Research into the Causes of Visually Undetectable Broken Spikes

A summary of the work by the University of Illinois Urbana-Champaign and Norfolk Southern

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Outline

- The broken spike problem
- Factors contributing to broken spikes
- Broken spike remedies
- Supporting data
- Conclusions & Recommendations

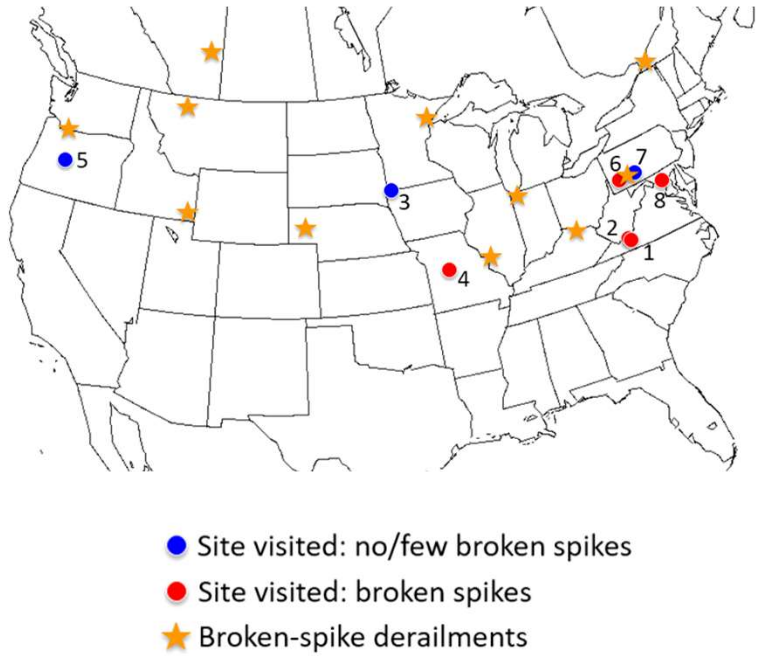
The broken spike problem

- In this presentation “spikes” includes drive spikes & screw spikes (“screw spikes”) and cut spikes
- The broken spike problem has gotten worse with the industry’s move from the traditional cut spike and anchor system to an elastic fastening system

Extent of Spike Fatigue Failure

Magnitude of spike fatigue failure problem based on site visits and industry survey by UIUC (2018):

- Fatigue failures identified on 7 railroads
  - One curve inspected had 23% broken spikes
- 11 derailments identified on 4 railroads
  - Likely more derailments that were identified simply as "wide gauge"
- Failures of both screw spikes and cut spikes

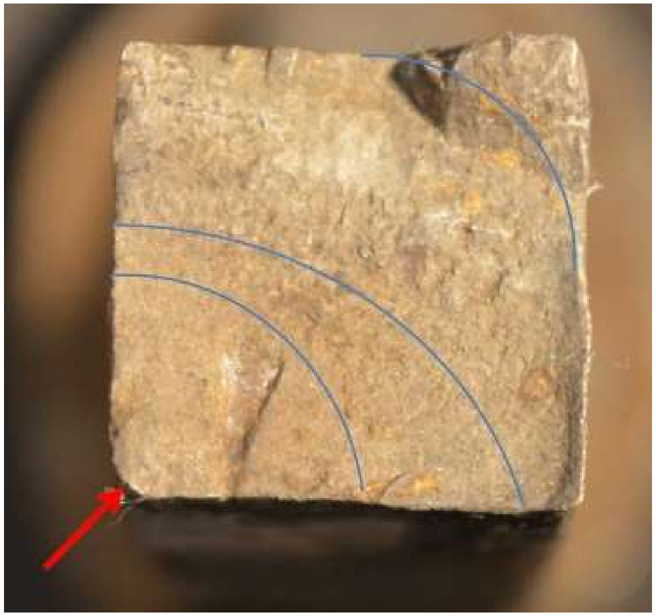


Where are broken spikes found?

- Elastic fastening systems in higher degree curves and special trackwork
- High rails (almost never low rails), in all spike hole positions (gage & field, rail and plate)
- Frequency of broken spikes is higher where there is significant tractive or braking forces
- Tie condition new or very good

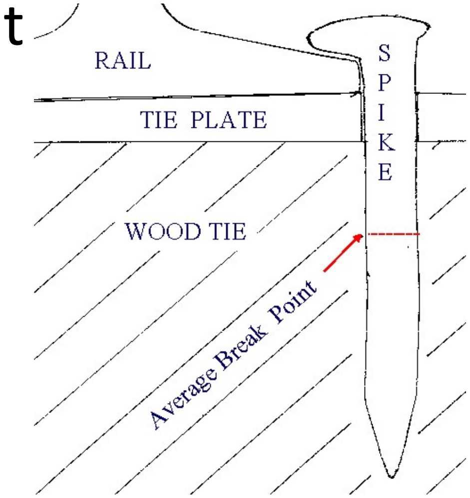
What a broken spike looks like

- Significant plate loading in longitudinal direction indicated by deformation on side of spike shaft (yellow arrow); depth of plate contact indicates a rail spike.
- Fracture is 1-3/8” below top of tie.
- Fracture initiation indicated by red arrow.



The fatigue fracture originated in the back corner and then propagated diagonally across the shaft

The depth of fracture is remarkably consistent

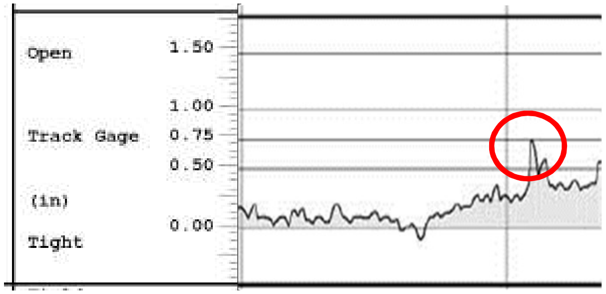


- Cut spikes tend to fail 1-1/2” below the top of tie. Hole position determines depth: rail spikes fail ~ 3-1/4” below the head, plate spikes ~ 2-1/2”.
- Screw spikes tend to fail near their top thread – at the change in cross-section. For the screws below, failure is ~2” below the head.

