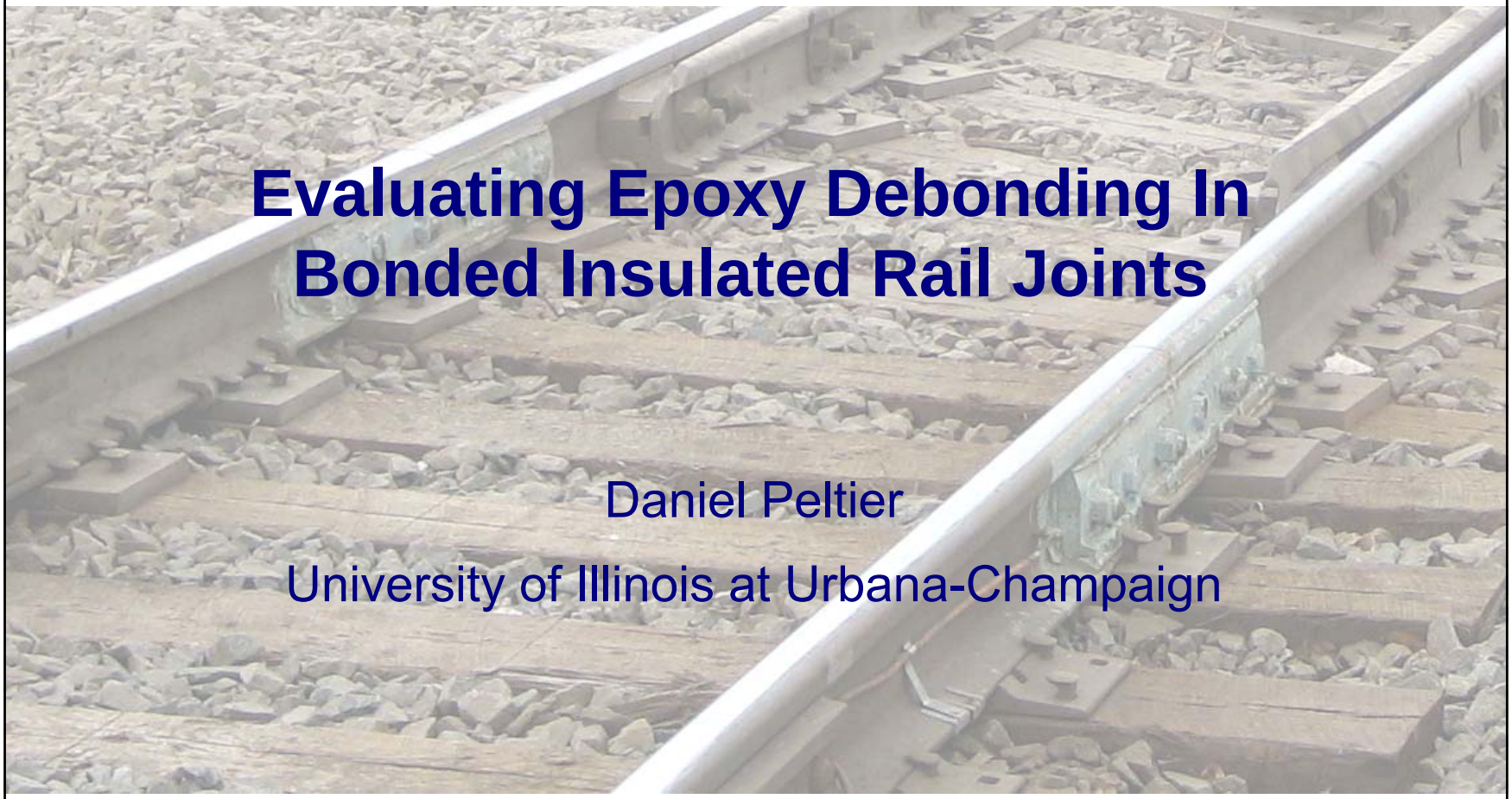

Evaluating Epoxy Debonding In Bonded Insulated Rail Joints

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ILLINOIS
RAILROAD ENGINEERING PROGRAM

Outline

- Problem definition
- Characterizing the debonded region
- Estimating the debonded area visually
- Assessing the effect of debonding on track stiffness
- Conclusions and future research opportunities

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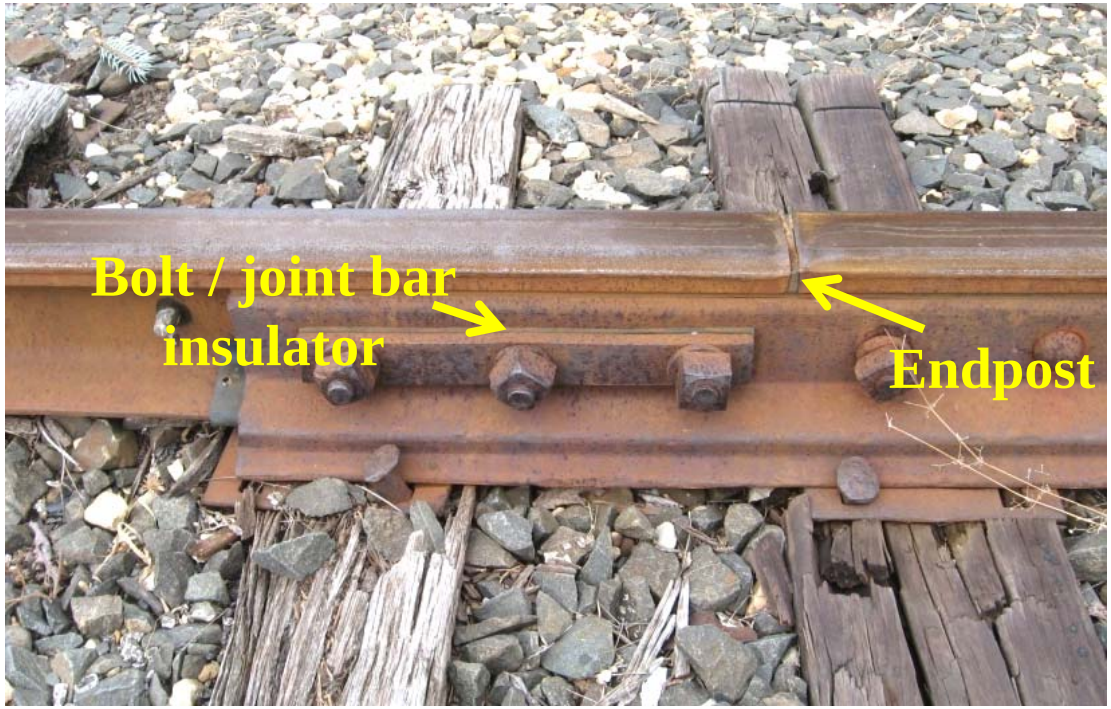
Problem definition

- Insulated joints (IJ's)
- Bonded insulated joints
- IJ failure modes
- Progressive epoxy debonding

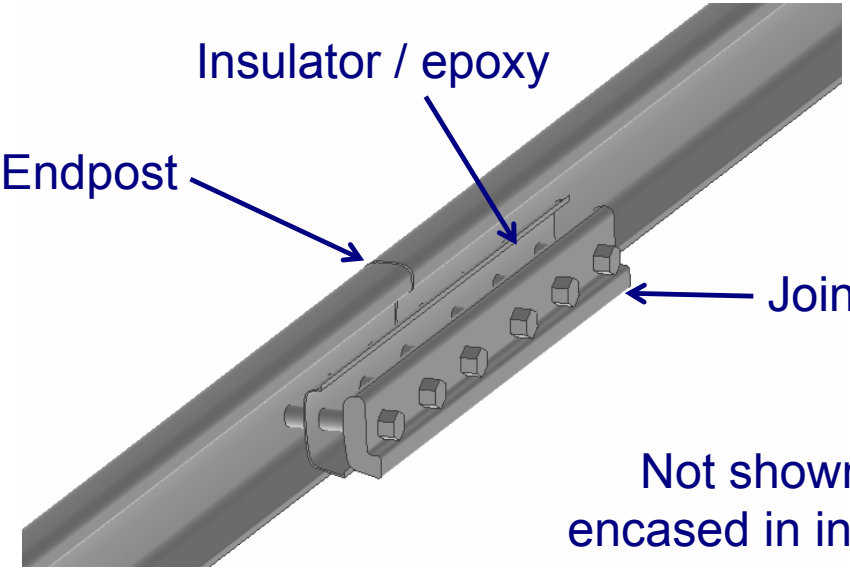
Insulated rail joint (IJ)

- Insulated joints used to isolate adjacent track circuits
- Traditional design: bolted rail joint with insulators



Bonded insulated rail joint

- Insulators glued to both joint bar and rail
  - Better transfer of shear and tensile stresses
  - Better resistance to CWR thermal stresses
  - Less deflection under vertical loads



Not shown: bolt shanks encased in insulating thimbles

Bonded insulated rail joint

IJ failure

- AAR / TTCI study: mean IJ life < 200 MGT in heavy axle load environment
  - Shorter than any other track component except high-angle crossing diamonds
  - Direct costs: $1,000's per mile per year for lines with heavy traffic
  - Indirect costs from traffic disruption

Davis, D.; Akhtar, M.; Kohake, E.; and Horizny, K. (2005) "Effects of Heavy Axle Loads on Bonded Insulated Joint Performance," *Proceedings of the AREMA 2005 Annual Conference*, Chicago, IL, USA.

