

Моделирование образования и развития поверхностных контактно-усталостных дефектов рельсов: обзор подходов

Surface Initiated Rolling Contact Fatigue Simulation in Rails: a Review of Approaches

Sergey M. Zakharov

SC «Railway Research Institute» (SC “VNIIZhT”), Moscow

Project РФФИ-офи –м РЖД № 17-20-01147 «ИПМех-РАН – АО «ВНИИЖТ»

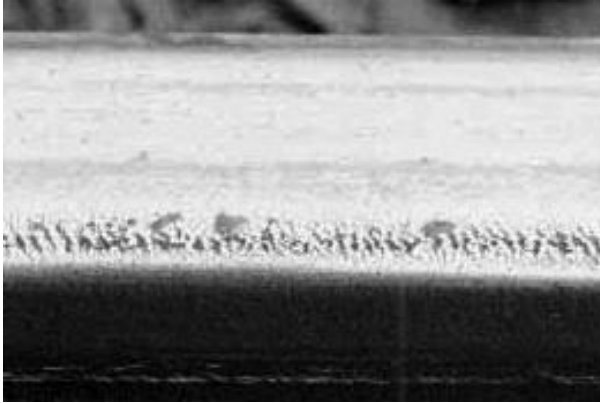
**Участники: Горячева И.Г., Абдурашитов А.Ю., Борц А.И., Заграничек К.Л,
Захаров С.М., Коган А.Я., Торская Е.В, Шур Е.А., Щербакова О.О**

Content

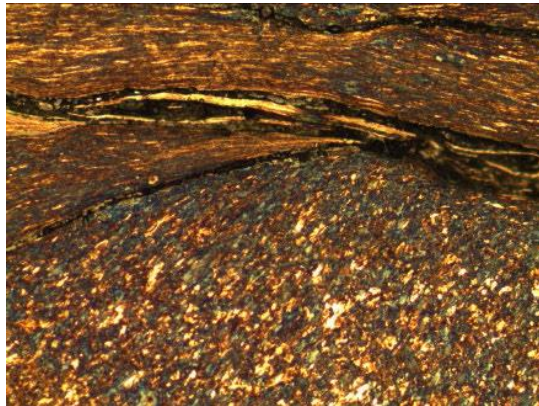
- Surface initiated RCF defects in rails
- Projects on RCF and wear
- Approaches to RCF simulation
- Prediction of RCF

Surface Initiated RCF in Rails

Head checks on rail running surface



Horizontal crack formation



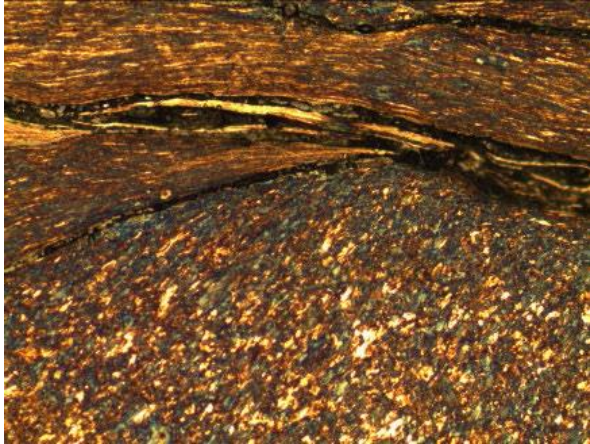
Change in the direction of horizontal crack propagation



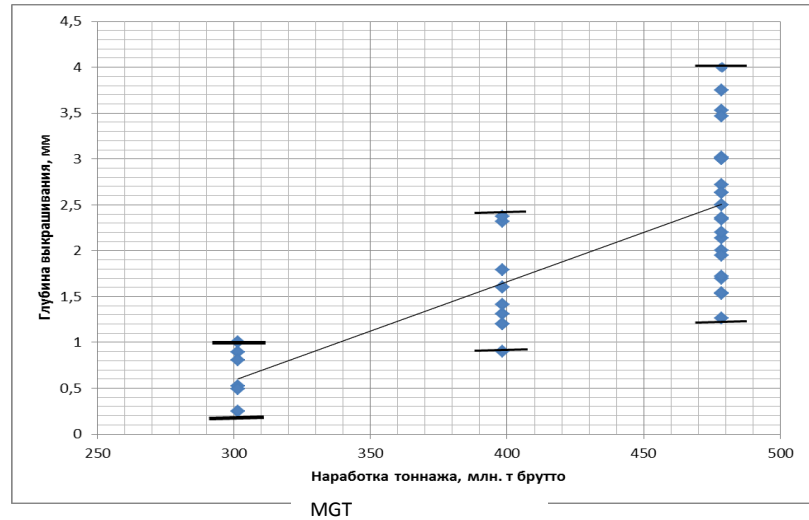
E. Shur, A.Bortz et al. Evolution of RCF defects in rails/Vestnik VNIIZhT, № 3, 2015, 3-9

