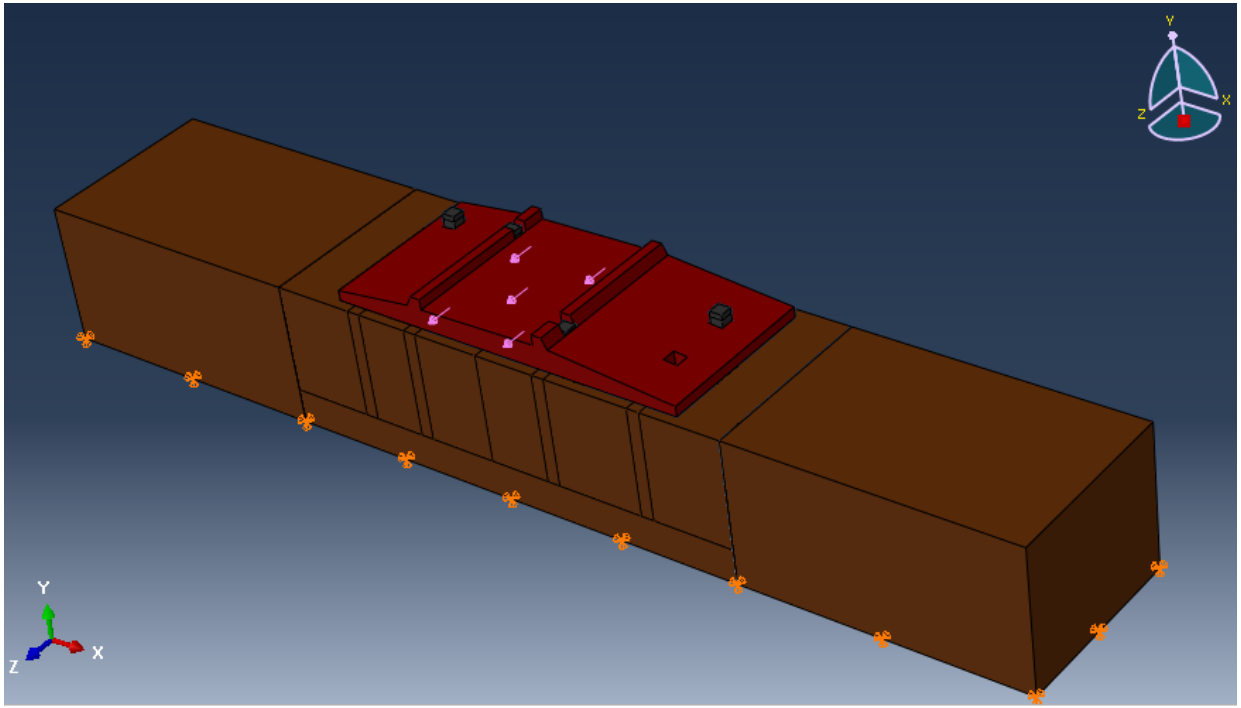






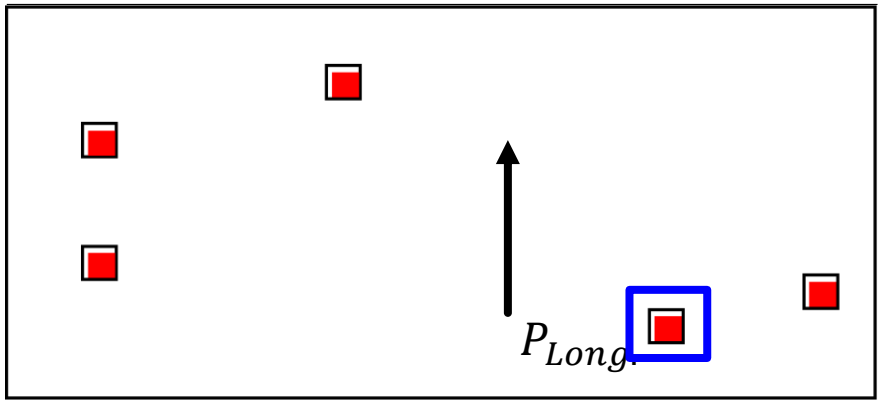
FEM Update | Model Overview

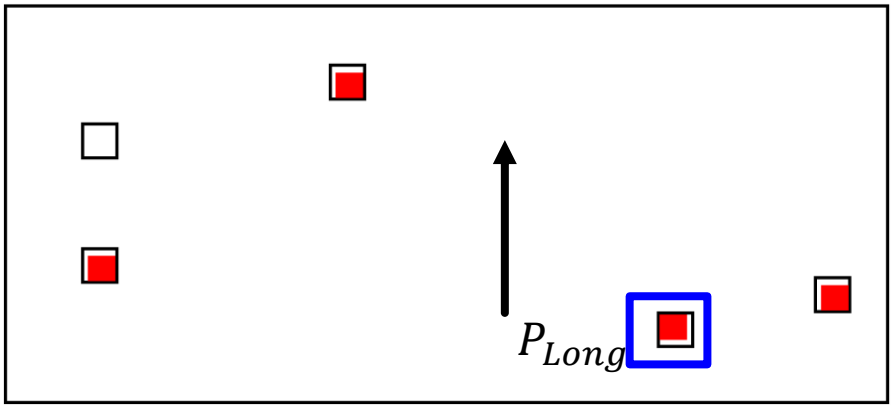
- From previous validated model
  - Interactions: spike – crosstie
  - Materials: spike and timber
  - Mesh: spike and timber (near plate/spikes)
- Loads applied in-line with field data (longitudinal only shown below)
  - Simplified as a traction distributed over the rail seat
  - No e-clips modeled for simplification