Left: The longer spikes are rail position, the shorter spikes are plate position

How do we find broken spikes?

It depends



- Single broken spikes are not easy to find.
  - *Visual detection is difficult*
- Because fracture depth is 1-1-/2" below top of tie, and the top of spike shaft is often pinched between tie and tie plate, the spike may not be loose.
  - *Broken spikes often must be hit or pulled to be detected*
- A small cluster of broken spikes in one or two ties can produce a "gage spike" during a geometry car inspection.

How do we find broken spikes?

A larger cluster of broken spikes:

- Significant tie plate movement
- Open gage that has existed for some time may show evidence of false flange contact

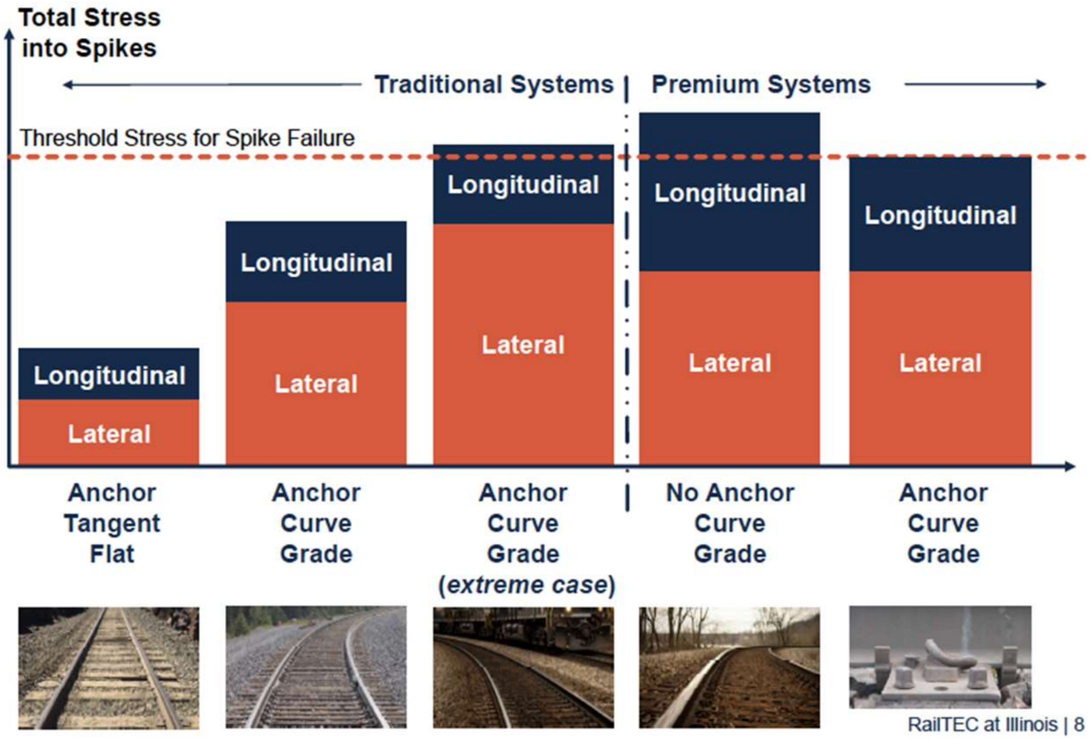
- A still larger cluster of broken spikes can allow enough gage widening to cause a derailment.

Factors that contribute to broken spikes

Researchers have identified three contributing factors, all related to the load transfer of elastic fastening systems:

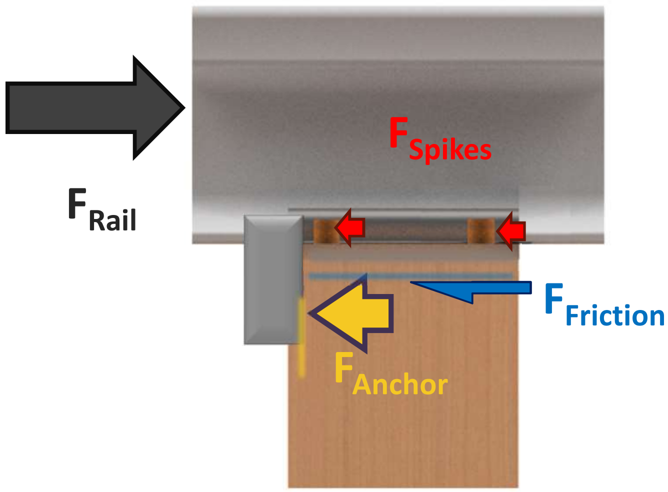
1. **Added longitudinal load:** The longitudinal rail restraint provided by the elastic clips is transferred to spikes. (Rail anchors are generally not used with an elastic system.)
2. **Reduced friction between plate and tie** due to rail uplift.
3. **Elastic clip systems are stiffer**, and therefore spread lateral and longitudinal loads over fewer ties.