IJ failure modes

- Electrical failure: metal surfaces come into contact
  - Worn or cracked insulator, rail end batter
  - Can be intermittent, hard to detect
- Mechanical failure: cracked or missing bolts, crack joint bars, bolt hole cracks in rail, battered rail ends, excessive shelling on rail head
  - All the reasons industry moved away from jointed rail!

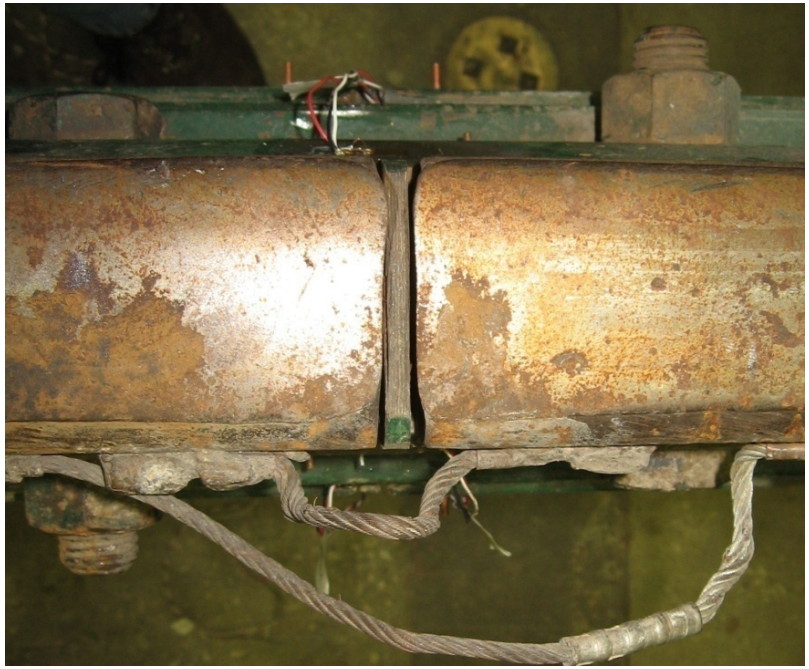
Progressive epoxy debonding

- Many problems appear to begin with deterioration in the epoxy that holds the joint together
- “Progressive epoxy debonding”: some of the epoxy comes unstuck from the rail, joint bar, or both
  - Begins near endpost (center of joint)
  - Grows outward towards edges of joint bar
  - Gradual reduction in stiffness and strength of epoxy bond

Complete epoxy failure

- As debonded region grows, shear strength of the bond decreases
- With enough debonding and high enough longitudinal loads, remaining bond breaks or insulator ruptures and the rails slip relative to joint bars
  - “Complete failure of the epoxy bond”
  - Reverts to bolted joint
    - Shear stress in bolts and bolt holes, increased deflections, wear on insulators, variable-size gap between rail ends

Complete epoxy failure



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Characterizing the debonded region

- **Test setup**
- **Inspecting disassembled IJ's**
- **Ambiguity; Inclusive (A_i) and Strict (A_s) measurements of debonded area**
- **Shape of debonded region**

Test setup

- Collected 6 IJ's with varying amounts of debonding
  - Four railroads, two regions, and two suppliers
  - Rail section either 132RE or 136RE
  - 6-bolt, 36" joint bars with holes spaced 2.5"-6"-6"-7"-6"-6"-2.5"
  - Joint bars varied by supplier
  - Materials, assembly differed by supplier
- All removed from track for unknown reasons after unknown traffic

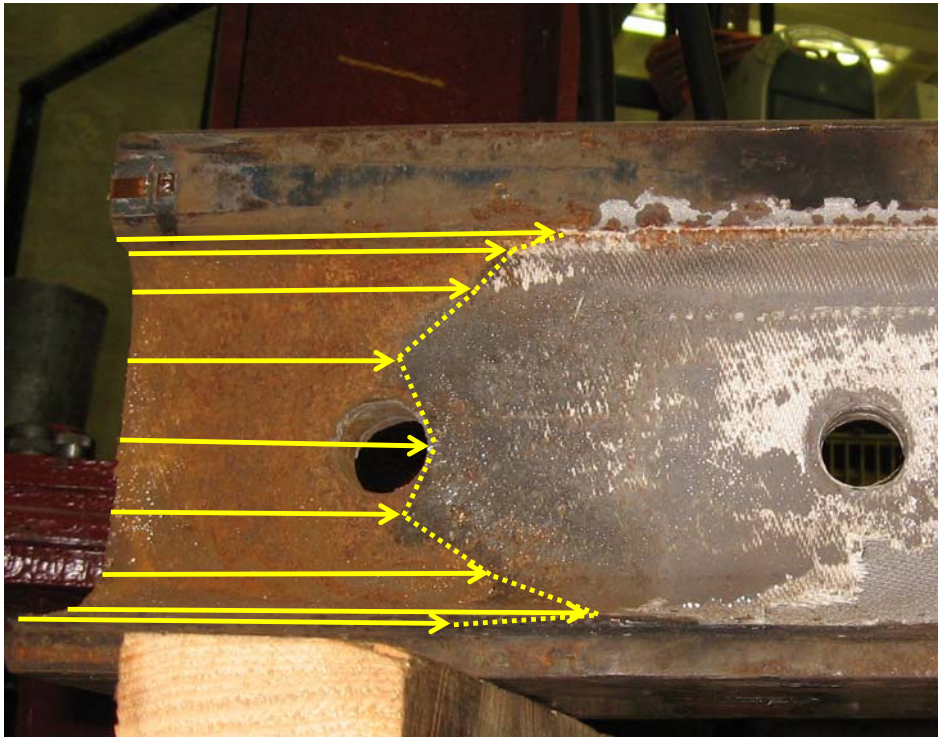
Inspecting disassembled IJ's

- When joint bars are removed from rails (not easy!), dark, rusty areas indicate debonded regions