Rate of Crack Depth Growth

Deformed structure in the crack area



Depth of crack (mm) versus MGT

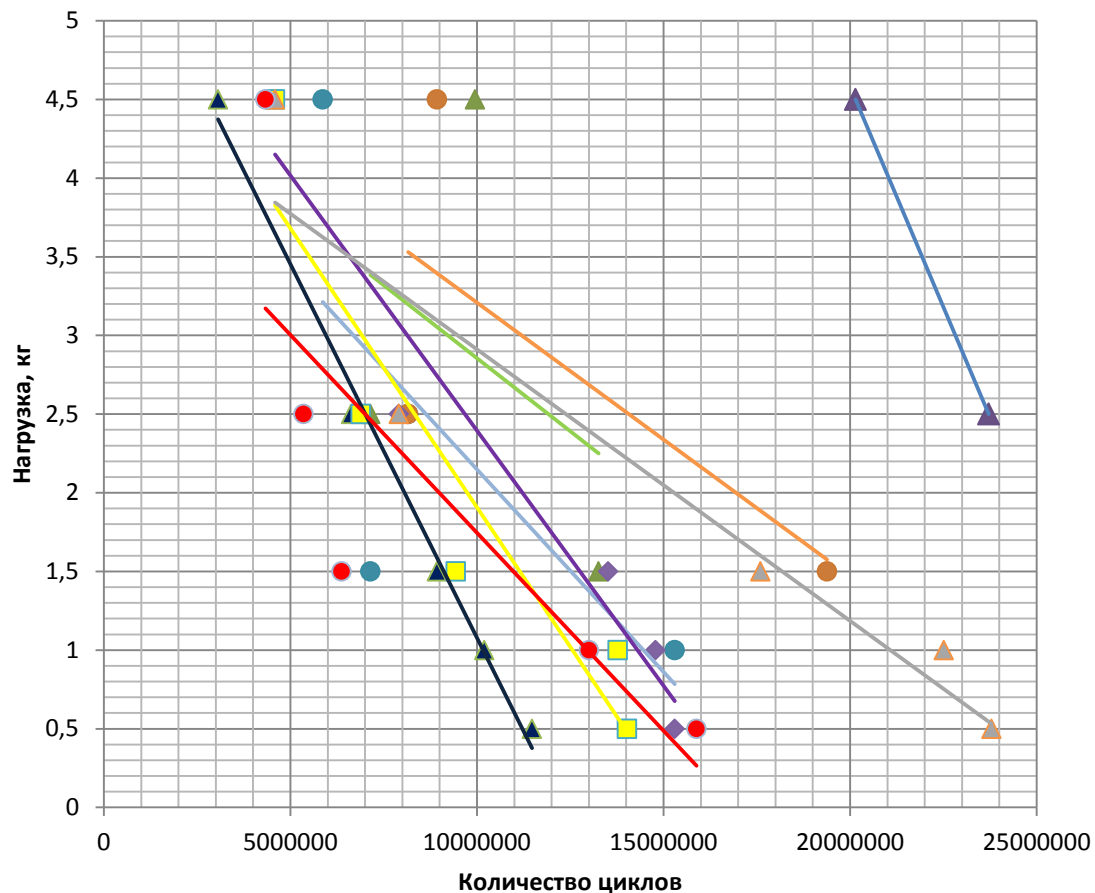


Change in Mechanical Properties of Rail Surface Layers

Depth from the surface	Ultimate strength, N/mm ²	Yield strength N/mm ²	Elongation,%
10 mm	1305	910	15,0
Close to the rolling surface	1054	919	3,7

E. Shur, A.Bortz et al.Evolution of RCF defects in rails/Vestnik VNIIZhT, № 3, 2015, 3-9

Contact Fatigue Tests of Rail Steels



Борц А.И., Долгих Л.Г., Заграничек К.Л. Испытания рельсов на выносливость, Путь и путевое хозяйство, 2014

АО "ВНИИЖТ"

Head Checks Formation Mechanism and Influencing Factors

- Head checks (HC) at the rail running surface initiate as a consequence that arise from incremental accumulation of plastic strain during each cycle of loading of the strain hardened material. Accumulation of a large number of unidirectional plastic strain ratchet the surface of the surface layer of material until its ductility is exhausted.
- Influencing factors:
 - mechanical properties of materials,
 - steering ability of bogies,
 - wheel and rail profiles.
 - rail cant, etc.

Approaches to RCF Cracks Initiation

Fatigue initiation models:

- High cycle fatigue - applicable for elastic shakedown response
- Low cycle fatigue - applicable for plastic shakedown and ratcheting material response (head checks formation).

The following groups of approaches and models:

- equivalent strain approaches
- critical plane models
- energy and energy-density based models
- combined energy-density and critical plane models
- empirical models.

J. Rinsberg. Review of models for fatigue initiation, Chalmers, Sweden, 2000

ICRI- International Collaboration Research Initiative

Initiated by NRC, Canada (Eric Magel) in 2013.

There are 12 subprojects, including RCF in rails:
Chalmers (Sweden) - ICON, INNOTRACK, et al
NRC (Canada), Virtual Vehicle (Австрия),
KTH (Sweden), Institute of Railway Technology
(Australia), “Huddersfield”,
VORtech CMCC“Contact”, etc.

RCF and Wear Simulation

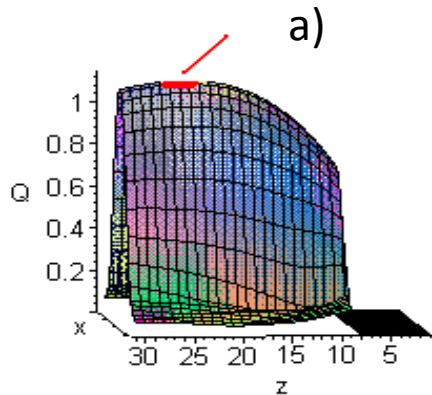
$$q(x, y, z, t) = c[\Delta\tau(x, y, z, t)]^m,$$

$q(x, y, z, t)$ - the rate of contact fatigue damage accumulation;

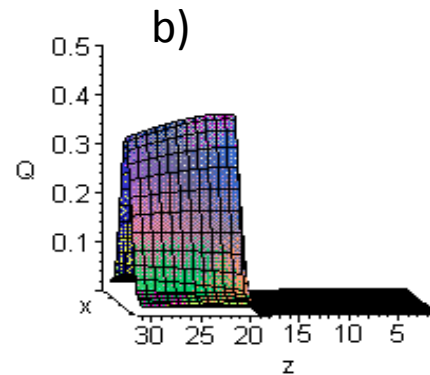
$\Delta\tau(x, y, z, t)$ - difference between maximal and minimal values of maximal tangential stresses in the point (x,y,z) for one cycle of loading;

c,d – coefficients taken from laboratory experiments on RCF

(Т.В.Ларин. В.А.Рейхарод. Д.П.Марков)



