NRC·CNRC

An ICRI task: Broken Rails

Eric Magel, Principal Engineer
Automotive and Surface Transportation

National Research Council Canada
Conseil national de recherches Canada

Canada

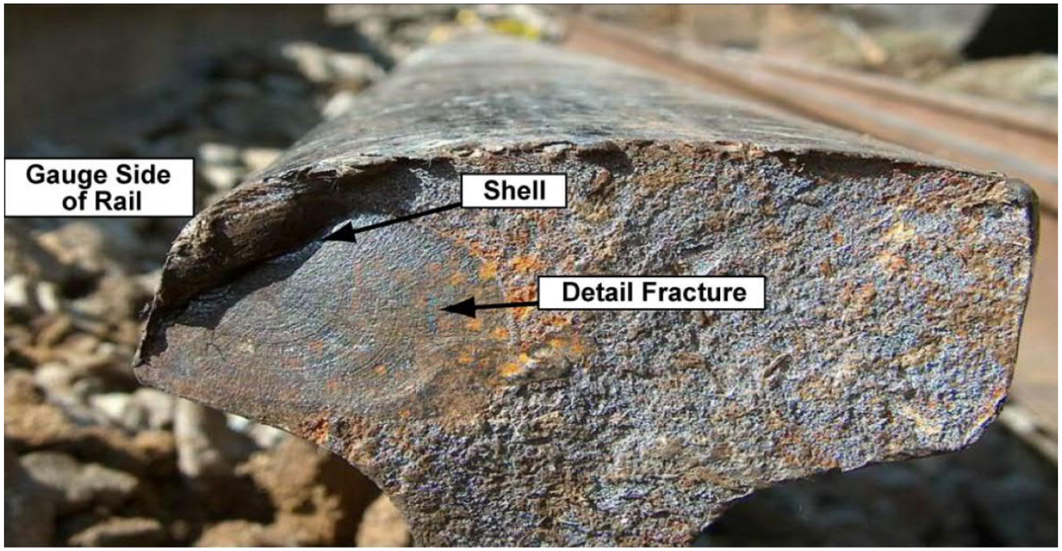
Broken Rail Derailments

Guernsey, Saskatchewan
09DEC19, 06FEB20
3.1 million litres of oil

Ellicott City, Maryland, 2012

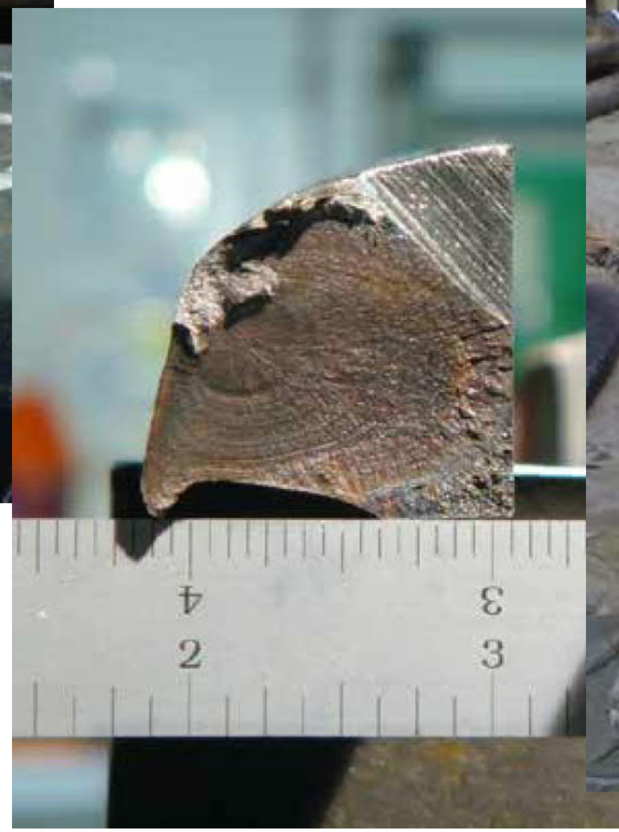
Columbus, Ohio, 2012

TSB #R05E0059 2005-08-03 CN Edson Wabamun, AB



800,000 litres of oil spilled into Wabamum Lake AB,

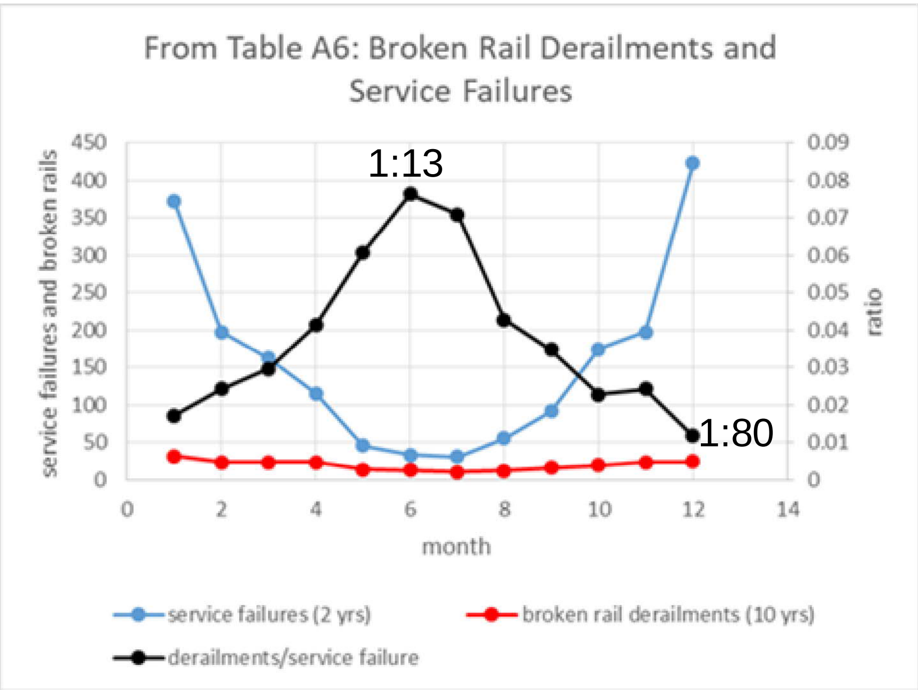
TSB #R13E0142 2013-10-19 CN Edson, Gainford, AB



13 fuel cars derailed, explosion, evacuation

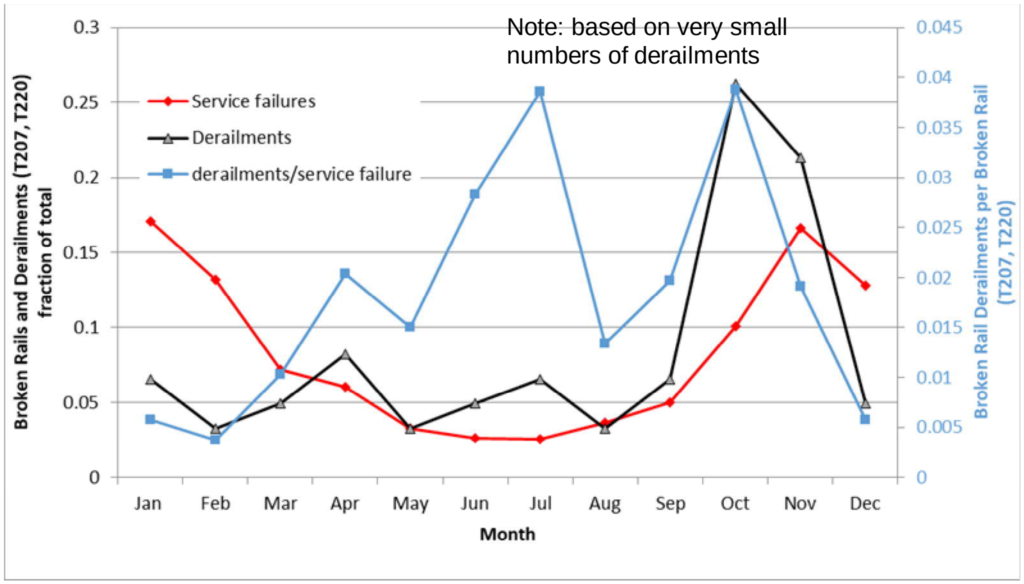
BR Derailments - Seasonality

from UIUC "SEASONAL EFFECT ON THE OPTIMIZATION OF RAIL DEFECT INSPECTION FREQUENCY", ASME, 2013



- # of broken rail derailments DOES NOT vary directly with the number of broken rails

2004-2015



ICRI-Broken Rails Group

65+ persons, online discussions via email

European example: horizontal cracks

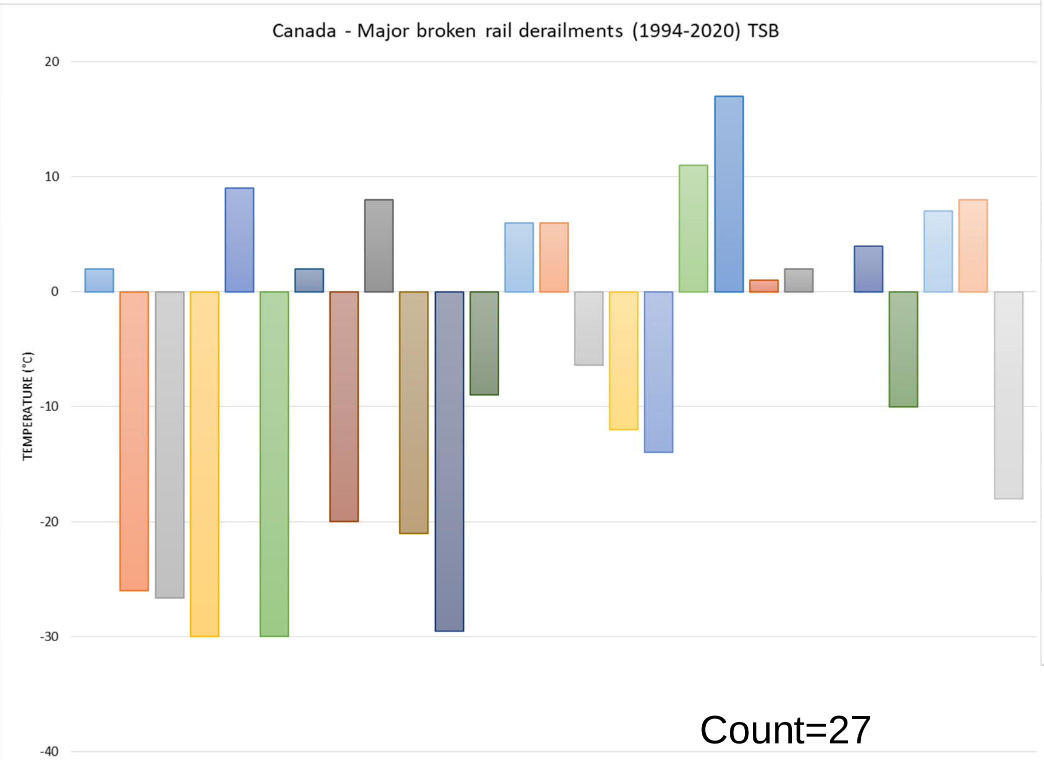
- C.J. Rasmussen
  - Example from passenger train derailment in Denmark. Crack propagated horizontally along rail until a section broke off. Suggests that in winter the rail would have had a more vertical break

"Survivable" vs "non-survivable"

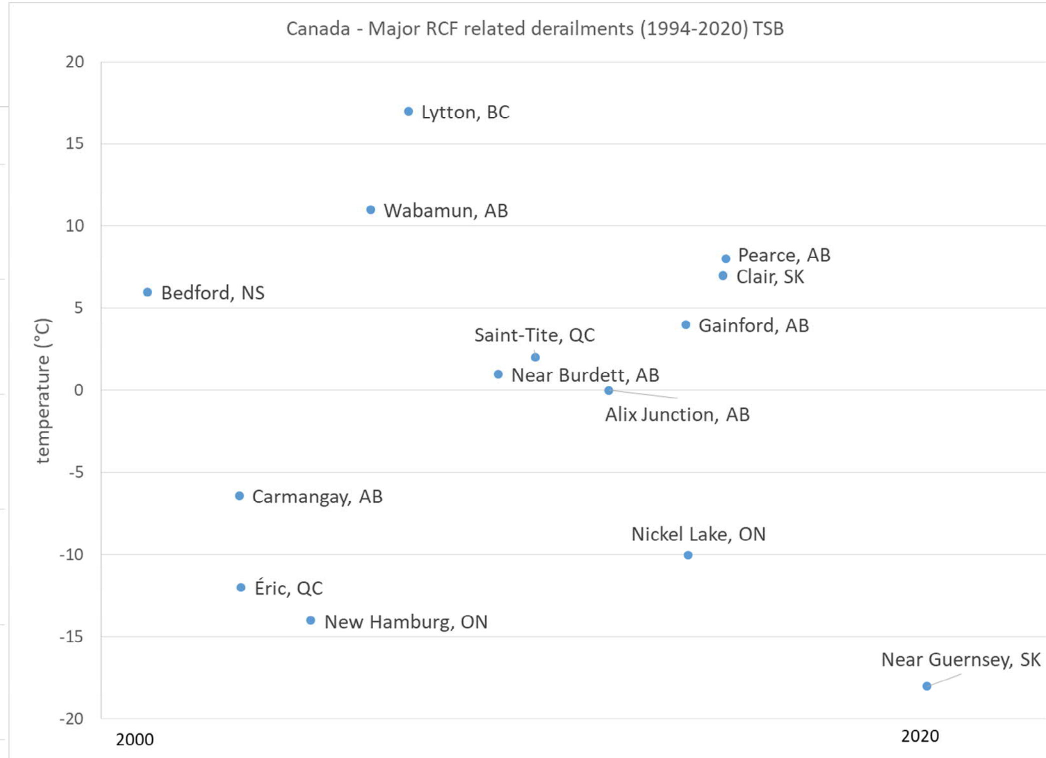
- N. Hooper
  - *This a 30-40 years ago problem. The issue is residual stress from rail straightening in the mill.*
  - *I still think a key to shatter is the residual stress from the rail manufacturing process.*
  - *I think if RR's looked at their defect types more in terms of survivable and fatal - see photos and then concentrated on those defects that the signal system wouldn't save them on they would get better outcomes.*

NRC·CNRC

Canada – TSB investigated broken rail derailments



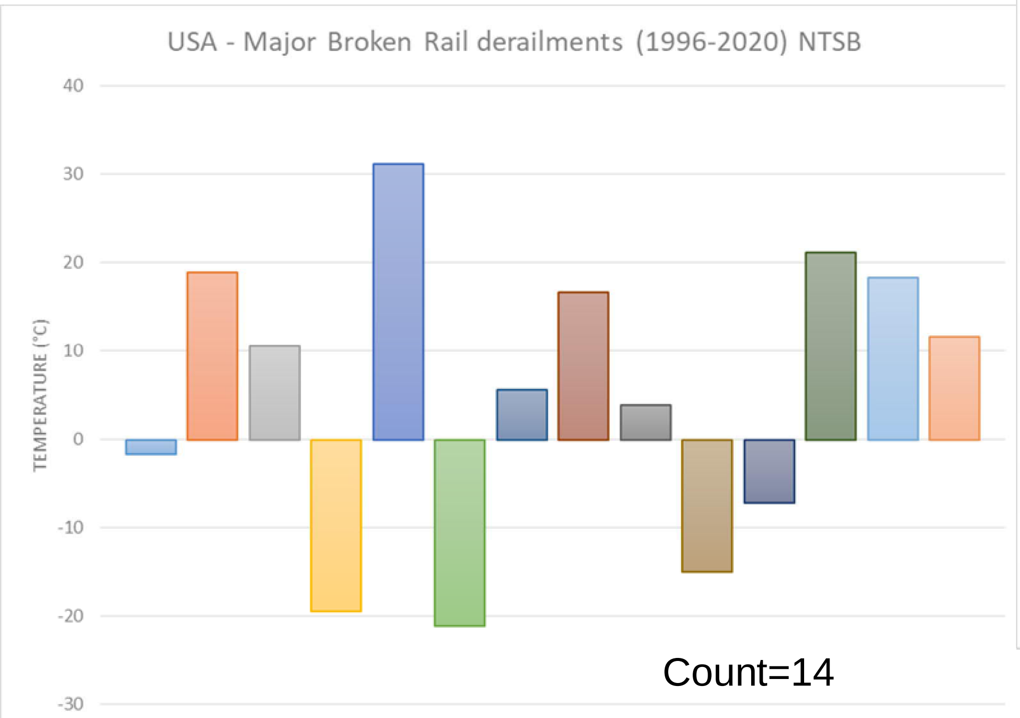
Count=27

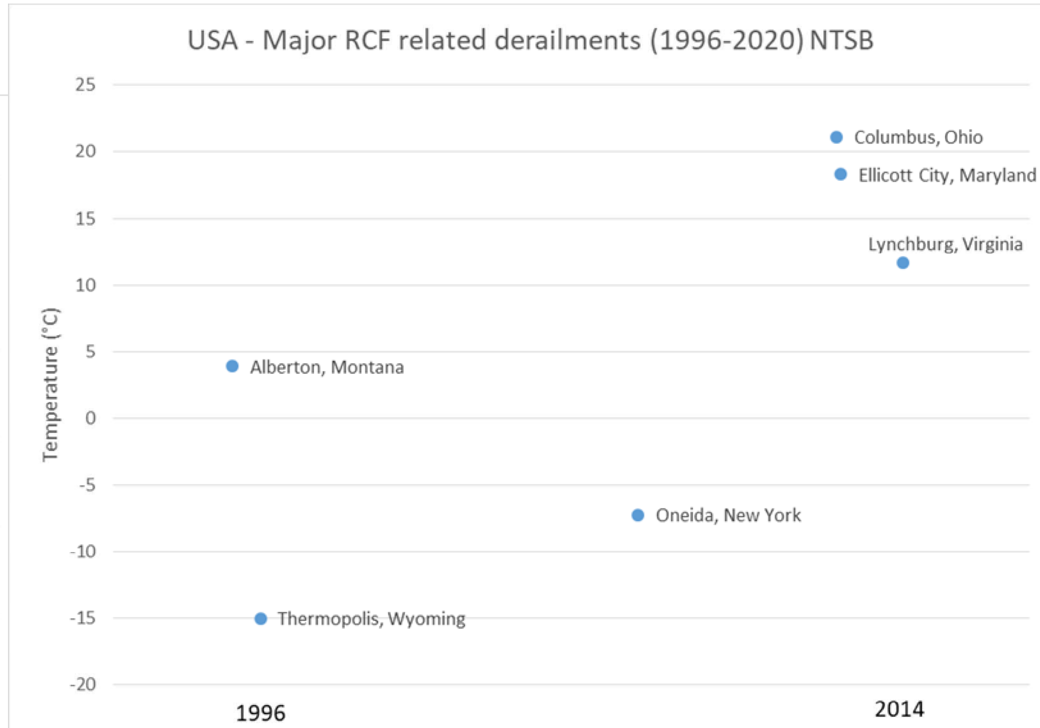


Count=14

USA – NTSB investigated broken rail derailments

None since late 2015





Count=6

NRC·CNRC

R&D topics?

