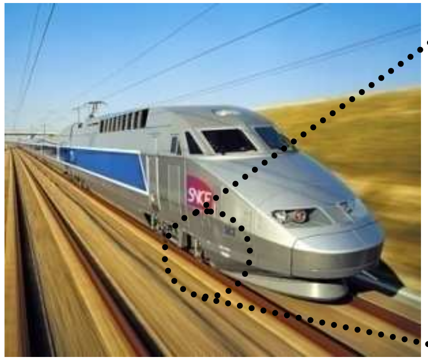
RESIDUAL STRESSES IN RAILS

Si Hai Mai, M.-L. Nguyen-Tajan

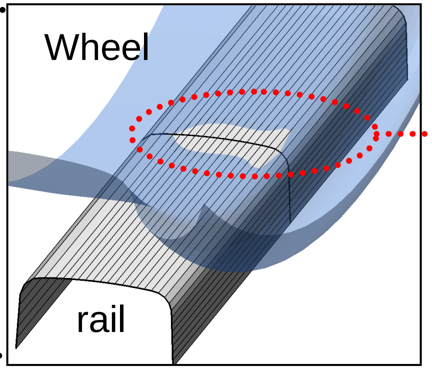
SF2M, 13th March 2014

SNCF - Innovation & Research, Paris

Context



Loading cycles on the rail = a lot of trains circulations



Wheel-rail contact

(Rolling contact)

High pressure on a small contact area

Ex: High Speed Train (TGV) = 12Tones/1cm2

Fatigue crack in the rail

Rail rolling contact fatigue is the cause of (From SNCF):
~ 50% of rail fractures (taking account weld's fracture)
~ 70% of the number of rail replacements

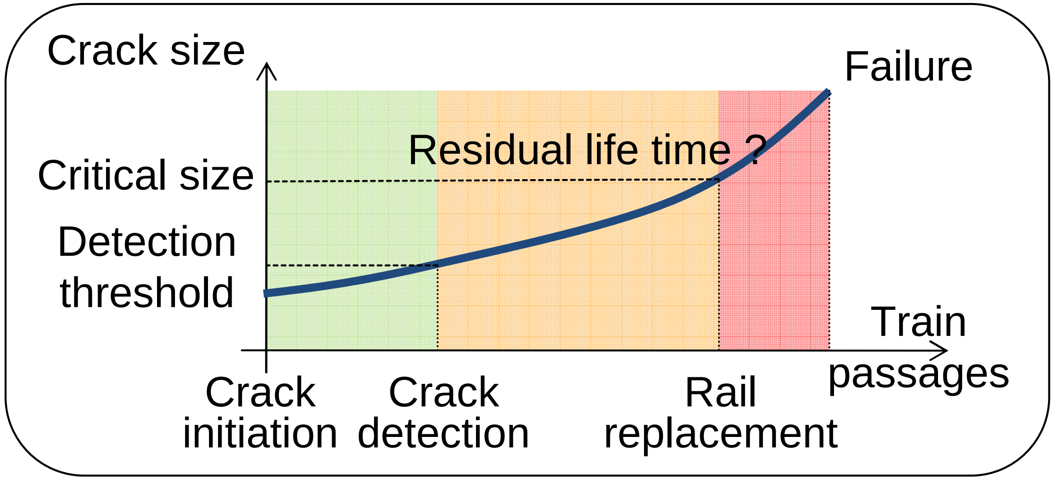
Context

Rail contact fatigue cracks

- Costly maintenance operations, train delays
- **Safety** issues (Ex: derailment causing by rail fracture)

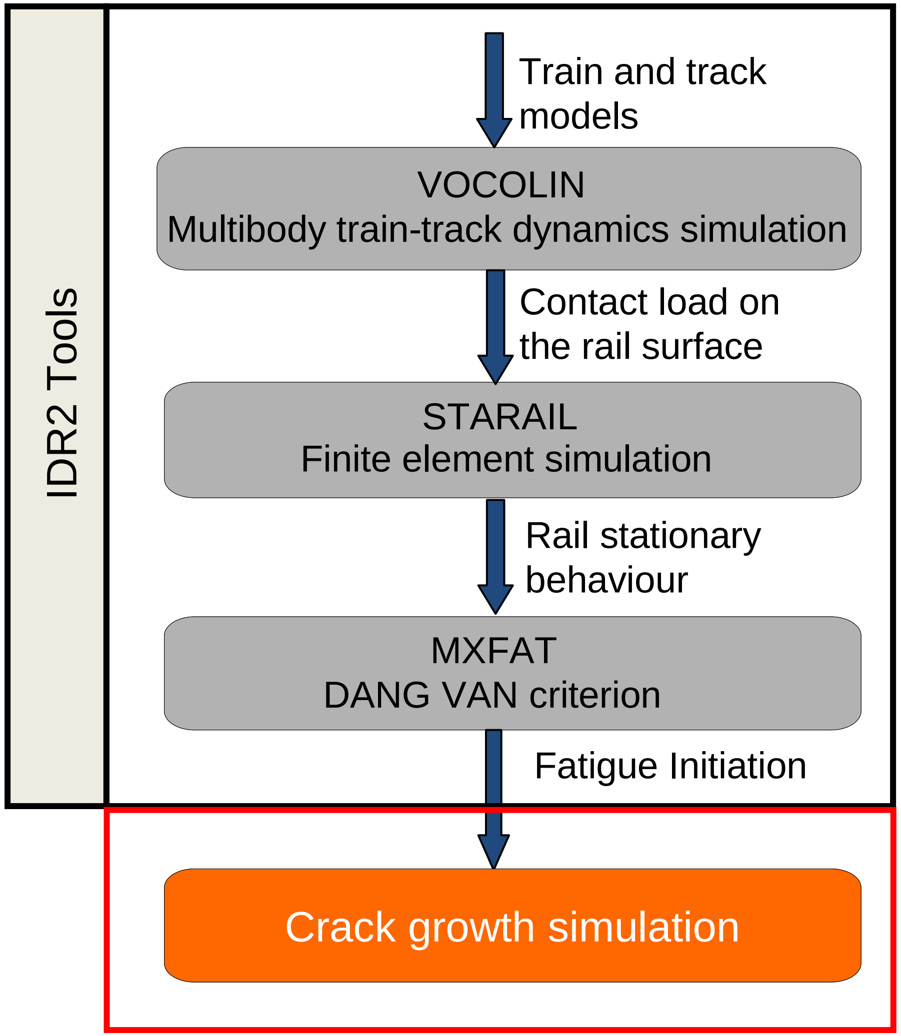
Objectives

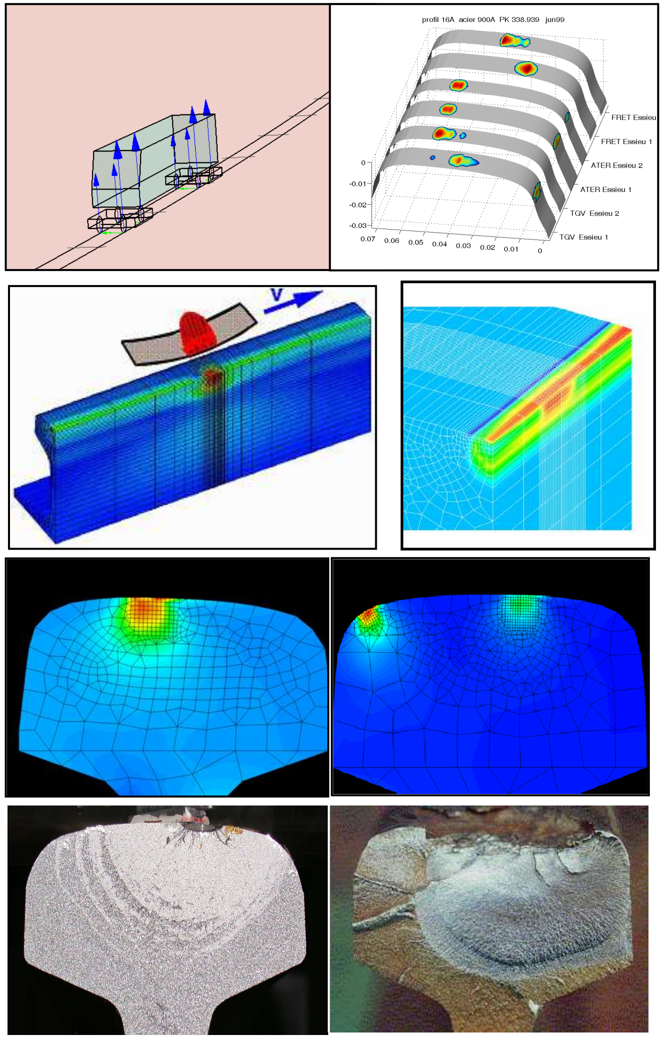
- Improve the understanding of the rail fatigue damage behavior
- Develop numerical tools for prediction of crack growth in the rail
- Optimize the maintenance strategy (grinding, inspection planning)

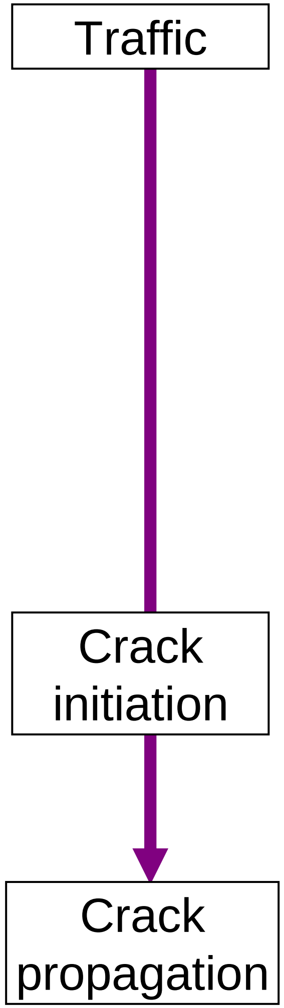


Context

From a dynamics simulation to the crack propagation







IDR2 = **I**nitiative for **D**evelopment **R**esearch on **R**ail

Outline

I. Context

II. Residual stresses in Rails

III. Fatigue crack growth simulations

IV. Conclusions

Sources of residual stresses in the rail

Two sources:

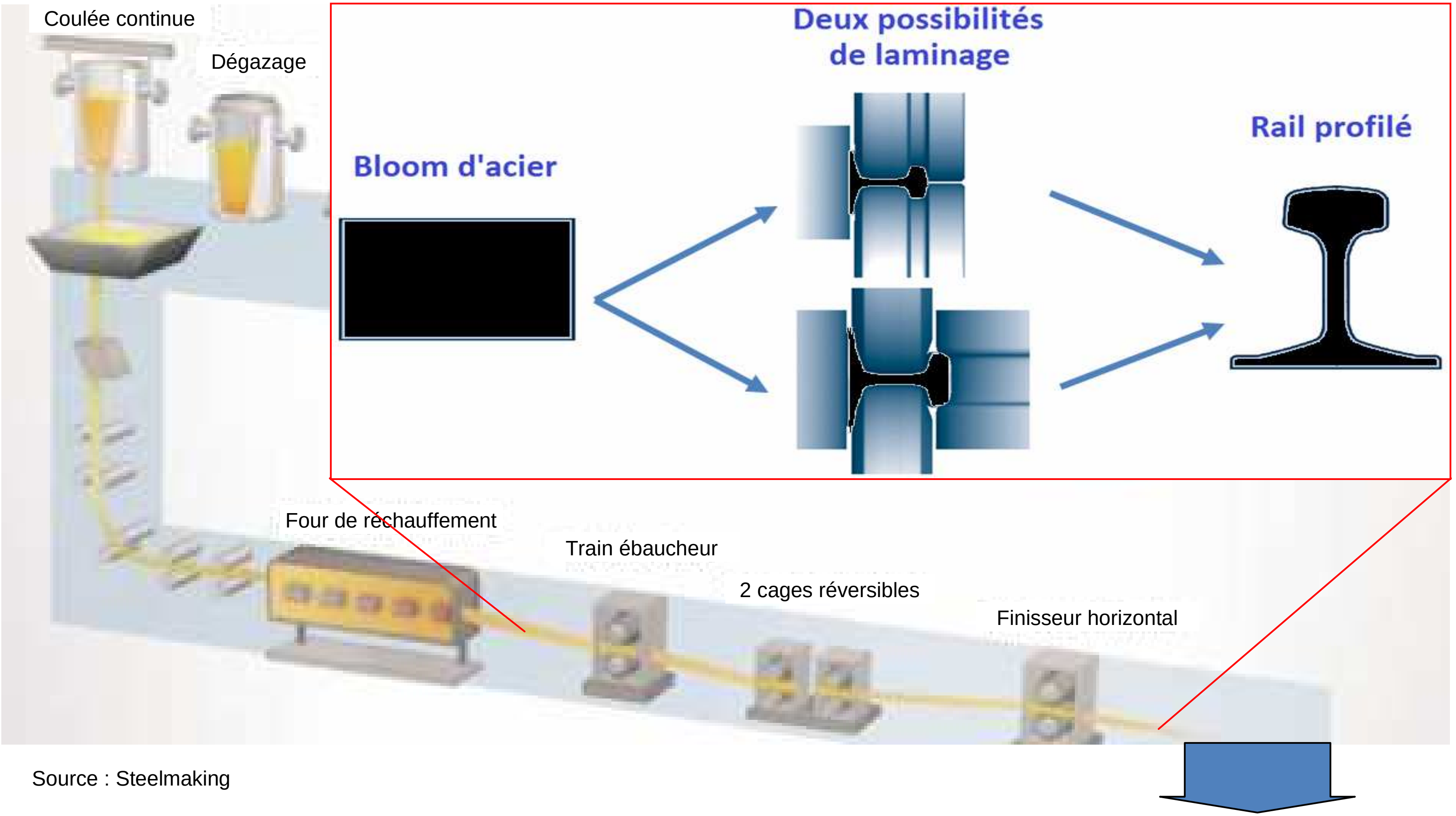
- **Roller straightening** = Manufacturing process

- **Train passages** = Plastic strain accumulation due to the repeated load

⚠ Thermal stresses (Summer – Winter) = Increase or decrease the risk of final Fracture

Sources of residual stresses in the rail

Manufacturing process



Source : Steelmaking

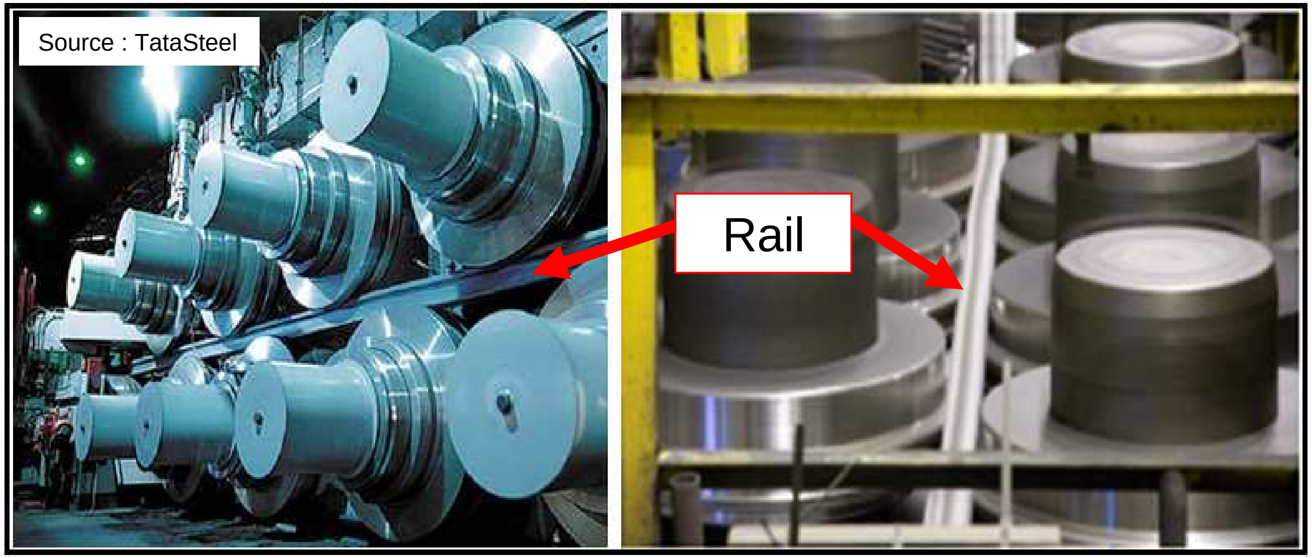
Sources of residual stresses in the rail

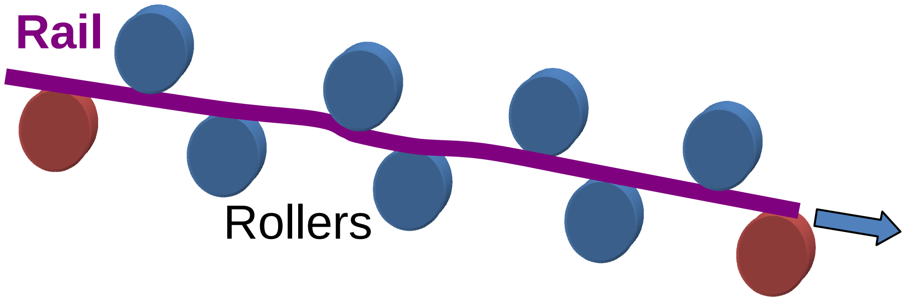
Manufacturing process

Source : Steelmaking

Sources of residual stresses in the rail

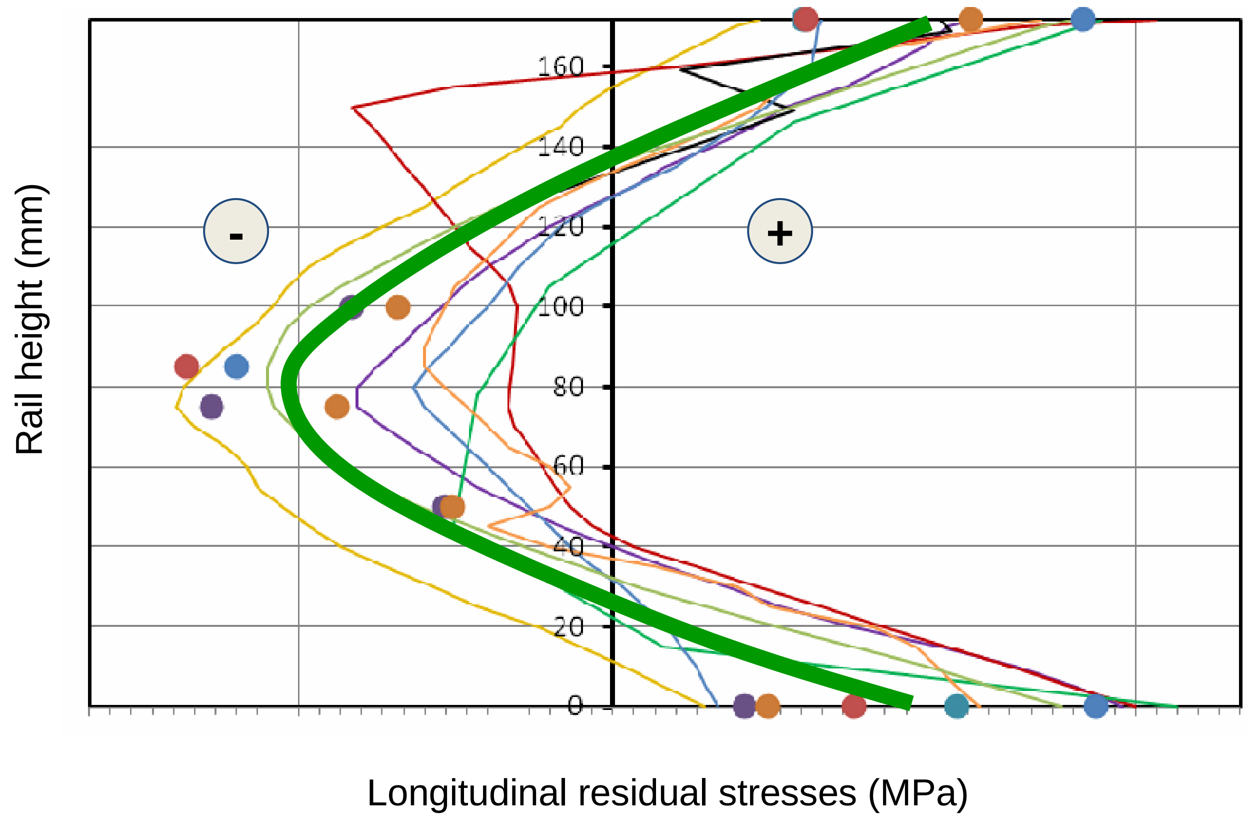
Manufacturing process (Roller straightening)

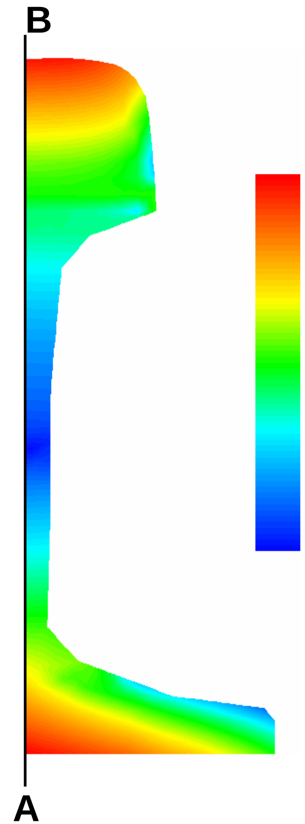




Sources of residual stresses in the rail

Manufacturing process (Roller straightening)