$$m = 2.1, \quad c = 0.91 \cdot 10^{-11}$$



$$m = 1, \quad c = 0.88 \cdot 10^{-14}$$

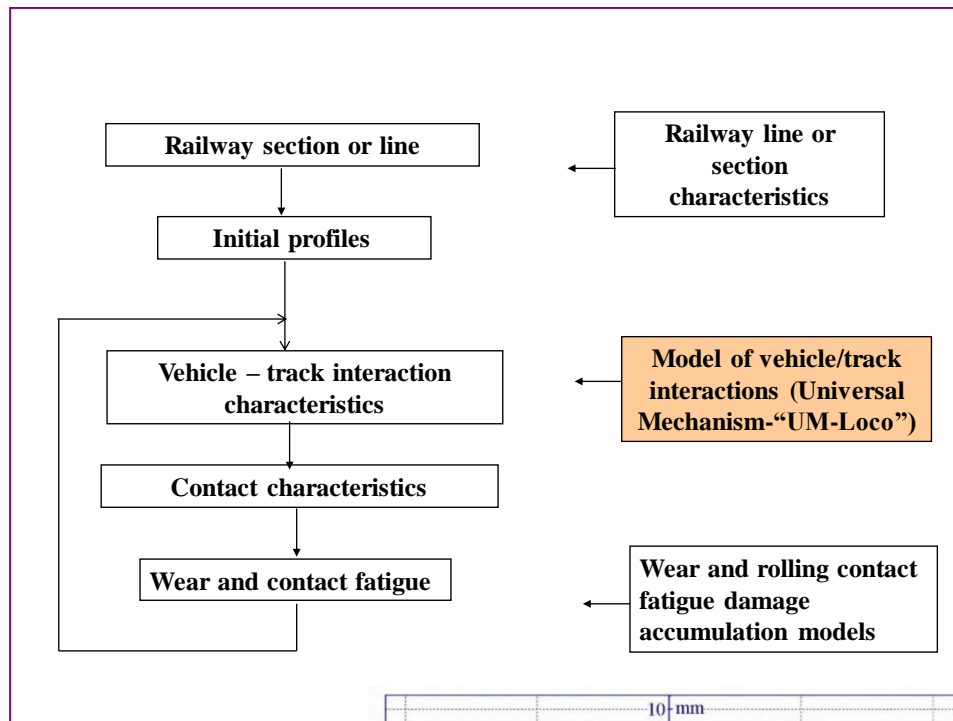
Rolling contact fatigue
considering competing
mechanism of wear

I.G.Goryacheva . *Contact Mechanics in Tribology*, Kluwer Pub., **1998**

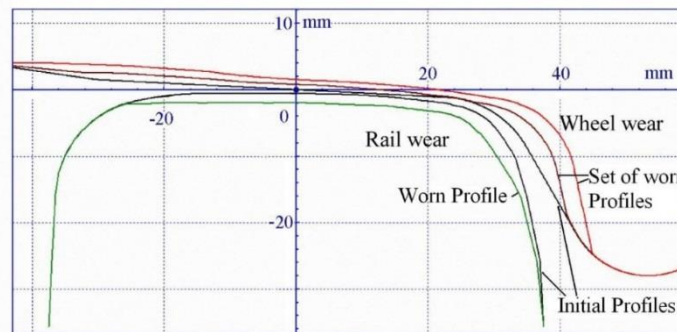
И.Г.Горячева, Е.В. Торская Моделирование условий образования контактно-усталостных повреждений поверхности катания/Под ред. С.М.Захарова, М.:Интекст.**2004** , стр 58-97

Tribodynamic Model of Vehicle-Track Interaction

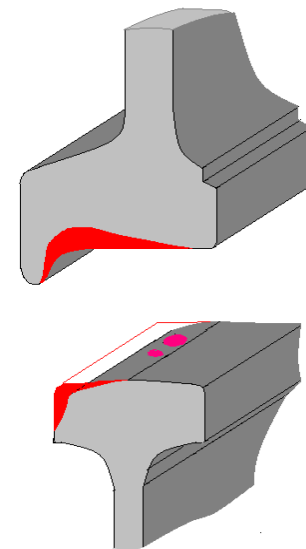
IPMech – UM, Bryansk-VNIIZhT (RFFI- 2007-2008)



Wheel and rail profiles evolution



RCF and Wear Simulation



Computer-aided simulation of the influence of track and vehicle parameters on wheel/rail interaction characteristics/ CM-2009, Florence pp1075-1083.

RCF Initiation Models

1. Combined energy-based and critical plane model (Jiang and Sehitoglu).

Fatigue parameter
$$FP = (\sigma^{max}) \frac{\Delta \varepsilon}{2} + J \Delta \tau \Delta \gamma$$

J – the constant accounts for the contribution of shear damage in the fatigue parameter

2. An empirical model (Kapoor). Number of cycles to crack initiation N

$$N_i = \frac{\varepsilon_c}{\Delta \varepsilon_r}$$

ε_c - a constant defined from twin dis tests,

$\Delta \varepsilon_r$ - an equivalent ratchetting strain per cycle

3. Finite element simulation (ABAQUS) for rolling contact. Three types of material were investigated in FE simulation:

- a nonlinear hardening model available in ABAQUS
- two nonlinear kinematic hardening models/

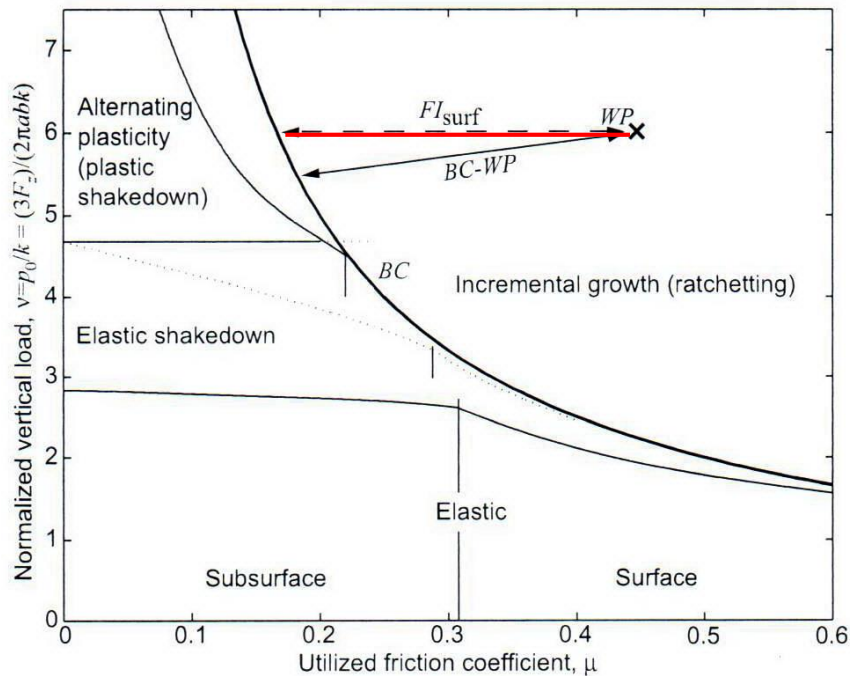
The material models can simulate ratchetting material response.