1. Is there evidence that greater resilience in summer, coupled with neutral or compressive thermal stress allowing the rail to accumulate greater damage before breaking?
   - Is the size of the TD recorded and could this be plotted against date of failure?
   - Is there more evidence of clusters in the summer?
2. Is there any evidence to suggest that cracks are more likely to propagate longitudinally in summer versus winter?
3. And even if so, what could we do with that knowledge?

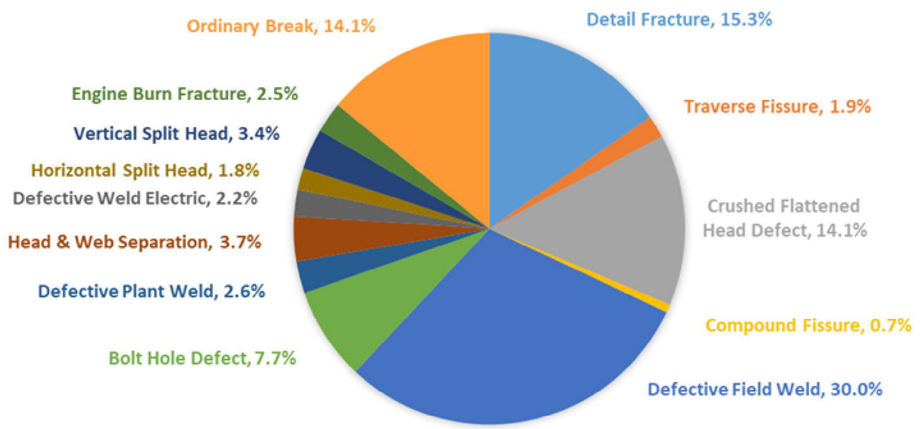
More, better data needed

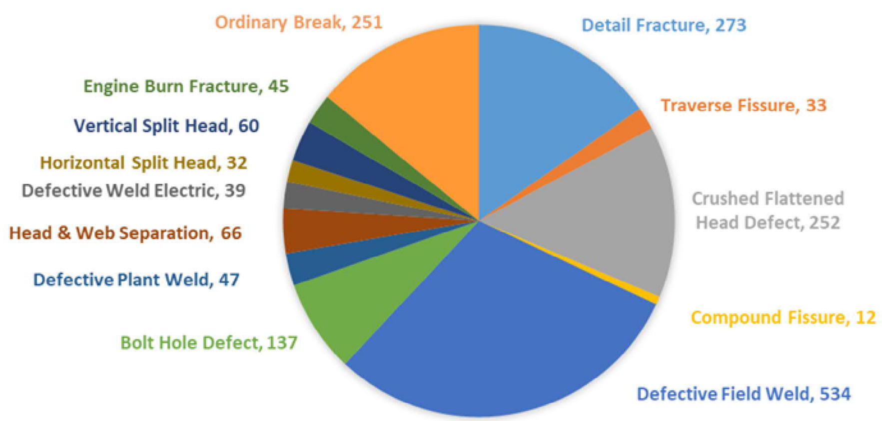
- G. Wolfe
  - statistical significance to the limited data we are seeing? Data being reviewed may no longer be relevant? Need a larger population of data from railways in climates with large seasonal temperature and moisture fluctuations
- D. Staplin

  Ideally, we should look at the broken rail derailment data for the summer months and see what type of fracture was involved and the circumstances surrounding *its occurrence. What we learn could then guide inspection policy.*
- J .Stanford
  - *While I questioned the data and relationships presented earlier there are a lot of unknowns within industry wide datasets which make it difficult to even guess what they represent sometimes and with no way to validate.*
  - BNSF data *"…a very consistent relationship between service failures and incidents regardless of seasonality*
- M .Burstow
  - *is there more detail to this data so that it can interrogated for the causes of rail break by time of year?*

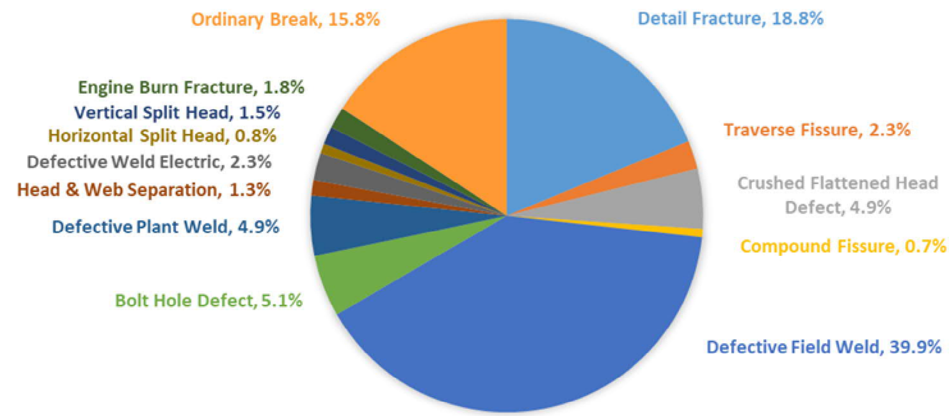
From: RSAC RIWG DATF Presentation, Nov 29, 2017, courtesy Robert Wilson, FRA

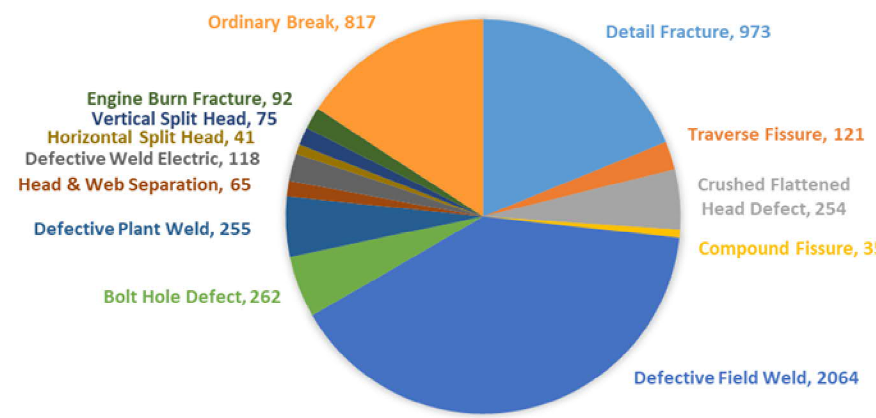
SUMMER SERVICE FAILURES (JUN-AUG, 2014 AND 2015)



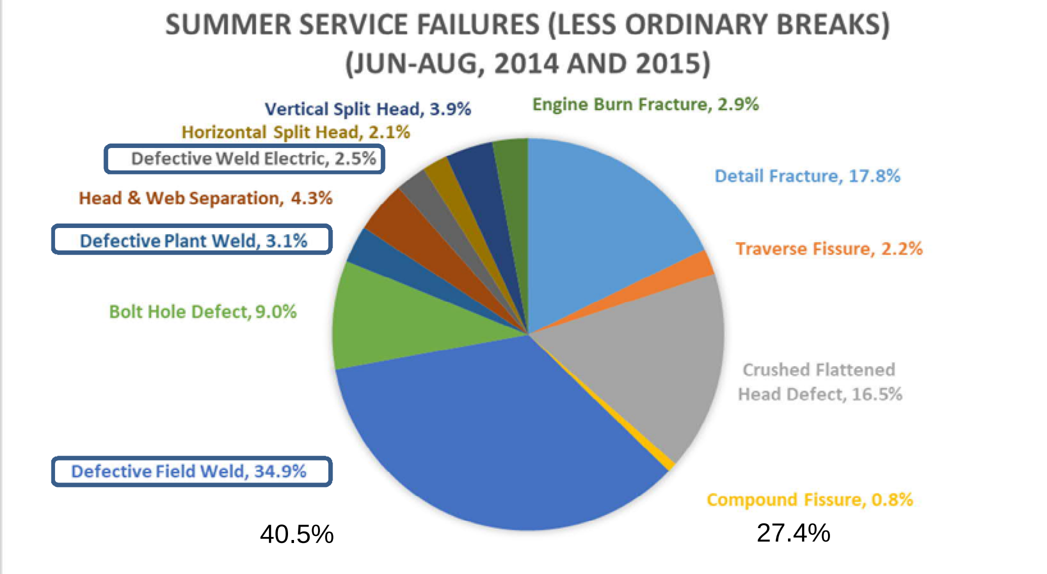


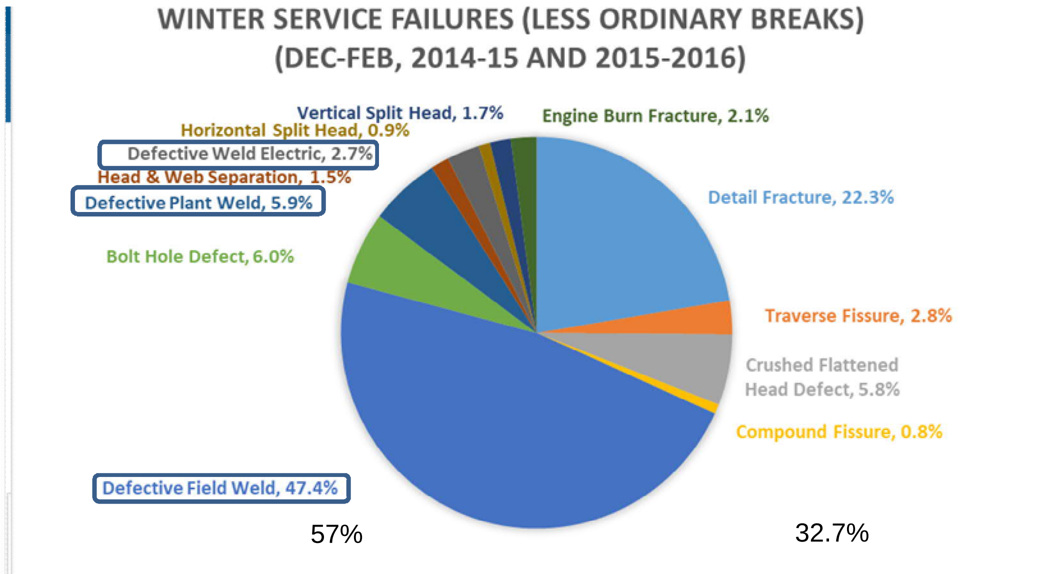
WINTER SERVICE FAILURES (DEC-FEB, 2014-15 AND 2015-2016)