Without thermal treatment

P.A. Rodesch and S.H. Mai 2013: Intern report, SNCF – Innovation and Research

Sources of residual stresses in the rail

Train passages

➡ **Plastic strain accumulation due to the repeated load**

Train and track models

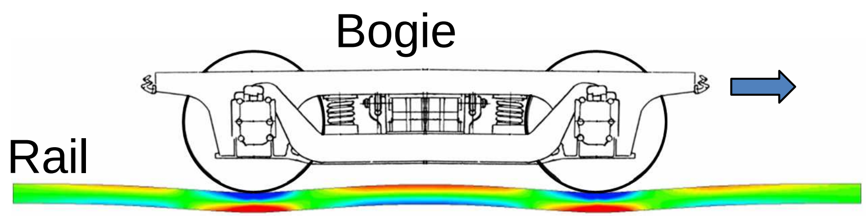
↓

VOCOLIN
Multibody train-track dynamics simulation

↓ Contact load on the rail surface

STARAIL
Finite element simulation

↓ Rail stationary behaviour [Mai.93]



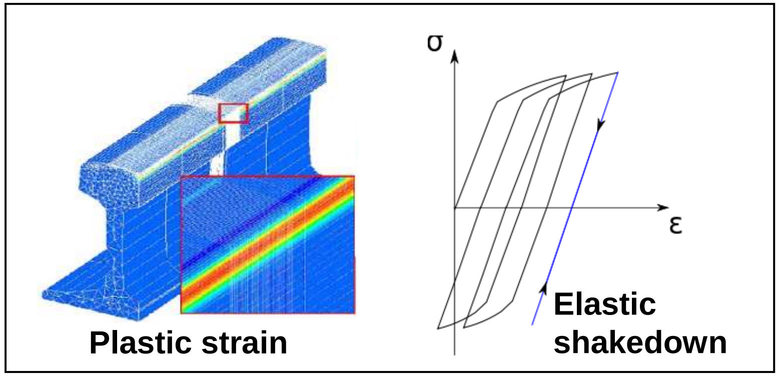
Stresses in the rail under one bogie

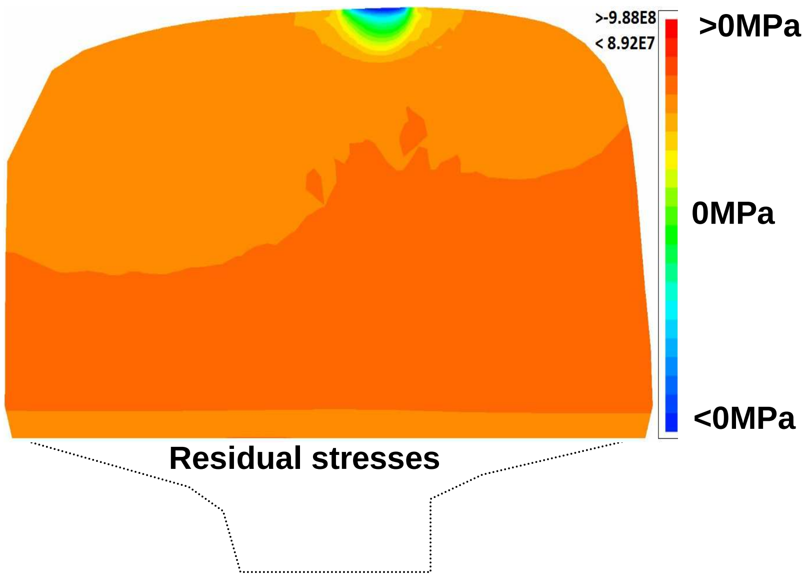
H. Maitournam and K. DangVan 1993: J. Mech. Phys. Solids, 41 (1993) 1691-1710

Sources of residual stresses in the rail

Train passages

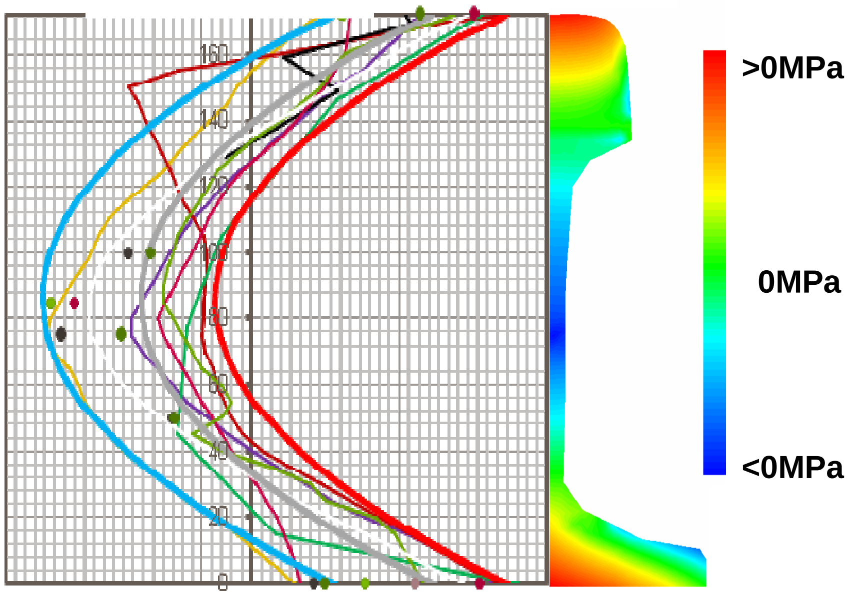
➡ **Plastic strain accumulation due to the repeated load**



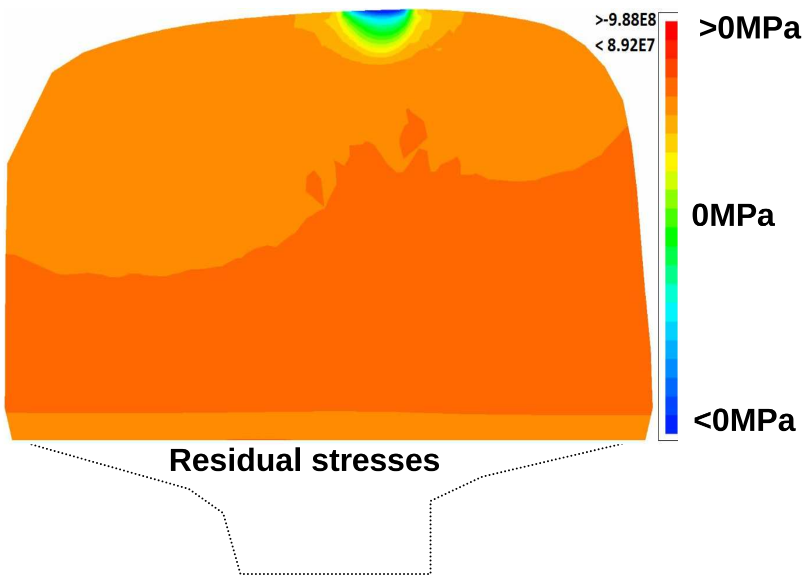


Sources of residual stresses in the rail

Two sources:



Manufacturing process



Train passages

Sources of residual stresses in the rail

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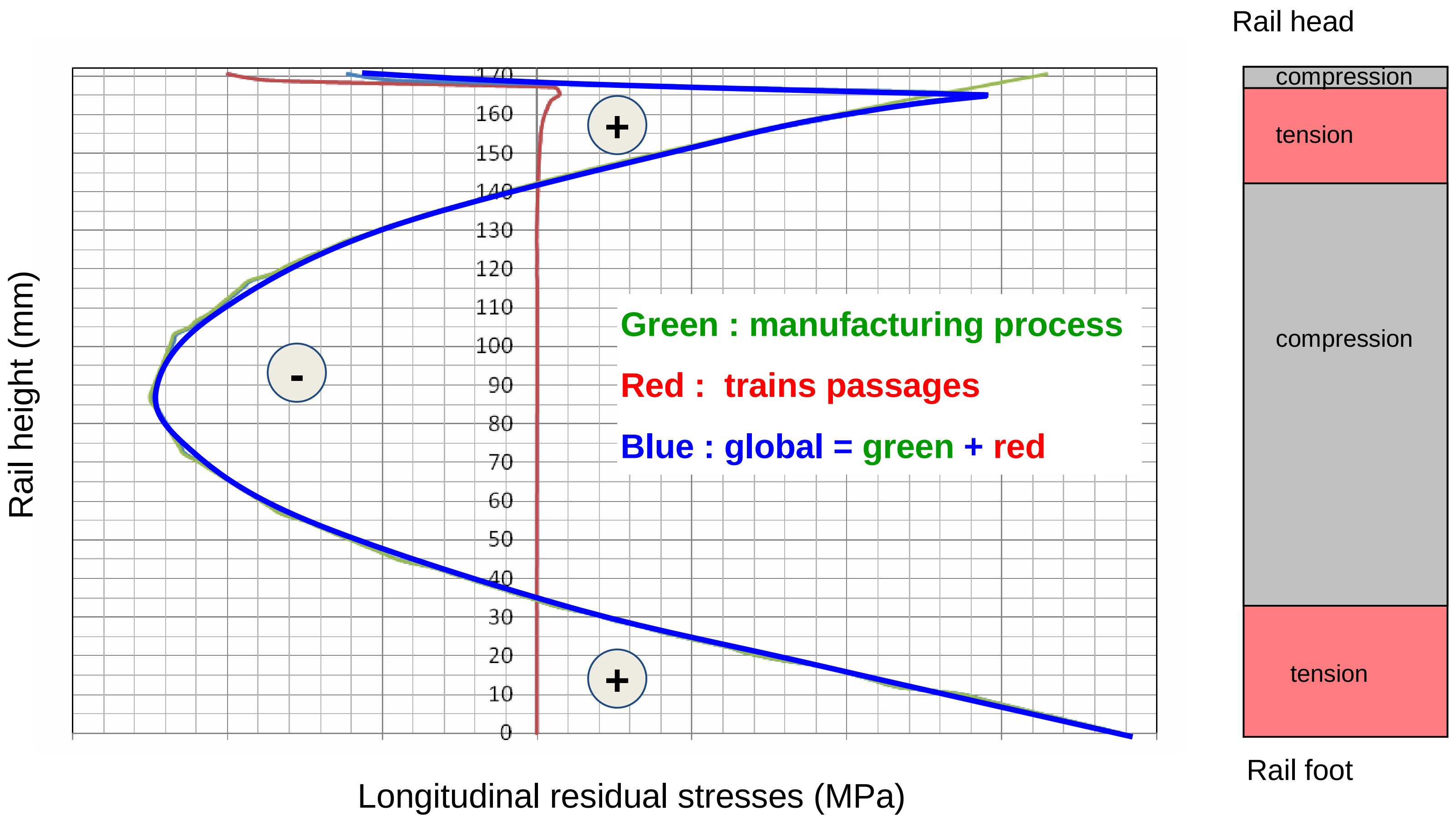
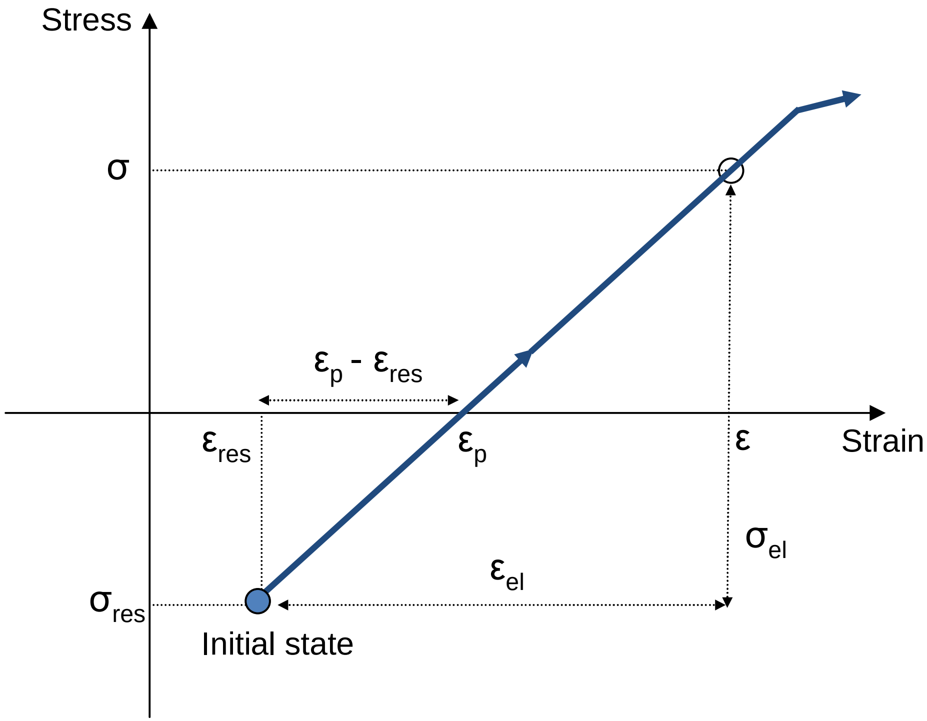