J. Ringsberg. RCF of Rails with Emphasis on Crack Initiation/PhD, Chalmers, 2000

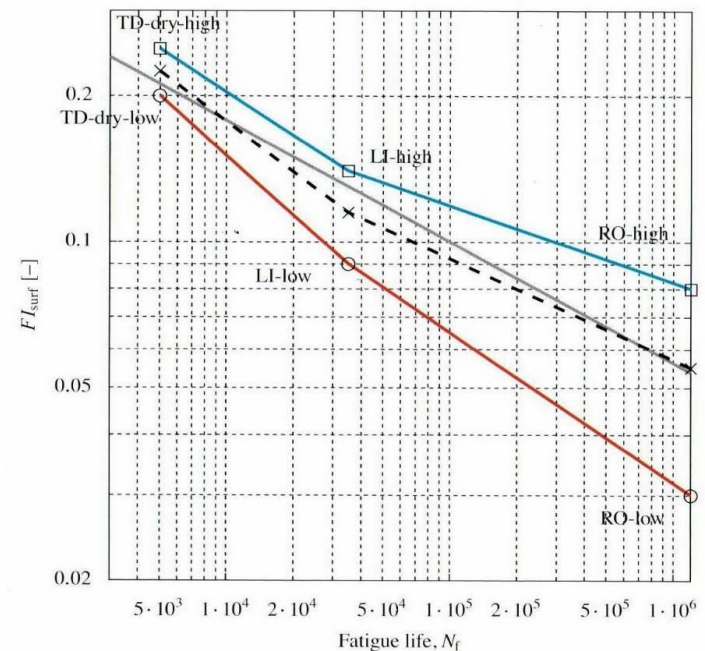
RCF Index Based on Shakedown Map and Laboratory Tests

Fatigue index $FI_{surf} = A(N_f)^B$
 N_f - fatigue life, A,B – tested material parameters;

Shakedown map



Fatigue Index FI_{surf} versus Fatigue Life, (N_f) of crack initiation obtained by three different test rigs*



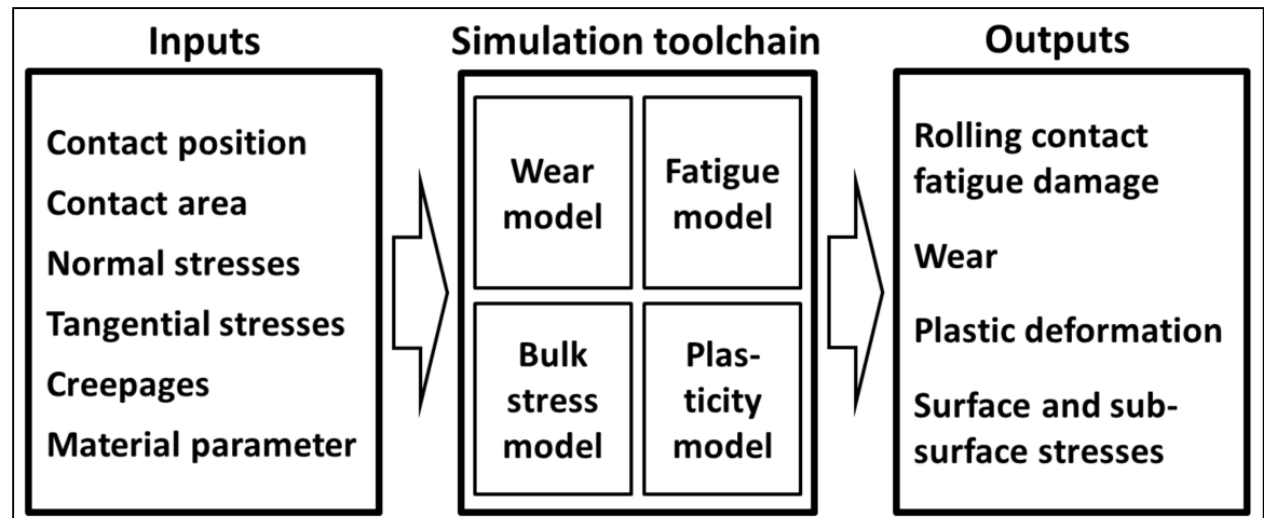
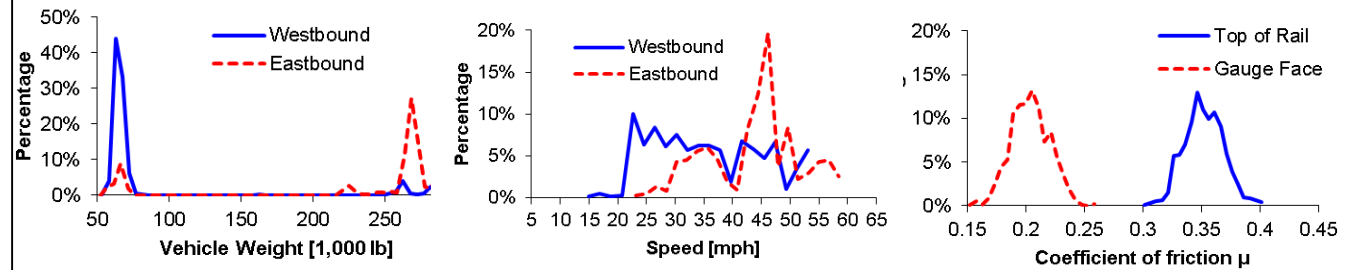
*E.Kabo, A. Ekberg Prediction of RCF from laboratory tests/INNOTRACK, 2010, p.131-133.

ICRI Data Package and Scheme of Simulation Model

ICRI data package:

- 426 m curve, track geometry, rail profiles, wheel profiles.
- VAMPIRE simulation input/output files;
- rail surface photo;
- crack depth data;
-

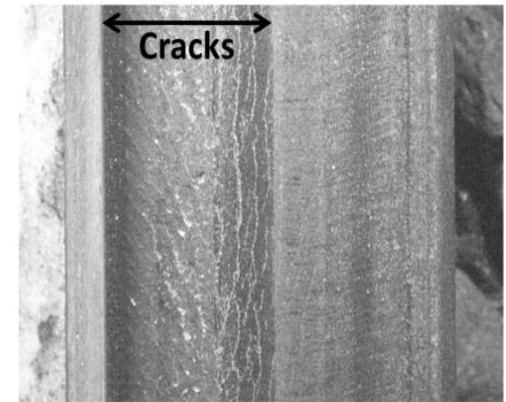
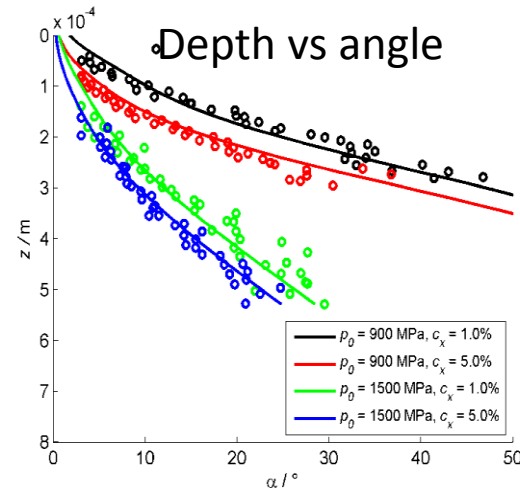
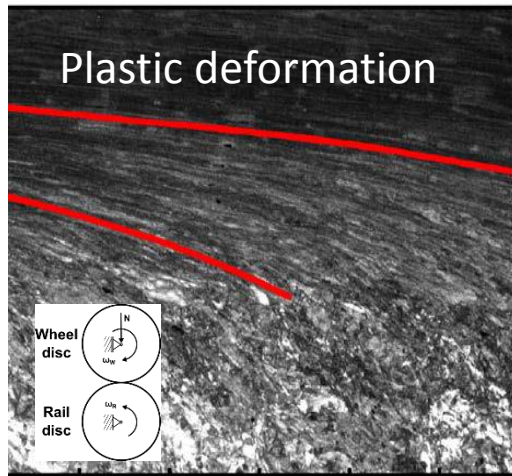
Distributions of vehicles weight, speed and friction of coefficient