Factor 1: Added longitudinal load – conceptual graph of stress state



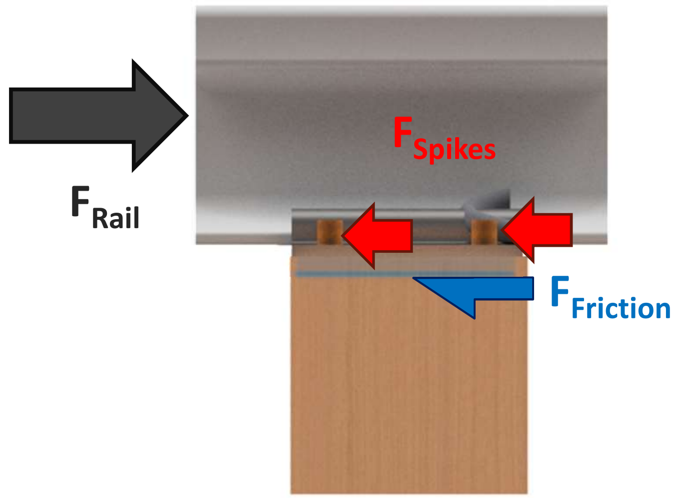
- This graph compares the relative contributions of lateral and longitudinal loading to total spike stress for traditional and elastic fastener systems.

Factor 1: Added longitudinal load – load transfer diagram



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

Traditional cut spike and anchor system:
Longitudinal rail load is resisted primarily by anchors; plate-tie friction and spikes play a supporting role.



$F_{Rail} = F_{Spikes} + F_{Friction}$

Elastic fastening system:
Longitudinal rail load is transferred to the clip-plate assembly; plate movement is then resisted by plate-tie friction and spikes.

Factor 2: Reduced tie plate friction due to rail uplift

Two screen shots from a video showing tie plate movement under a train.

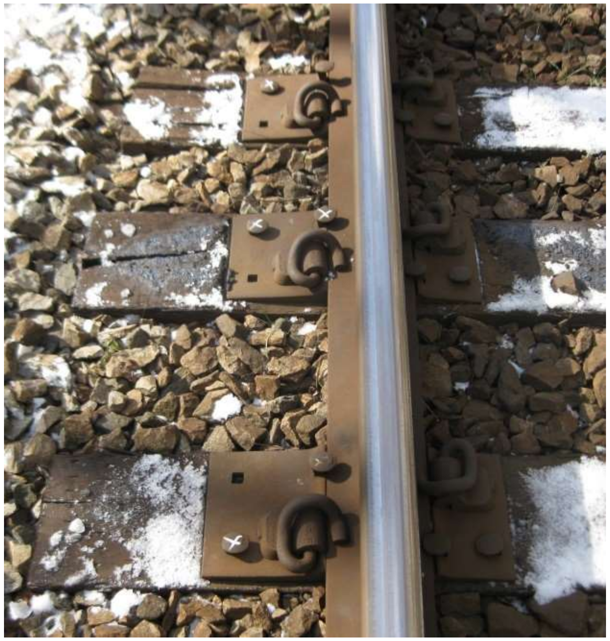
- Left - plate is bearing on the tie (wheel is directly above plate)
- Right - the impact of rail uplift; the plate lifts ~ 1/8” off the tie (wheel is several ties away)

Wave action of the rail causes plate uplift, eliminating contact (and friction) between plate and tie.

Factor 2: Reduced tie plate friction due to rail uplift - video

- Video shows the field side of a Victor plate under a train.
  - Rail uplift causes the tie plate to move up and down approx. 1/8”.
- Loss of plate-to-tie contact means loss of plate/tie friction.
  - Without this friction, lateral and longitudinal wheel loads are transferred directly to the spikes.

Factor 3: Increased fastener stiffness



- Elastic systems are stiffer than the traditional cut spike & anchor system
- The lateral and longitudinal loads are distributed over fewer ties

Broken spike remedies

The industry has tried several modifications to the elastic system:

1. Adding rail anchors
2. Replacing square-hole plates and cut spikes with round-hole plates and screw spikes

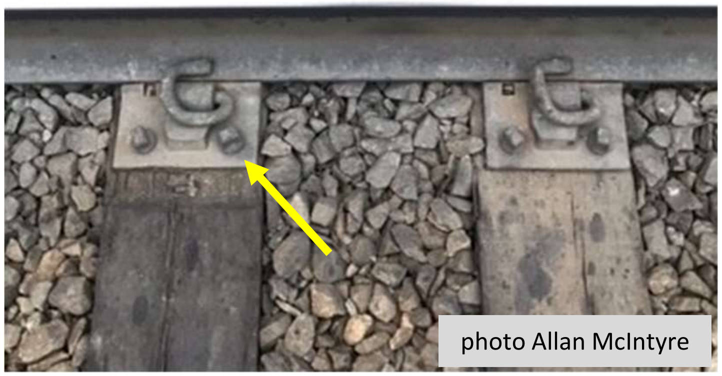


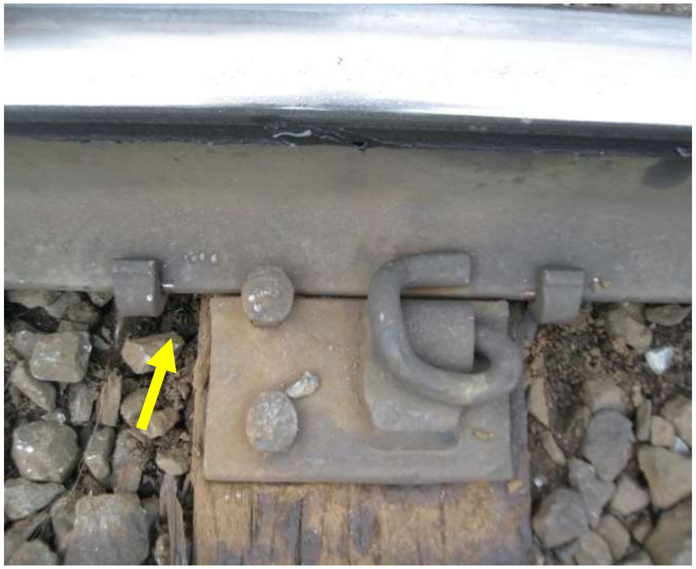
photo Allan McIntyre

Remedy – rail anchors

Adding anchors is intended to reduce the longitudinal load applied to the spikes.

Are anchors an effective fix?