Procedure of integration of residual stresses

$$\begin{cases} \underline{\xi} = \underline{\xi}_{res} + \underline{\xi}_{el} \\ \underline{\underline{\varepsilon}} = \underline{\underline{\varepsilon}}_{res} + \underline{\underline{\varepsilon}}_{el} \\ \underline{\underline{\sigma}} = \underline{\underline{\sigma}}_{res} + \underline{\underline{\sigma}}_{el} \end{cases}$$

$$\begin{cases} \underline{\xi} = \left[\underline{\underline{\underline{K}}}^{-1}\right] \cdot \left[-\underline{div}(\underline{\underline{\underline{\underline{C}}}} : \underline{\underline{\varepsilon}}_p) + \underline{F}_{el} \right] \\ \underline{\underline{\varepsilon}} = \frac{1}{2}(\underline{\nabla}\underline{\xi}_{res} + {}^T\underline{\nabla}\underline{\xi}_{res}) + \frac{1}{2}(\underline{\nabla}\underline{\xi}_{el} + {}^T\underline{\nabla}\underline{\xi}_{el}) \\ \underline{\underline{\sigma}} = \underline{\underline{\underline{\underline{C}}}} : (\underline{\underline{\varepsilon}}_{el} + \underline{\underline{\varepsilon}}_{res} - \underline{\underline{\varepsilon}}_p) \end{cases}$$



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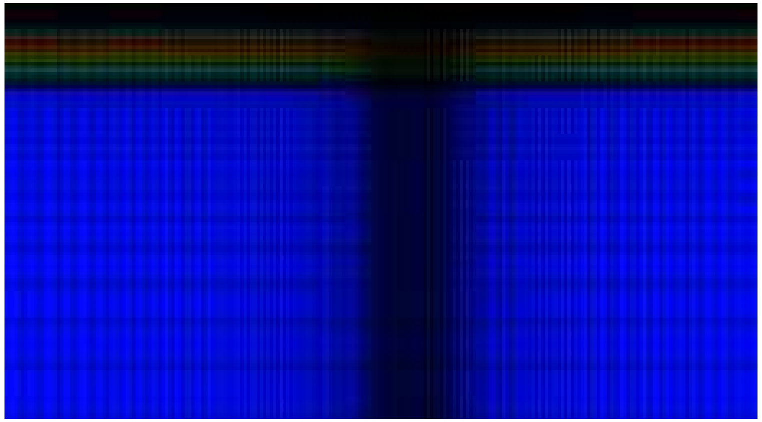
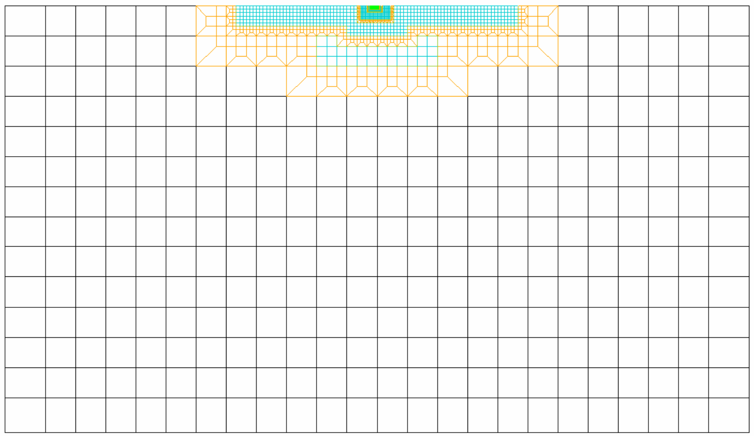


Stationary calculation (FEM)

Different meshes

Projection



Crack propagation (XFEM)

Outline

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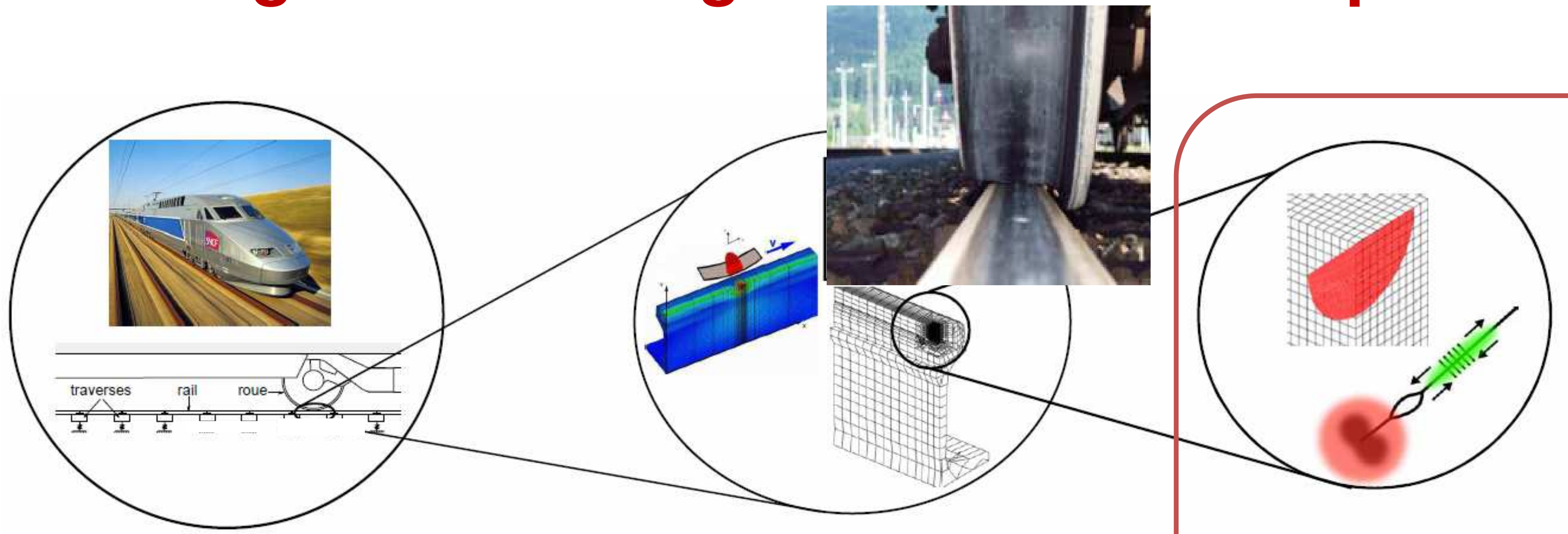
Rolling contact fatigue : a multi-scale problem



System scale

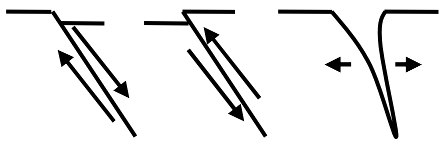
- Rail bending

Rail scale

- Wheel rail contact

Crack scale

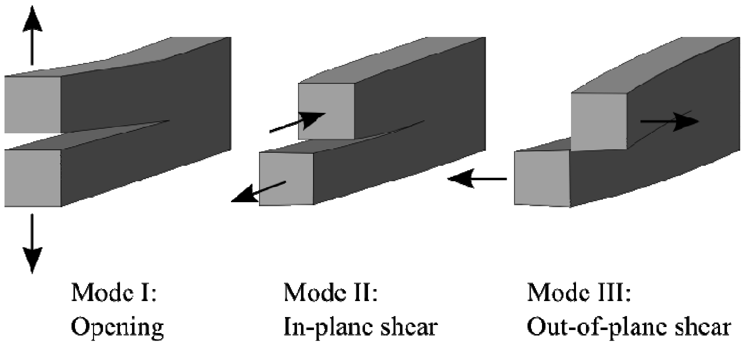
- Opening/contact
- Sticking sliding



Benoit TROLLE : PhD 2014, Fatigue crack propagation in rails, 20/03/2014 Lyon

Methodology

Linear Elastic Fracture Mechanics



Stress singularity at the crack front

$$\sigma_{ij} = \frac{K_I}{\sqrt{2\pi r}} f_{ij}^{I}(\theta) + \frac{K_{II}}{\sqrt{2\pi r}} f_{ij}^{II}(\theta) + \frac{K_{III}}{\sqrt{2\pi r}} f_{ij}^{III}(\theta) + o\left(\sqrt{r}\right)$$