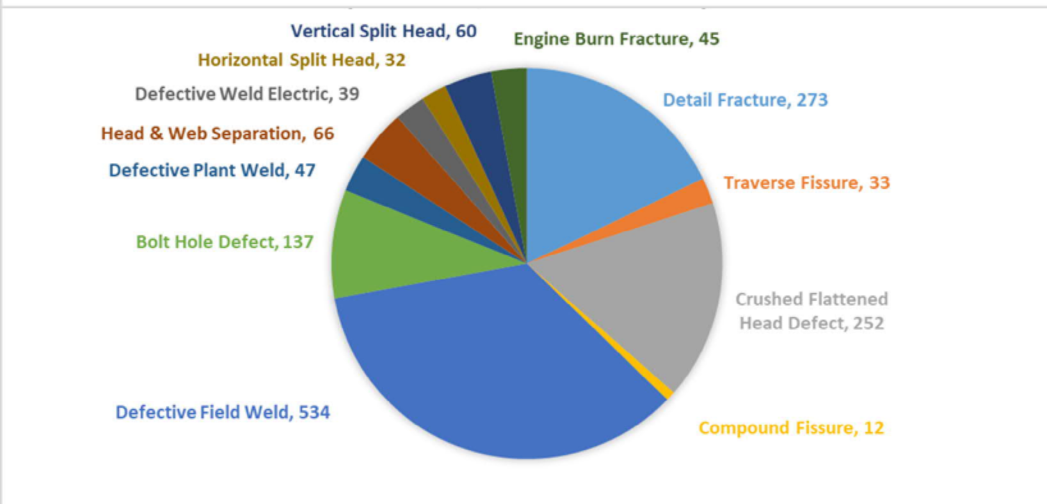


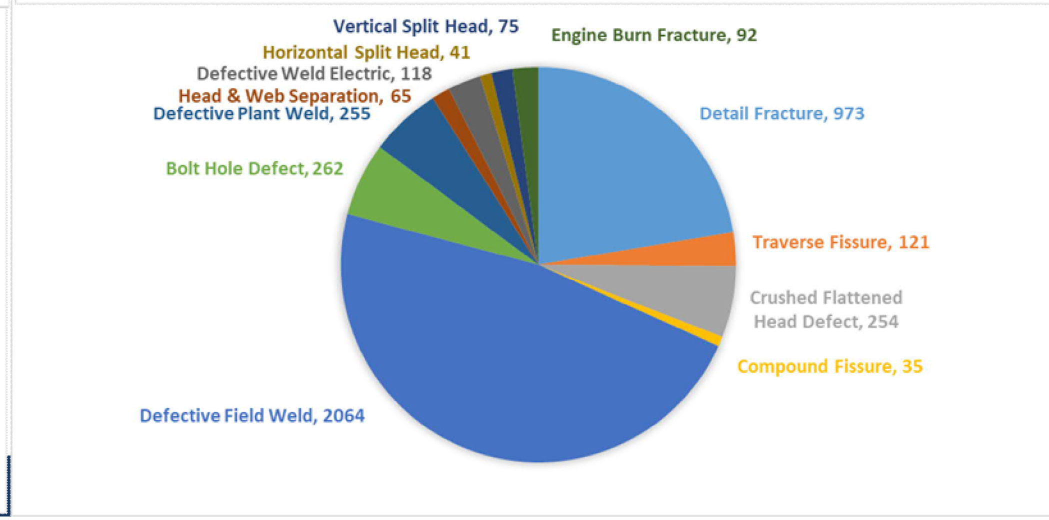


Peter Mutton suggests need to look at weld failures

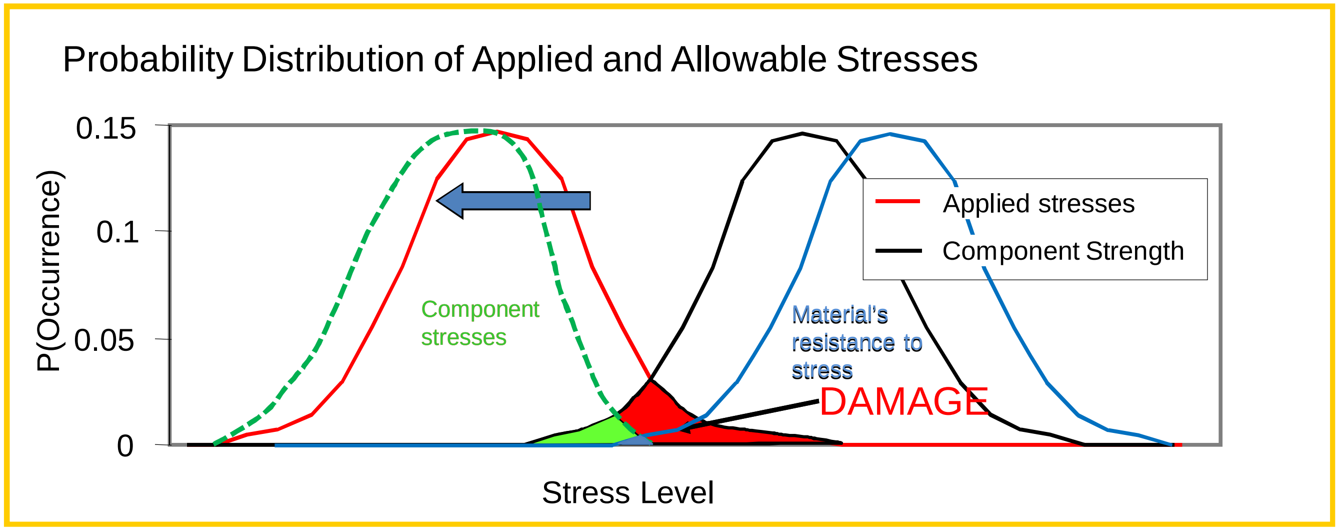




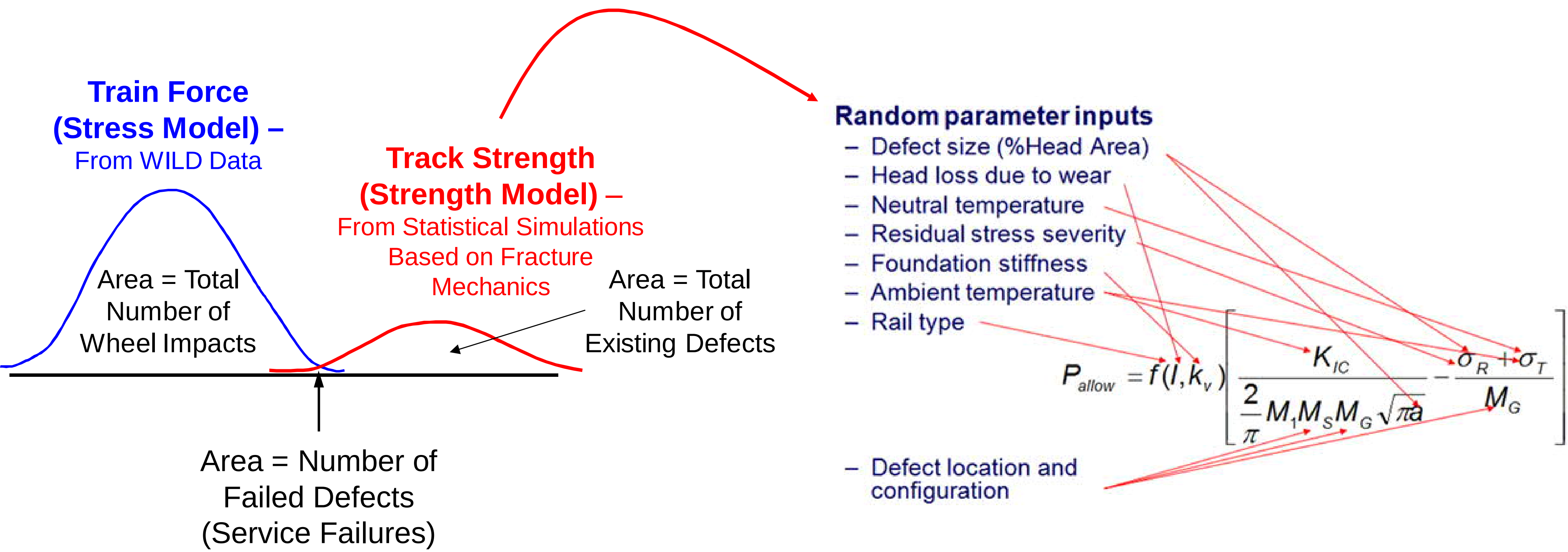




Stress vs Strength

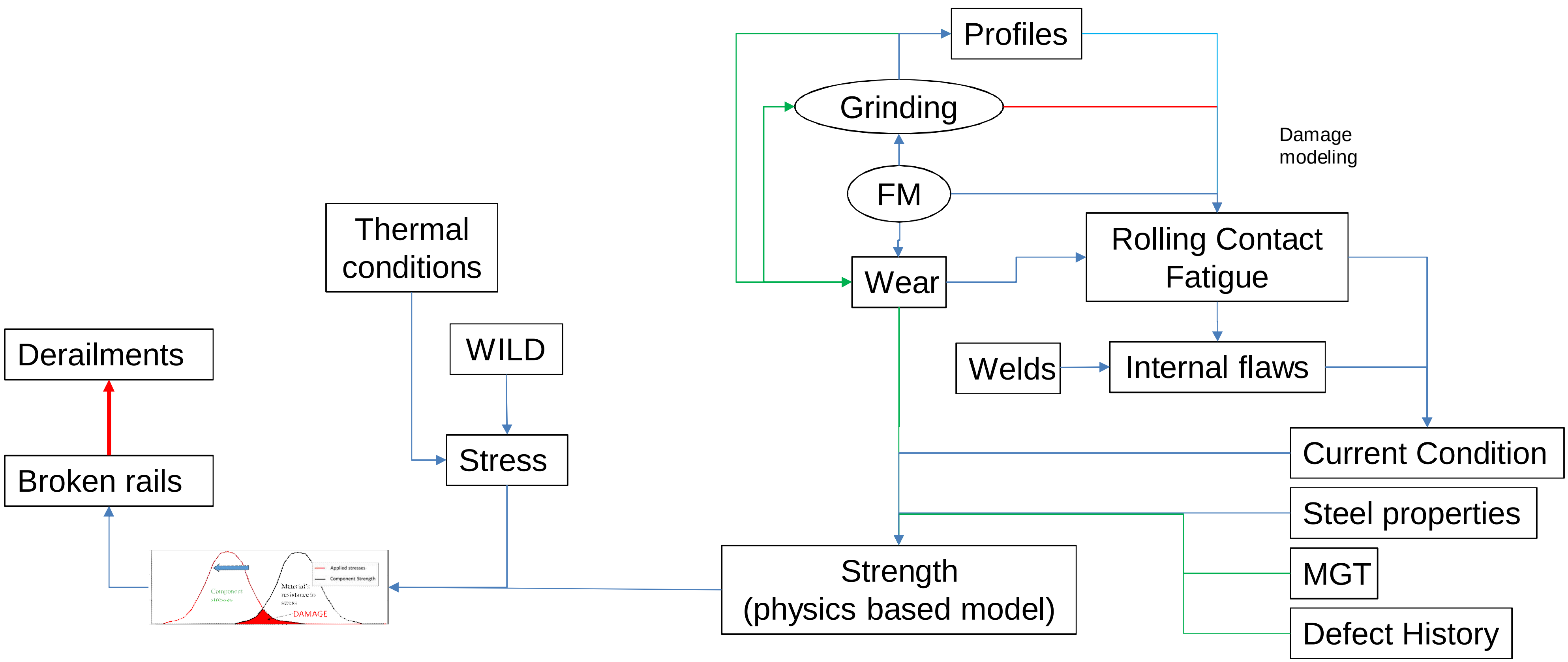


Stress-Strength concept – THAW model



NRC·CNRC

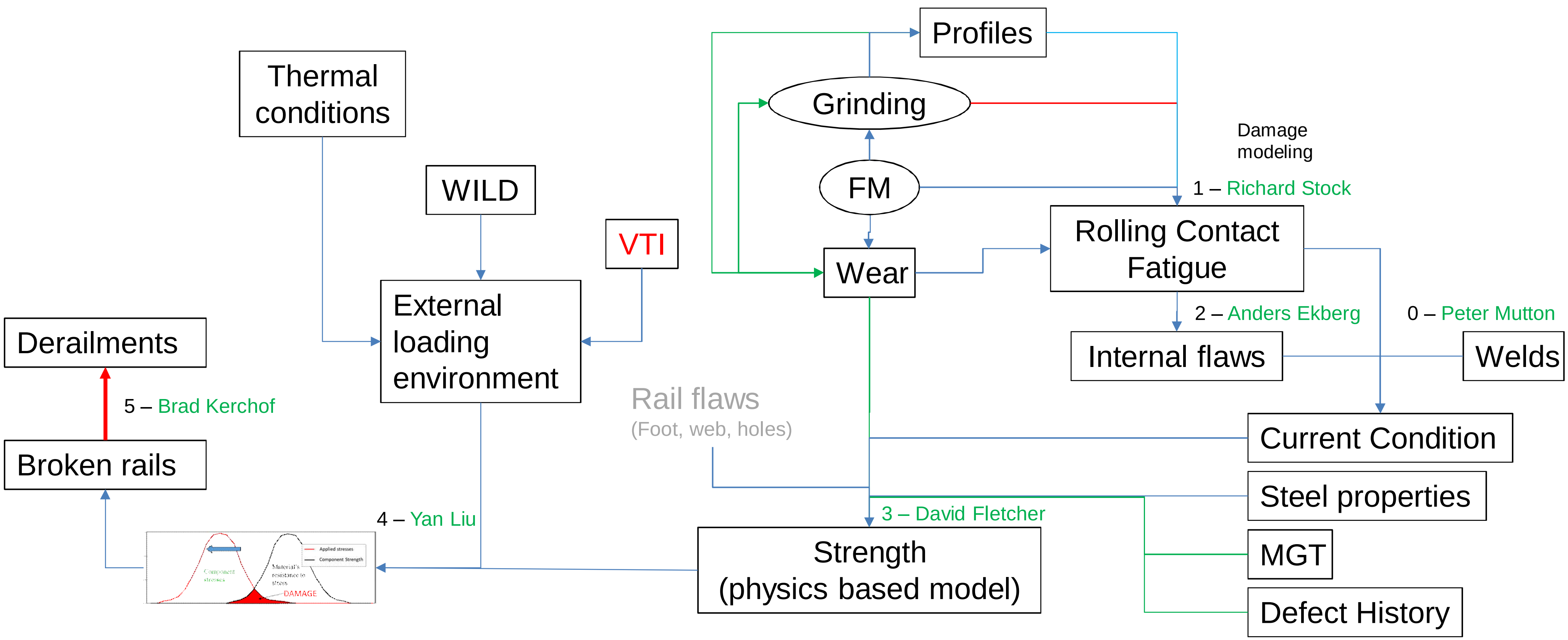
Stress-Strength Approach to Modeling Broken Rails



Procedure

- Establish a framework for attacking the problem (one has been proposed but may need refinement).
- Identify key functional elements of that framework to allow small groups to focus on
- **Determine the research gaps associate with each of those elements.**
- Coordinate groups to work together on those gaps
- Develop an integrated effective model for assessing the impact of maintenance practices and materials on broken rails and broken rail derailments.

Stress-Strength Approach to Modeling Broken Rails



Understanding and reducing broken welds

Peter Mutton

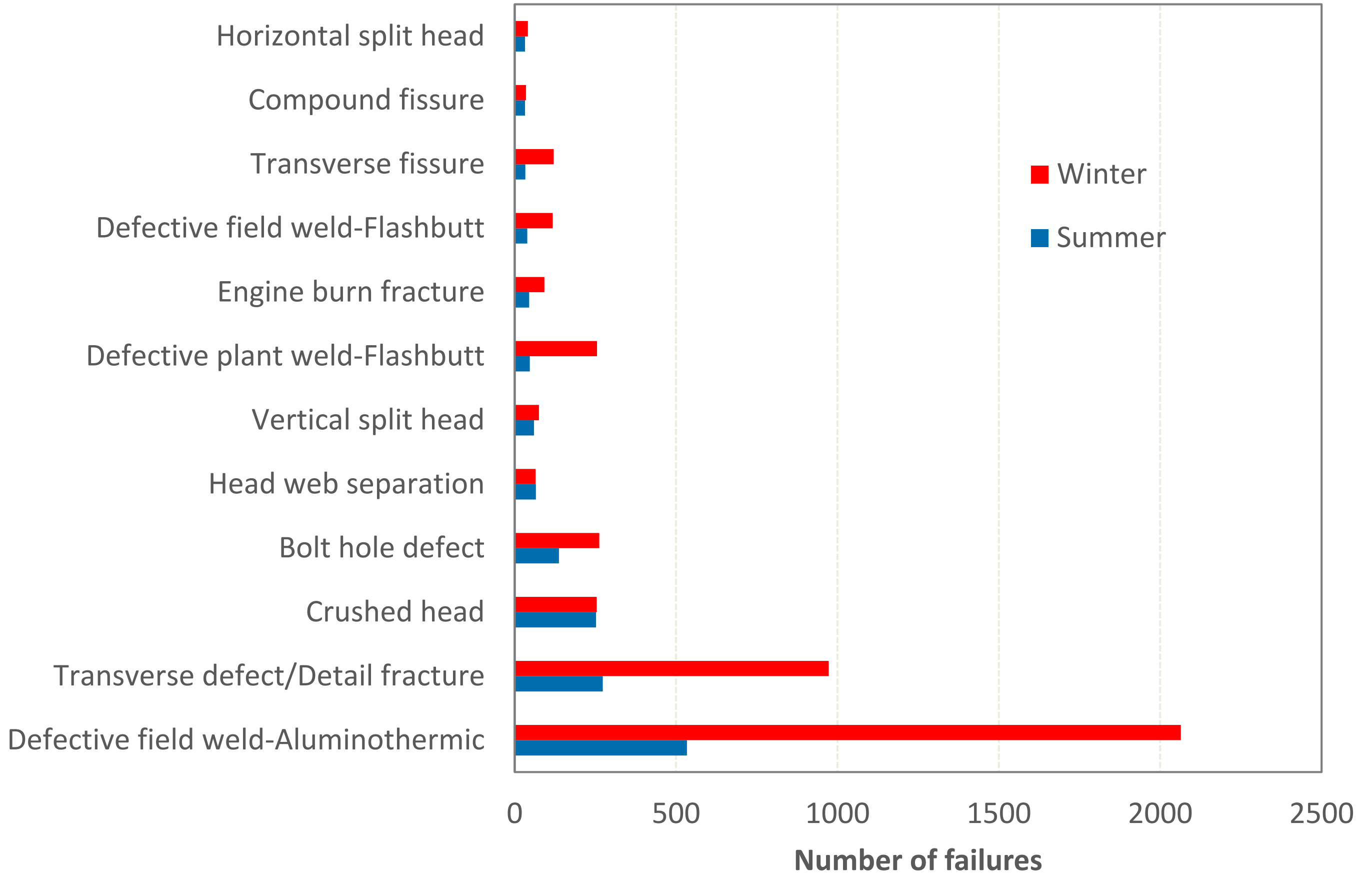
peter.mutton@monash.edu

MONASH University

Monash Institute of Railway Technology

GROUP OF EIGHT AUSTRALIA

North American service failure statistics: 2014/15 & 2015/16[1]



- Welds represent 40% of failures in summer, increasing to 56% in winter
- Aluminothermic (thermite) welds:
  - Comprise majority (~85%) of weld failures, irrespective of season
  - Show the greatest increase (~2.9 times) in failures between summer and winter

[1] *ICRI Broken Rails Review, July 2020*

Template Version 1 Copyright © 2019 Monash University. All rights reserved

Welds and broken rails

- How representative are the North American statistics?
  - If not, are they better (or worse) and why?

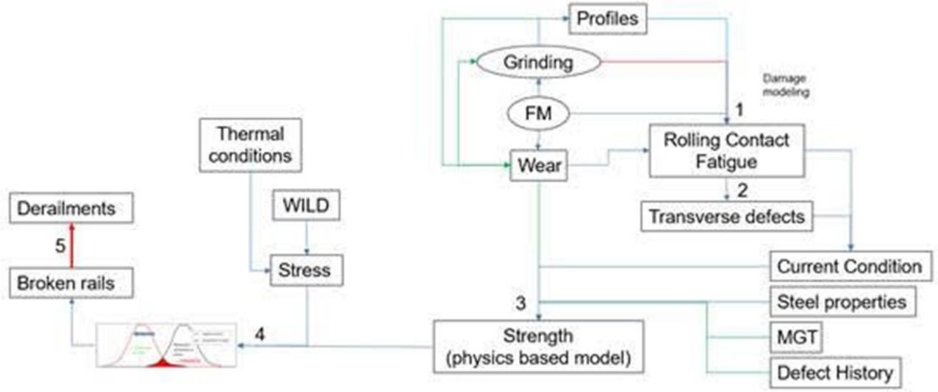
- Why do welds show the greatest summer-winter increase in failures?

- How many broken welds result in derailments?
  - Is the risk of derailments at welds higher or lower than in parent rail?
  - Does the risk of derailment vary depending on the weld failure type?

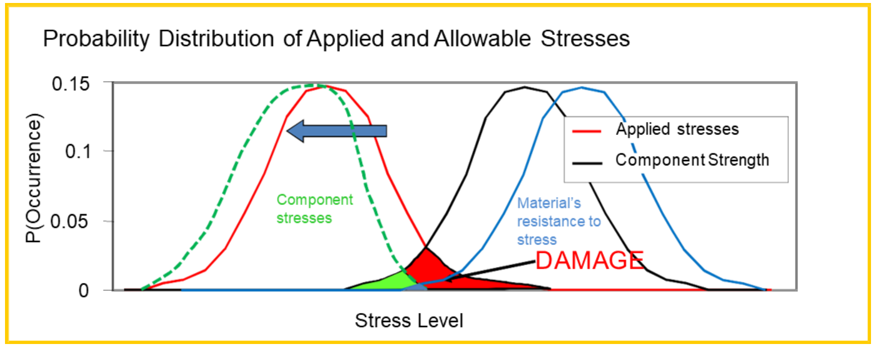
Template Version 1 Copyright © 2019 Monash University. All rights reserved

Applicability of stress-strength modelling approach

- To what extent can weld failures be predicted by a stress-strength modelling approach?
  - Are there gaps in our understanding of the relationship between the characteristics and performance of welds relative to that for parent rail?