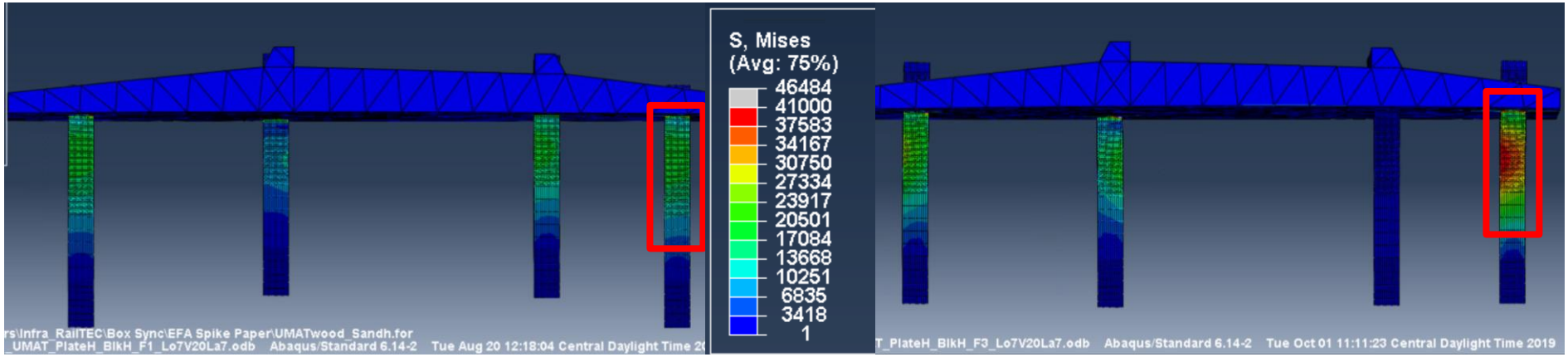


FEM Update | Preliminary Results

- Effect of spike engagement
  - Loading (P): 7,000 lb. longitudinal





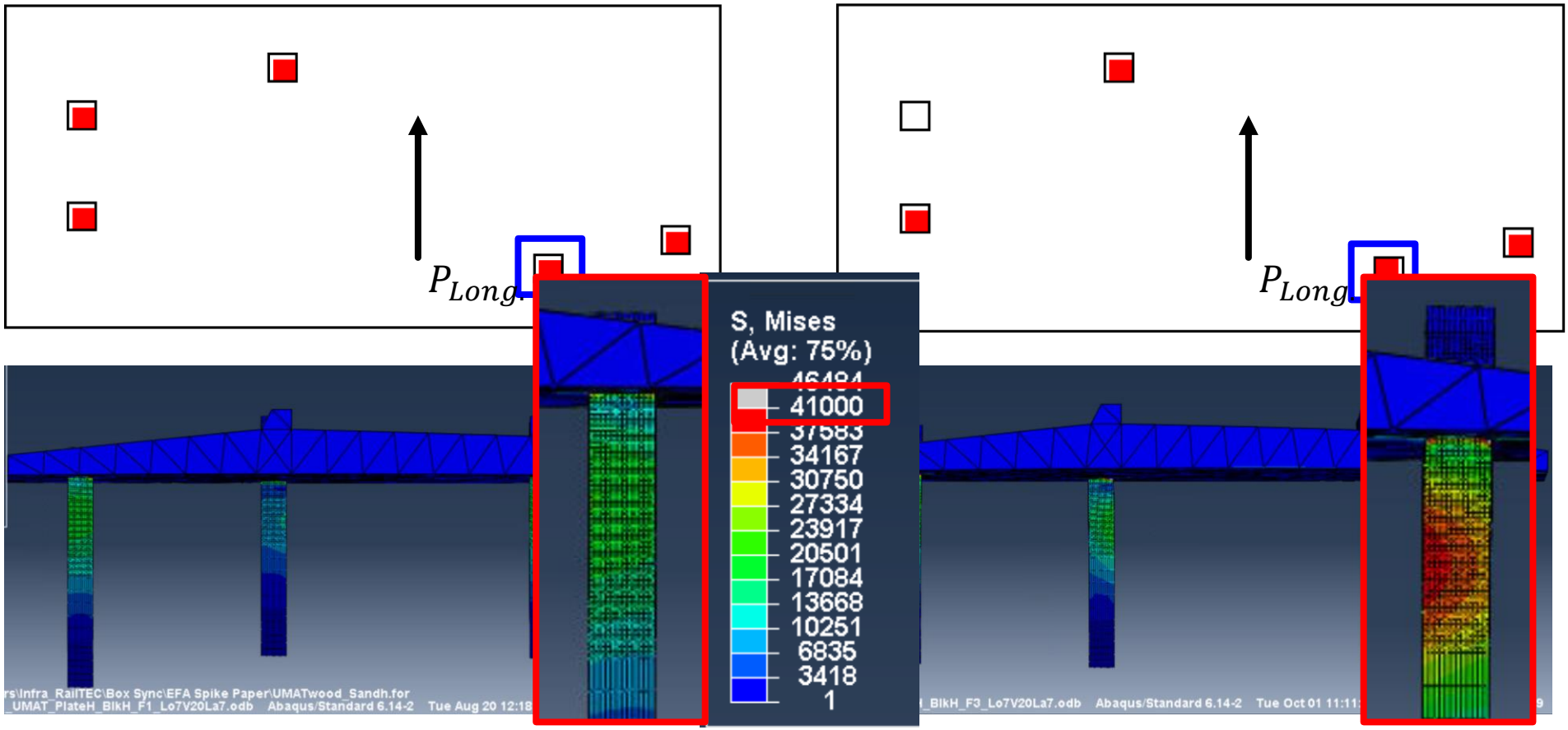


**Fatigue Limit is ~33ksi*

- Spike stress is effected by spike engagement
  - There is a ~100% increase in maximum spike stress from plate on left (~20 ksi) to plate on right (~40 ksi)