Photo by TTCI

Inspecting disassembled IJ's

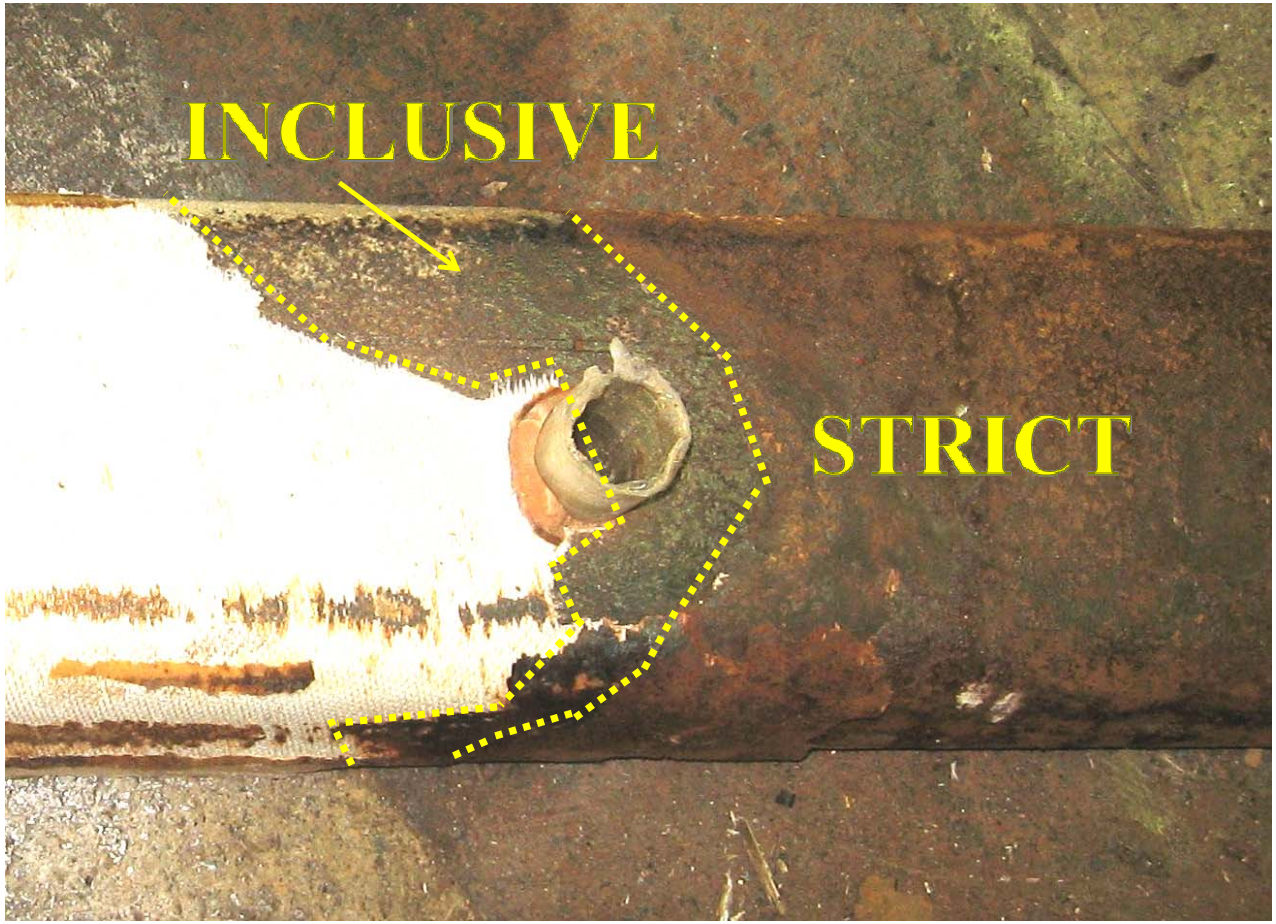
- Estimated area with a series of linear measurements from endpost to beginning of intact epoxy bond



Ambiguity

- Difficult to tell whether some areas were debonded
  - Speckled light and dark; dark but not rusty
- Two different measurements of debonded area:
  - "Inclusive" area ($\boldsymbol{A_i}$) includes ambiguous regions
  - "Strict" area ($\boldsymbol{A_s}$) only includes regions with heavy, consistent rust or dirt
  - Inclusive debonded area A_i between 5% and 280% bigger than Strict area A_s

Ambiguity



Shape of debonded region

- Debonded region tends to extend further along top and bottom sections of interface – “U” or “V” shape

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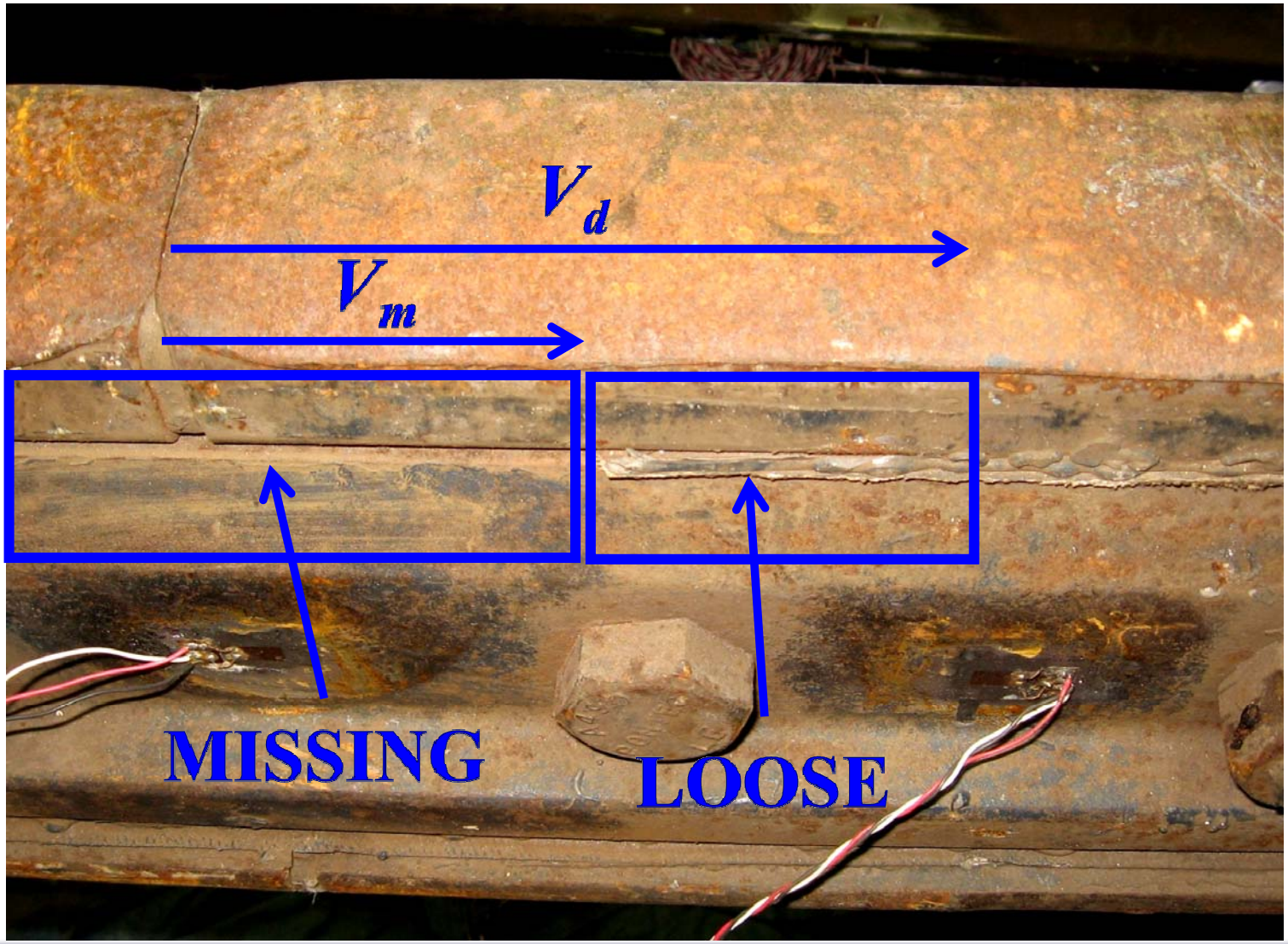
Estimating the debonded area visually

- Visual metrics V_m and V_d
- Correlations between those metrics and debonding
- Estimating debonded area from V_d