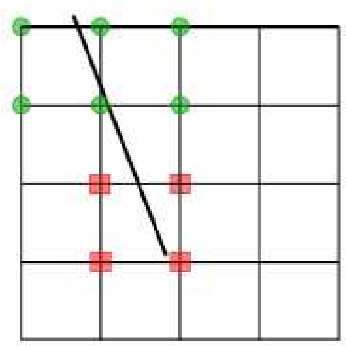
K_i characterizes the sollicitations at the crack tip (= Magnitude of each cracking mode)

The eXtended Finite Element Method (X-FEM) [Gra.11]

- Two scale approach :

  $U = U_{bulk} + U_{crack}$

- Two kinds of enrichment :
  - ● Discontinuous (lips displacement)
  - ■ Singular (crack tip)

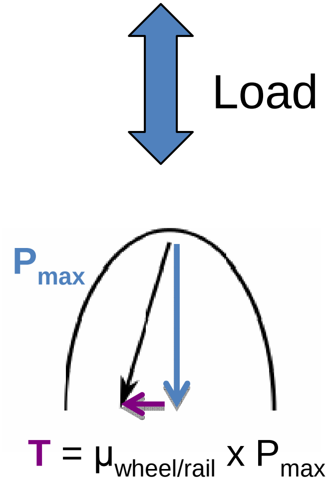


CAST3M

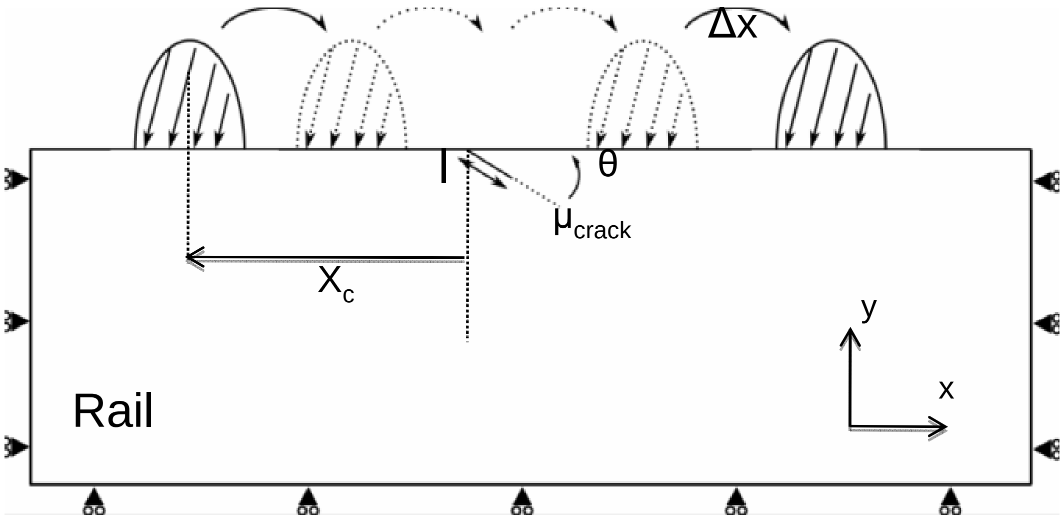
Gravouil, Combescure, Pommier and Moës 2011 : *XFEM for crack propagation*

Modelling of the cracked rail

1 loading cycle = 1 wheel traveling from the left to the right on the surface of the rail (quasi-static simulation)

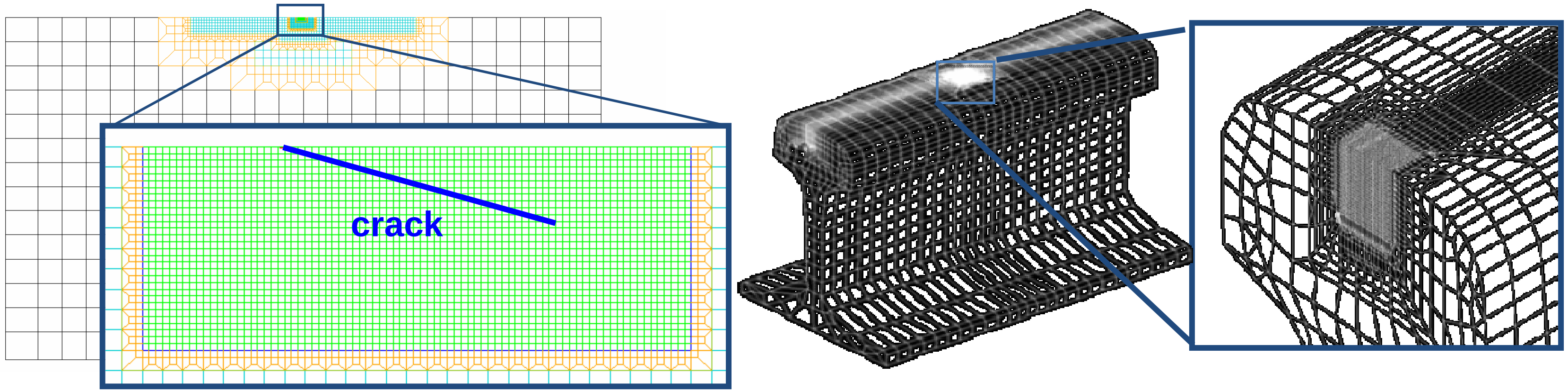


HERTZIAN LOADING



Modelling of the cracked rail

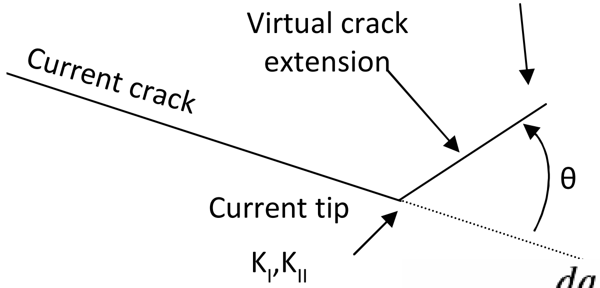
- Multi-scale parametric mesh (software CAST3M)



- Crack growth rate law: Mixed mode (ICON) [Dub.02]

$$\frac{da}{dN} = 2.10^{-9}(\Delta K_{eq})^{3.33} \quad \Delta K_{eq}^2 = \Delta K_I^2 + 0.772 * \Delta K_{II}^2$$

- Crack branching criterion: Multi-axial and non proportional loading [Hou.82]

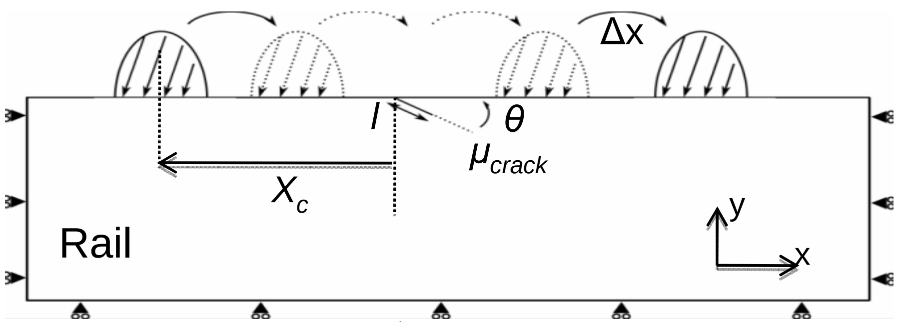


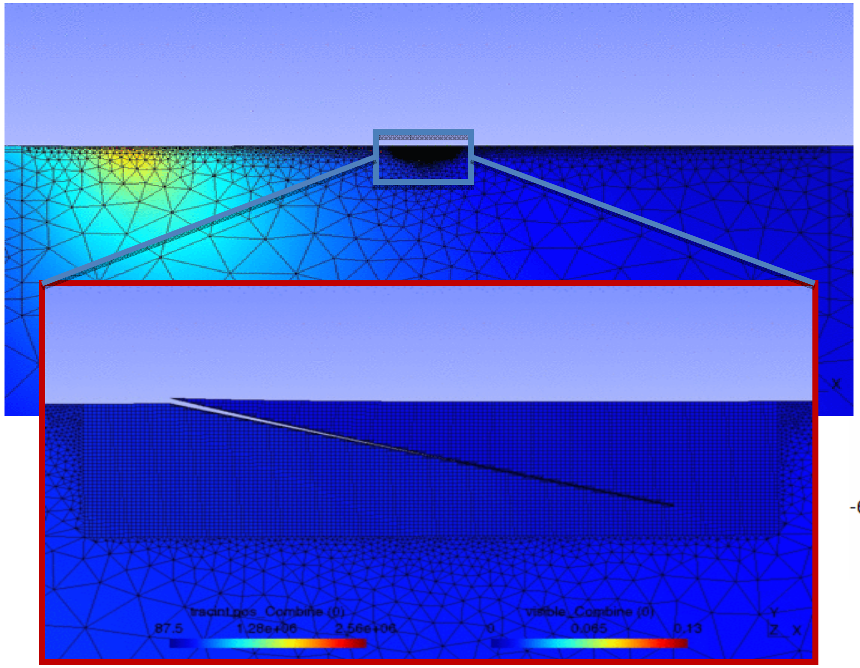
$$\max_{\theta,t} \frac{da}{dN}(\theta, t)$$

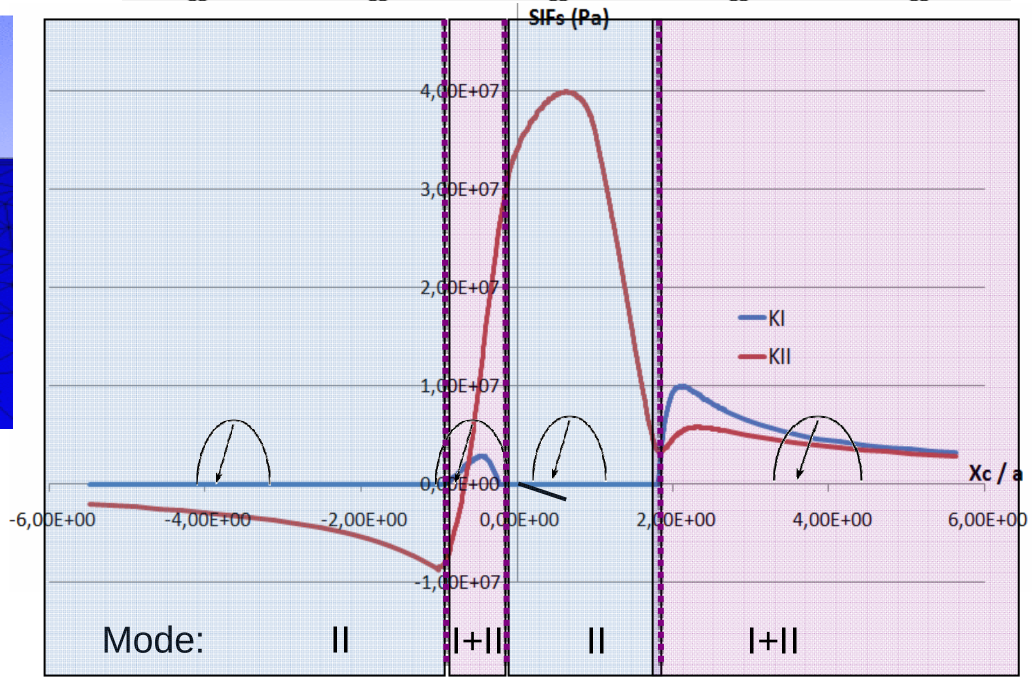
Dubourg 2002: *Journal of Tribology, Vol. 124.*
Hourlier nad al. 1982 : *Institut de Recherche de la sidérurgie française, IRSID, No RE958*

