Institute of Physics of Materials
Academy of Sciences of the Czech Republic

Residual life time assessment of railway axles

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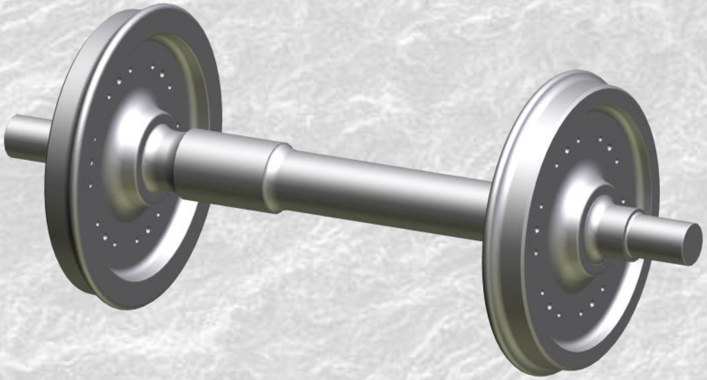

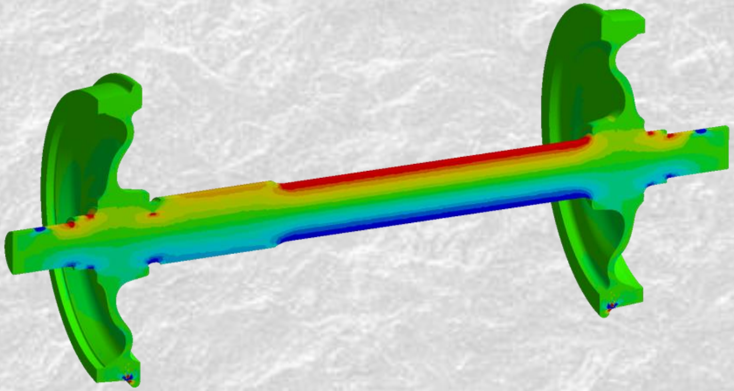

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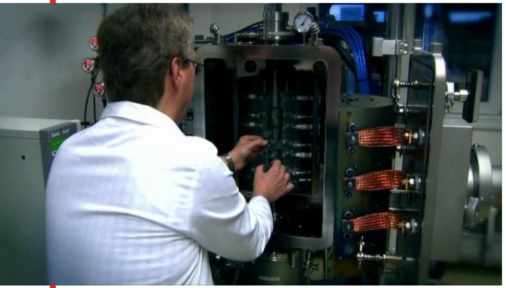

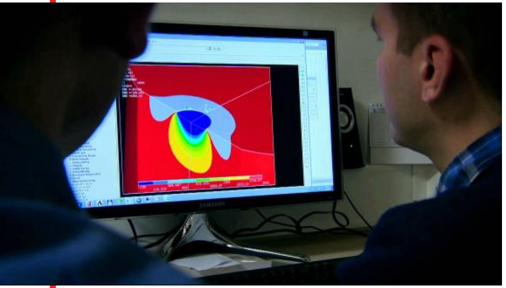

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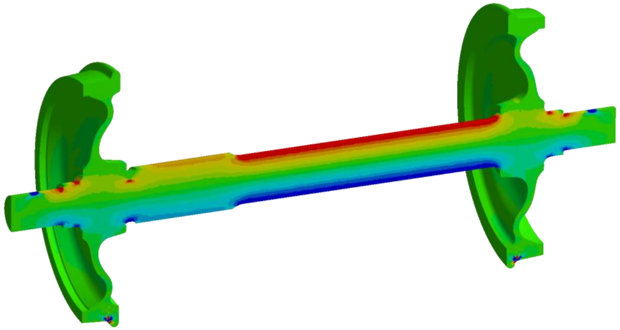
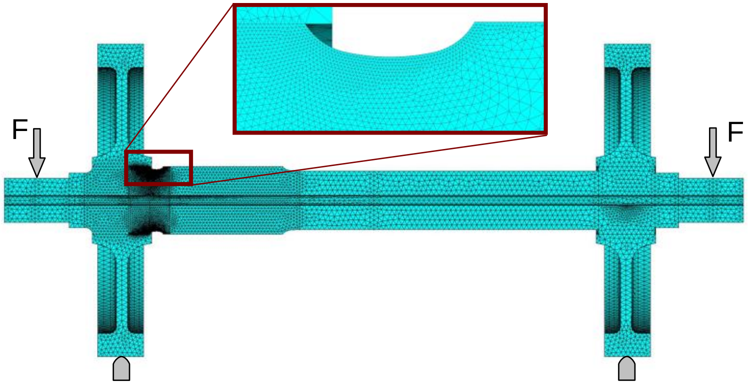
Outline