- Initially, yes.
- Over time, no. Anchors become less effective due to wood deformation & rail movement.
- Any rail movement allowed by a loose anchor will be resisted by the elastic clips and plates, and, ultimately, the spikes.
- Field results on NS showed that initially, anchors eliminated broken spikes. But after several years, broken spikes reappeared.



Any space between anchor and tie results in the transfer of the longitudinal load to the spikes.

Remedy – screw spikes

While screw spikes are not stronger in terms of cross section, they do create a plate-to-tie clamping force that produces plate/tie friction, which, in turn, reduces the lateral & longitudinal forces applied to the screws.

Spike (type/location)	Cut	Screw (Upper Shaft)	Screw (Threads)
Cross Section	0.625" × 0.625"	0.469"	0.344"
Area Moment of Intertia Formula	$bh^3/12$	$\pi r^4/4$	$\pi r^4/4$
I (in^4)	0.0127	0.0380	0.0110
y (in.)	0.3125	0.4690	0.3438
Stress ($force/in^2$)	24.6 × M*	12.3 × M*	31.3 × M*

*where M represents the internal moment in force-in.

Stress (σ) is a function of the moment (M), distance from the neutral axis (y) and area moment of inertia (I)

$$\sigma = My/I$$

Expectations based on geometry, screw spikes vs. cut spikes:

- Increased bending strength at the upper shaft
- Decreased bending strength at the threads
- Higher stress at the threads at equivalent loads

Remedy – screw spikes


photo Allan McIntyre

Are screw spikes an effective fix?

- Initially, yes. Screw spikes apply a clamping force between plate and tie.
- Over time, these spikes can lose clamping force, due to spike rotation or plate cutting.
- Results from TTCI and one railroad show that screw spikes (without spring washers) can eventually fail.

Remedy – screw spikes every 3rd tie

Where: 12-degree 10-mph curve with a history of broken spikes

What: NS, in 2016, installed round-hole plates and screw spikes on every 3rd tie

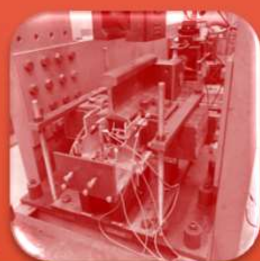
Result: After 4 years of 40 MGT traffic, the curve has not had any more broken spikes

Q: Why have there been no cut spike failures in the intermediate ties?

A: We believe that the screw spikes' clamping force, even when applied to every third tie, has been sufficient to resist longitudinal rail forces.

Project Methods

Each area provides data informing decisions or advancing work in other areas



Laboratory

Controlled experiments to better characterize load transfer and rail displacement/slip of various fasteners

Analytical Modeling

Quantification of load distribution and spike stress while investigating key factors affecting load transfer

Field

Quantification of loading demands (vert., lateral, long.) and fastener response to service loading

Field Experimentation

Horseshoe Curve | Altoona, PA

Site Overview:

- 3-track curve in Norfolk Southern's Pittsburgh line
- Westbound track has primarily **uphill** **empty** trains
  - Most failures occur on Track 3 high rail
- Eastbound track has primarily **downhill** **loaded** trains
  - Fewer failures occur on Track 1 high rail

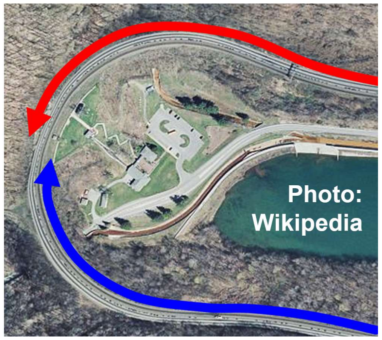
Key Feature:

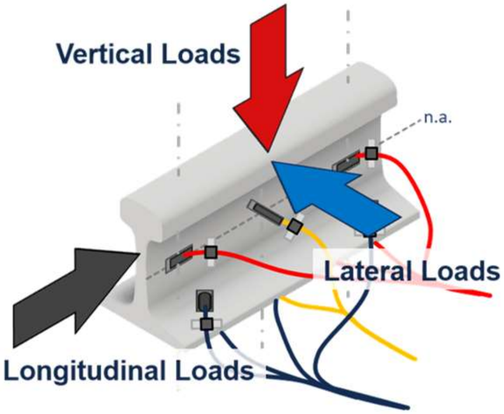
- Tracks have the same curvature, grade and climate allowing for control of variables leading to fastener failures

Load Quantification

- Load circuits installed in the center of the crib on both high and low rails to quantify:
  - Vertical, lateral, and longitudinal loads