G.Trummer, K.Six, A. Woelfle et. al, Comparison of rolling contact fatigue crack initiation models under heavy haul conditions/IHHA-2017, SA

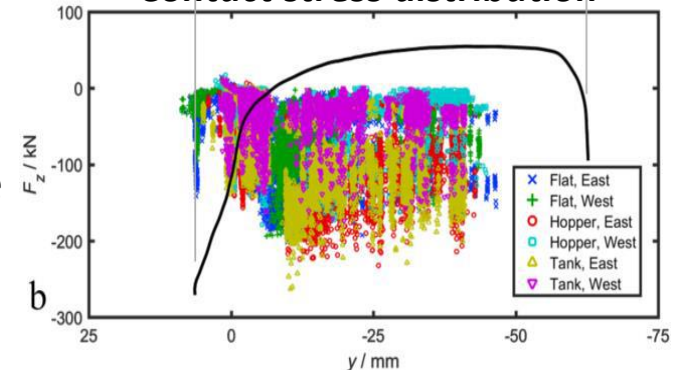
K.Six, A. Woelfle. E.Magel Simulating RCF damage and correlation with field observations/Virtual Vehicle, NAational Research Council, Canada

“Wedge” Crack Initiation Model



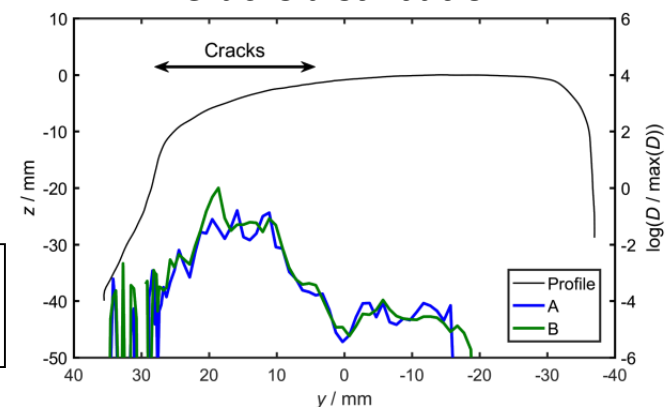
a

Contact stress distribution



b

Cracks distribution

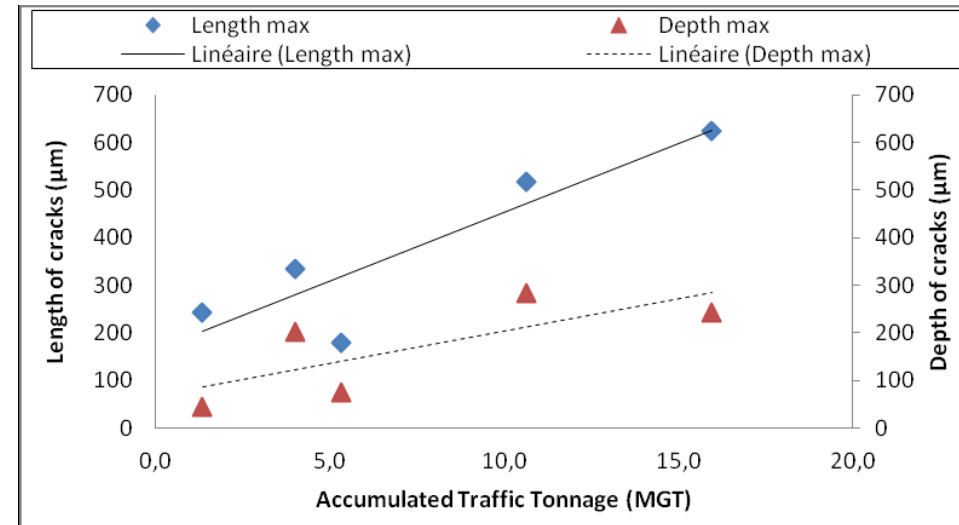
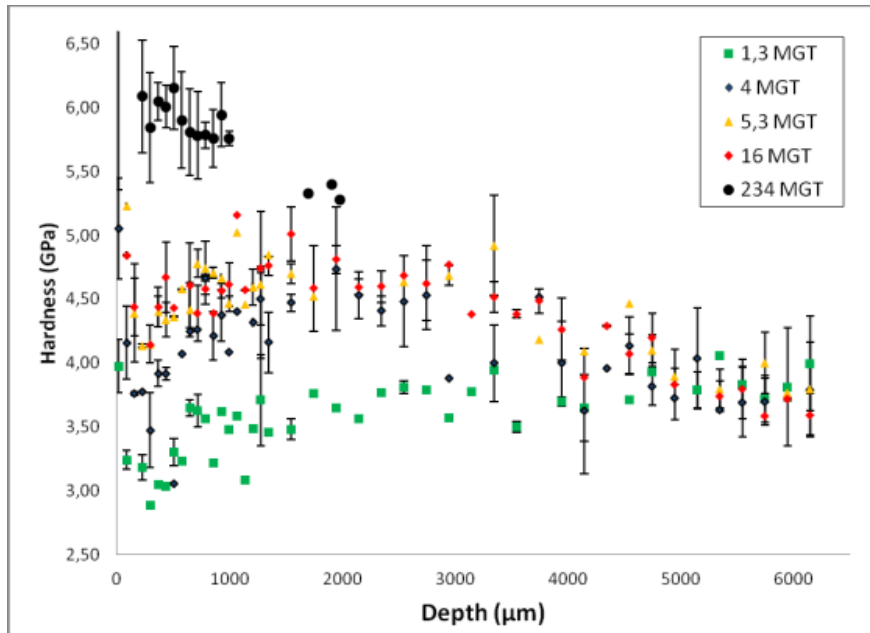


The crack initiation :

- based on the maximum (tensile) principal stress and the state of plastic shear deformation near the contact surface;
- is facilitated when a favourable shear-deformed microstructure exists
 - which promotes microscopic crack paths at an oblique angle away from the surface,
 - extends a few tenths of a millimetre below surface.