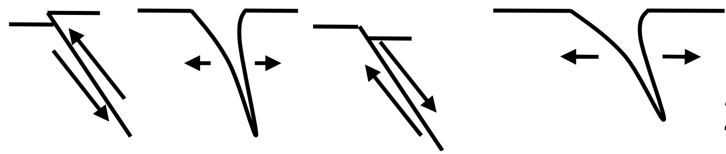
Calculation of SIF for one loading cycle : 2D

Stress **I**ntensity **F**actors (**SIF**)
are computed for each time step
(each loading position)

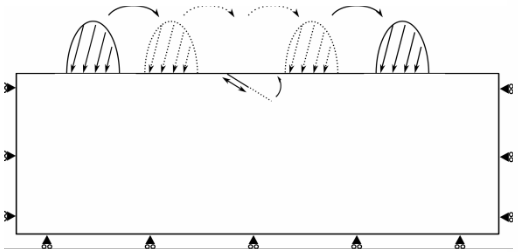




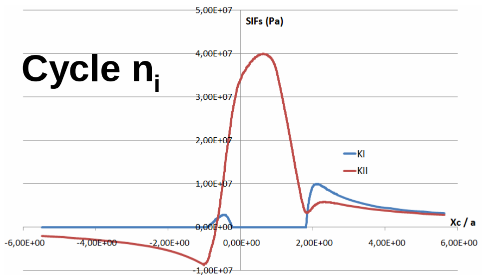




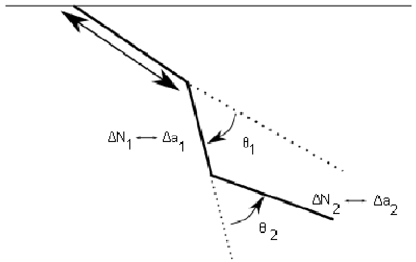
Fatigue crack growth simulation process

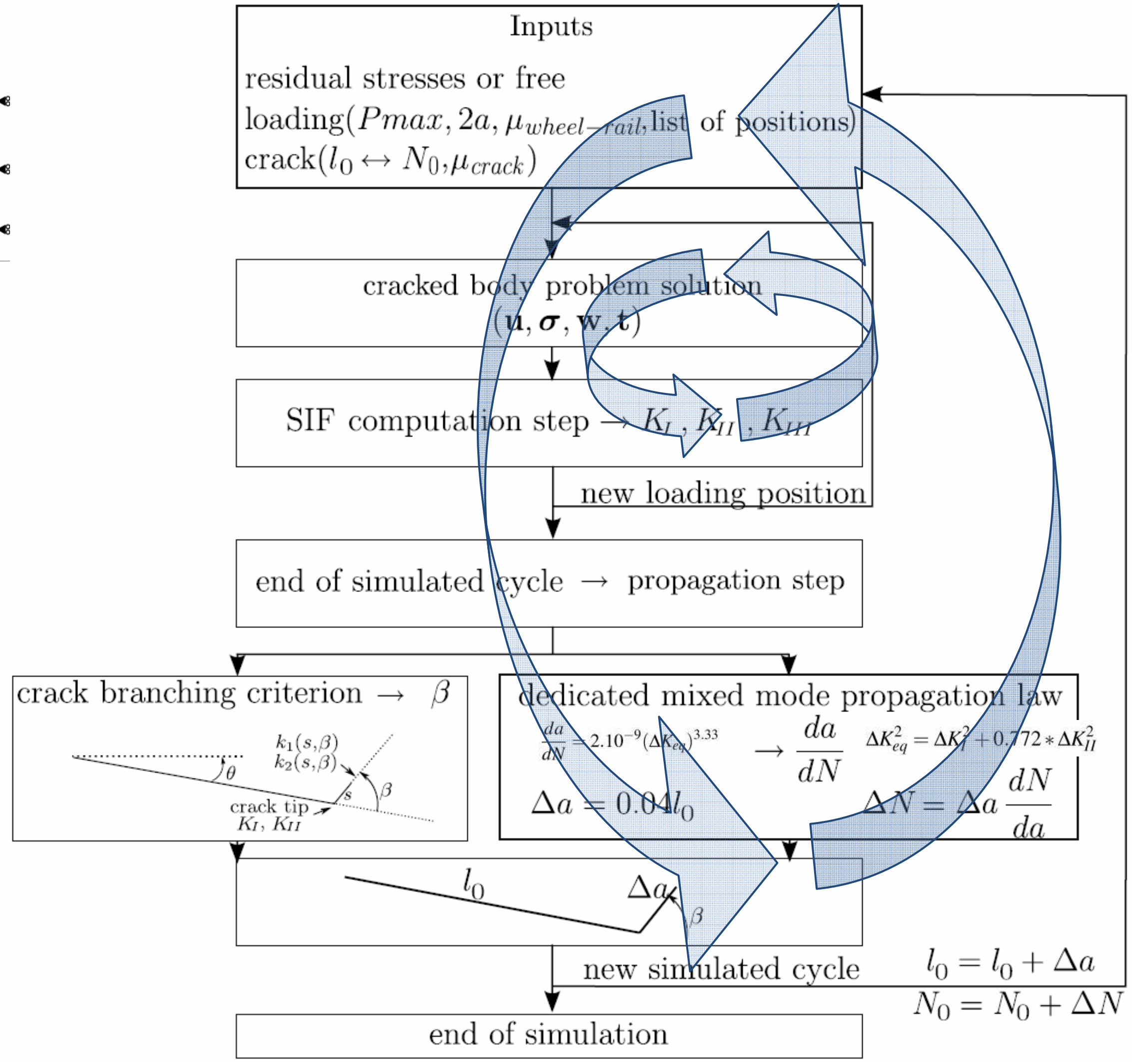


SIF computation for each loading position

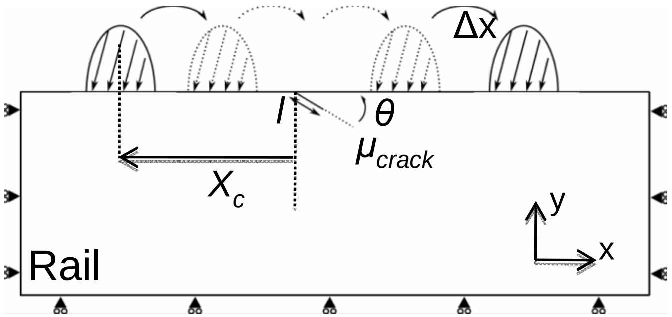


Propagation at the end of each cycle



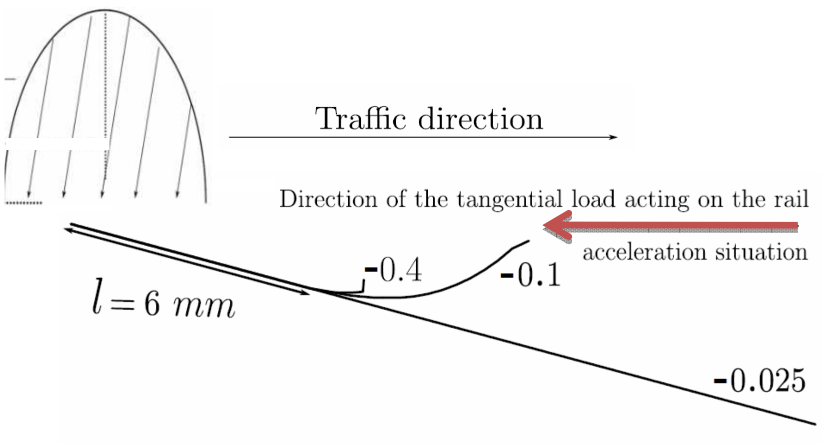


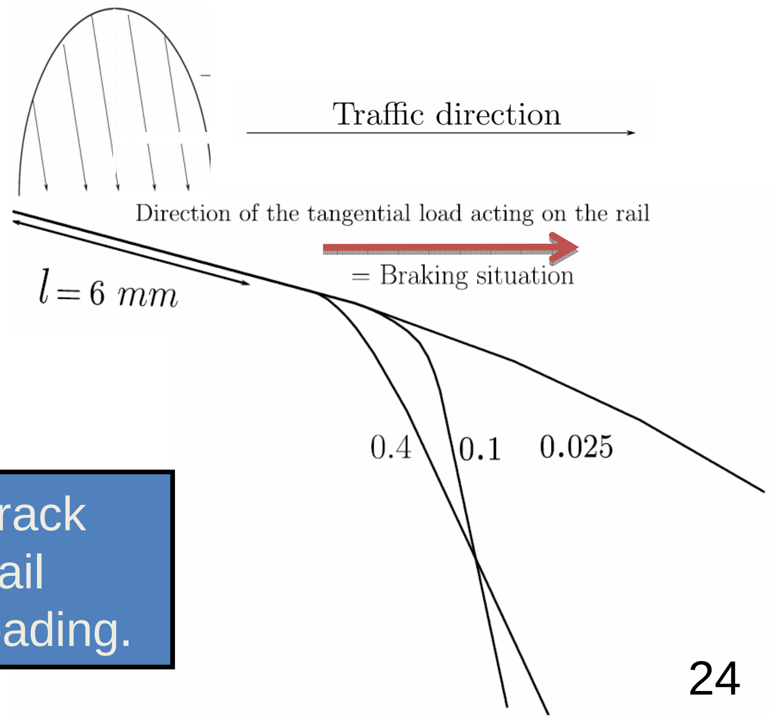
Influence of the friction coefficient between the wheel and the rail



Inputs:

- P_{max} = 845 MPa
- $2a$ = 13.5 mm
- $\mu_{wheel / rail}$ Variable
- 126 load steps using a variable Δx
- l = 6mm ; θ = 15°; μ_{crack} = 0.5;



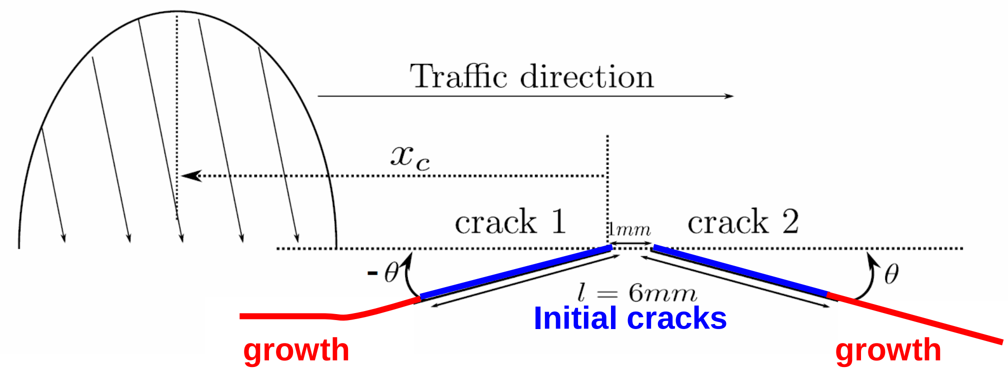


A high tangential loading provokes earlier crack branching upwards or downwards in the rail depending on the direction of the tangential loading.