NORFOLK SOUTHERN

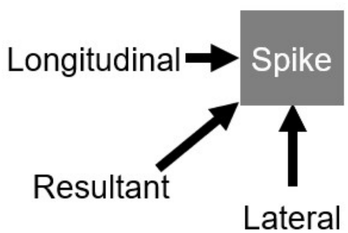


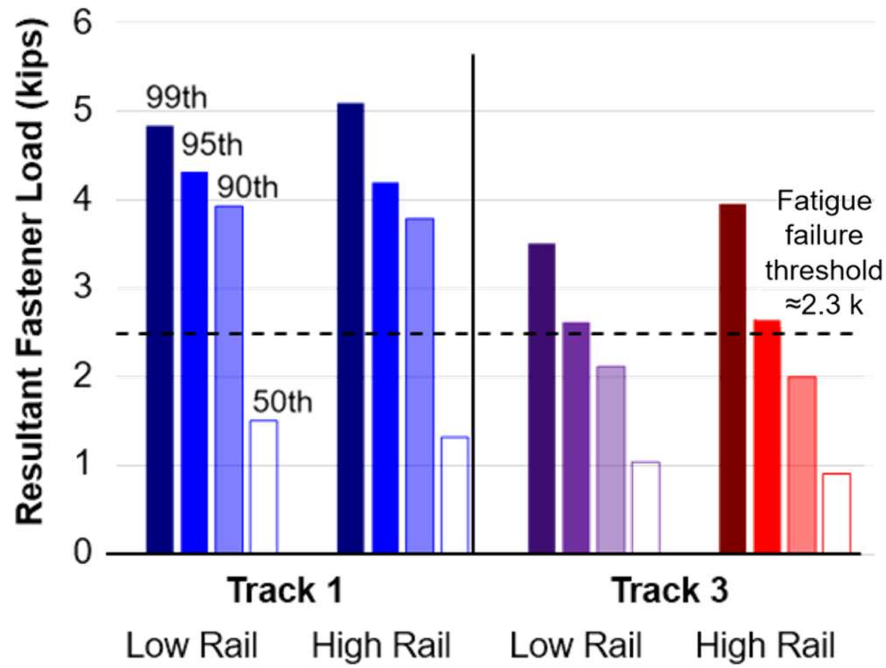


Lateral and Longitudinal Spike Loads

- Lateral fastener loads can exceed 7 kips
- Longitudinal fastener loads can exceed 2.8 kips
- Simplified calculation of total spike load, not considering friction

$$Resultant = \sqrt{Lateral^2 + Longitudinal^2}$$

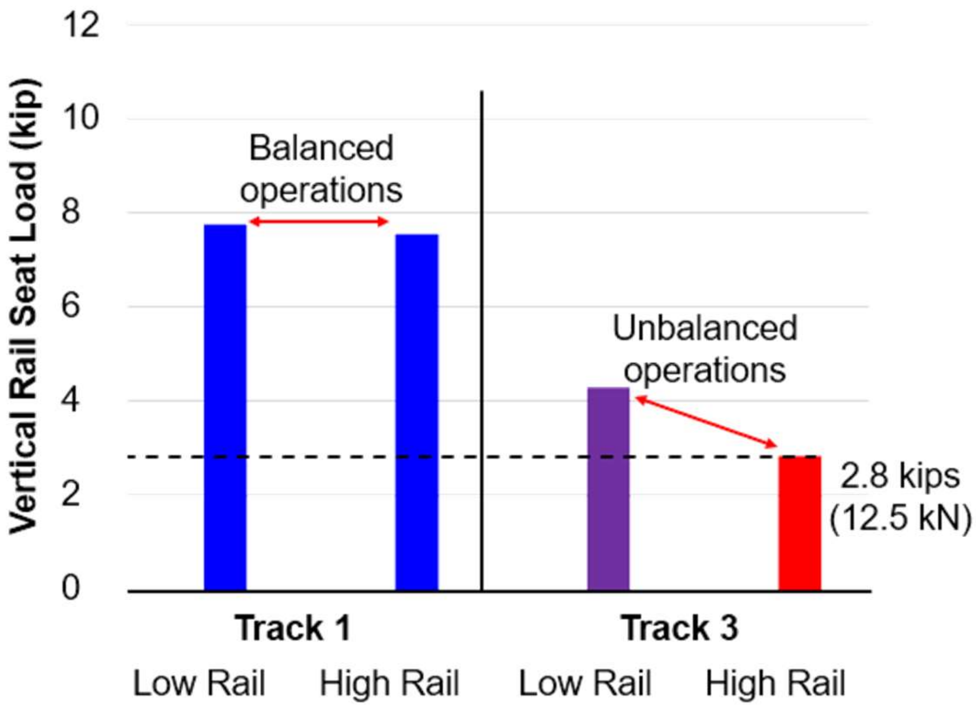




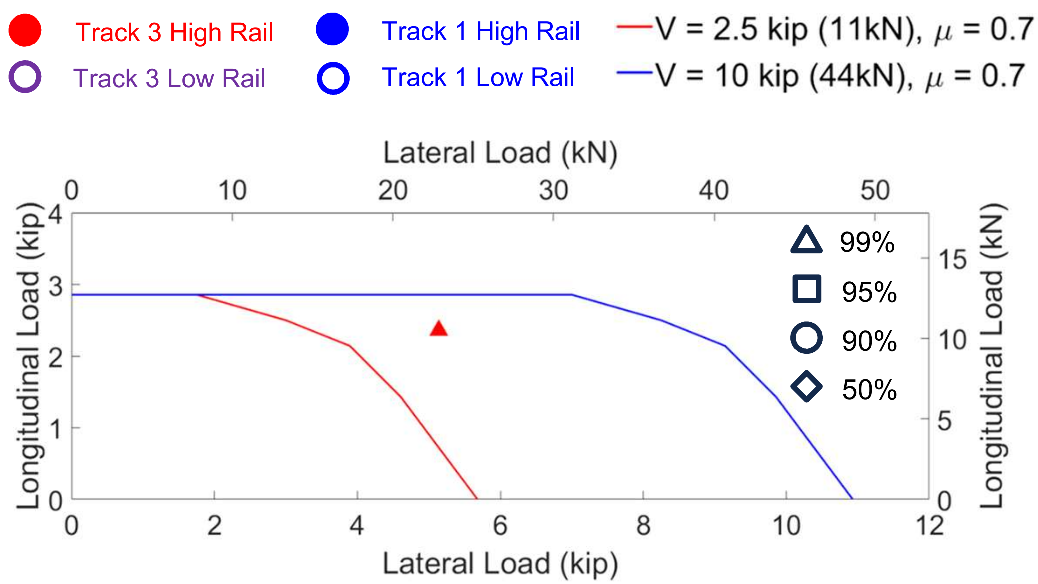
- Spike fatigue failures would be expected on every rail

Vertical Rail Seat Loads (50th Percentile)

- Track 1 saw largest magnitude vertical loads
  - 50th percentile ≈ 8 kips
- Track 3 subjected to unbalanced operations
  - High rail 50th percentile load ≈ 2.8 kips