K. Six, G. Trummer, A. Woelfle, E. Magel (Virtual Vehicle RC, NRC)
G. Trummer et al/ IHHA-2017, Cape Town, SA

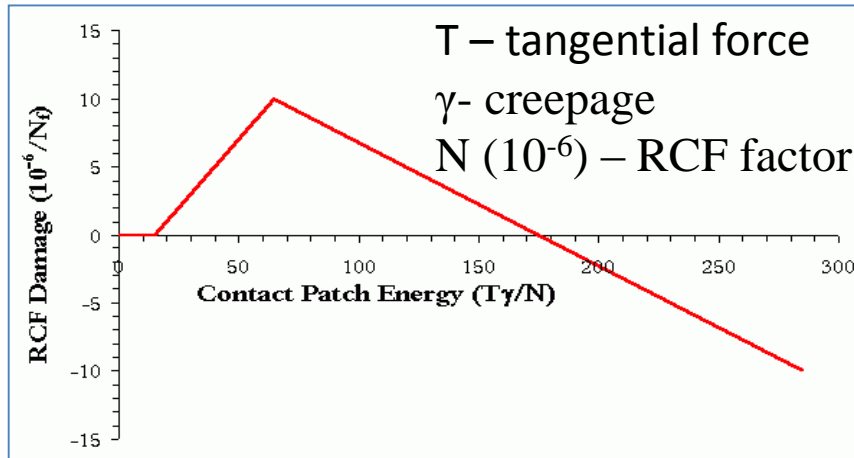
EVOLUTION OF MECHANICAL PROPERTIES IN THE NEAR SURFACE



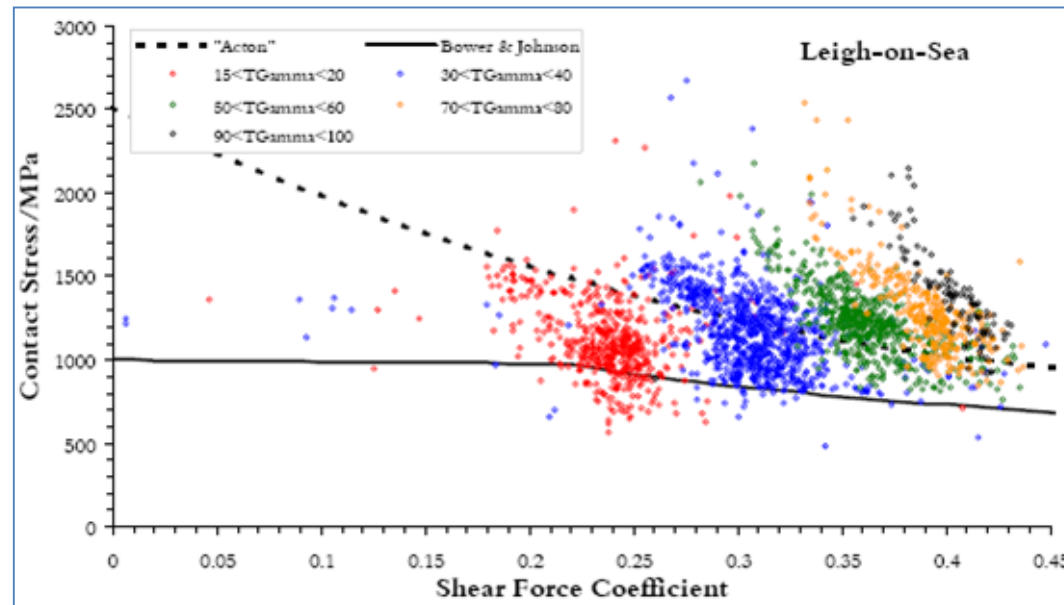
Cracks initiation at rail surface after 5.3 and 10.6 MGT

Dylewski Benoît, Bouvier Salima, Risbet Marion, Multiscale characterization of head check defect on rails under rolling contact fatigue: mechanical and microstructure analysis/CM 2015, Colorado, USA

T γ Model of RCF and Wear (WLRM)



	Energy in contact
Low level of RCF	- $T\gamma < 15 \text{ J/m}$
Moderate level of RCF	- $15 < T\gamma < 65 \text{ J/m}$
Transition to wear	- $65 < T\gamma < 175 \text{ J/m}$
Wear	- $T\gamma > 175 \text{ J/m}$