- Can weld failures be reduced just by:
  - Selecting more suitable weld types, and
  - Making better quality welds



Template Version 1 Copyright © 2019 Monash University. All rights reserved

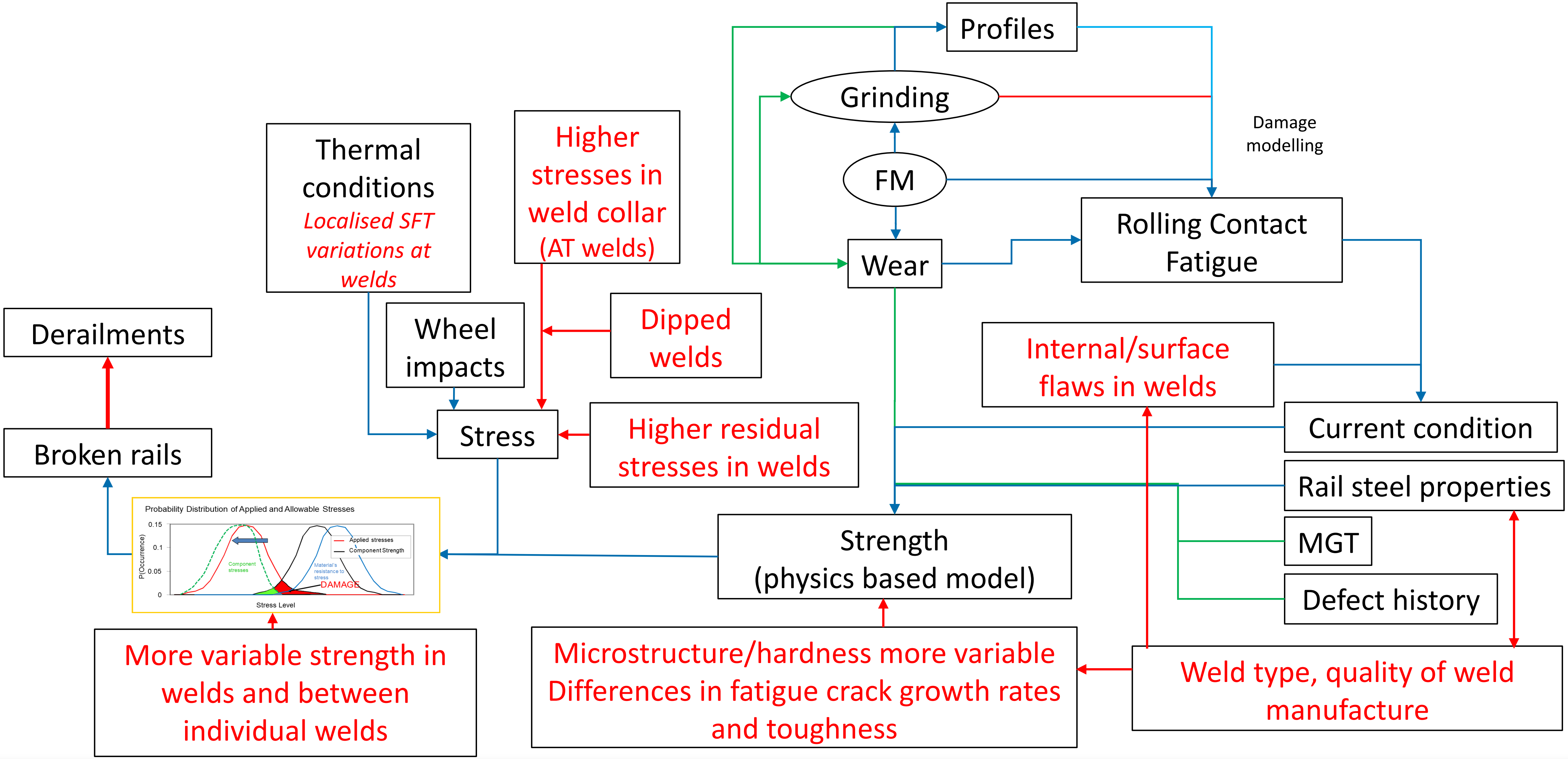
What is different about welds compared to parent rails?

- Rail welds exhibit a range of attributes that differentiate them from parent rails:
  - Sensitivity to deformation, wear, and RCF varies from parent rail
  - Increased potential to develop defects in service

Attribute	Influence of weld type (FB vs AT)	Effect
Residual stresses	Generally higher in FB welds than AT welds	Increased fatigue crack growth rates and smaller critical flaw sizes
Variable microstructure/hardness	Generally more variable in AT welds May be influenced by parent rail characteristics in FB welds	Localised plastic deformation, wear and RCF (including at HAZs) compared to parent rail
Strength & toughness	Poorer in AT welds	Smaller critical flaw sizes
External dimensions	Larger and more variable in AT welds Influenced by weld dressing (grinding) in FB welds	Higher bending stresses relative to parent rail Presence of stress concentrators
Surface condition	Poorer in AT welds. Shear drag in FB welds	Fatigue crack initiation
Alignment	May be more variable in AT welds	Increased dynamic loads, higher surface traction particularly in curves

Template Version 1 Copyright © 2019 Monash University. All rights reserved

Impact of welds on proposed stress-strength modelling approach



Template Version 1 Copyright © 2019 Monash University. All rights reserved

Prediction of weld failures by a stress-strength modelling approach

Modelling approaches need to consider:

A. Structural response
   - Behaviour of the weld below the immediate wheel-rail contact zone
     - Loading conditions, and hence stress distributions
     - Strength and fatigue characteristics of weld zone
     - Residual stresses

B. Behaviour in wheel-rail contact zone
   - Influence of variations in microstructure/hardness/deformation resistance on deformation, wear and ratcheting behaviour

Structural response and behaviour in wheel-rail contact zone are linked, as changes in wheel-rail contact conditions resulting from localised degradation will alter loading conditions on an iterative basis

Template Version 1 Copyright © 2019 Monash University. All rights reserved

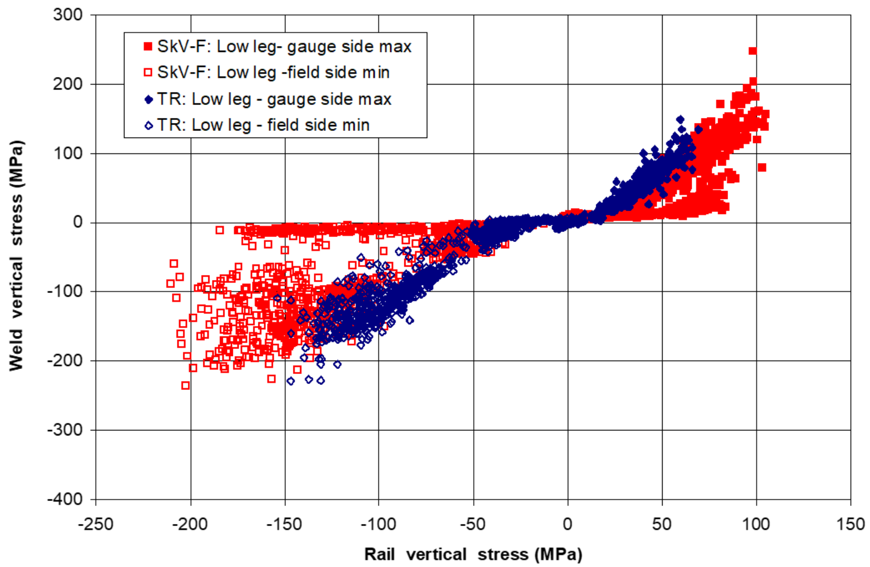
Assessing structural response of welds

- Determination of stresses in weld relative to parent rail
  - Measurement under actual service conditions
  - FEA under simulated loading conditions
- Determination of residual stress distribution
- Fatigue testing under simulated service conditions

OR

- Fatigue assessment based on FEA results
  - Fatigue strength of weld material

Measured stresses, 873m radius curve, low rail



- *Peak stresses on outside of weld collar typically up to 1.5 times parent rail stresses under same service conditions*
- *Increased risk of web fatigue failures*

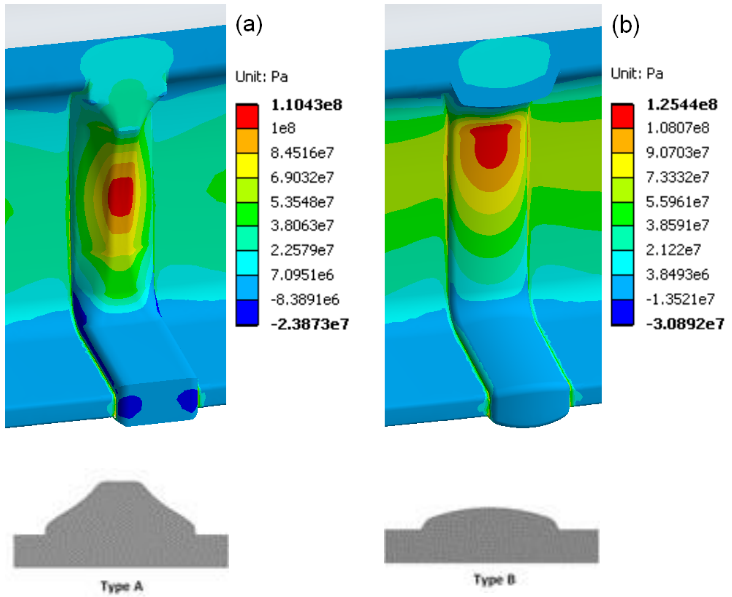
Duvel J, Mutton P, Alvarez E and McLeod, J (2005), Rail requirements for 40 tonne axle loads, Proc. 8th Int. Heavy Haul Conf.

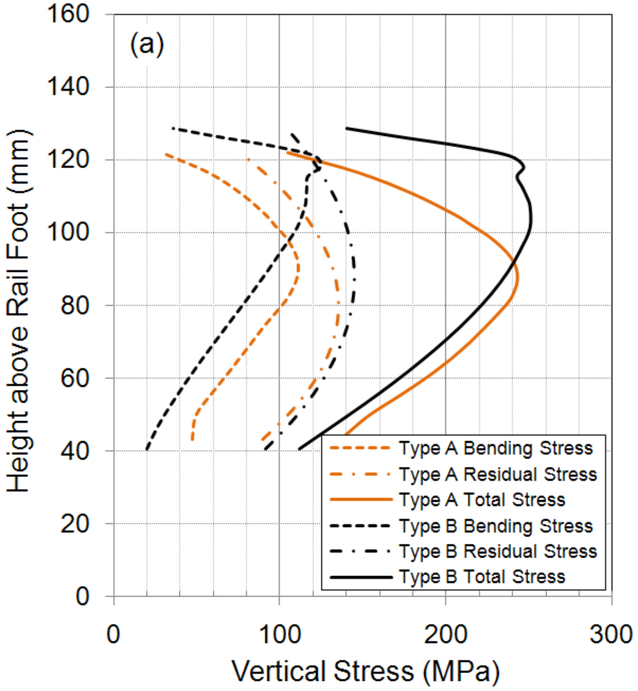
Template Version 1 Copyright © 2019 Monash University. All rights reserved

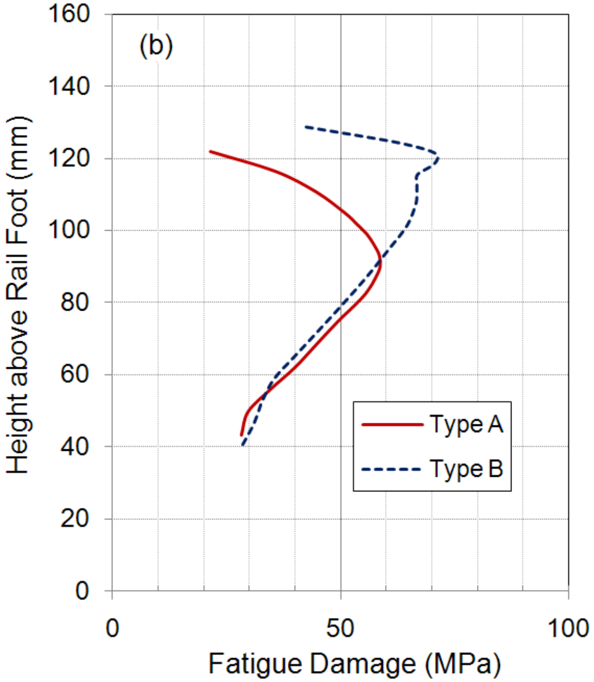
Assessing fatigue response of welds

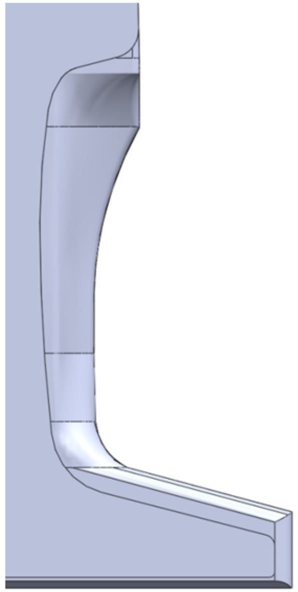
Influence of AT weld type on fatigue behaviour

- Loading conditions based on measured stresses under service loading
- FEA predicted stresses under simulated loading conditions
- Measured residual stresses
- Multi-axial fatigue analysis based on Dang Van criterion







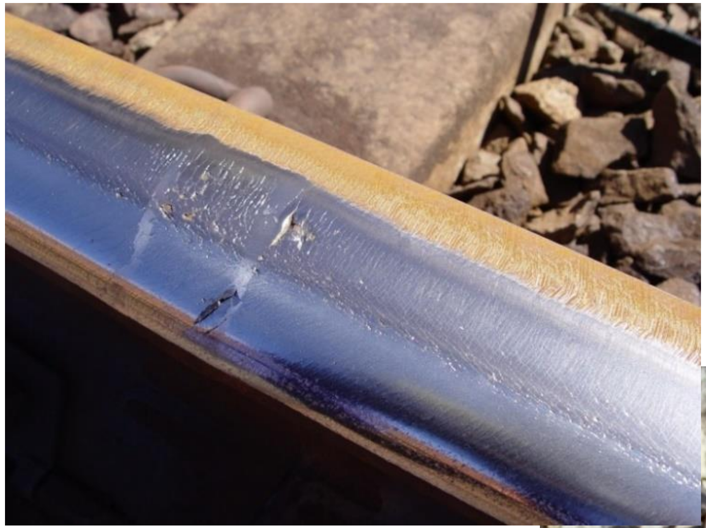


I. Salehi, P. Mutton and A. Kapoor, Analysis of damaging factors in thermite welds through multi-axial fatigue criterion, Proc. International Heavy Haul Association Conference 2011

Template Version 1 Copyright © 2019 Monash University. All rights reserved

Behaviour in wheel-rail contact

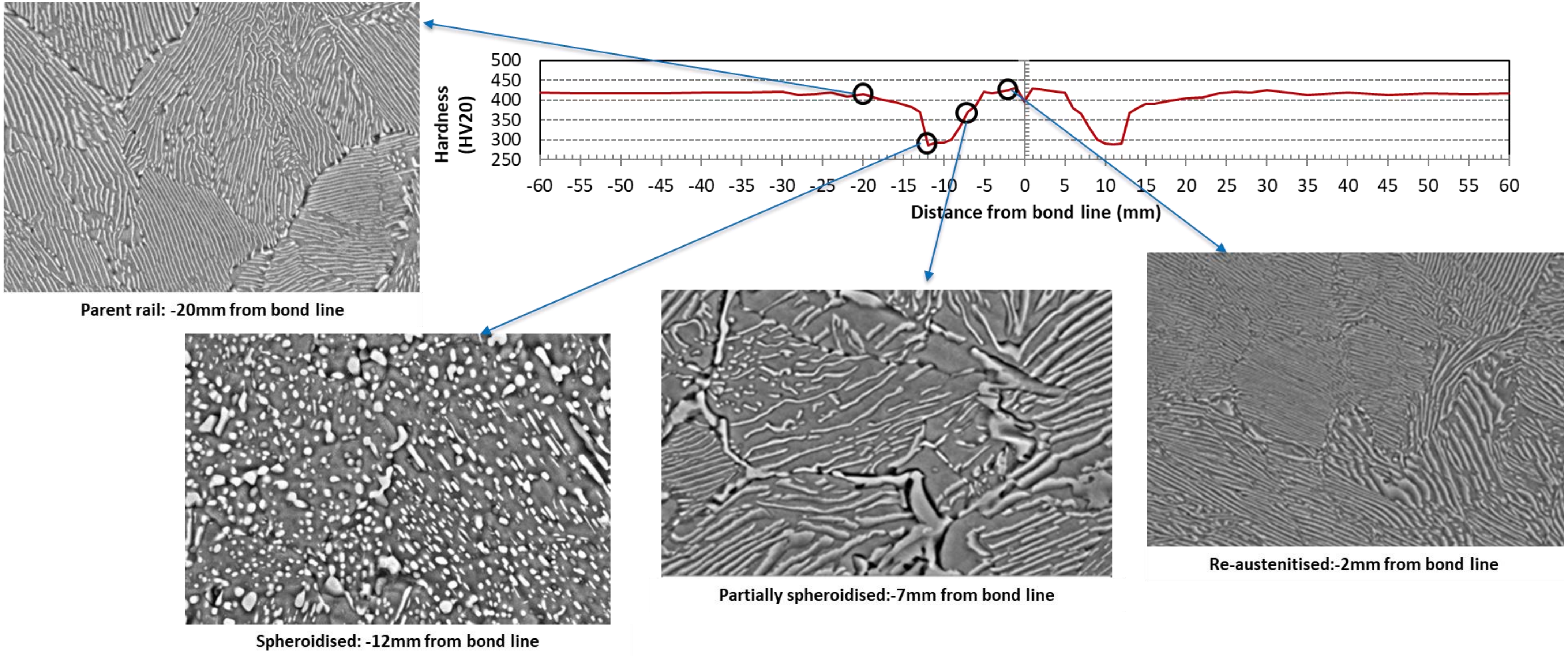
Localised plastic deformation, wear and rolling contact fatigue associated with variation in material characteristics



Mutton P, Cookson J, Qiu C, Welsby D (2015), Microstructural characterisation of rolling contact fatigue damage in flashbutt welds, 10th Int. Conf. on Contact Mechanics (CM2015), Colorado Springs, Colorado, USA