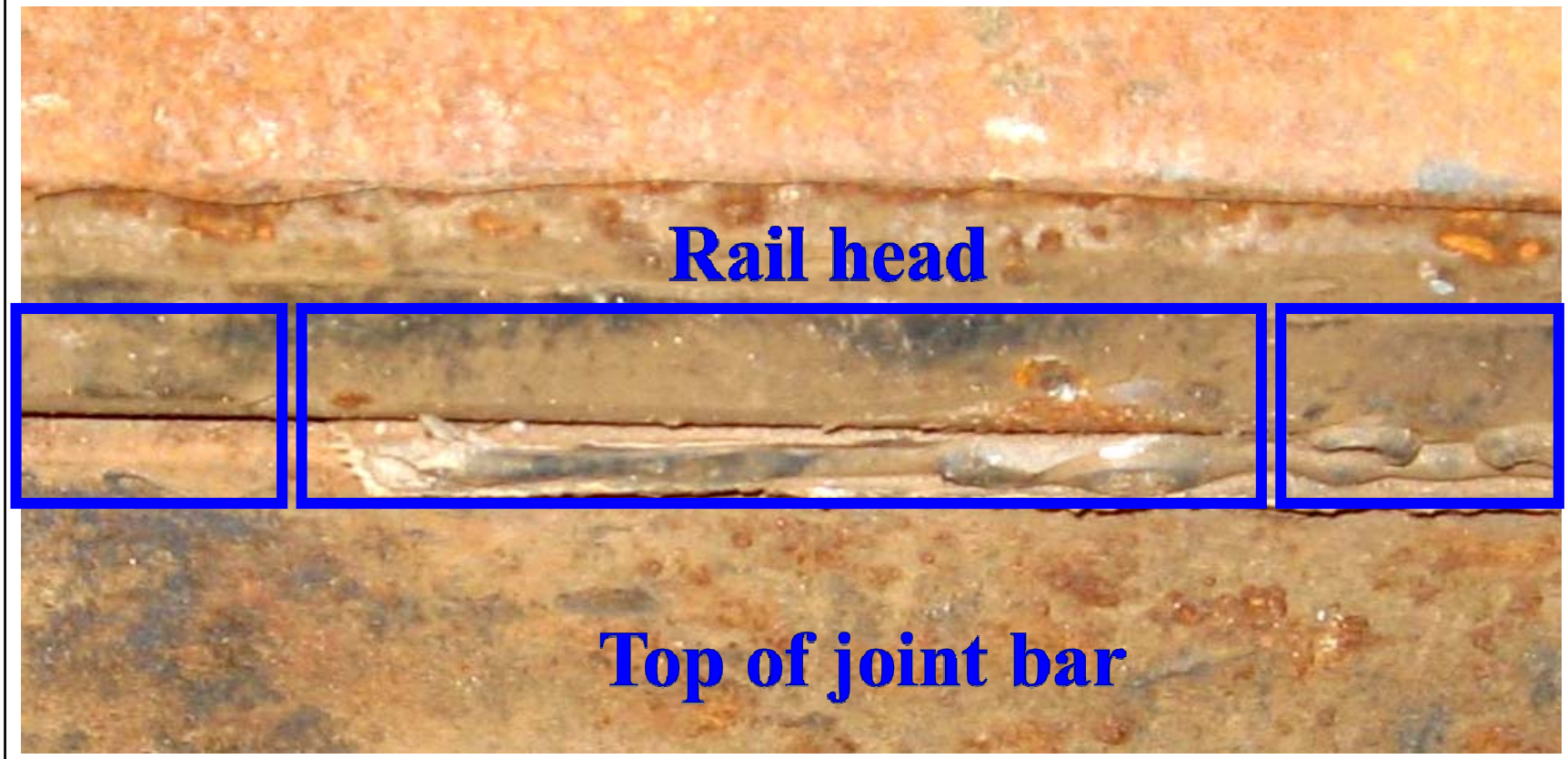
Visual metrics V_m and V_d

- Progressive epoxy debonding occurs mainly on hidden surfaces; only the edges of insulator layer are visible in an in-track IJ
- Practitioners estimate extent of debonding by examining these edges. Does this work?
- Two metrics adopted
  - V_m: Extent of missing top edge of insulator layer
  - V_d: Extent of damaged (missing or loose) top edge of insulator layer