Methodology for estimation of residual fatigue lifetime of railway axles based on Damage tolerance approach:

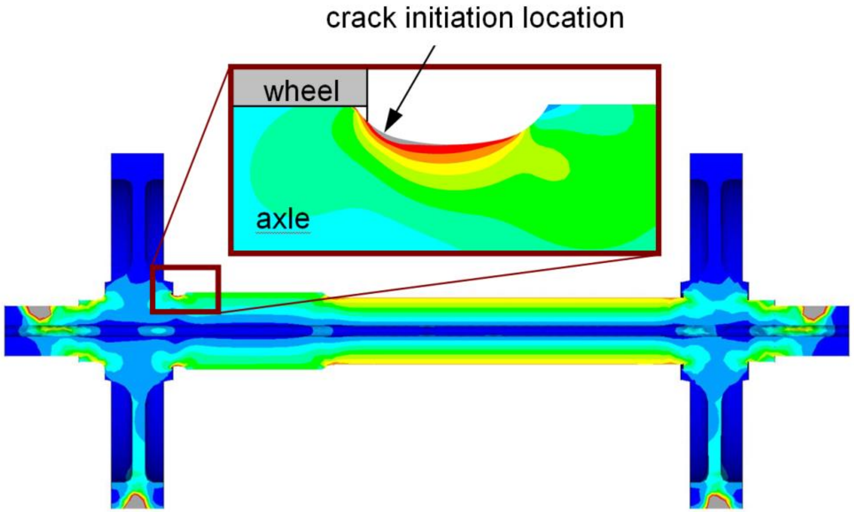
1) position and geometry of fatigue crack
    - searching of critical crack position
    - determination of fatigue crack front
2) stress intensity factor determination
    - load due to movement and mass of train
    - load due to press-fitted wheel
    - load due to residual stress field
3) residual fatigue lifetime estimation
4) comparison with experimental data



Position of considered crack



3D FE model of considered railway axle with press-fitted wheels going on straight track (without crack)



Distribution of axial stress component in the railway wheelset

The methodology is shown on one particular railway axle. However, the procedure is general.