Effect of Friction & Vertical Load



- Vertical load and friction increase the required lateral load to exceed fatigue threshold
- Longitudinal load threshold remains constant given plate uplift
- Track 3 high rail vertical load (2.8 kips (12.5 kN)) leads to lowest failure threshold
- Track 3 high rail lateral and longitudinal loads exceed higher friction thresholds

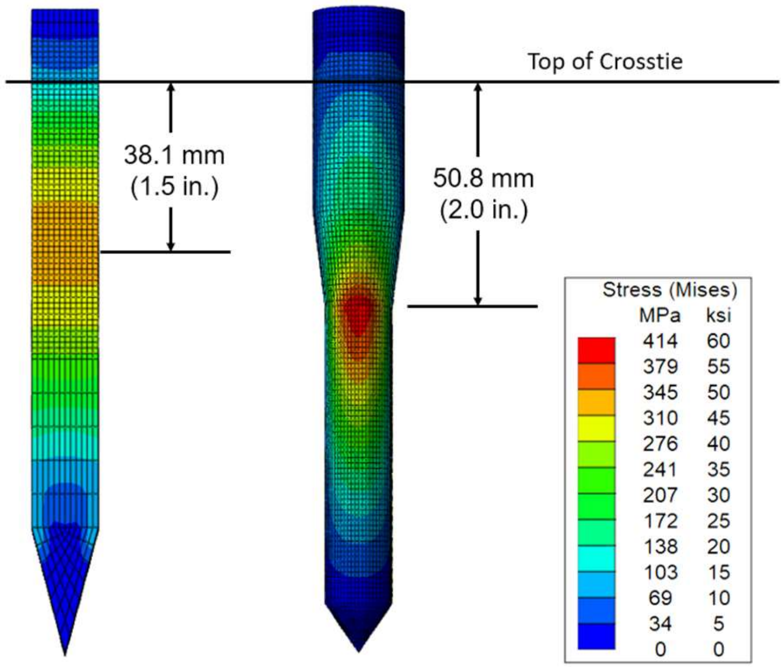
FEA modeling – comparison of cut spike vs. screw spike

<u>FEA modeling conditions</u>

- 2500 lb. longitudinal load applied to spike

<u>FEA results</u>

- Maximum spike stress depth aligns with field findings:
    - Cut spike: 1.5”
    - Screw spike: 2.0”
- Cut spike exhibits stress over larger area
- Screw spike stress concentrated at the threads



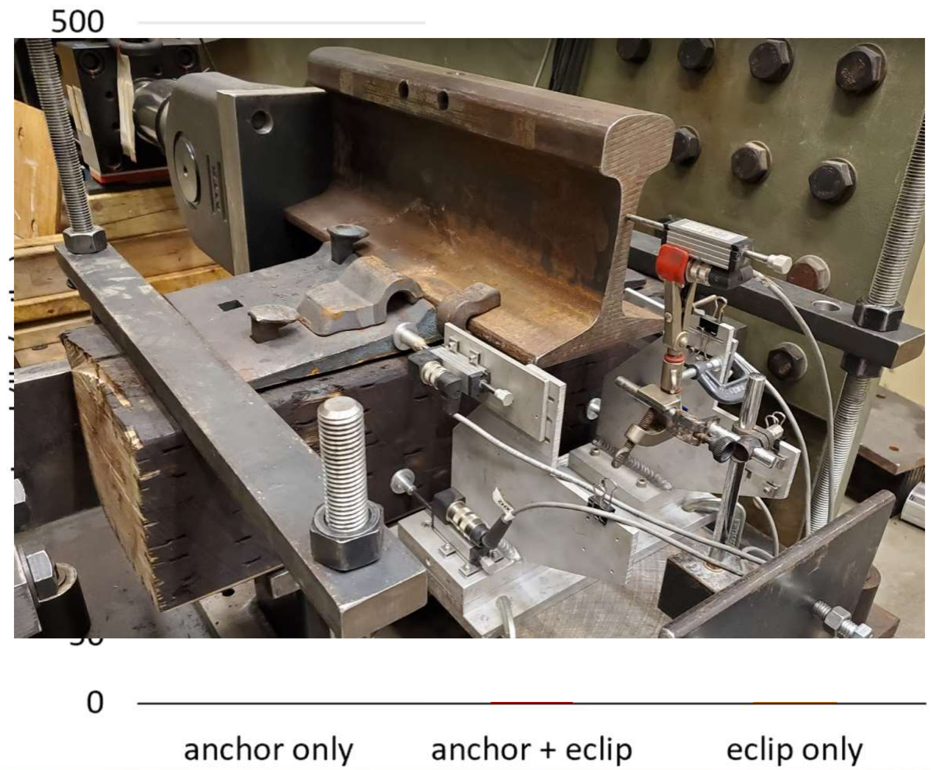
Impact of using rail anchors with elastic fasteners (Lab Study)

Laboratory Setup

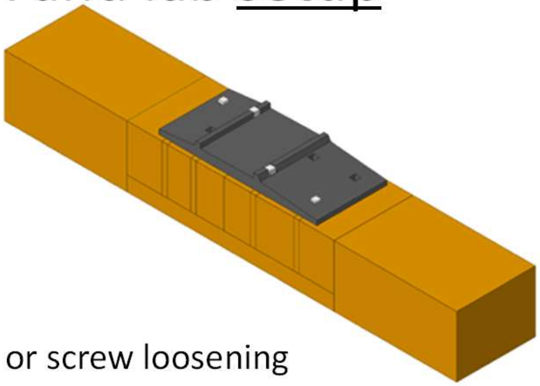
- Timber block, plate and 4 instrumented spikes
- A 2,500 lb. longitudinal load applied to the rail

Laboratory results

- Anchor only: Spikes take no longitudinal load
- Anchor + e-clip: Spikes take a portion of the longitudinal load
  - Dependent on anchor engagement, tie stiffness, etc.
- E-clip only: Spikes take approximately 95% of longitudinal load
- Anchors only useful when fully engaged