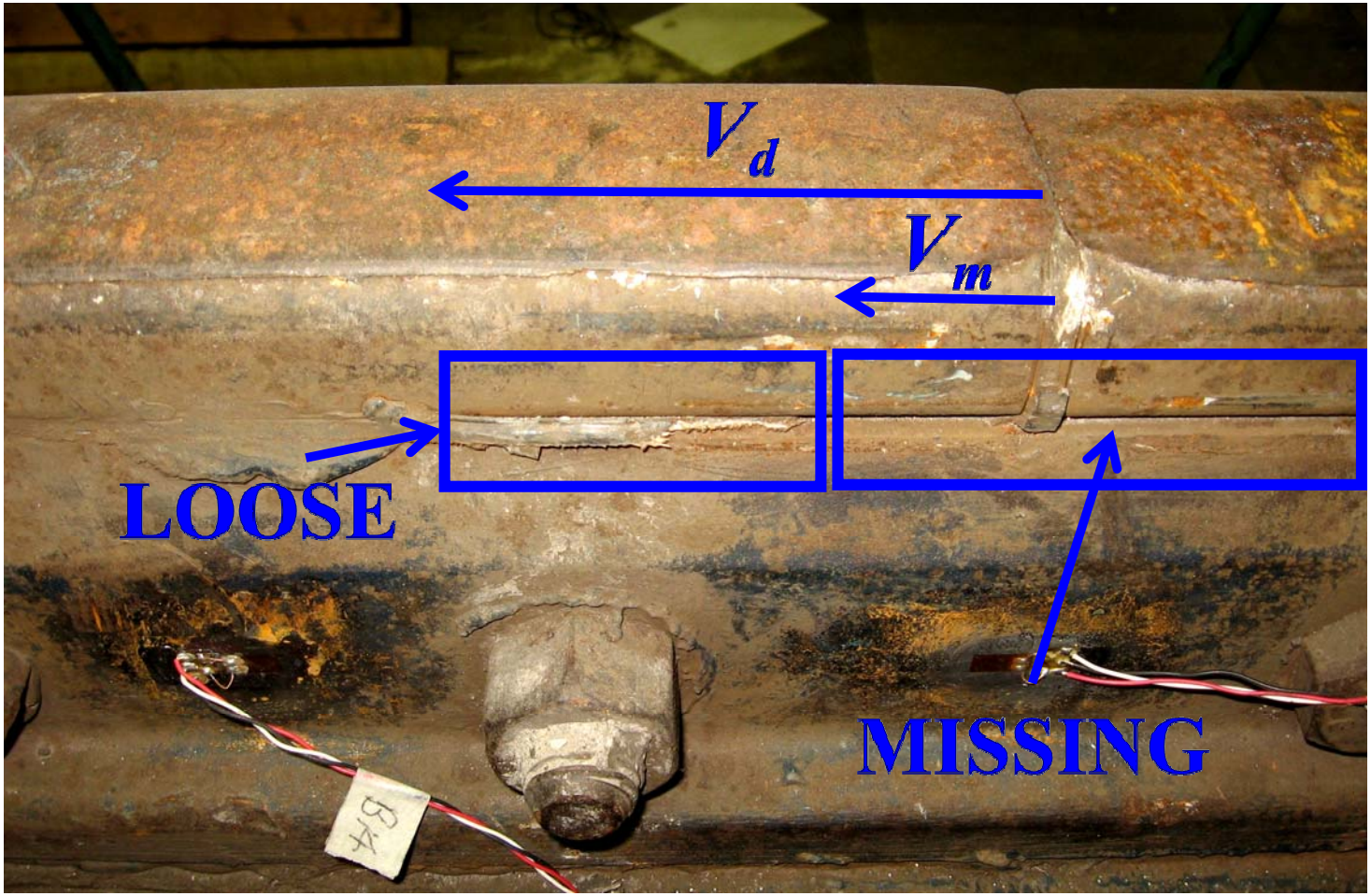
Visual metrics V_m and V_d



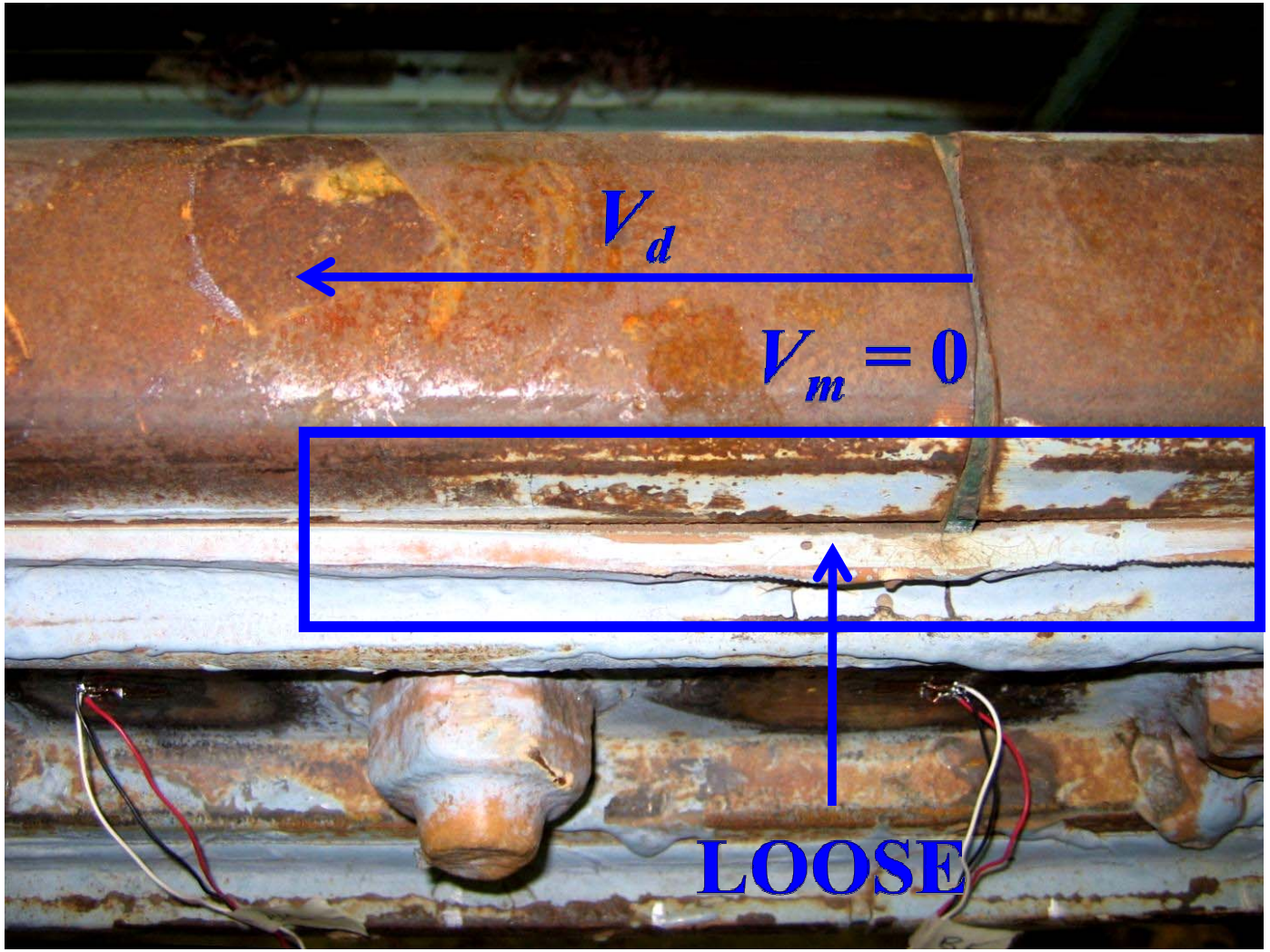
Visual metrics V_m and V_d



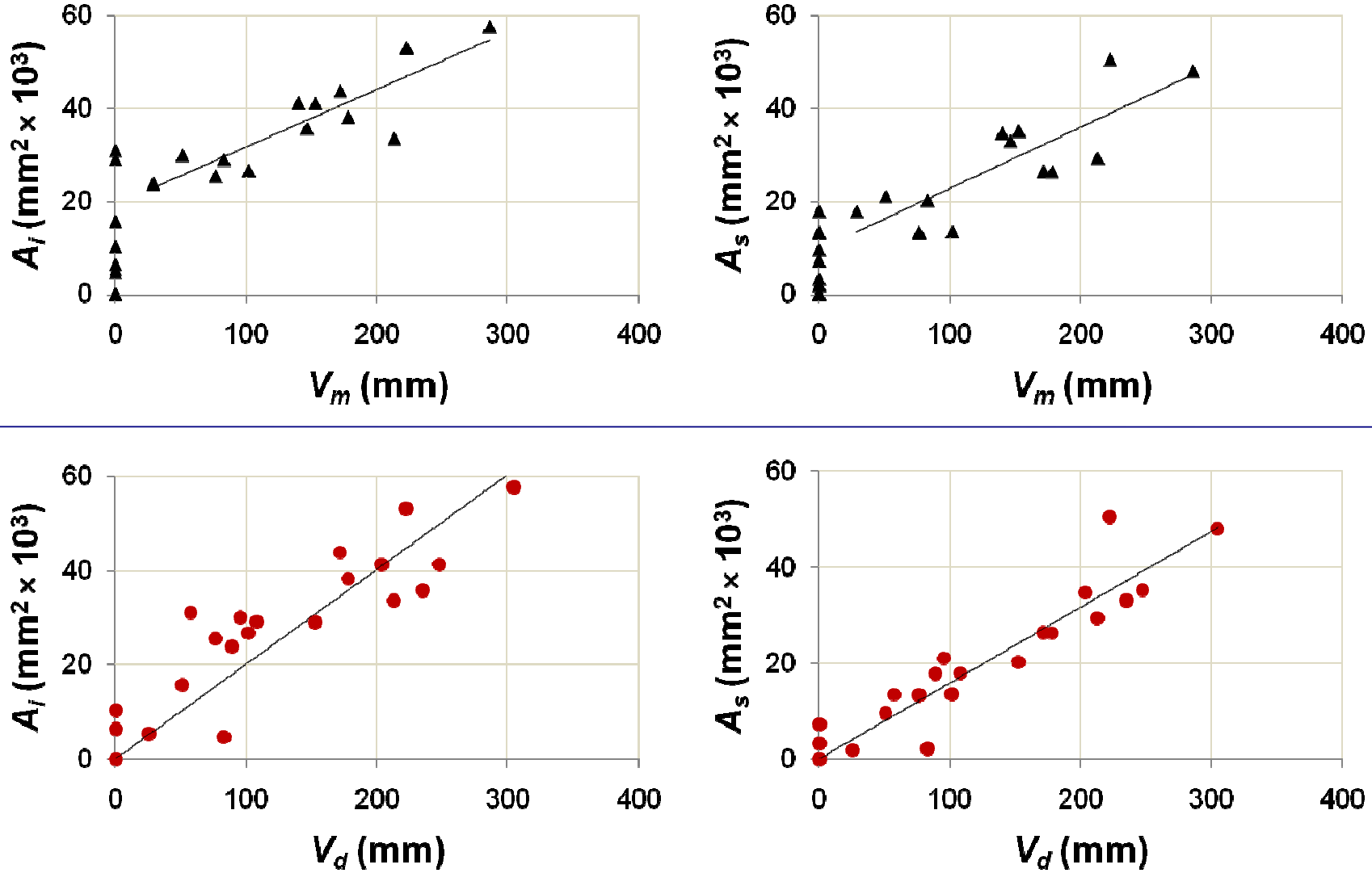
Visual metrics V_m and V_d



Visual metrics V_m and V_d



V_m, V_d and debonding



Estimating debonding from V_d

- V_d better than V_m for estimating debonded area
  - V_m can be zero with small / moderate debonding
  - Even with extensive debonding, V_d correlates better
  - Disadvantage: V_d harder to measure, more subjective and judge

Estimating debonding from V_d

- 80% Confidence interval for whole joint:

$$A_i = V_d \times 206 \text{ mm} \pm 27{,}000 \text{ mm}^2$$

$$A_s = V_d \times 161 \text{ mm} \pm 11{,}000 \text{ mm}^2$$

- "Unofficial" 80% C.I. for a single rail / joint bar interface:

$$A_i = V_d \times 201 \text{ mm} \pm 10{,}000 \text{ mm}^2$$

$$A_s = V_d \times 159 \text{ mm} \pm 6{,}000 \text{ mm}^2$$

  – Not enough data to prove certain statistical assumptions; use with caution

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Assessing the effect of debonding on track stiffness