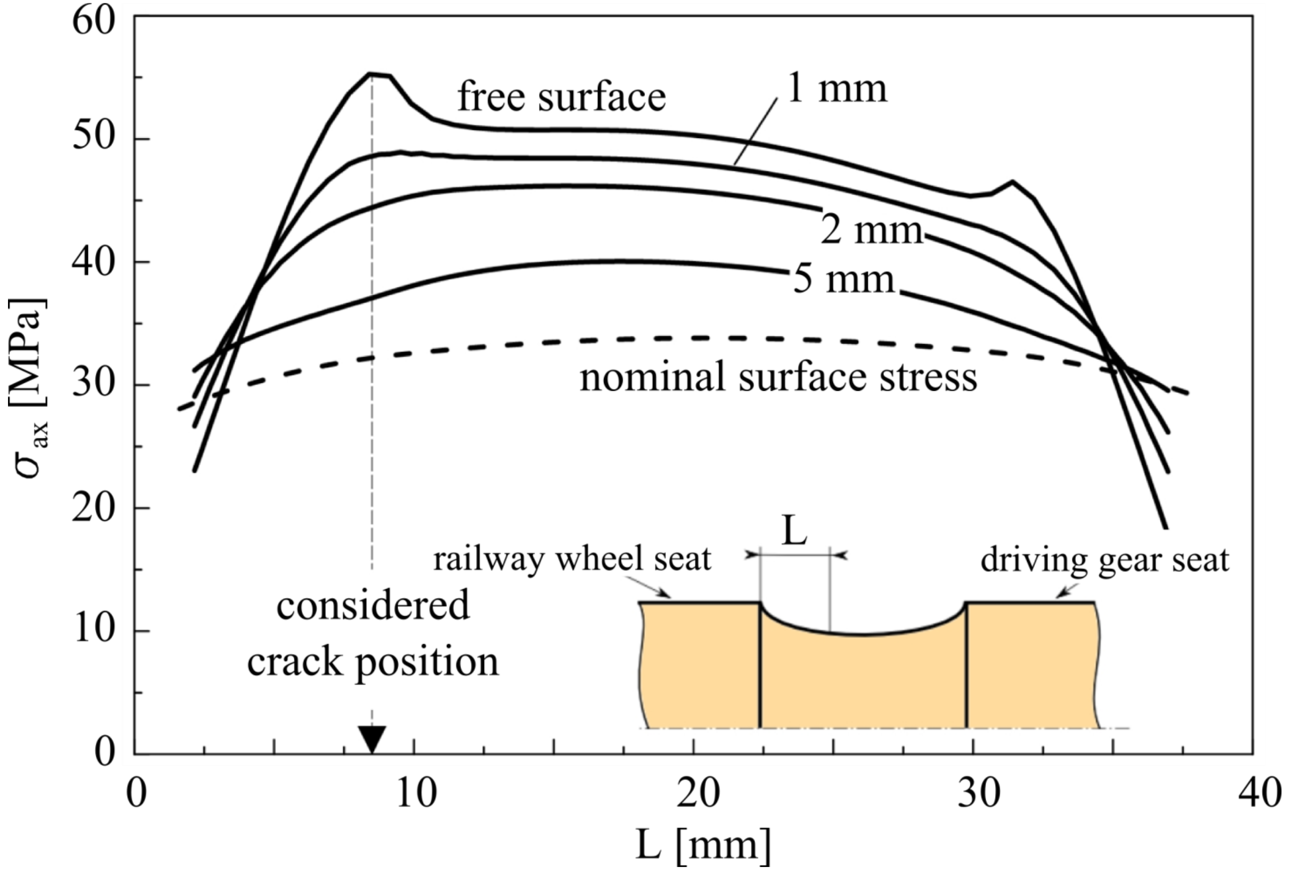
A fatigue crack could initiate on several spots, but for **conservative approach** the crack should be considered at the position where potential crack causes **the shortest residual fatigue lifetime**.

An initial crack is considered at the notch between railway wheel seat and driving gear seat, i.e. in the location with considerable stress concentration.

Position of considered crack

Critical position of the crack is determined from:

1) **maximal value of stress component** (e.g. longitudinal stress)