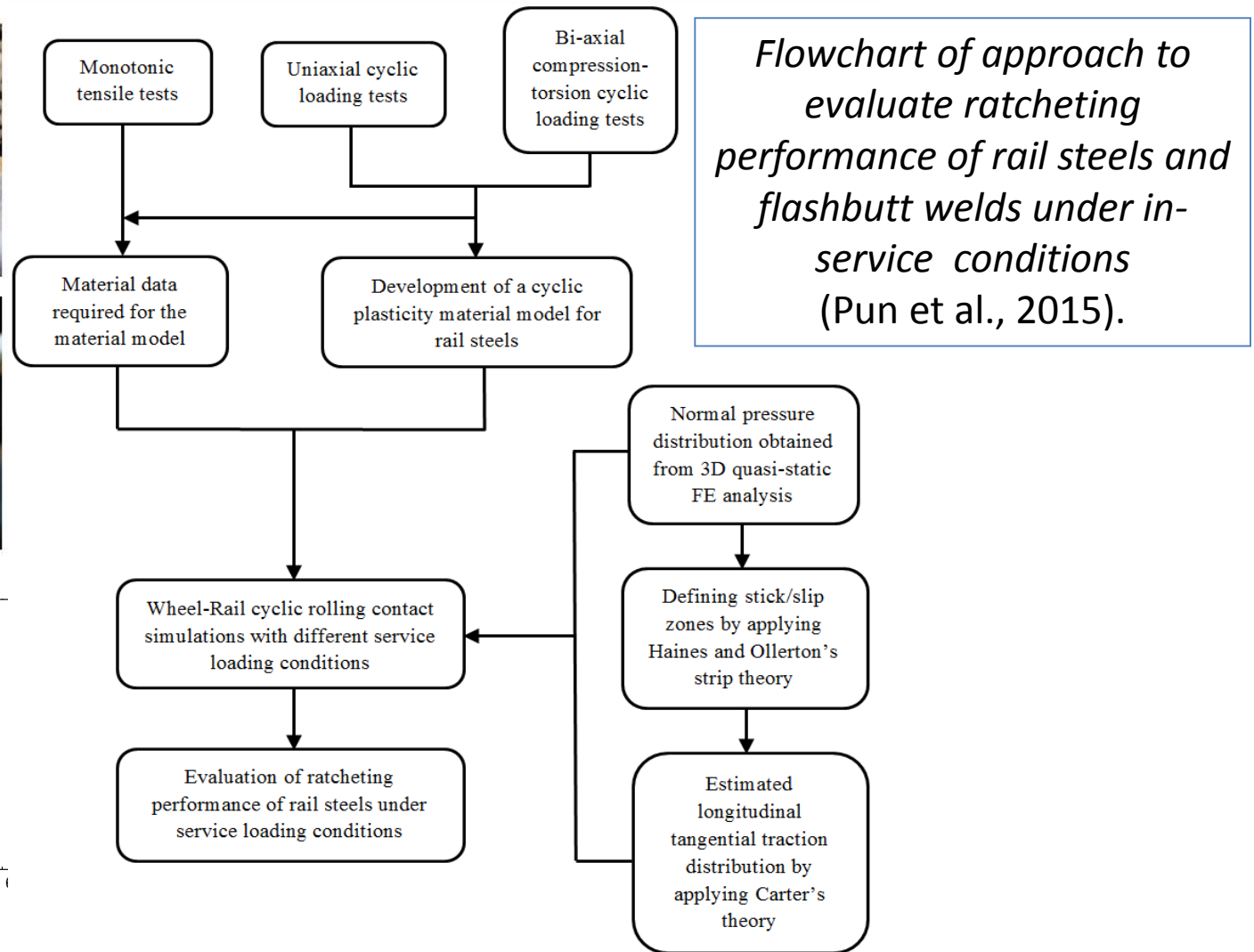
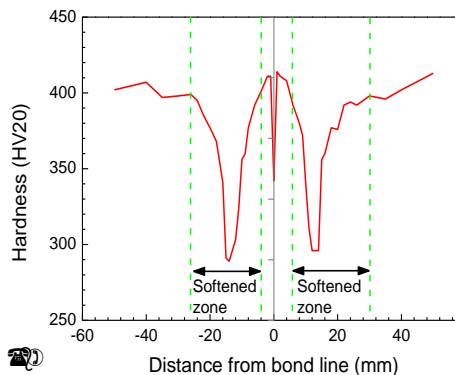
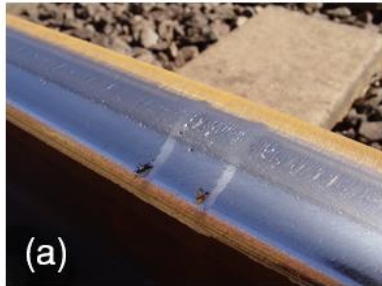


Fatigue damage function describes proportion of fatigue life consumed by each load cycle to determine material failure (crack initiation)

Shakedown diagram and distribution of different levels of $T\gamma$, J/m
 (15-20; 30-40; 50-60; 70-80; 90-100)

M. Burstow. WLRM (Whole Life Rail Model). Rail surface damage modelling (Network Rail)/ICRI Workshop, 2016

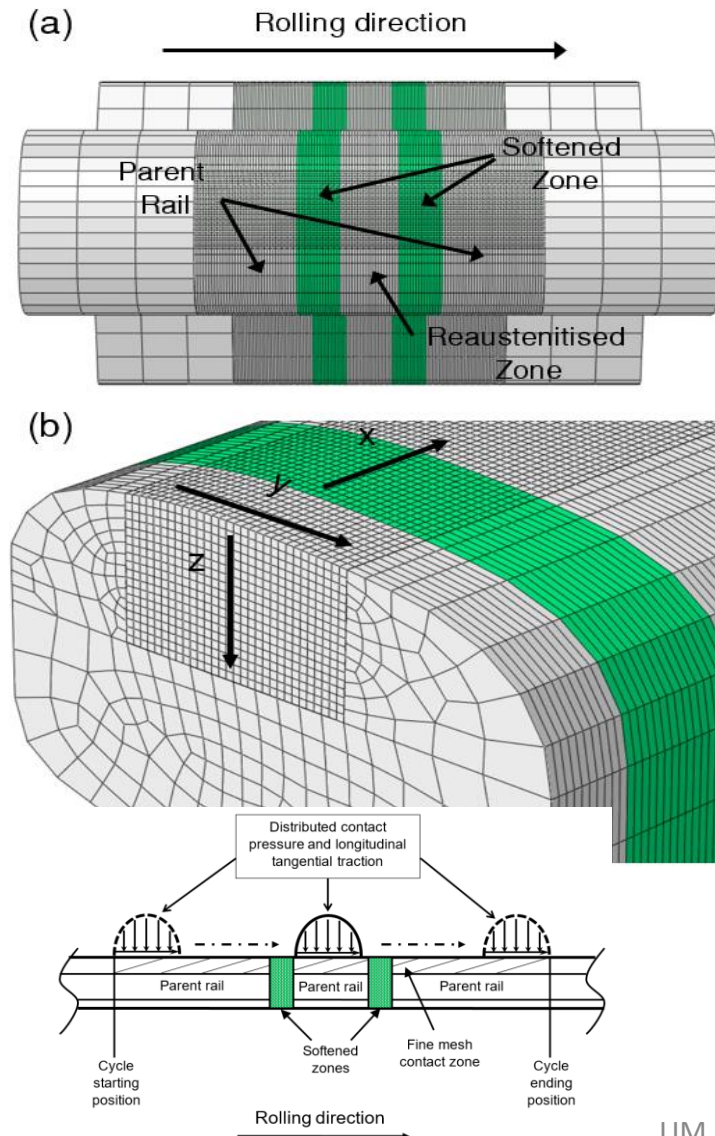
Rolling Contact Fatigue Life Prediction in Rail/Welds



Chung Lun Pun, Darrien Welsby, Peter Mutton, Wenyi Yan. Rolling contact fatigue life prediction in rails and welds // Institute of Railway Technology, Australia, IHHA-2017, Cape Town.