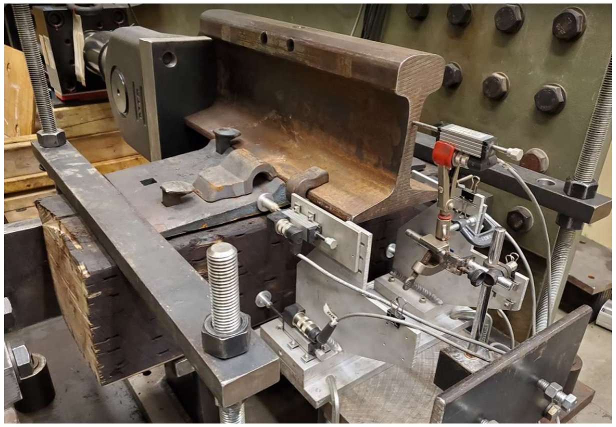


Effect of plate-to-tie hold-down force | FEA and lab setup



FEA modeling conditions

- Model consisted of timber block, plate and 4 screw spikes
- A 2,500 lb. longitudinal load applied at tie plate shoulder
- Plate hold-down force applied at each screw spike via 3 spring washer preloads:
  - 0 lbs. (control), representing no spring washer
  - 4,000 lbs. total (1,000 lbs./spike), representing minimal plate cutting or screw loosening
  - 13,600 lbs. total (3,400 lbs./spike), representing a new installation



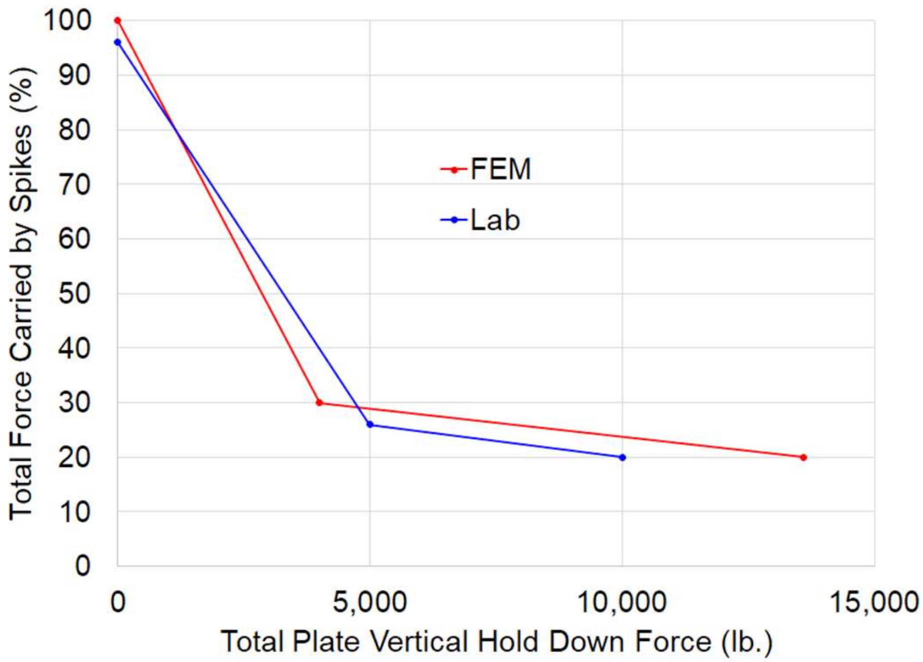
Laboratory conditions

- Timber block, plate and 4 instrumented spikes
- A 2,500 lb. longitudinal load applied to the rail
- Plate hold-down force applied to the rail at three magnitudes:
  - 0 lbs. (control), representing no spring washer
  - 5,000 lbs. total (1,250 lbs./spike)
  - 10,000 lbs. total (2,500 lbs./spike)

Effect of plate-to-tie hold-down force | FEA and lab results

Hold-down force results compared to 0 hold-down force case

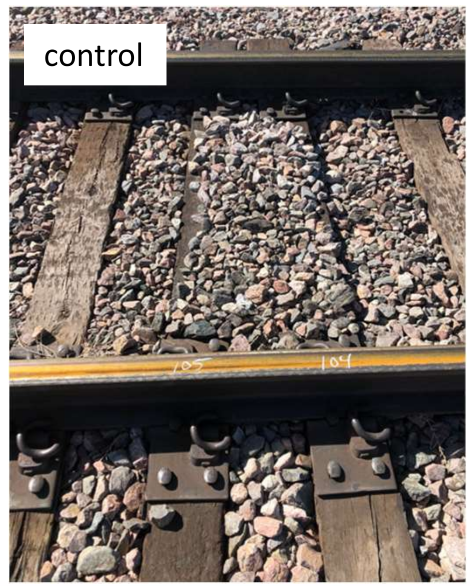
- ~70% reduction with reasonably applied load (e.g. ~1,000 lbs./spike)
- ~80% reduction with higher applied load (e.g. ~2,500 lbs./spike)
- Most of the longitudinal force can be resisted by plate-to-tie friction with reasonable vertical hold-down forces
- There is a non-linear benefit from increasing hold-down force; indicating an opportunity for further optimization