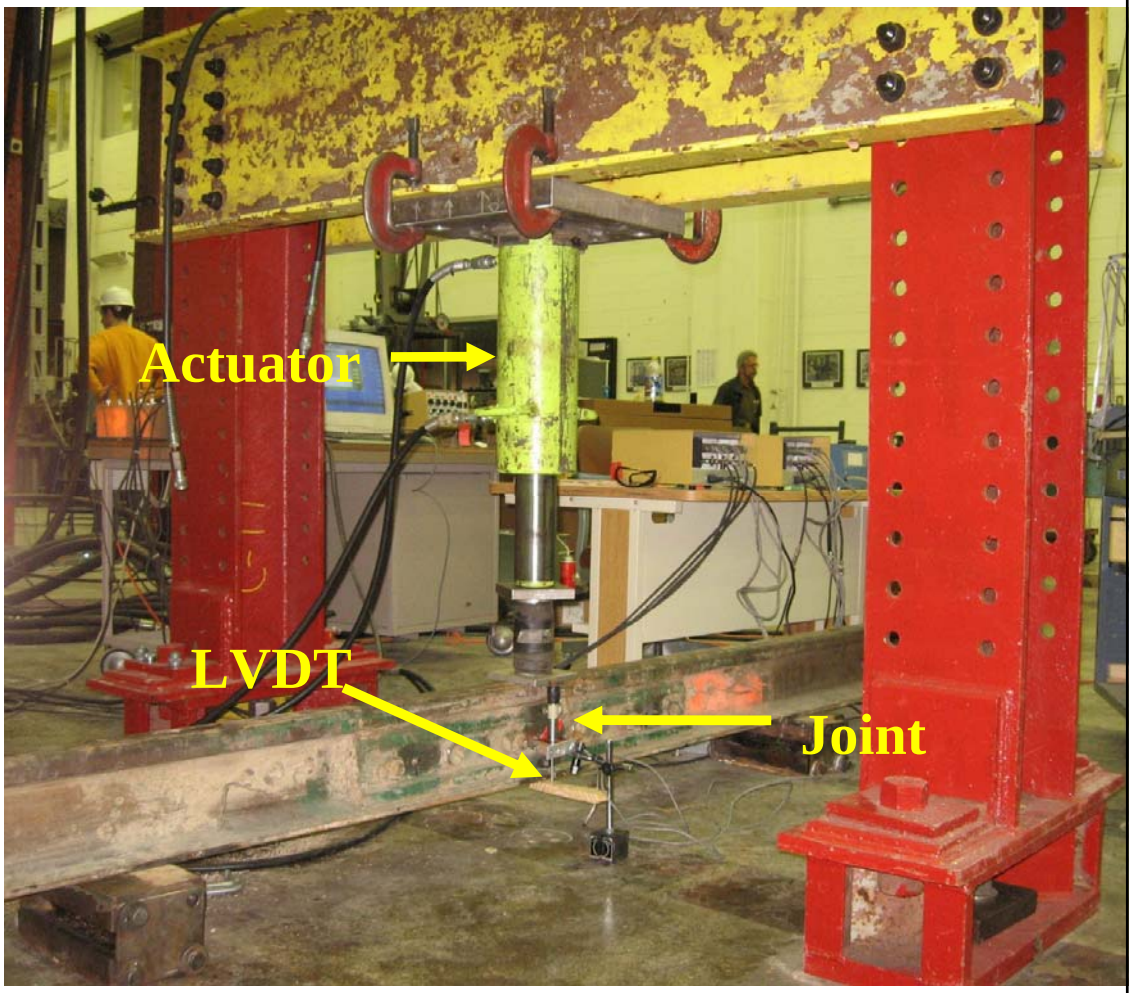
- Test setup
- Joint stiffening, endpost stress, bilinear spring stiffness
- “Rotational spring” model for characterizing joint stiffness
- Spring stiffness vs. debonding
- Effects on in-track IJ

Test setup

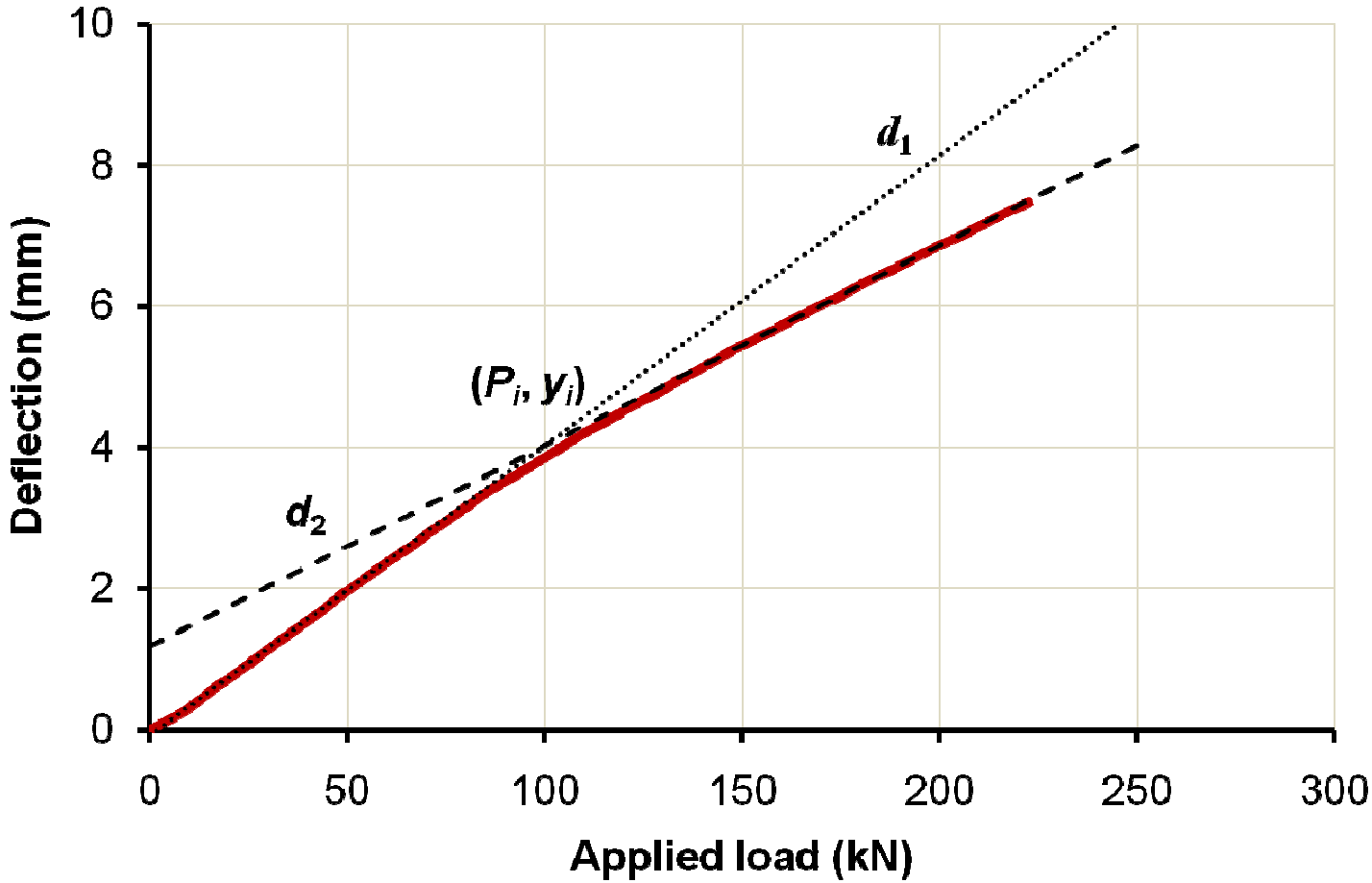
- Same 6 IJ specimens as in previous test
  - Varying amounts of progressive epoxy debonding
- 3 additional samples
  - 2 new, unused control specimens (from different suppliers)
  - 1 specimen with complete epoxy failure