FEM Update | Preliminary Results

- Effect of spike engagement
  - Loading (P): 7,000 lb. longitudinal



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- Spike stress is effected by spike engagement
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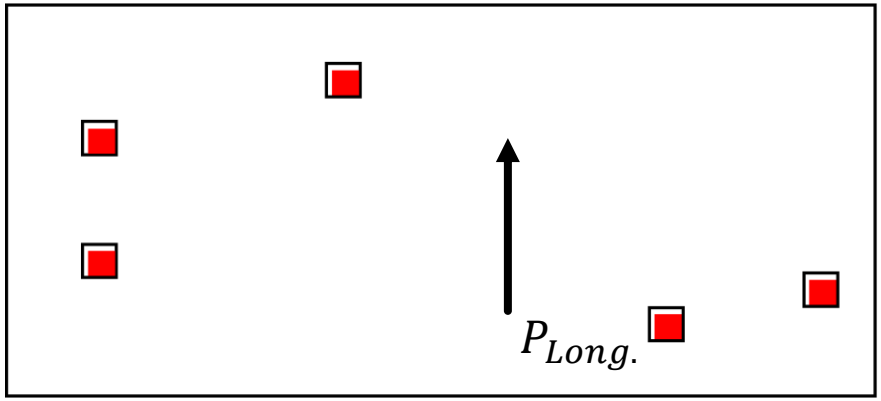
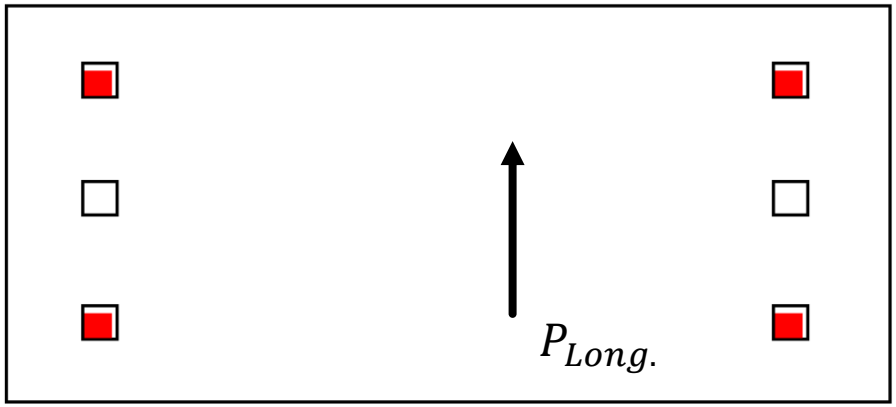
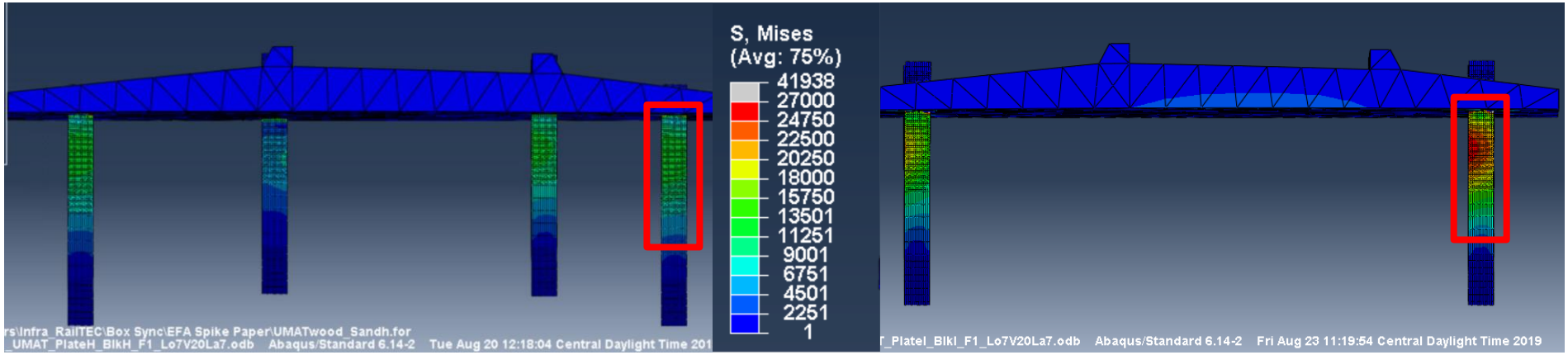
FEM Update | Preliminary Results