Template Version 1 Copyright © 2019 Monash University. All rights reserved

Hardness and microstructure variation in rail flashbutt welds

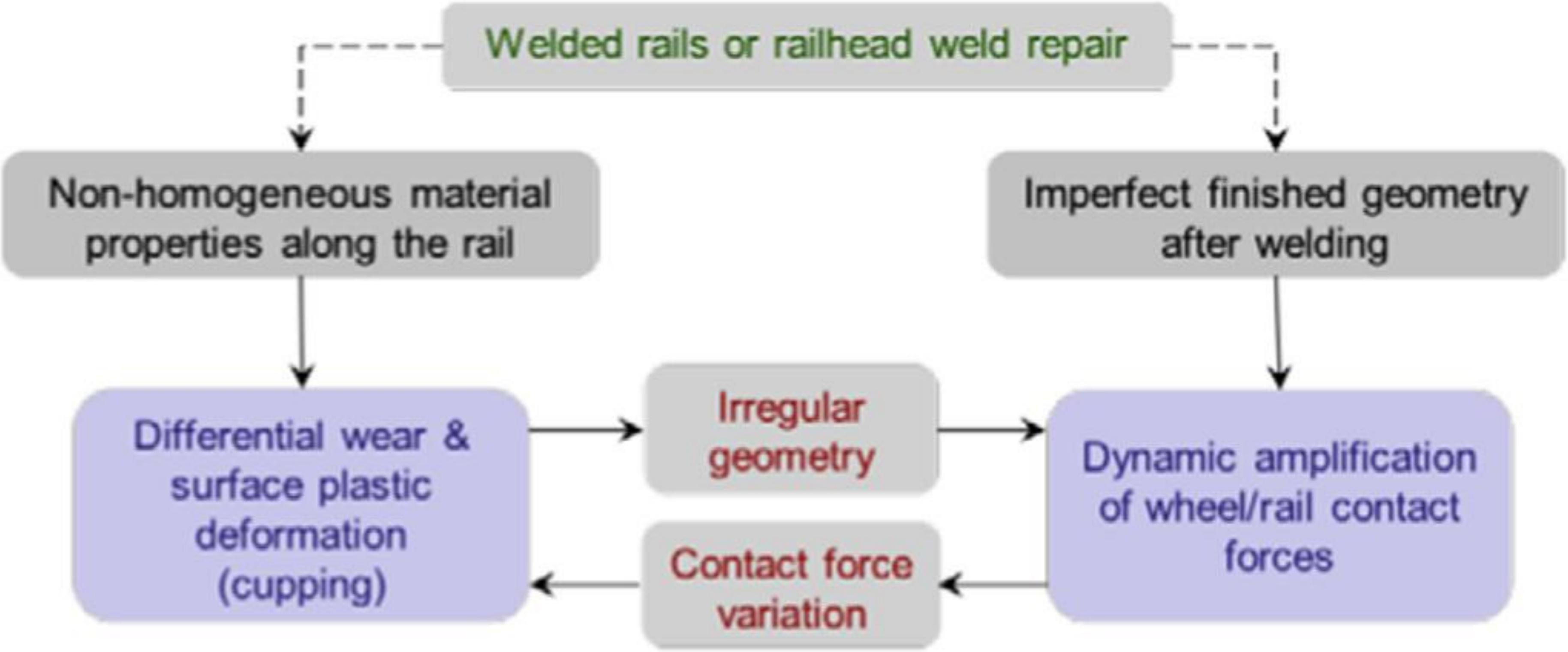


Mutton P, Cookson J, Qiu C, Welsby D (2015), Microstructural characterisation of rolling contact fatigue damage in flashbutt welds, 10th Int. Conf. on Contact Mechanics (CM2015), Colorado Springs, Colorado, USA

Template Version 1 Copyright © 2019 Monash University. All rights reserved

Predicting behaviour at the running surface of welds

Deterioration due to material and geometrical imperfections at welds

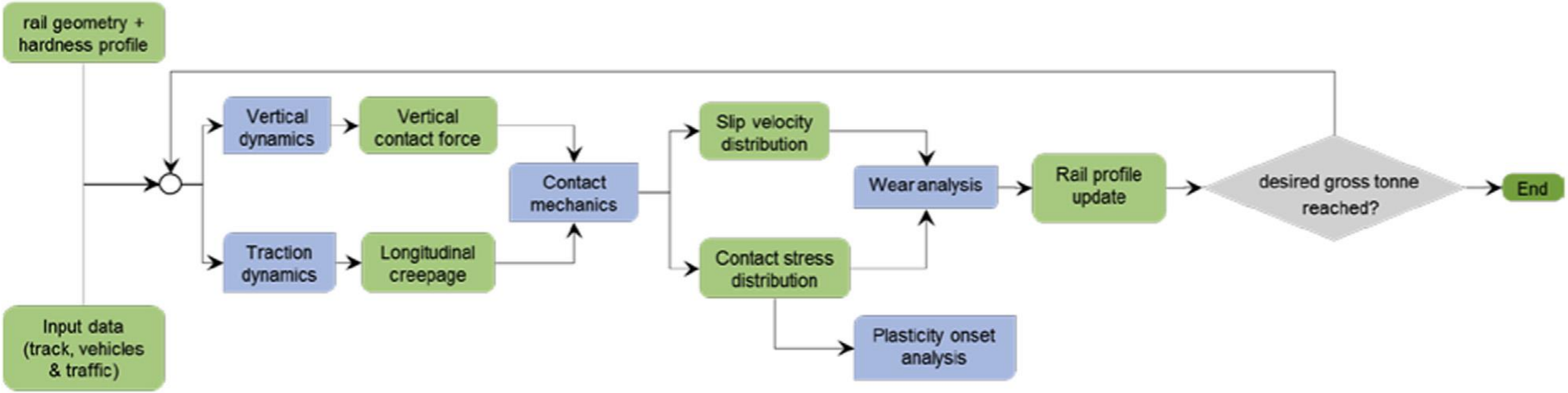


M. Sichani, Y Bezin, Differential wear modelling – Effect of weld-induced material inhomogeneity on rail surface quality, Wear 406–407 (2018) 43–52

Template Version 1 Copyright © 2019 Monash University. All rights reserved

Predicting wear damage at the running surface of welds

Methodology for calculation of differential wear due to hardness variation along the rail.



M. Sichani, Y Bezin, Differential wear modelling – Effect of weld-induced material inhomogeneity on rail surface quality, Wear 406–407 (2018) 43–52

MONASH University

Monash Institute of Railway Technology

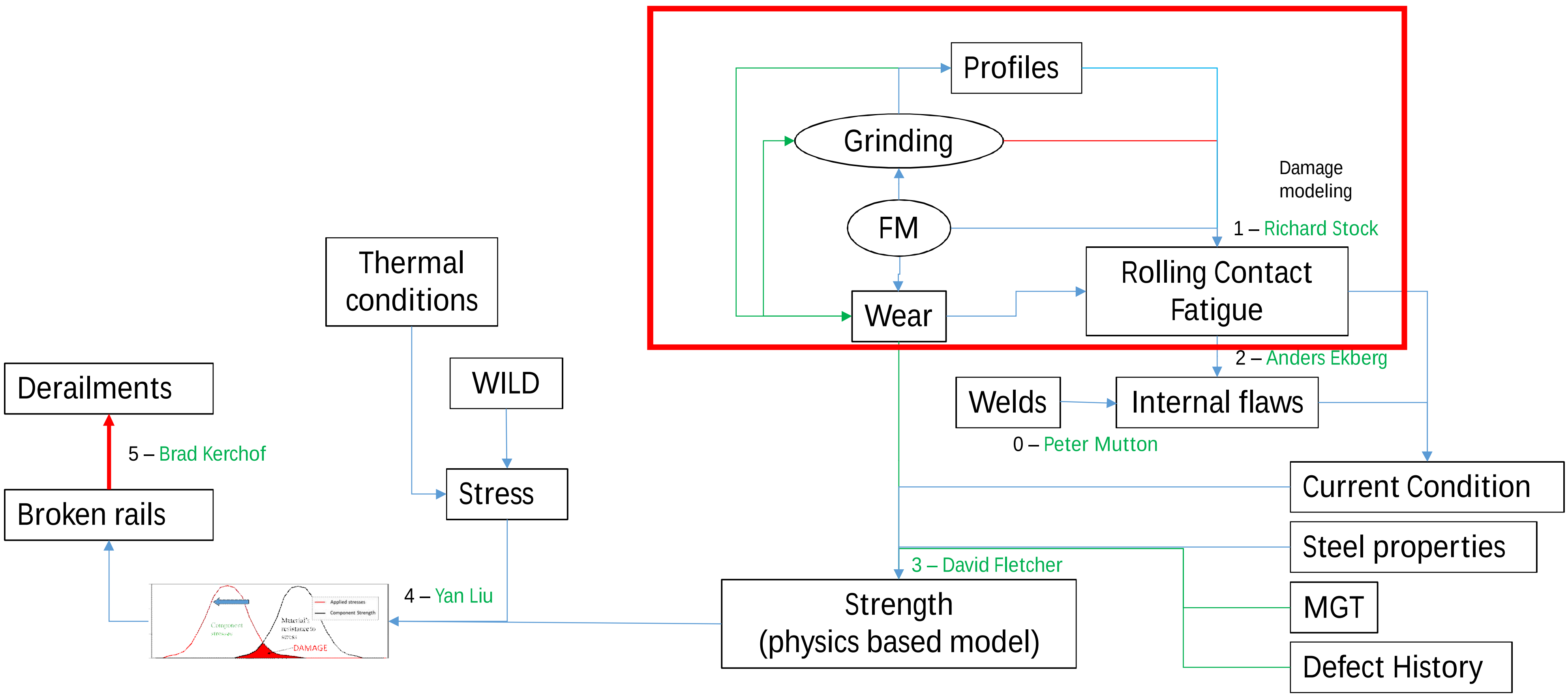
www.irt.monash.edu

ICRI Broken Rails Workshop

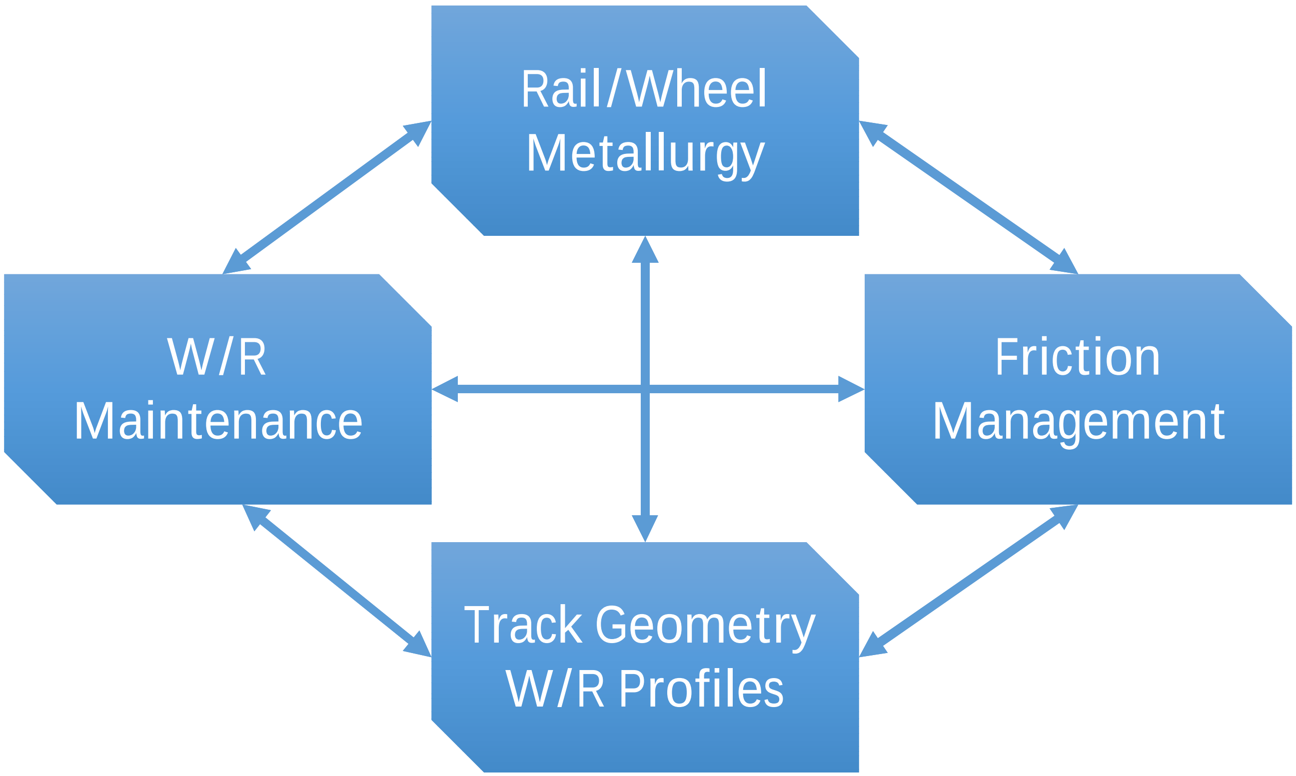
Impact of reprofiling (grinding and milling), w/r profiles, wear and friction management on rolling contact fatigue

December 2/3 2020

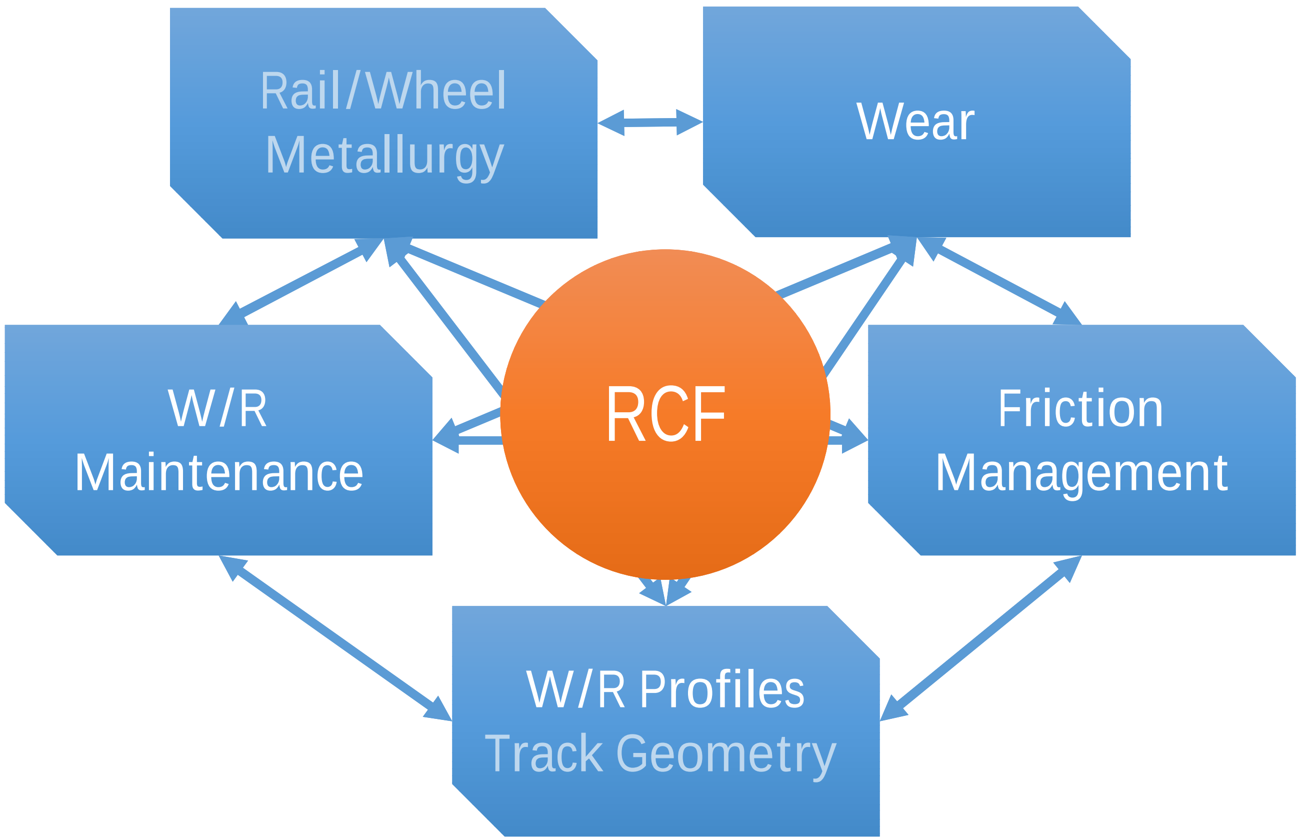
Stress-Strength Approach to Modeling Broken Rails