3-point bending tests

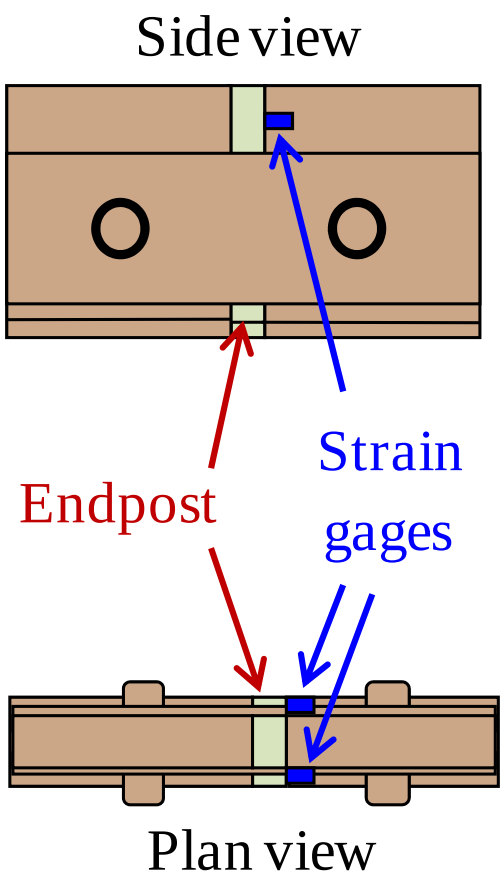
- IJ plug simply supported
- Applied load at joint center
- Measured deflection at joint center



Bilinear stiffness, joint stiffening, rail head compression at endpost

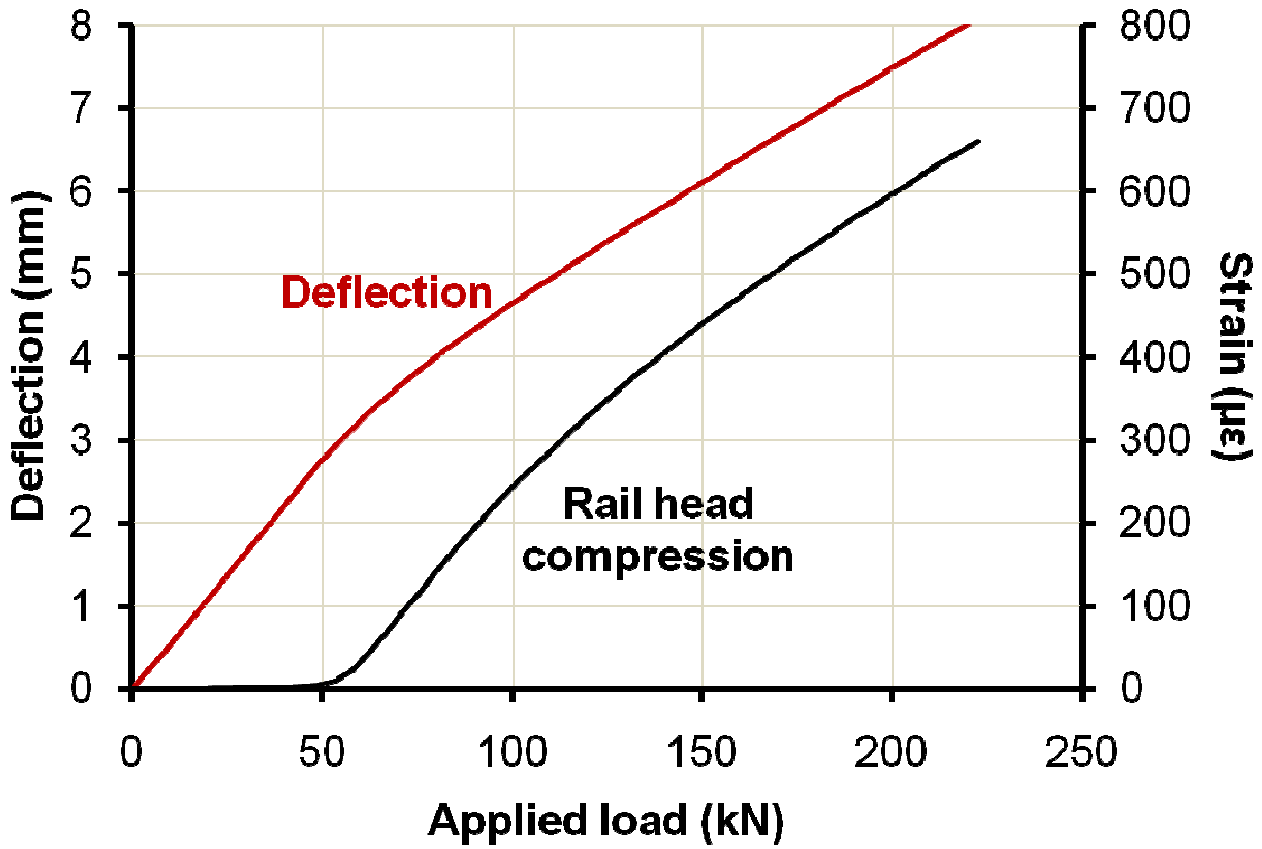


Bilinear stiffness, joint stiffening, rail head compression at endpost



- Hypothesis: increases resistance to deflection at high loads comes from compressive stresses developing in the railhead at the endpost
- Test: apply strain gages to several specimens

Bilinear stiffness, joint stiffening, rail head compression at endpost



Joint stiffening in track (?)

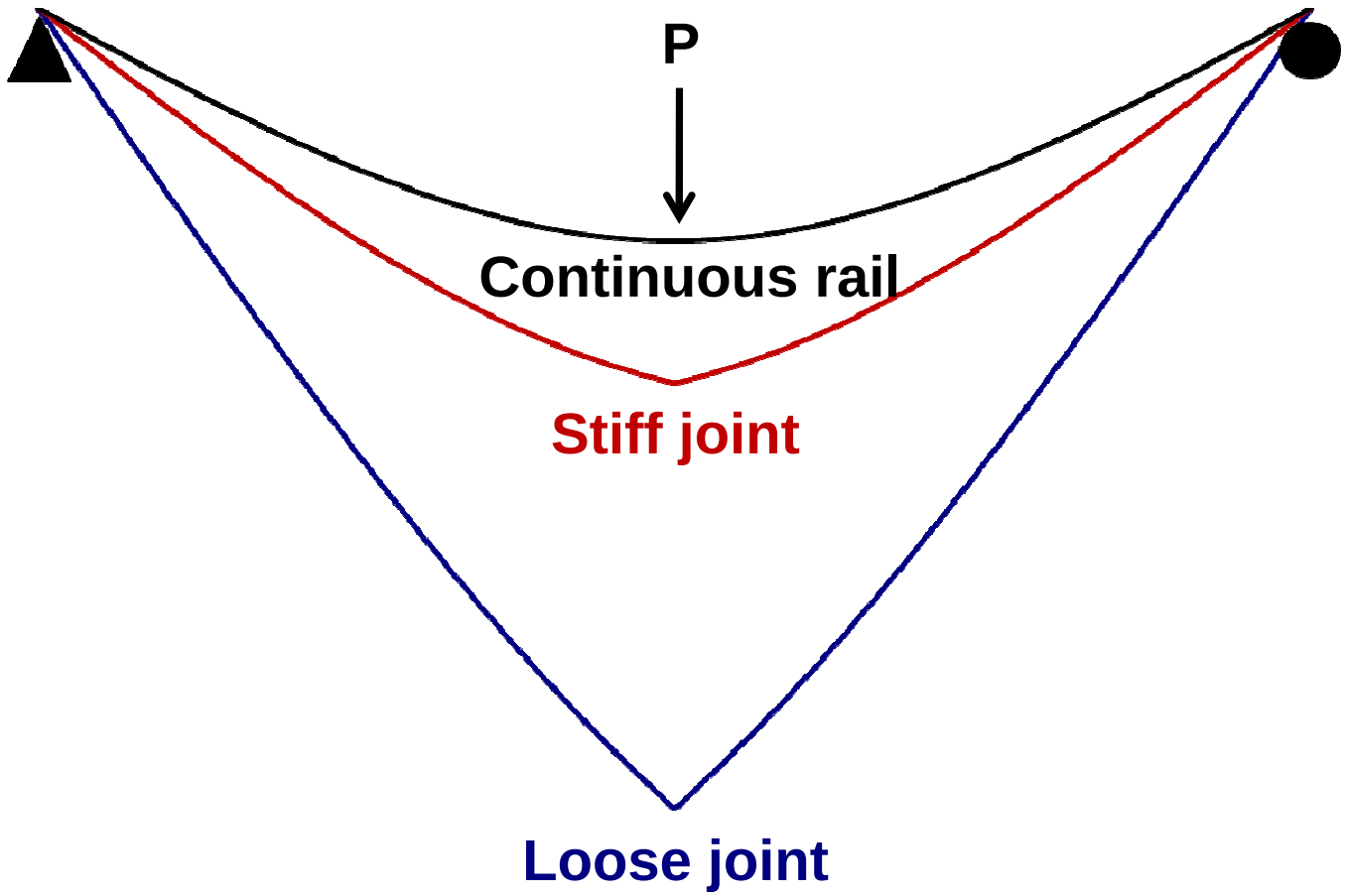
- Compressive rail head stresses wouldn't have much effect under typical 160-kN static wheel load
- Our static model doesn't necessarily reflect what would happen under higher dynamic wheel loads
- Longitudinal tension in the rail might prevent compressive stresses from developing in rail head
- Conservative approach: assume no stiffening
  - Assume joint stiffness is always that indicated by the response at low static load levels