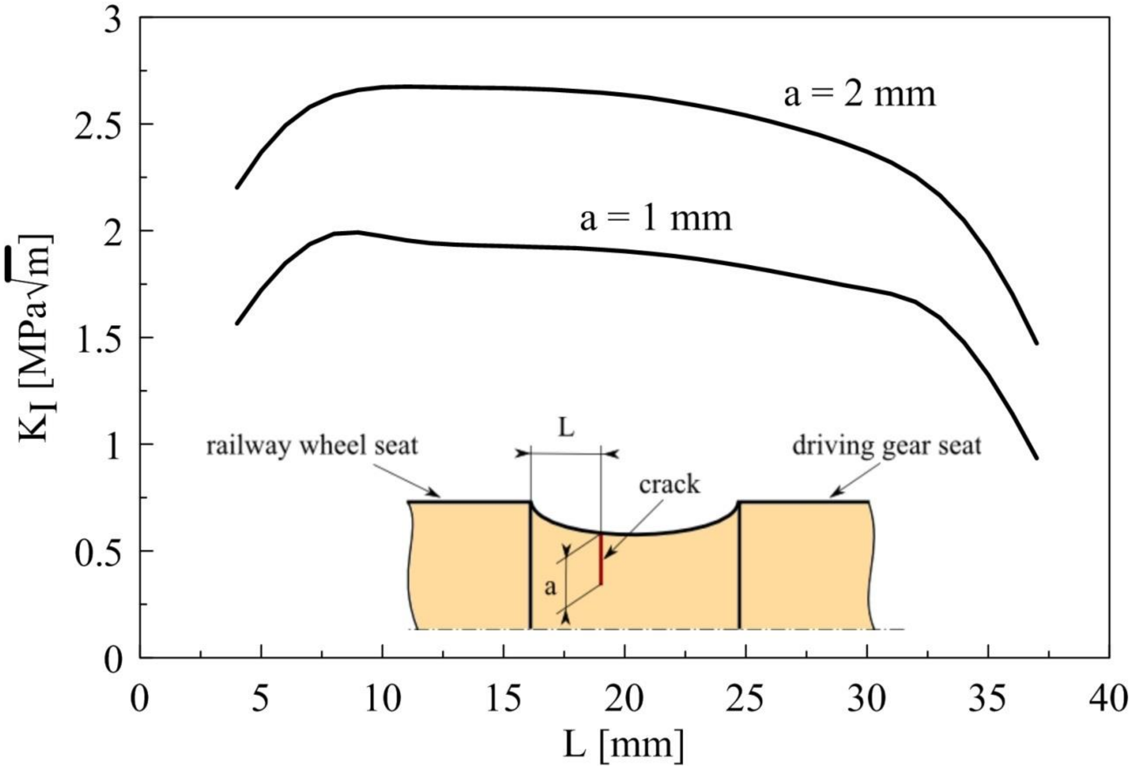


Distribution of the longitudinal (axial) stress at the notch

Position of considered crack

2) **Fracture mechanics** approach (e.g. by using of **stress intensity factor**)

- Based on experiences the considered fatigue **crack grows perpendicular** to railway axle axis. (perpendicular to maximum principal stress).



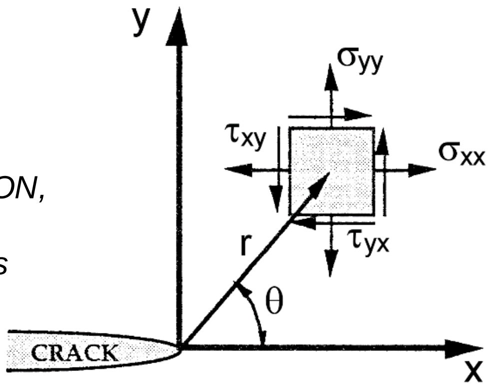
Distribution of the stress intensity factor at the notch

- The crack front has semi-elliptical shape (it will be shown in following slides)

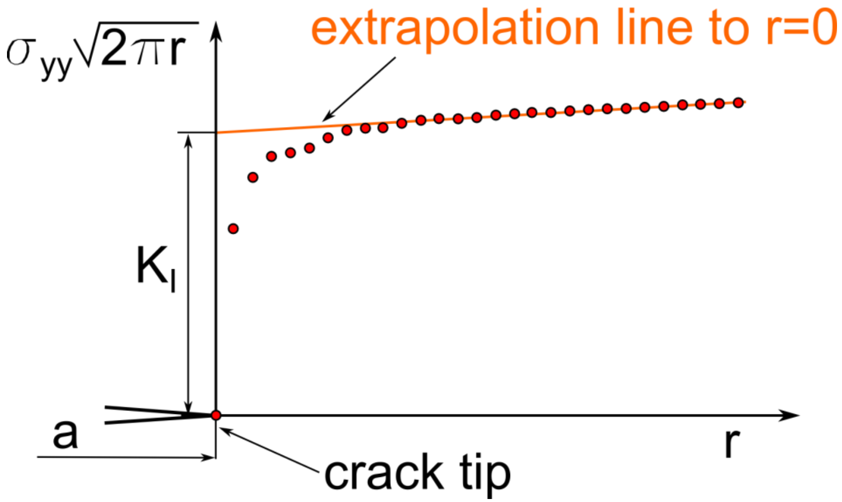
Description of fatigue crack behavior

The description of the of fatigue crack is based on the stress intensity factor **(SIF)** *K* approach.