A Problem on a System Level



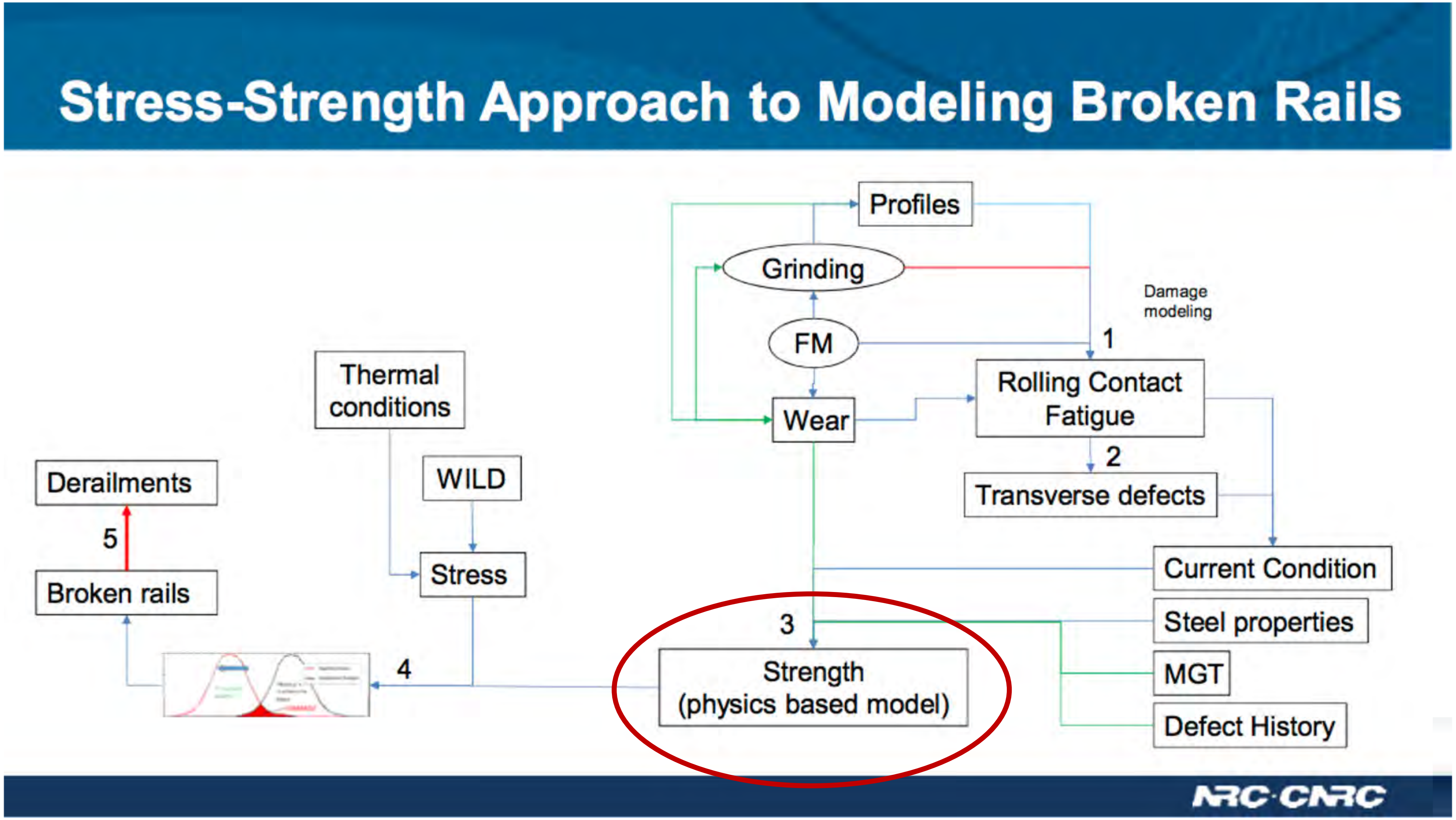
A Problem on a System Level (modified)

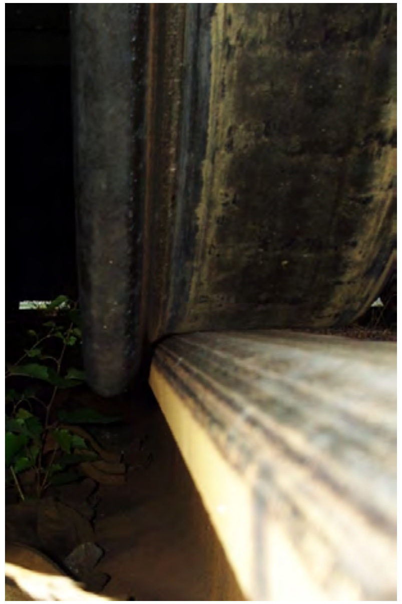


Questions for each factor

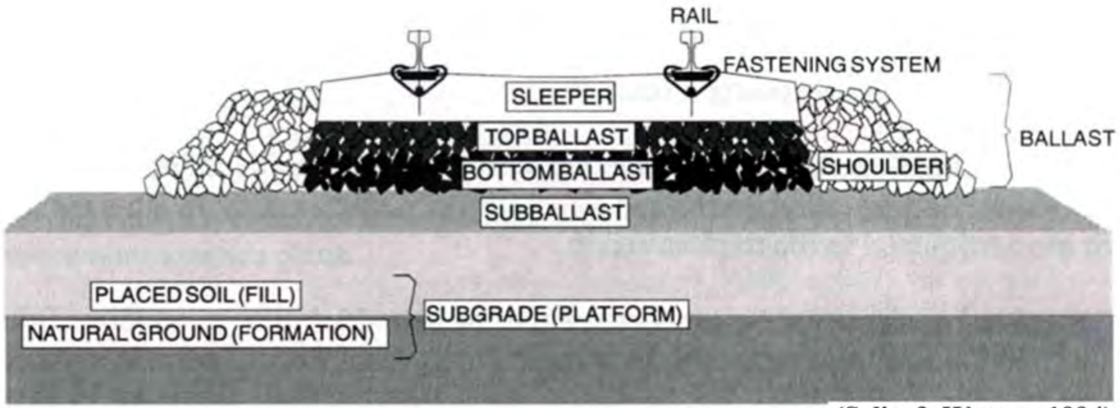
- Well understood?
- Measurable?
- Manageable?
- Impact on other factors?
- Impact on RCF?
- Knowledge Gaps?
- Impact on broken rails?

Stress-Strength Approach to Modelling Broken Rails





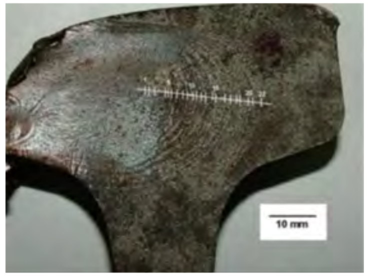
Whole system:
RCF, defects, wear plus metallurgy and loading history (vehicle side of interface)



(Selig & Waters, 1994)

The University Of Sheffield.

Question: How do the current conditions (RCF, defects, wear) plus metallurgy and loading history affect the ability of the rail to resist breakage?



For discussion:

1. Identify inputs to the rail/track strength model.
2. Which are well understood, measurable or can be modelled, and which are not.
3. How do these factors make the rail more vulnerable to breakage?

Outcome: a model of the strength of the track at a location/segment as a function of the various inputs. Ideally quantitative, or maybe values relative to "perfect" track?

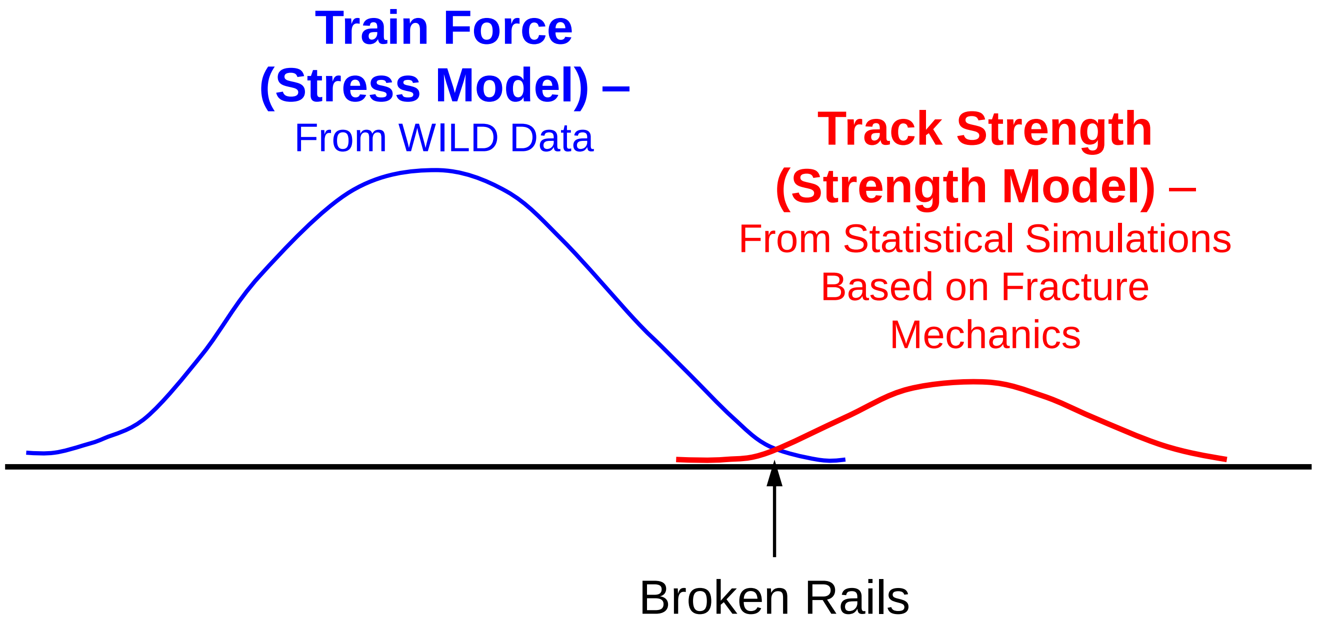
Stress-vs-Strength Approach to Broken Rails

- ICRI Broken Rails workshop

Yan Liu, Ph. D

December 2, 2020

Stress - Strength Concept



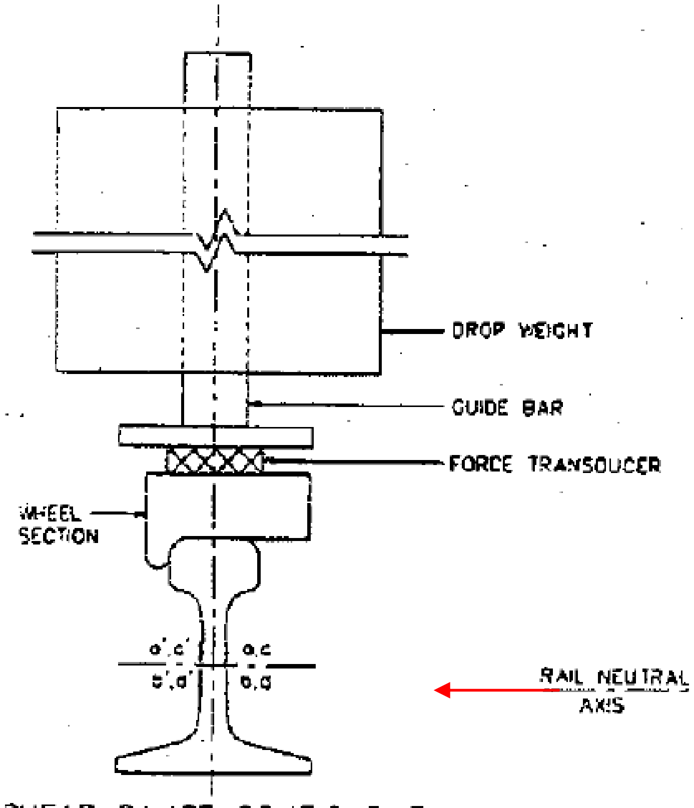
NRC·CNRC

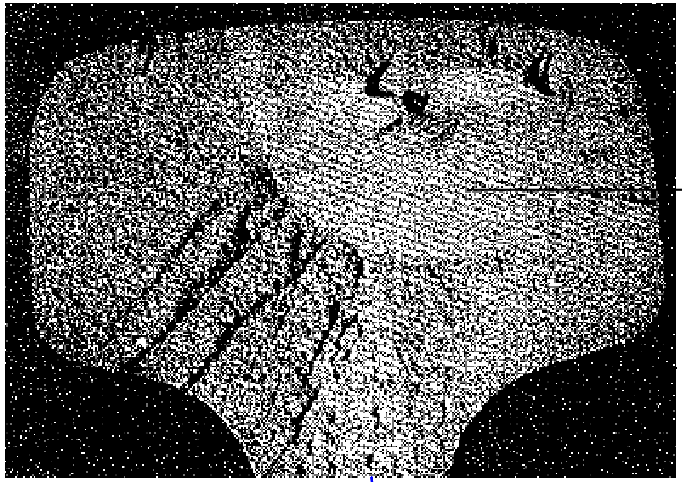
$K_I \geq K_{IC}$

Rail Break Test of CP Rail Sample
(Transport Canada Report TP 11570E, CIGGT Report 92-11)

$$K_I \geq K_{IC}$$

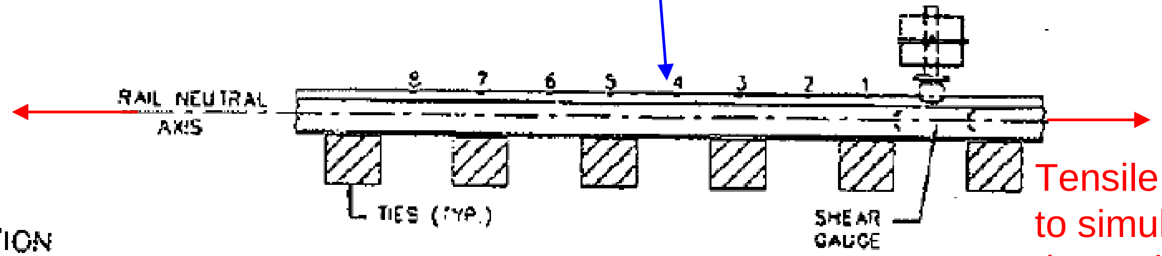
$$K_I = \frac{2}{\pi} M_1 M_S (\sigma_R + \sigma_T + M_G \sigma_{B1}) \sqrt{\pi a}$$





Broken at the section with detected transverse defect

Impact force σ_{B1}



Tensile force to simulate thermal effect σ_T

NRC·CNRC

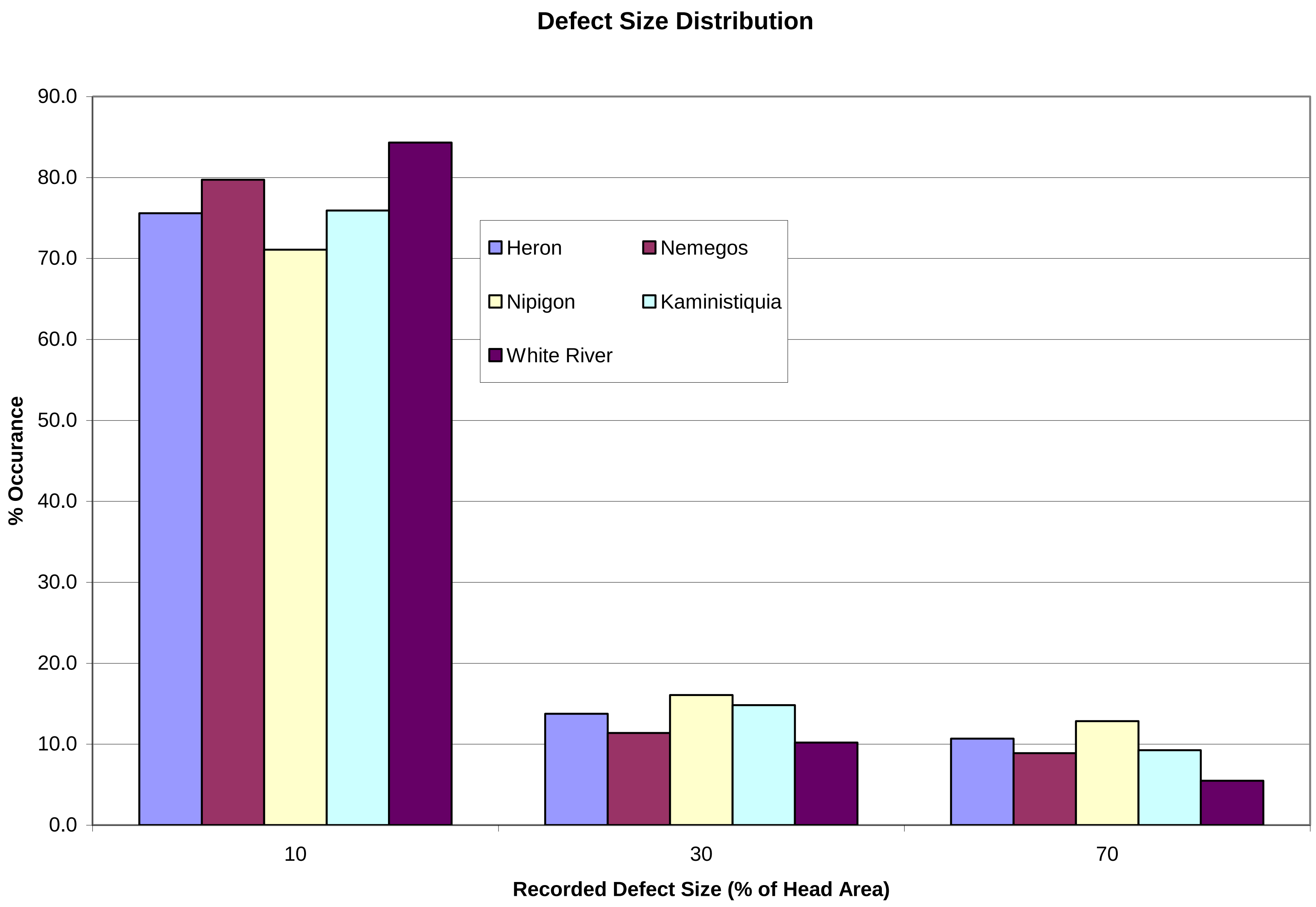
Allowable Impact Force based on Fracture Mechanics

- **Random parameter inputs (Monte Carlo method)**
  - Defect size (%Head Area)
  - Head loss due to wear
  - Neutral temperature
  - Residual stress severity
  - Foundation stiffness
  - Ambient temperature
  - Rail type

$$P_{allow} = f(I, k_v)\left[\frac{K_{IC}}{\frac{2}{\pi} M_1 M_S M_G \sqrt{\pi a}} - \frac{\sigma_R + \sigma_T}{M_G}\right]$$