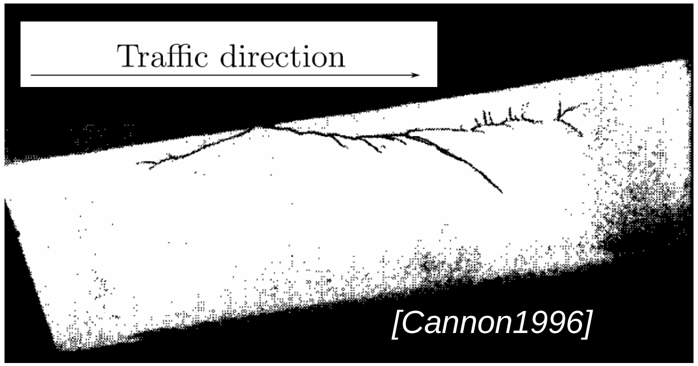
Crack network : “squat configuration”

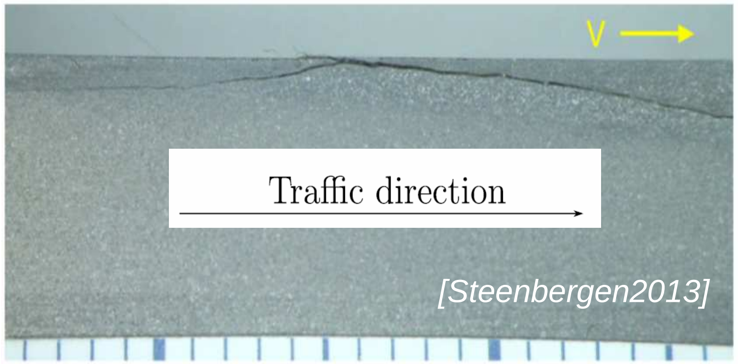
<u>Inputs</u>:

- P_{max} = 845 MPa
- 2a = 13.5 mm
- $\mu_{wheel / rail}$ = 0.025
- Two initial cracks:
  - μ_{cracks} = 0.01
  - θ = 15 °

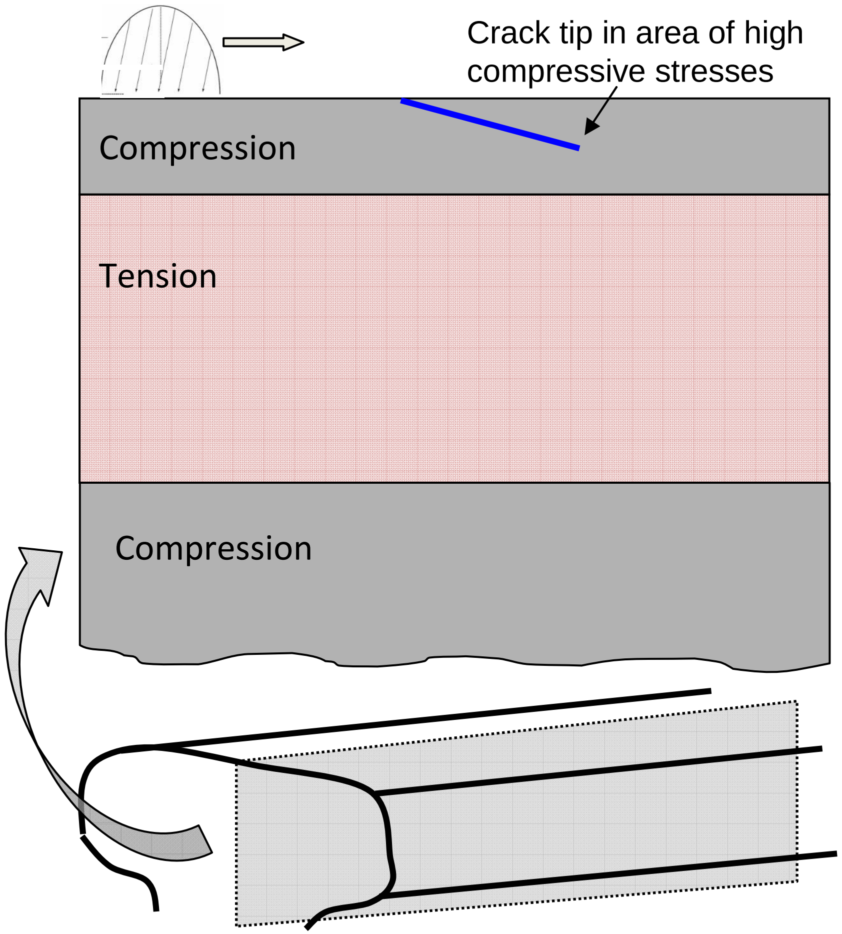


Longitudinal rail head section through a squat



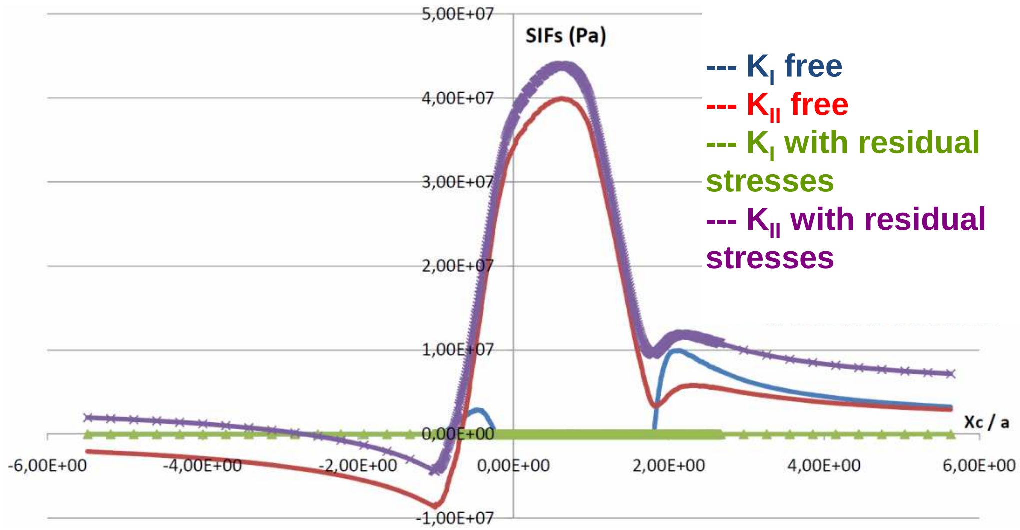


Influence of the residual stresses



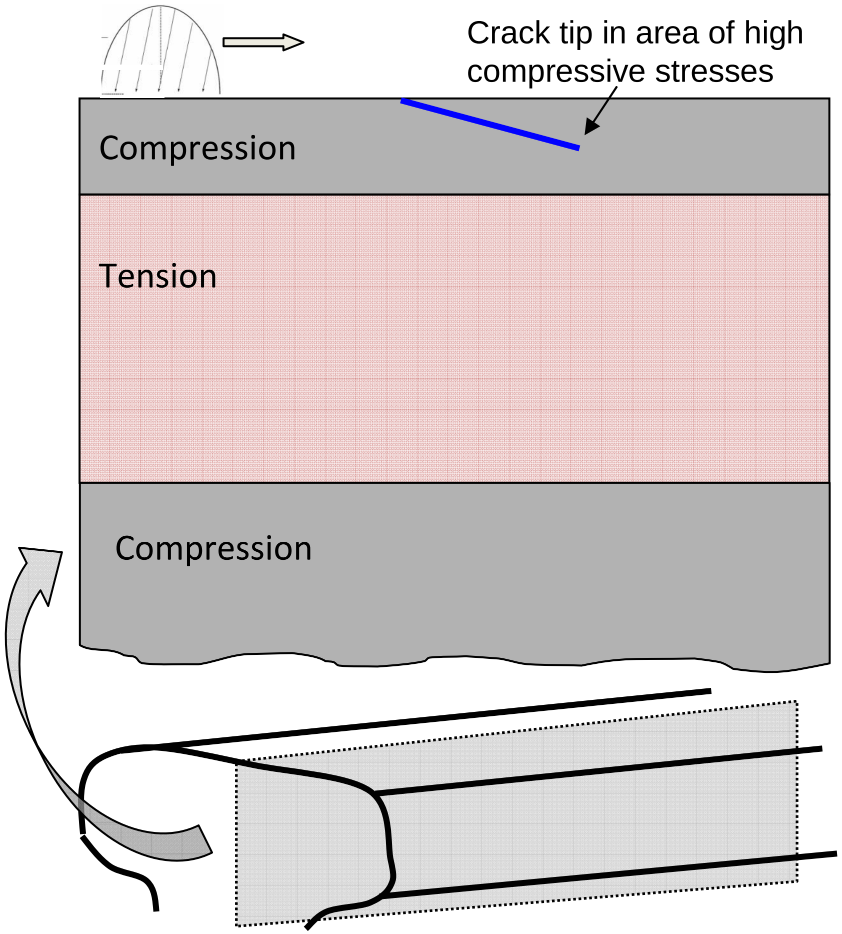
Residual stresses in the rail's head

SIF: one loading cycle



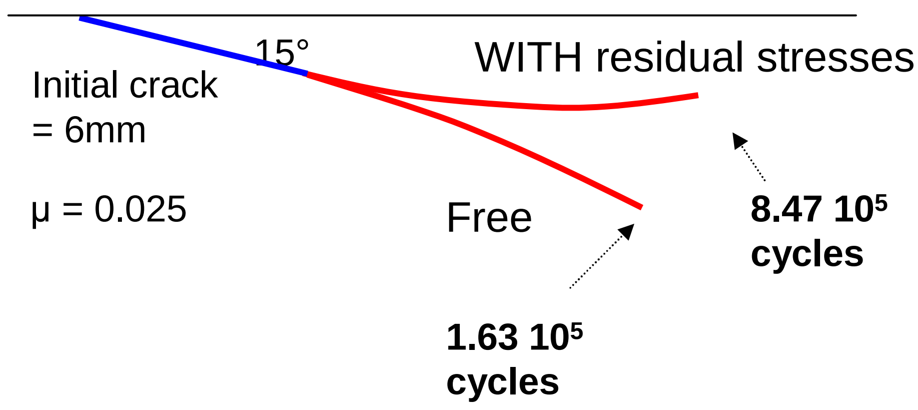
- The crack is always closed during the first loading cycle with residual stresses ($K_I = 0$)
=> Crack growth with shear mode (K_{II} # 0)