Finite Element Analysis of Rail Weld

Finite element model:



Crack initiation life:

$(d\varepsilon_r/dN)_{\max,sta}$ the stabilized maximum ratcheting strain rate

$$\frac{(d\varepsilon_r/dN)_{\max,N} - (d\varepsilon_r/dN)_{\max,N-1}}{(d\varepsilon_r/dN)_{\max,N-1}} < 0.5\%$$

$(d\varepsilon_r/dN)_{\max,N}$ the maximum ratcheting strain rate in the current loading cycle and

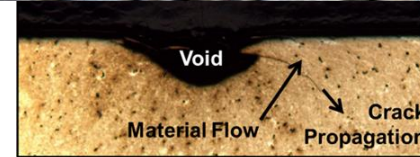
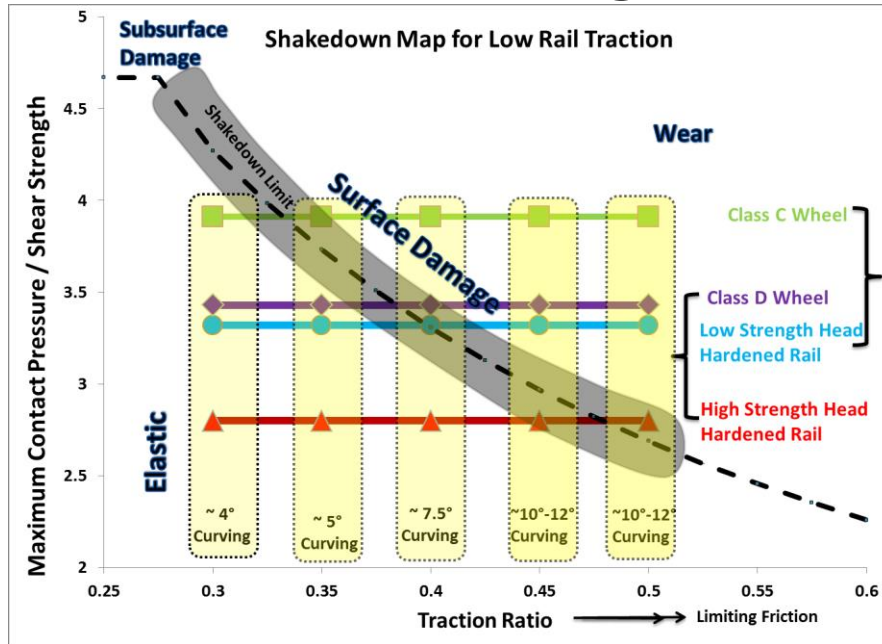
$(d\varepsilon_r/dN)_{\max,N-1}$ is the maximum ratcheting strain rate in the previous loading cycle.

Crack initiation life

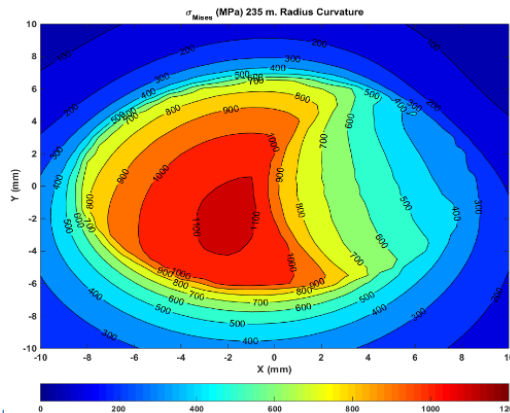
$$N_i = \frac{D}{(d\varepsilon_r/dN)_{\max,sta}}$$

Chung Lun Pun, Darrien Welsby, Peter Mutton, Wenyi Yan. Rolling contact fatigue life prediction in rails and welds // Institute of Railway Technology, Australia, IHHA-2017, Cape Town.

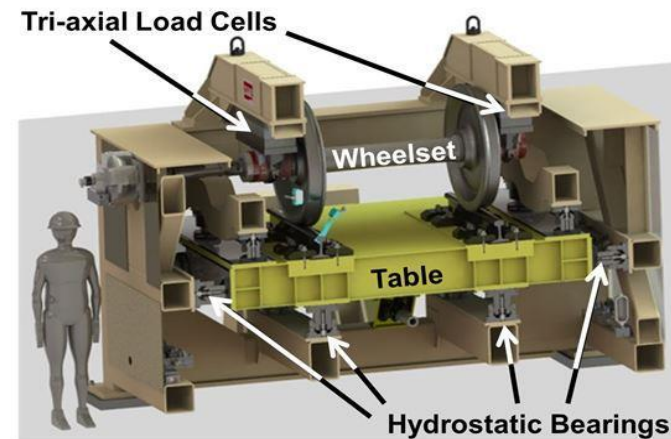
Rail and Wheel Surface Damage under High Traction using CONTACT and RCFS



Rolling contact fatigue simulator (RCFS)



3-Piece bogie (truck) low rail wheel von Mises stress distributions on contact patch, 235 m curve (CONTACT).



H. M. Tournay, Sabri Cakdi. Predicting Wheel Tread Surface Damage under High Traction in Heavy Haul Operations using CONTACT, CM2015.

RCF Tonnage Prediction Based on Known RCF Rail Life

$$n_1 D_1 = n_0 D_0 = G = \text{const.}$$

n_1 - number of axles that can pass on Section 1 before RCF resource is exhausted

D_1 - RCF damage index on the Section 1 after passes of one axle;

n_0 - number of axes passed test section before RCF resource is exhausted;

D_0 - RCF damage index on the test section after one axle pass;

$$n_1 = \frac{T_1}{\langle P_1 \rangle}; n_0 = \frac{T_0}{\langle P_0 \rangle},$$

T_1, T_0 – gross tonnage on the target (T_1) and test (T_0) sections before RCF resource is exhausted, $\langle P_1 \rangle, \langle P_0 \rangle$ – average axle load on section 1 and test section,

$$T_1 = T_0 \cdot \frac{D_0}{D_1} \cdot \frac{\langle P_1 \rangle}{\langle P_0 \rangle}$$

АО "ВНИИЖТ"

Scheme of Rail RCF Failure Prediction Based on Known Track RCF Strength

Track loading considering variety of trains on the track section



Measure of rail RCF damage for one cycle of loading on the test track



Track loading considering all trains on target track section



Measure of rail RCF damage for one cycle of loading on the target track section



Predicted gross tonnage of target section before RCF resource is exhausted

Work in Process

- Influence of rail steel microstructure on crack initiation and propagation
- Condition of horizontal crack transformation to the transverse crack
- Study of residual rail life with originated cracks
- Contact fatigue in welds
- Influence of intermediate layers (i.e.friction modifiers) on RCF crack initiation.

Thank you for attention!