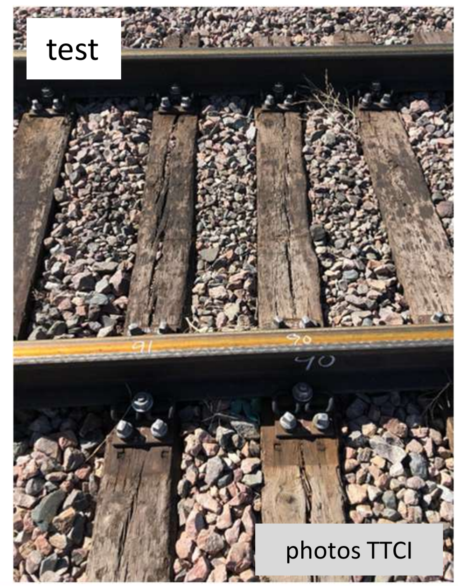


Evaluation of elastic fastening system with spring washers at TTC

- **Control zone**: 20 ties with 18” Victor plates, e-clips & 5 cut spikes
- **Test zone**: 30 ties with 14” plates, tension clamps & 4 screw spikes with spring washers
- Installed Fall 2019 & accumulated 170 MGT through June 2020


photo Marcus Dersch

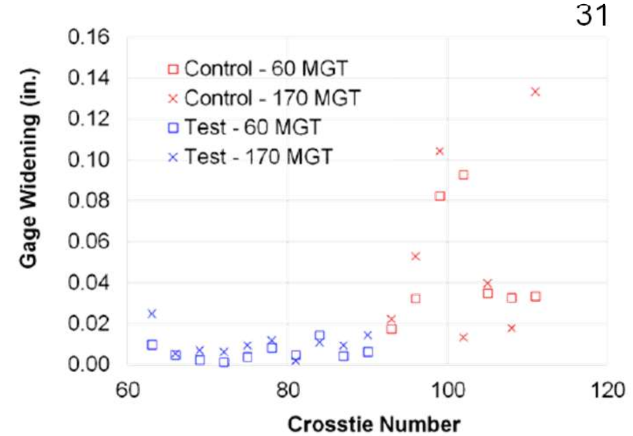




photos TTCI

Field test observations after 170MGT

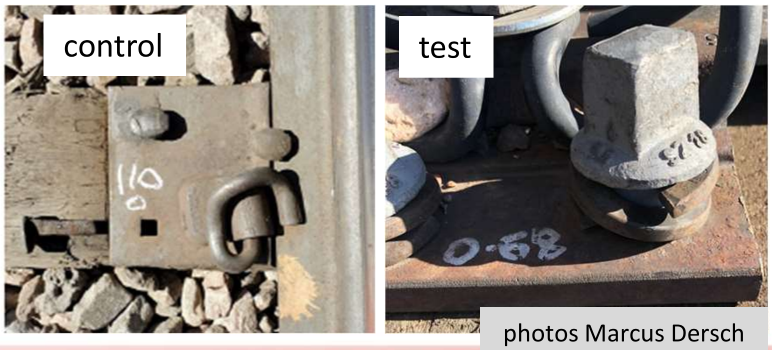
- Test zone 14” plates had less plate cutting than control zone 18” plates
- Test zone screw spike loosening was minimal on 5 rail seats (out of 60) (typically 1/16” spring expansion, *in working range of the spring washer*)
- Control zone had 6 broken spikes
- Test zone had less gage widening than the control zone



Rail base widening at 9 kips of lateral load using PTLF; measurements every 3rd tie

- Lab, FEA, and Field work indicate spring washers should provide a benefit

	Control Zone	Test Zone
Plate Cutting	Minimal	None
Broken Components	6 broken spikes	None
Loosened Components	Spike uplift	3 spikes at 60 MGT; Additional spikes at 170 MGT
Plate Movement	Some evidence	None
Skewed Crossties	Many ties, significant	2 ties, minimal

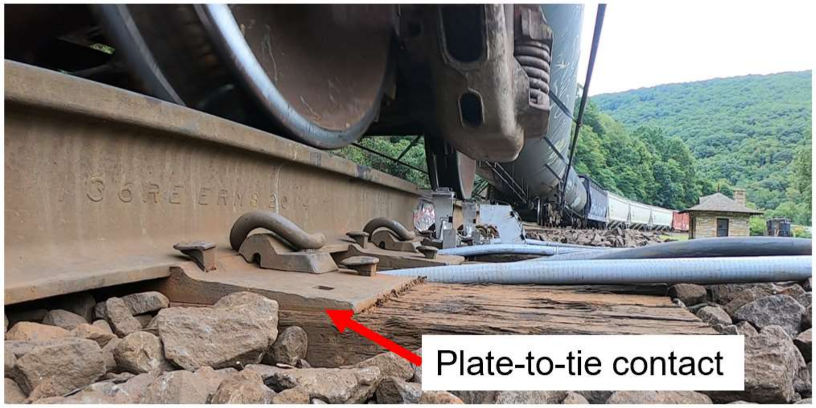


photos Marcus Dersch

Conclusions - primary causes

Primary causes of broken spikes in elastic fastener systems:

1) **Spike overloading** – primarily due to the addition of longitudinal force.
2) **Loss of plate/tie friction** – due to loss of plate-to-tie clamping force. Loss of clamping force exposes spikes to the full longitudinal and lateral loading.



Conclusions - remedies

1) Adding rail anchors to a cut spike system addresses longitudinal loading, but only for a limited time.

2) A more effective remedy is to maintain plate/tie friction, thereby reducing the longitudinal loading applied to the spikes.
   - Screw spikes maintain their hold-down force longer than anchors maintain their tight fit to a tie.

3) The most effective long-term remedy appears to be a screw spike with a spring washer.

4) Testing at TTC indicates that the tension-clamp spring-washer system showed fewer broken spikes and reduced gage-widening.

photo TTCI

Recommendations

To confirm the effectiveness of the plate-to-tie clamping force...

- Additional revenue service testing of the screw spike / spring washer system.
- A railroad should install an elastic fastener system with spring washers on a curve with a history of broken spikes.


photo TTCI

<u>Knowledge gaps and future research objectives</u>

- Q: Are unbalanced operations reducing the failure threshold? *More data is needed to comment on this further*
- Q. Can an engineered composite crosstie be used to reduce failures? *Preliminary lab data is promising, but additional revenue service testing is needed. Planned work on UPRR in 2022*

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