Source : ANDERSON, Fracture mechanics



$$\boxed{\lim_{r\to 0} K_I = \sigma_{yy}\sqrt{2\pi r}}$$ (for $\theta = 0$)



Methodology of the direct method

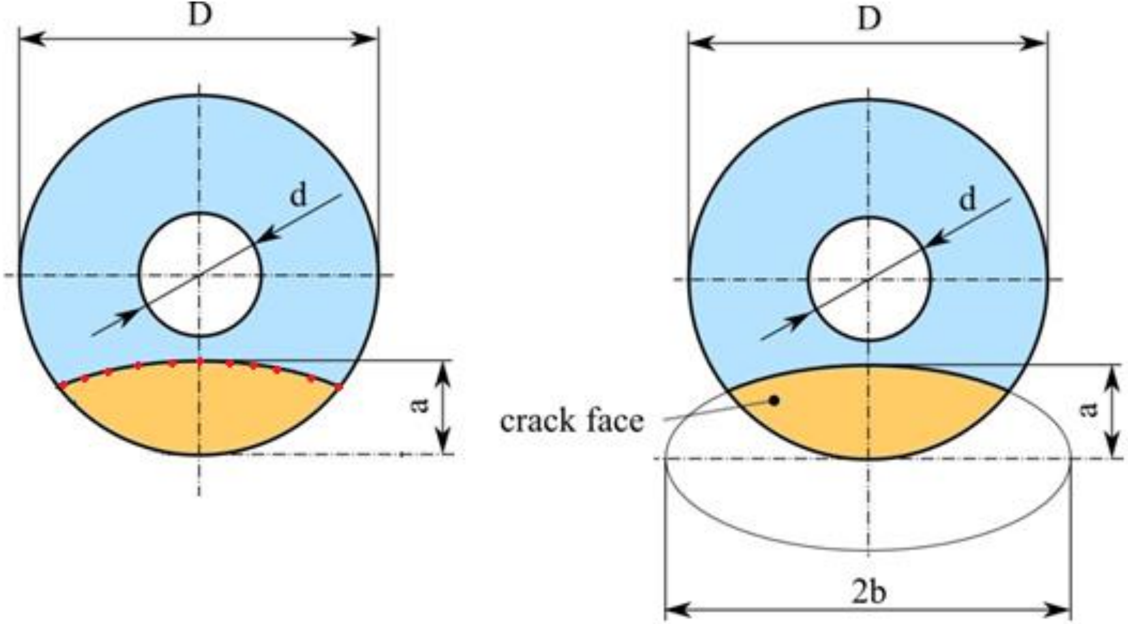
where:

r	radial coordinate with origin at the crack tip
σ_{yy}	stress component (opening stress obtained by FEM modeling)

The SIF **is calculated numerically for each railway axle** to reach accurate results of residual fatigue lifetime.