"Rotational spring" model of joint

- Cox and Kerr, University of Delaware (1993)
- Two beams (the rails) connected by a rotational spring (the joint)
  - Rail ends deflect downward by equal amounts
  - Relative rotation between rail ends resisted by spring
- Stiffness of the joint characterized by a single parameter (the rotational spring stiffness)

$$M = s\Delta(y')$$

"Rotational spring" model of joint



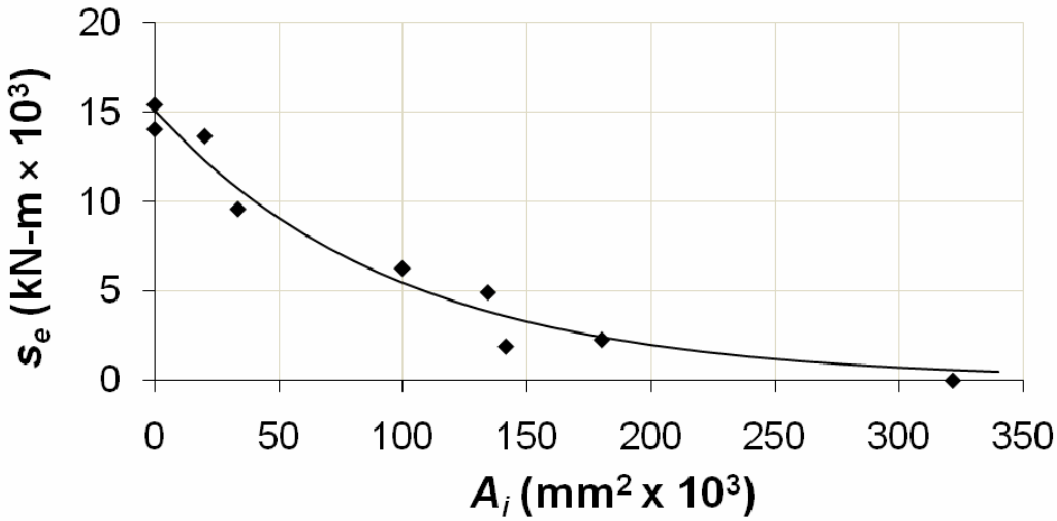
Rotational spring stiffnesses

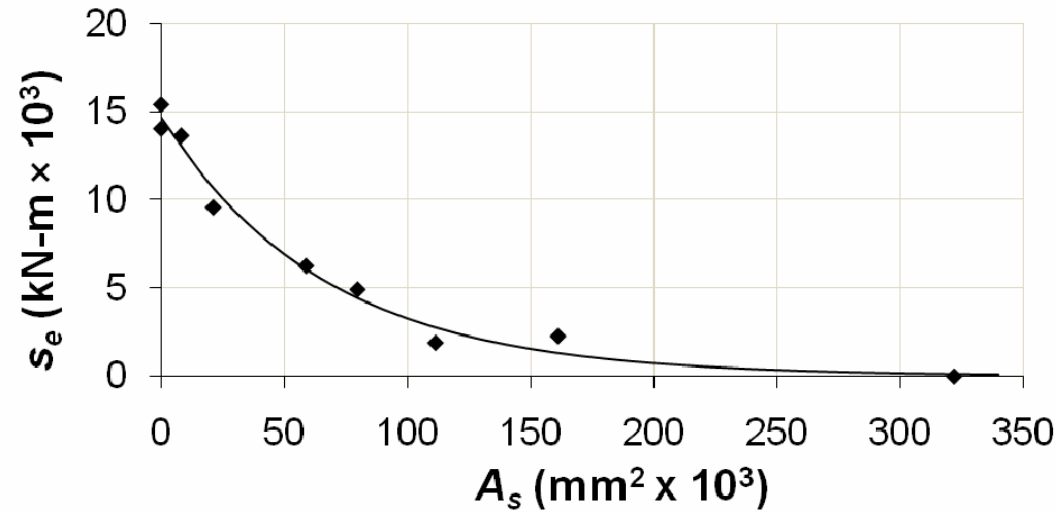
Specimen	s_b (kN-m)
CA1	17,400
TA1	9,600
TA2	8,200
TA3	5,600
CB1	18,700
TB1	12,900
TB2	17,000
TB3	5,200
TB4	3,300

Spring stiffness vs. debonding

- Even an IJ with complete epoxy failure has some stiffness, so decompose s into $s = s_u + s_e$
  - s_u = stiffness of an "unbound" joint
  - s_e = increase in stiffness due to epoxy bond
  - Estimate s_u = 3,300 kN-m from 3-point bending test on a joint with complete epoxy failure

Spring stiffness vs. debonding





80% Confidence intervals for stiffness parameters

Parameter	Estimated value (kN-m)	Range (kN-m)
s_e based on A_i	$15{,}000e^{-0.0102A_i}$ (1)	± 1,800
s_e based on A_s	$14{,}700e^{-0.0150A_s}$ (1)	± 1,300
s_u	3,300	N/A

(1) A_i and A_s measured in $mm^2 \times 10^3$

Effect of loss of stiffness

- Lower spring stiffness leads to:
  - Higher deflections
  - Increased loads on the cross ties nearest the joint
  - Higher dynamic loads
- Increased damage to ballast and / or subgrade likely
- Increased damage to IJ itself (cracks, insulator wear, etc.) likely

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A_i versus A_s

- Recall: A_i (the "inclusive" debonded area) counted some ambiguous areas as debonded, while A_s (the "strict" debonded area) did not
- A_s correlated better with both visual evidence of debonding and loss of joint stiffness
- Not determined: which measurement is more indicative of longitudinal strength?

Debonding pattern

- Debonding tends to extend farther along top and bottom of interface (~30 mm on average)
- Tends to be more debonding on one end of the joint than the other
- No significant difference between gage and field side

Visual inspection

- Examine top edge of epoxy / insulator layer
- For best results, include places where the epoxy bead has started to separate from metal but not yet broken off
- For whole joint (80% confidence):

$A_i = V_d \times 206 \text{ mm} \pm 27{,}000 \text{ mm}^2$

$A_s = V_d \times 161 \text{ mm} \pm 11{,}000 \text{ mm}^2$

Effect of debonding on stiffness

- Ignoring any stiffening effects from compressive stresses in the railhead at the endpost, the rotational spring stiffness parameter of an IJ is reduced by:
  - ~80% with complete epoxy failure
  - > 30% with 50,000 mm^2 of debonding (about 15% of total epoxy surface)
- Potential increase in dynamic load factors and load concentration on nearby ties
  - Accelerated ballast and subgrade degradation

Future research opportunites

- Similar experiments to determine relationship between debonded area and longitudinal epoxy strength
- Experimentally verified dynamic model that can account for debonding
- Effect of debonding on joint bar cracks
  - Dynamic loads increase
  - Reaction forces concentrated on nearby ties, so bending moment carried by joint bars decreases
  - Net effect unknown

Future research opportunites (cont)

- Study relationship between mechanical degradation and electrical failure
- Develop inexpensive, fully-automated systems for measuring both electrical integrity and mechanical condition of joint
  - Leave-in-place sensors vs. “inspection”
  - One leave-in-place system for measuring debonded area described in my thesis – needs more work

Big picture

- Make sure that all problems are being addressed
  - Dynamic load & effects on plates, fasteners, ties, ballast, subgrade, and wheels
  - Electrical failure
  - Cracks & derailment risks
- Alternatives to IJ's
  - Jointless track circuits
  - Axle counters in lieu of track circuits
  - CBTC with GPS and / or location beacons

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