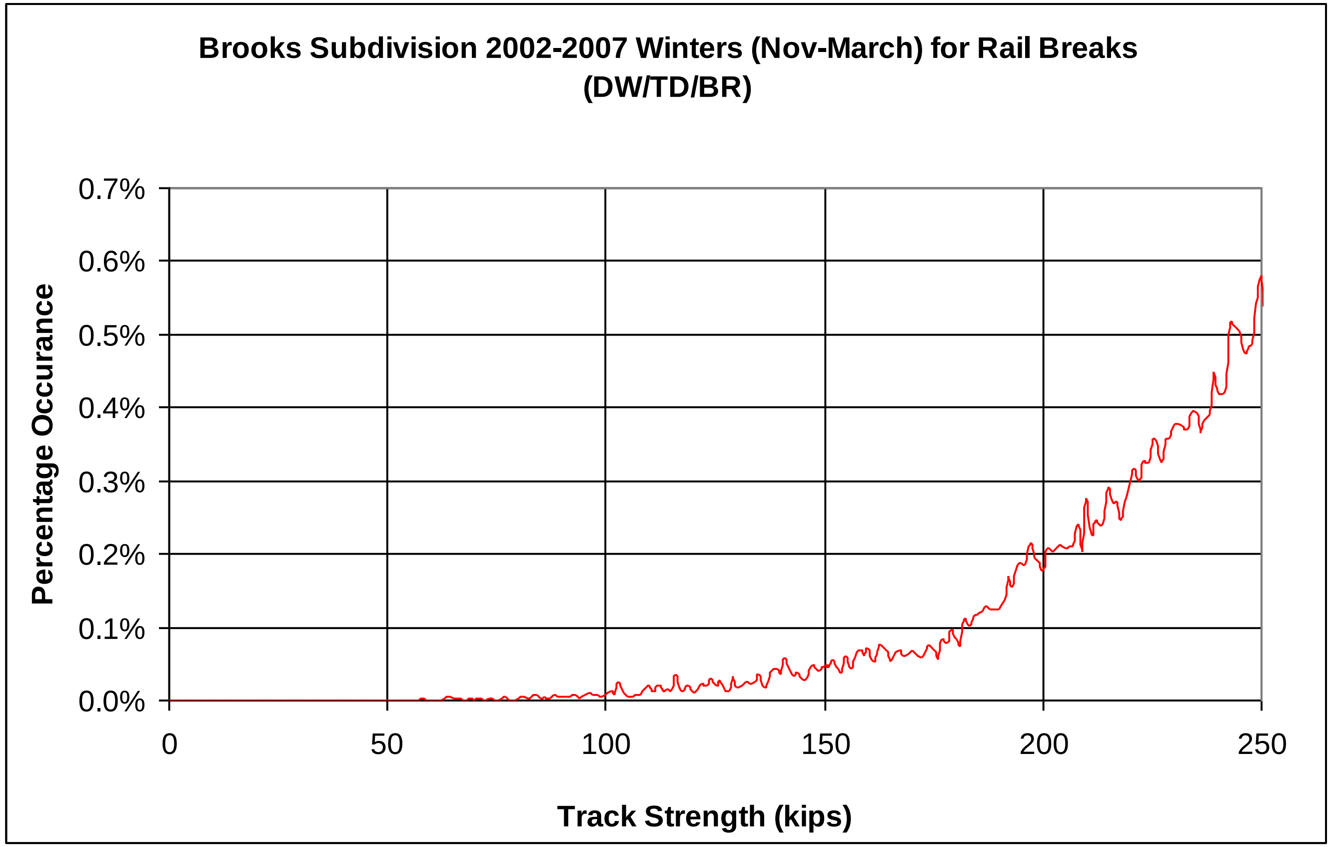
  - Defect location and configuration

NRC·CNRC

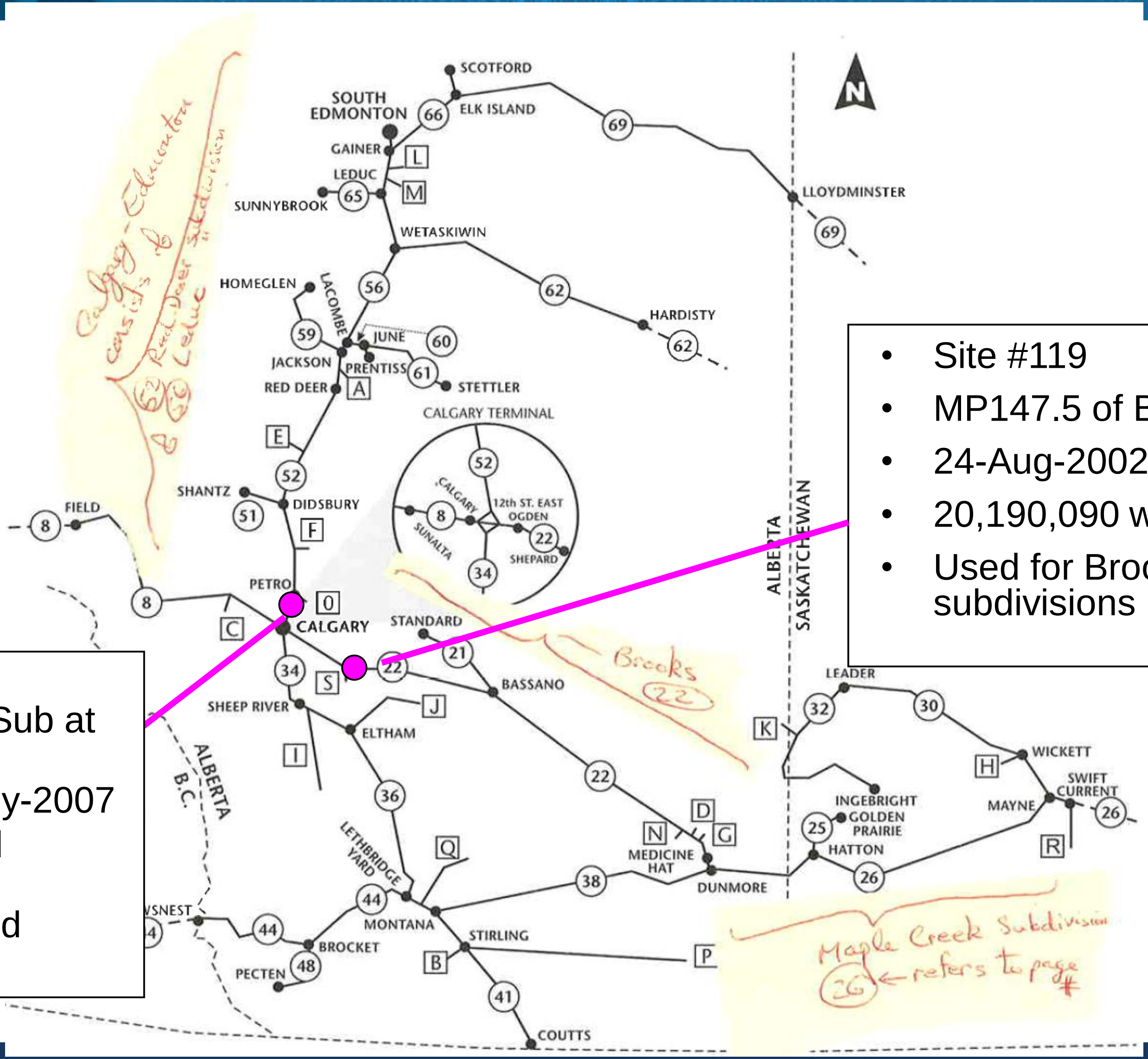

Defect Size Distribution
90.0
80.0
70.0
60.0
50.0
40.0
30.0
20.0
10.0
0.0
% Occurance
Heron
Nemegos
Nipigon
Kaministiquia
White River
10
30
70
Recorded Defect Size (% of Head Area)

NRC·CNRC

Track Strength Distribution – Brooks



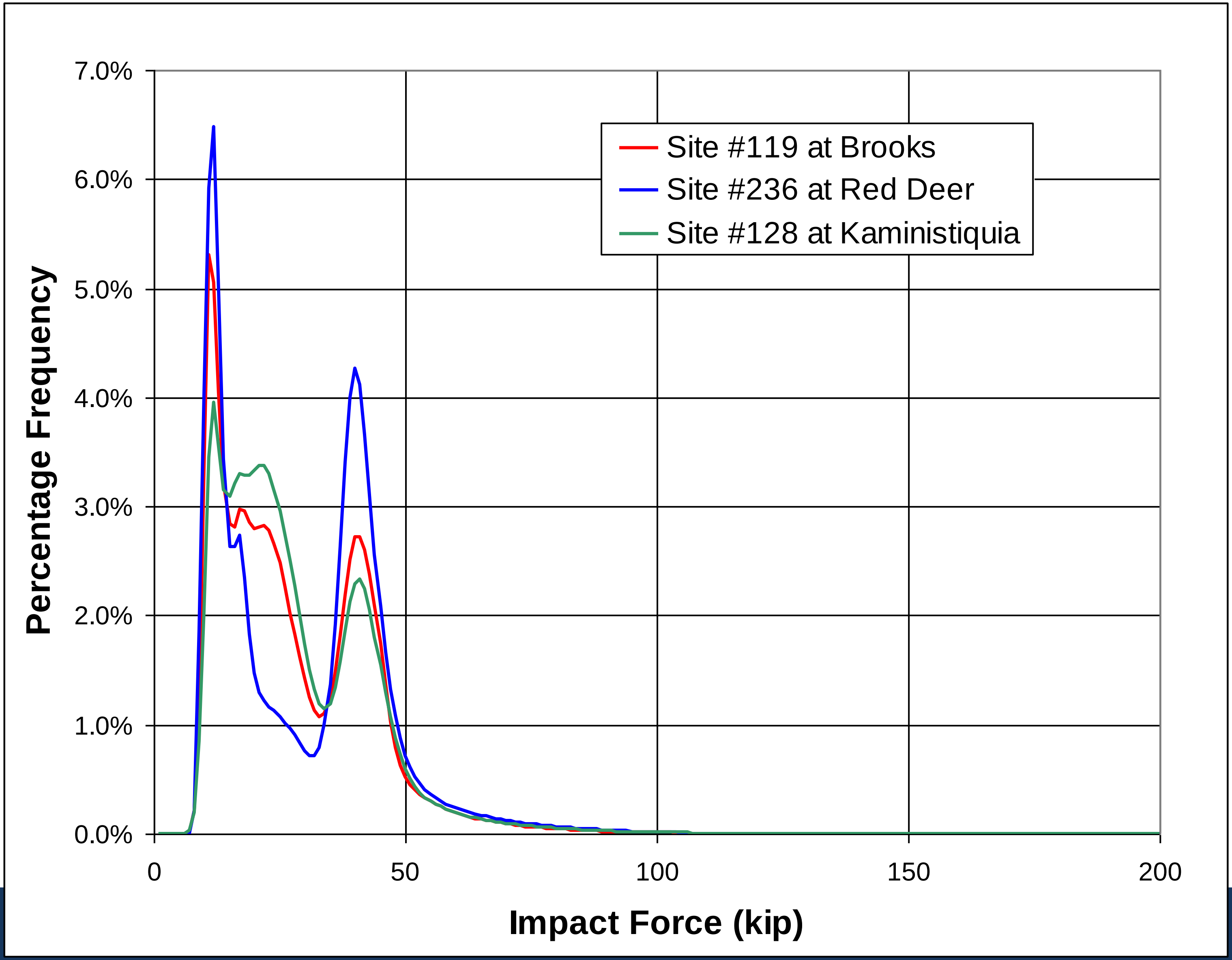
Subdivisions and WILD Sites



- Site #119
- MP147.5 of Brooks Sub at Carseland
- 24-Aug-2002 to 30-Apr-2007
- 20,190,090 wheels and 30,919 trains
- Used for Brooks and Maple Creek subdivisions

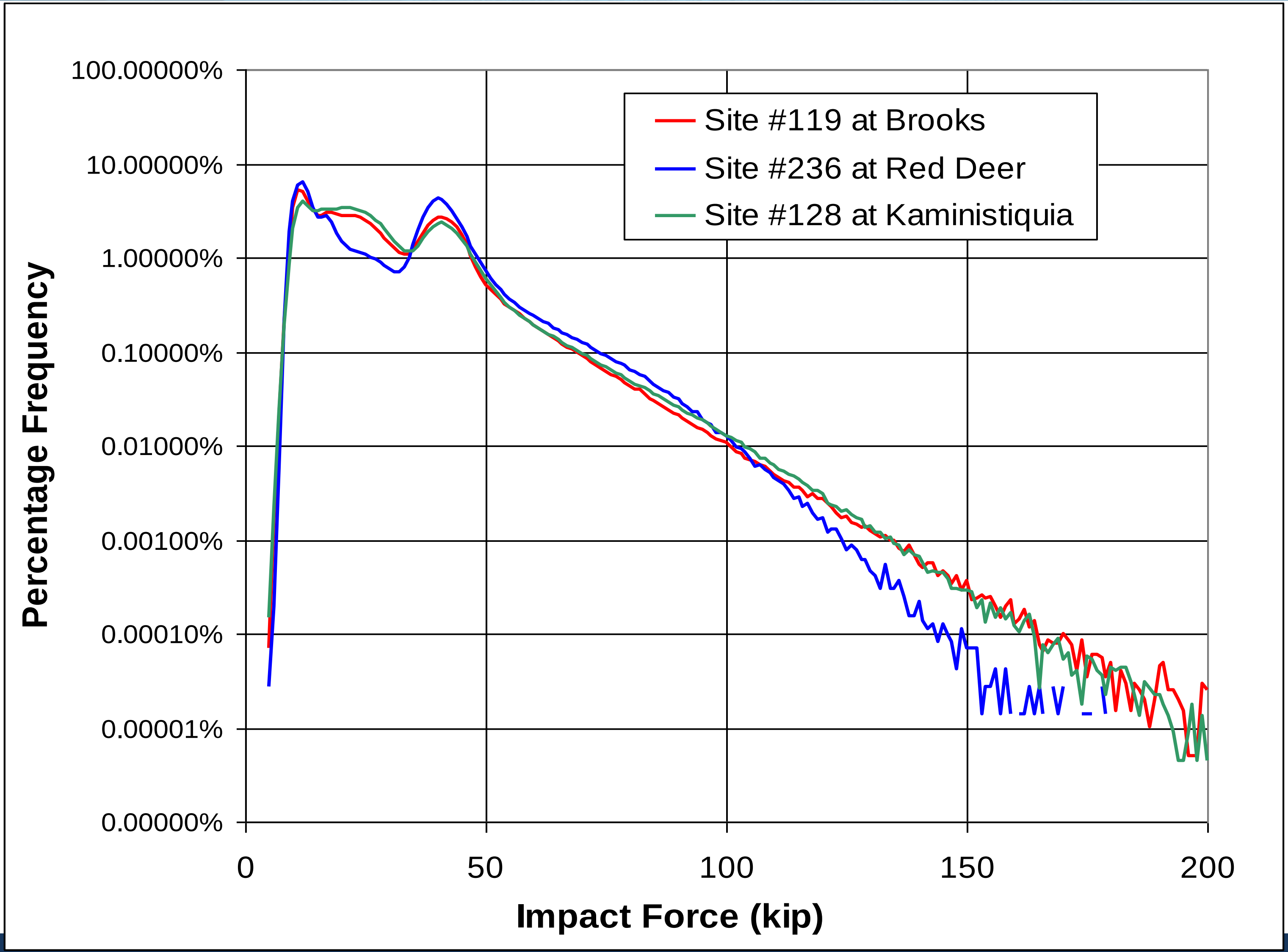
- Site #236
- MP22.7 of Red Deer Sub at Airdrie
- 26-Jan-2005 to 31-July-2007
- 7,417,500 wheels and 12,347 trains
- Used for Red Deer and Leduc subdivisions