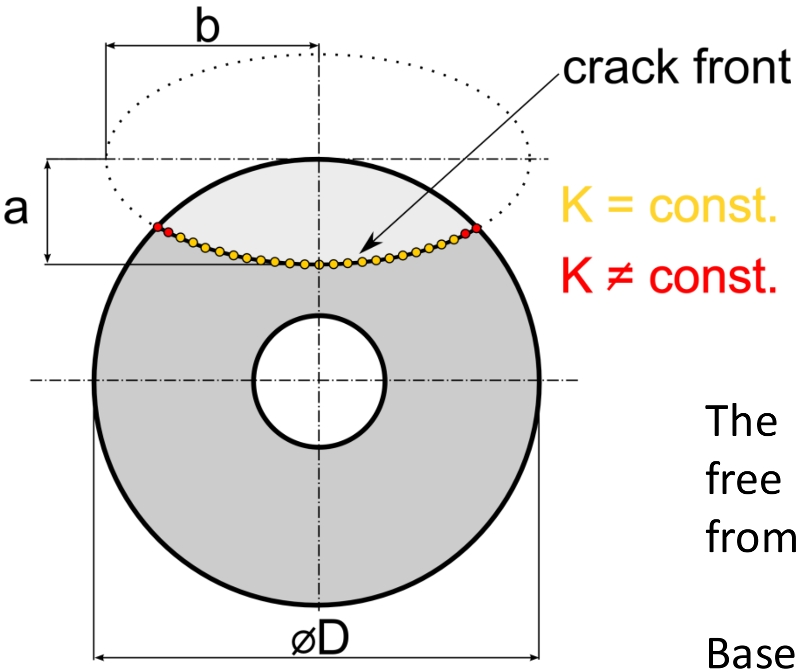
Determination of a shape of fatigue crack front

The shape of propagating crack is given by **minimization of energy for crack propagation**. In the framework of linear elastic fracture mechanics there is direct relation between strain energy density and stress intensity factor. This ideas leads to the assumption, that **iso-lines with constant stress intensity factor** correspond to energy considerations, and well describe fatigue crack fronts experimentally observed .



- The model shape of fatigue crack front is generally assumed as **semi-elliptical (determined points of fatigue crack front are fitted by ellipse)**.

Determination of the shape of fatigue crack front



crack front shape in the railway axle

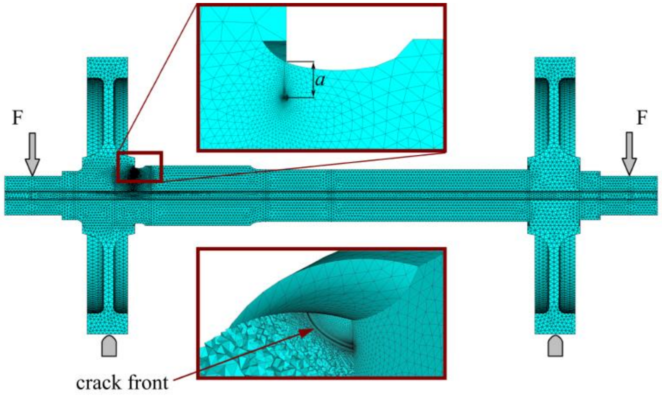
The semi-elliptical crack front shape relatively good complies the constant stress intensity factor **except the points close to free surface** (different stress distribution field due to free surface)*.

The points of semi-elliptical crack front close to free surface are determined by **extrapolation** from „inner“ points.