- Effect of spike arrangement
  - Loading (P): 7,000 lb. longitudinal





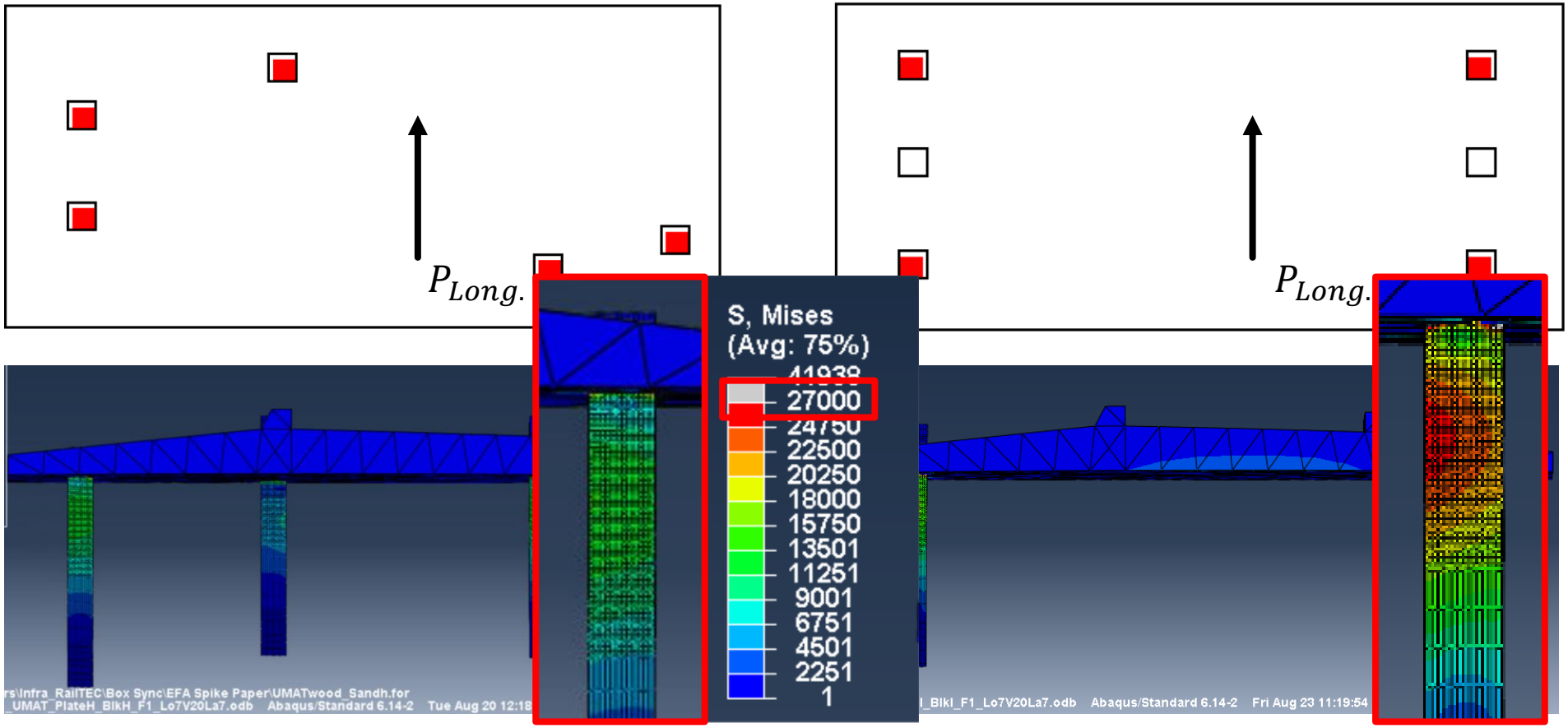


**Fatigue Limit is ~33ksi*

- Spike stress is effected by arrangement
  - There is a ~30% increase in maximum spike stress from plate on left (~20 ksi) to plate on right (~26 ksi)

FEM Update | Preliminary Results

- Effect of spike arrangement
  - Loading (P): 7,000 lb. longitudinal



**Fatigue Limit is ~33ksi*

- Spike stress is effected by arrangement
  - There is a ~30% increase in maximum spike stress from plate on left (~20 ksi) to plate on right (~26 ksi)

System FEM – Preliminary Findings

- Current tolerances do not ensure all spikes are engaged at one time
- There can be different spiking patterns for a given premium fastening systems
- The effect of spike engagement can significantly effect spike stress
  - In the example provided, by up to 100%
  - This led to a stress that exceeded the fatigue limit
- The effect of spike arrangement can effect spike stress
  - In the example provided, by up to 30%
- Therefore, additional work will investigate if there might be any reasonable recommendations that can be made to reduce risk of increasing spike stress

Acknowledgements

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PANDROL

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NURail Center

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