Influence of the residual stresses



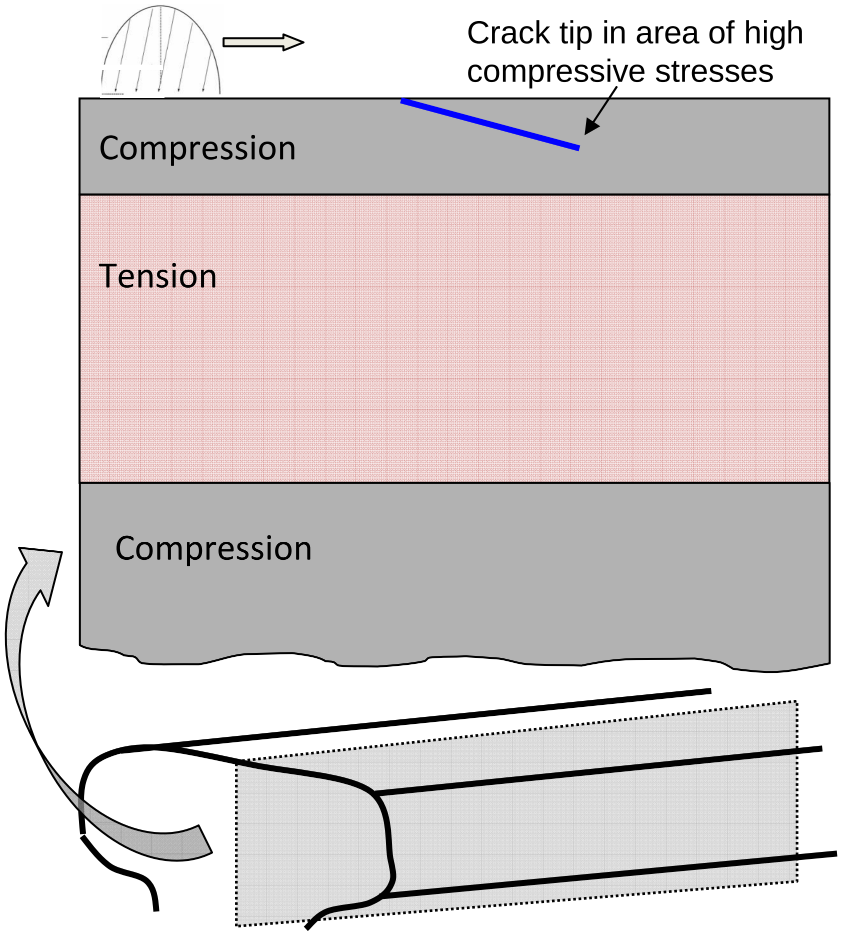
Residual stresses in the rail's head

Propagation path and crack growth rate

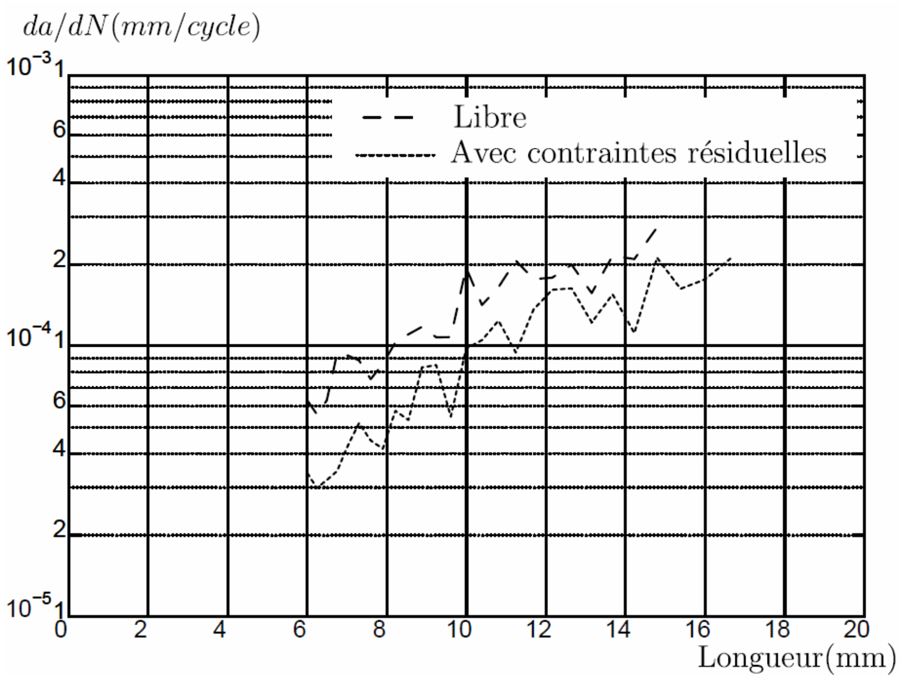


The crack branches upwards with a slower propagation rate If residual stresses are taken into account.

Influence of the residual stresses



Residual stresses in the rail's head



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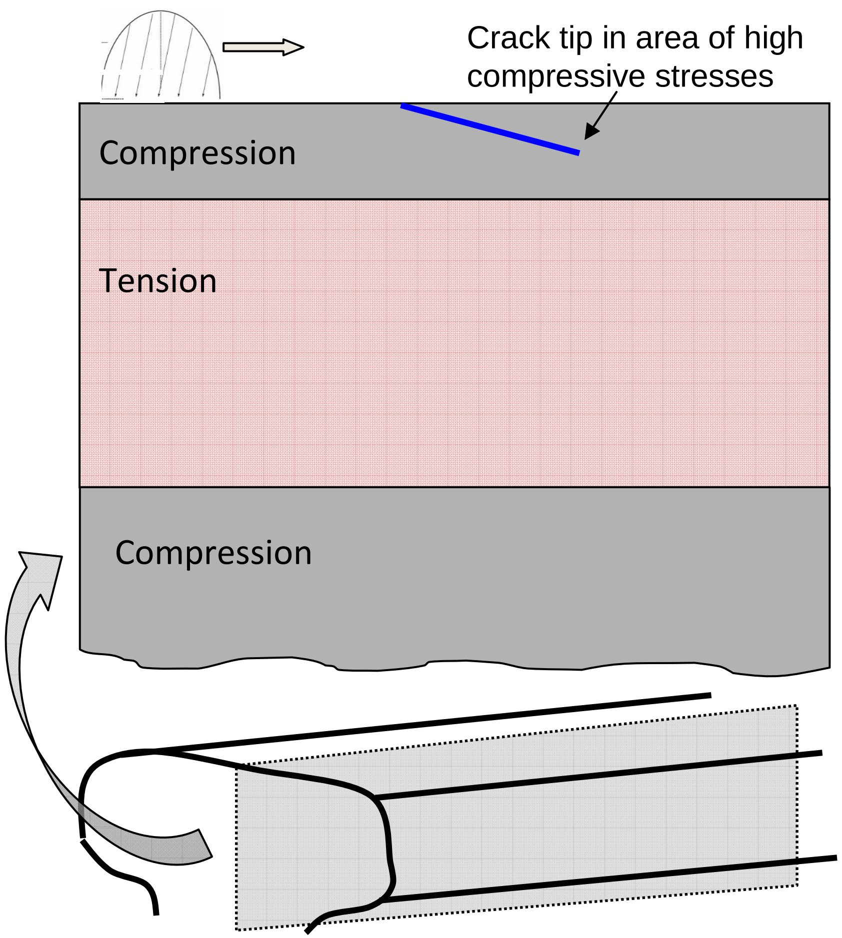
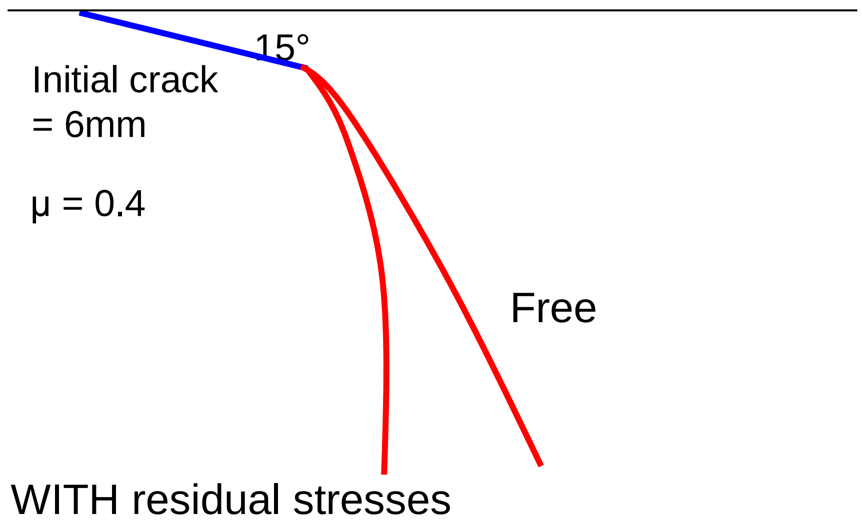
Influence of the residual stresses



Residual stresses in the rail's head

Propagation path and crack growth rate



Other inputs

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Conclusions

• Two sources of residual stresses in the rail: manufacturing process (C - form) and train passages (local)

• Development of a robust numerical tool to simulate the fatigue crack growth in rails taking into account [Benoit Trollé] :

- Contact and friction between the crack lips,
- Mixed mode fatigue law and non-proportional crack branching criterion,
- Residual stresses (manufacturing process + train traffic),
- Bending moment (not presented here).

• Rail contact fatigue crack growth simulations: Residual stresses has to be taken into account since they modify the growth rate and the propagation path.

Acknowledgments

- **LaMCoS,** Laboratory of contact and structural mechanics at INSA Lyon, France (M.-C. Baietto and A. Gravouil)

- **CEA,** French Atomic Energy Commission, in Saclay, France (B.Prabel), www-cast3m.cea.fr.

- **IDR2** consortium, Initiative for Development and Research on Rails composed by SNCF, RATP, Tata Steel, IFSTTAR, MECAMIX, LAMCOS.

THANK YOU FOR YOUR ATTENTION !

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