WILD Force Distribution
- In linear scale



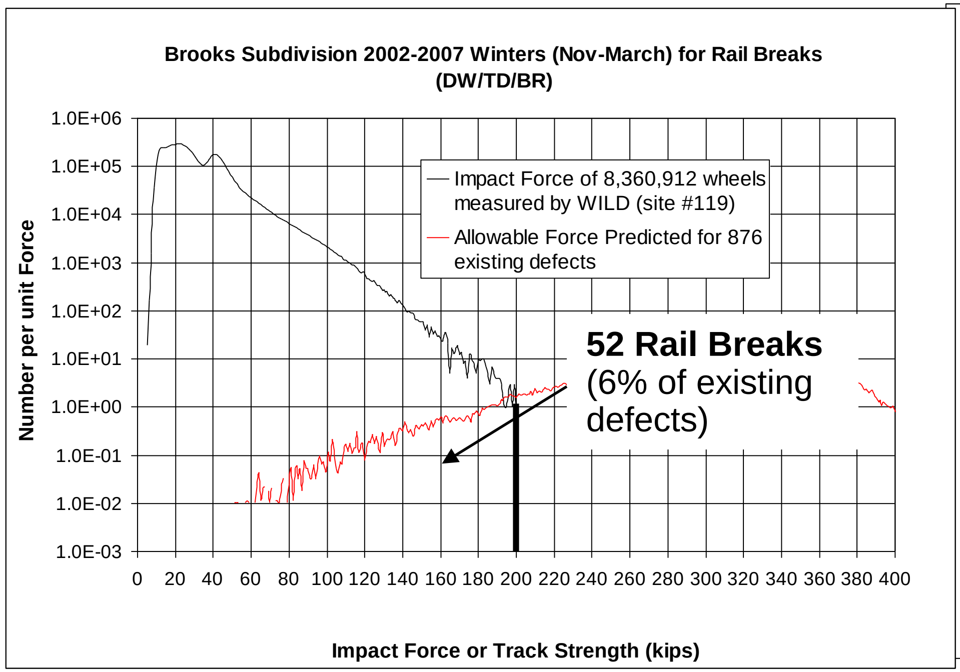
NRC·CNRC

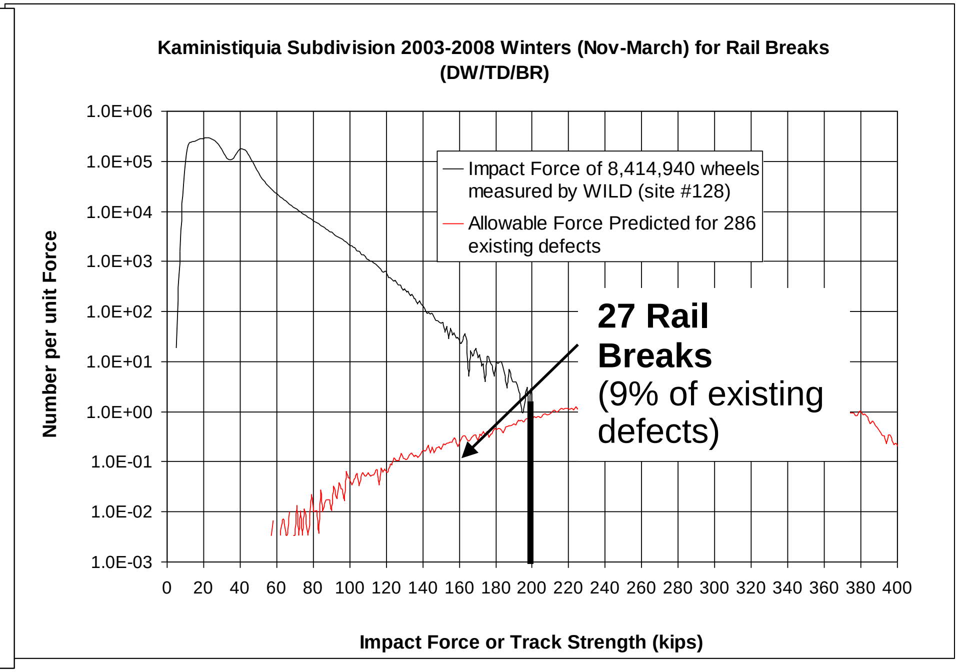
WILD Force Distribution
- In logarithmic scale



NRC·CNRC

Rail Break Model by Stress – Strength Approach (Logarithmic Scale)





A New Operating Rule in Winter

- ✓ CP has revised its operating rules since 2010 to take the stress-strength model into account.
- ✓ CP reduced cold-weather transit time for more than half its trains.
- ✓ Derailments also went down in the first year alone.

Liu, Y., Ladubec, C., Preston-Thomas, J., Magel, E. and Roney, M. Cold Weather Train Speed Optimization Based on Stress-Strength Approach. 9th International Heavy Haul Conference, Shanghai, China, 2009, 8 pages

Challenges to “Predict” Broken Rails

- ❑ Many different failure mechanisms
  - Transverse defect (size and shape)
  - Welds (HAZ, plastic deformation)
  - Many other types need to be included
  - Interaction of defects
- ❑ Loading conditions affected by many factors
  - Train forces impact (WILD!), how about longitudinal and lateral force?
  - Impact of good wheels to welds and other rail “dips”
  - Ambient vs rail temperature
  - Fatigue crack growth? Can a frequent ultrasonic inspection cover it?
- ❑ Seasonal effects,
  - Foundation stiffness
  - Material properties, K1c etc.
- ❑ Unknown conditions
  - Neutral temperature
  - Residual stress

Thank You…

Yan Liu, Ph.D
Principal Researcher and Team Leader
National Research Council of Canada
Phone: 613-991-5026
Yan.Liu@nrc-cnrc.gc.ca

Despite hundreds of rail breaks, very few cause a derailment. What other conditions are needed for a broken rail to cause a derailment?

Brad Kerchof
Advanced Rail Management

Director Research & Tests
Norfolk Southern (retired)

The majority of broken rails do not cause a derailment

A straight break on reasonably good track will pass a train safely. (“Good track” supports the rail ends so that they do not mismatch enough to catch a wheel flange.)

In 2019, NS reported 1012 broken rails… but only 6 FRA-reportable broken-rail derailments

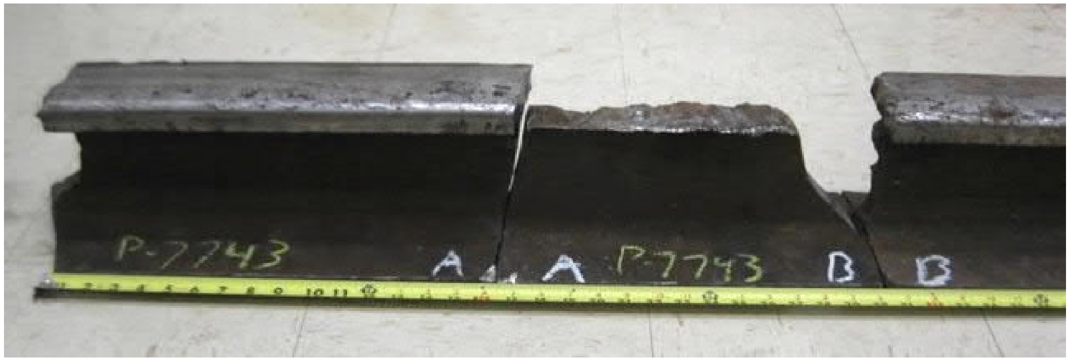
This straight break passed trains for at least two weeks! (This detector car image is from a test conducted two weeks prior to a broken-rail derailment.)

What are the indications of a broken-rail derailment?

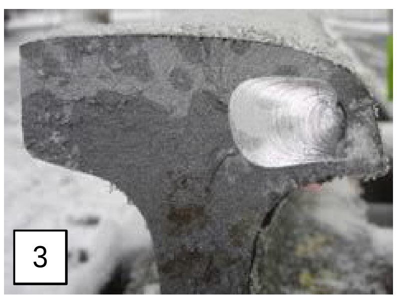
- Sudden and total track destruction with no prior indication of derailment
- Derailed cars in a pile
- One or more broken rails, each with
    - an internal defect
    - receiving end batter
- Impact mark on wheels ahead of those derailed
- History of rail defects
- Often, confirming the cause may be difficult because evidence is buried under the pile-up

When is a broken rail likely to cause a derailment?

When there is a second break - either a completely new break, typically within several feet of the first, or a progressive fracture of the first break



NS archives: Examples of broken rails that cause derailments



Broken rails originating from these type defects:

1. Reverse TD (TDR)
2. Transverse defect detail (TDD), often from surface cracks on gage corner of high rail
3. Gage-corner shell (high rail)
4. Center shell (example here - stock rail)
5. Vertical split head (VSH)

Reverse TD (TDR)

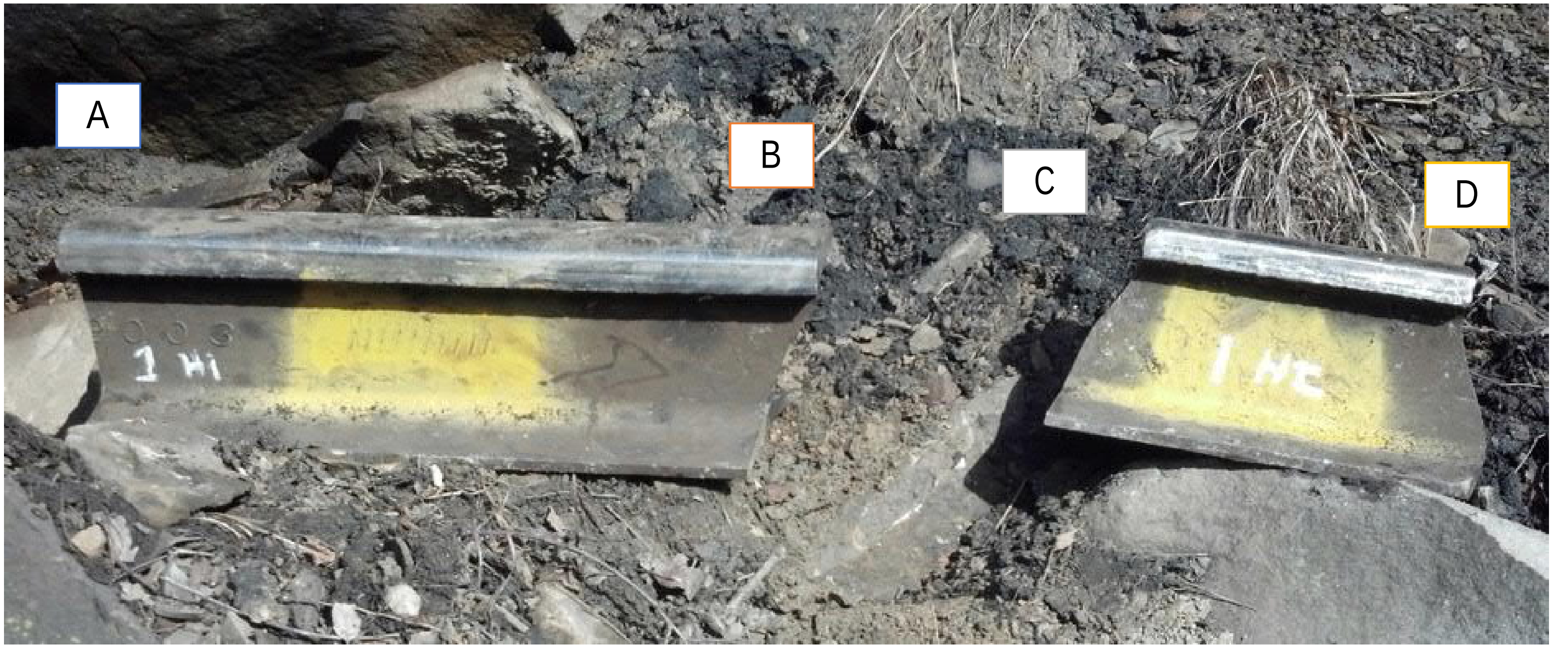
- Found in curve-worn high rails

The following applies to TDRs and other RCF defects:

- One break, by itself, is unlikely to cause a derailment
- However, the conditions that generate a reverse TD are present elsewhere (in other words, one TDR is a predictor of additional TDRs)
- If a TDR fractures, and if there is a second TDR located within several feet, the increased wheel impact caused by the first break may accelerate the fracture of the second
- The resulting short rail is unstable and will cause a derailment

Multiple Reverse TDs - Kimball, WV

DIRECTION OF TRAVEL →



Multiple Reverse TDs - Kimball, WV

Multiple Reverse TDs - Kimball, WV

DIRECTION OF TRAVEL

Multiple Reverse TDs - Kimball, WV

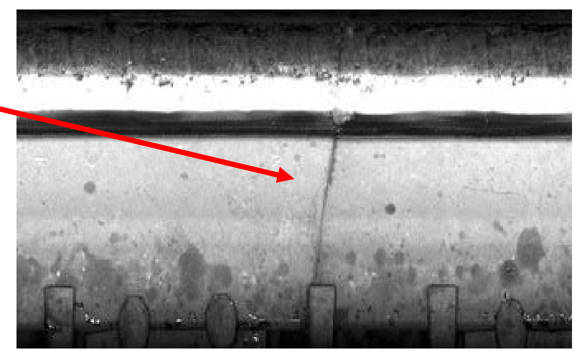
Multiple Reverse TDs - Kimball, WV

Multiple TDDs – Pittsburgh, PA

Both broken rails were caused by TDs originating from RCF at the gage corner.

The fracture face on the right is polished due to the rail ends rubbing.

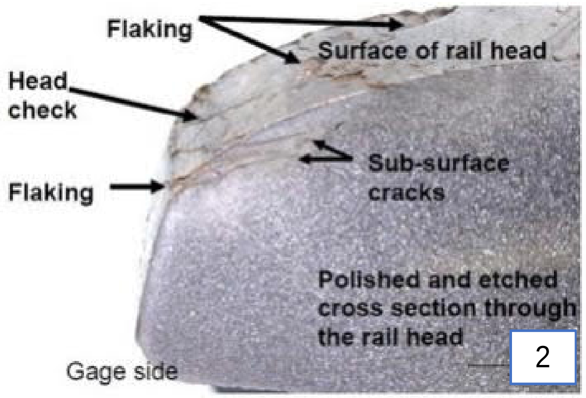
The fracture on the left was the second break that caused the derailment.

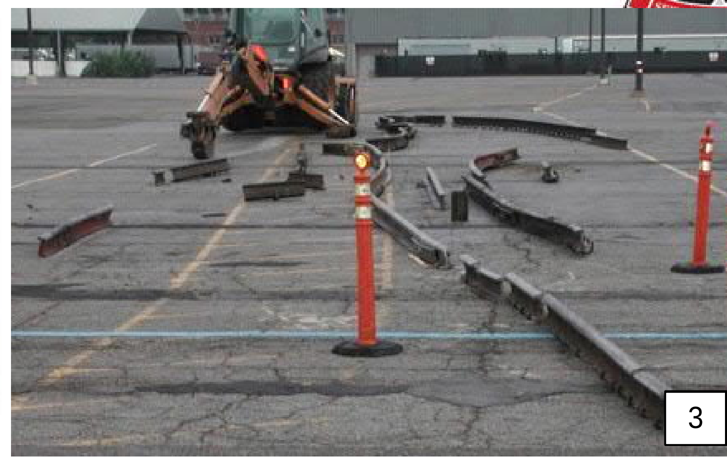


1

Multiple TDDs - Columbus, OH

1. Aerial view
2. Cross-section of high rail (not at defect) from NTSB report
3. High rail laid out in parking lot





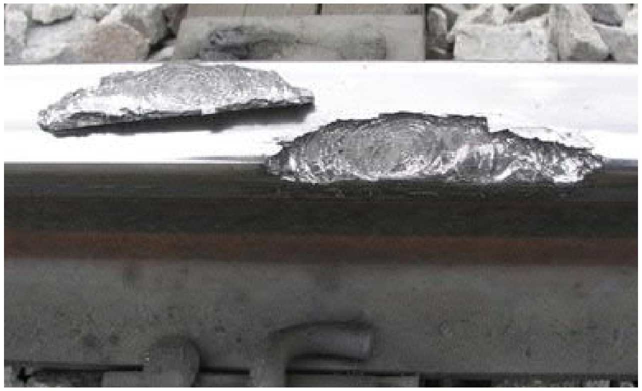
Derailment cause: Multiple TDDs (originating from surface cracks)

The back story: A worn-out low rail from a nearby curve (132RE, 7/16” top wear) was relocated to this 9^{o} curve to replace a curve-worn high rail. Three months passed between installation and derailment. During the first month, the Sperry car found 3 TTDs. During the second and third months, there were 5 TDD broken rails.

Multiple TDs - gage corner shells (high rail) - Wilton, AL

Derailment cause: Multiple TDs (at least two) that developed beneath gage-corner shells of a moderately curve-worn high rail

But not all gage-corner shells are problematic!



Some gage-corner shells exist for years
without causing a broken rail!

Multiple TDs - center shells (stock rail) - Frey Creek, SC

The straight stock rail and next rail broke into 21 pieces; 19 pieces were recovered

Leaving end of intact stock rail

Receiving end of the adjacent piece

Both leaving and receiving ends of the initial break showed a significant center shell

Multiple TDs - center shells (stock rail) - Frey Creek, SC

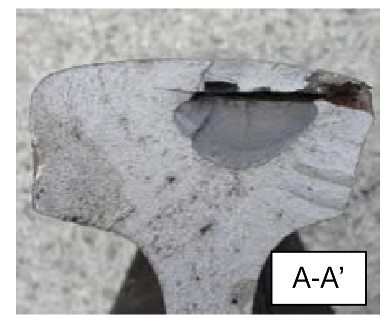
We hand-mapped 5 shells with 12 inches of the initial break

Leaving end of intact stock rail → | The first piece to break out

Shell S3 developed a TD, which caused the first fracture. The resulting wheel impacts contributed to subsequent fractures at shells and TDs downstream.

Multiple TDs - center shells (stock rail) - Frey Creek, SC

' indicates leaving end;
otherwise, receiving end



A-A' is the mate fracture face to A. This was the first break.

Vertical split head - Ft Wayne, IN

A VSH (a longitudinal separation in the head of the rail) can cause a derailment when the defect turns out (or in) and a piece of the head breaks out.

Other longitudinal defects, such as horizontal split head, head-web separation and piped rail, have a similar risk profile.

An exception to the second break rule: a broken field weld

Most broken field welds are straight breaks (and do not cause derailments)

Some field welds may fracture with a more complex geometry - such as a longitudinal component. If enough of the head breaks out, a derailment can occur.

Are there remedies for these types of broken rails?

Yes!

Fortunately, it is not unusual for a rail to give fair warning of impending disaster.

- It is important to recognize that the first detect, or the first broken rail, caused by a TDR, shell or surface RCF is an indication of more to come

This warning gives us the opportunity to change out the rail or increase rail test frequency.

About rail defect testing:

- Have a clear understanding with your rail test operator of how to handle unusual transducer responses (such as loss of bottom, high density head or intermittent side-looker responses).
- Defects that develop from RCF are often visible to a rail test car over several tests , giving us time to evaluate and respond.

Discussion

This broken rail certainly fits the multiple break category. But it did not cause a derailment!