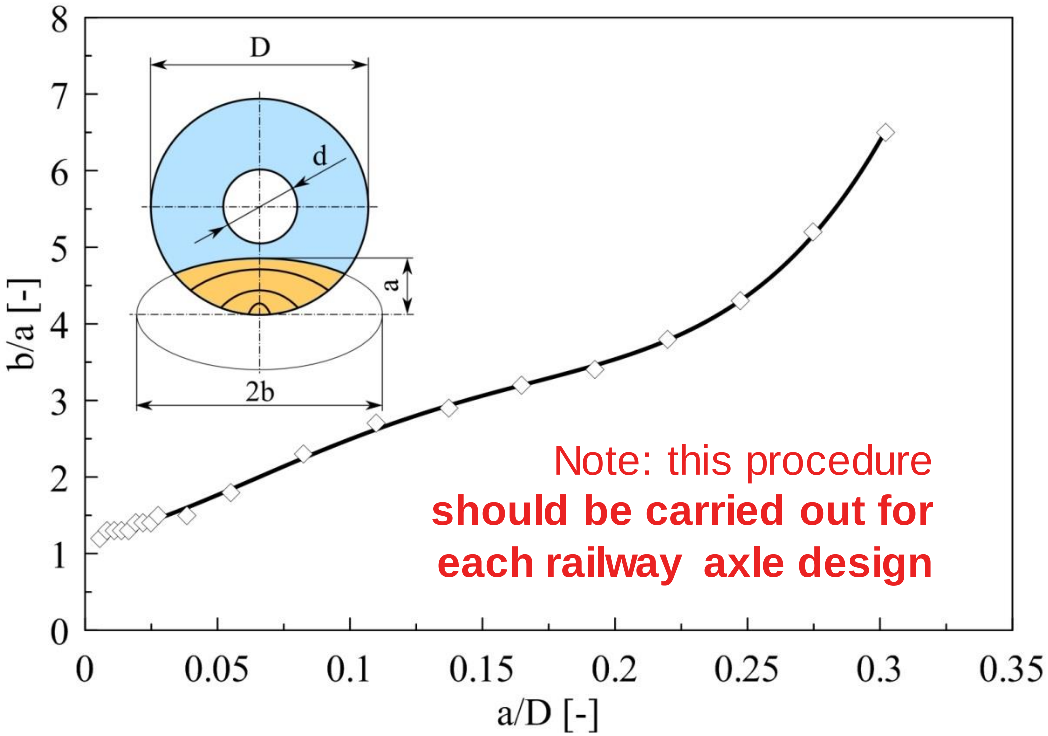
Based on observations the ratio between semi-axes *a* and *b* of the ellipse is continuously changing during crack propagation.

**more details in Ševčík et al., Numerical estimation of the fatigue crack front shape for a specimen with finite thickness, International Journal of Fatigue 39 (2012)*

Determination of the shape of fatigue crack front



FE model of considered railway axle with press-fitted wheels



Note: this procedure **should be carried out for each railway axle design**

Development of the crack front shape in the railway axle

The fatigue crack front shape evolution was determined for railway axle loaded due to:

- **bending due to weight of the train**
- **press-fitted wheels**

Stress intensity factor (SIF)

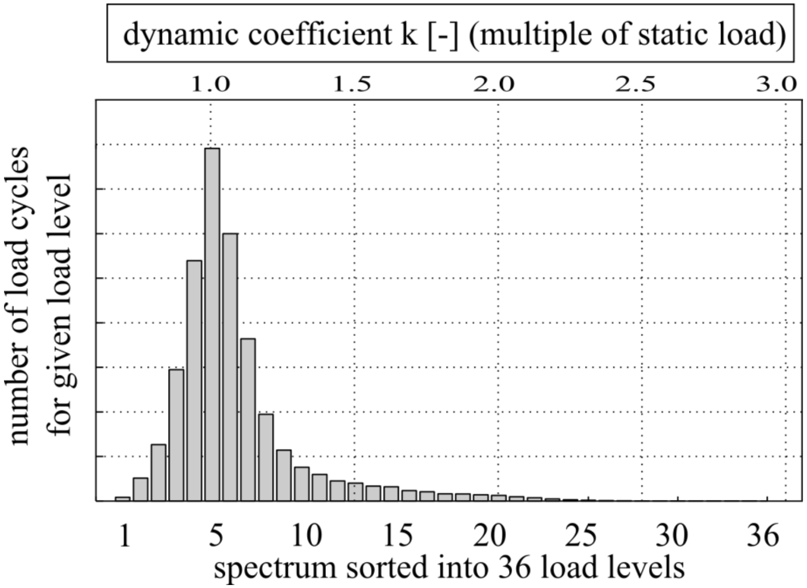
loading due to:

- movement and mass of train (causes dominantly bending loading)
- press-fitted wheel
- residual stress field

$$K_{I,total} = \boxed{K_{I,bending}(a,t)} + \boxed{K_{I,press-fit}(a)} + \boxed{K_{I,residual\_stress}(a)}$$

$$\boxed{K_{I,bending} = k.K_{I,bending,static}}$$

Bending loading **is not constant** for specific crack length and it is described by load spectrum

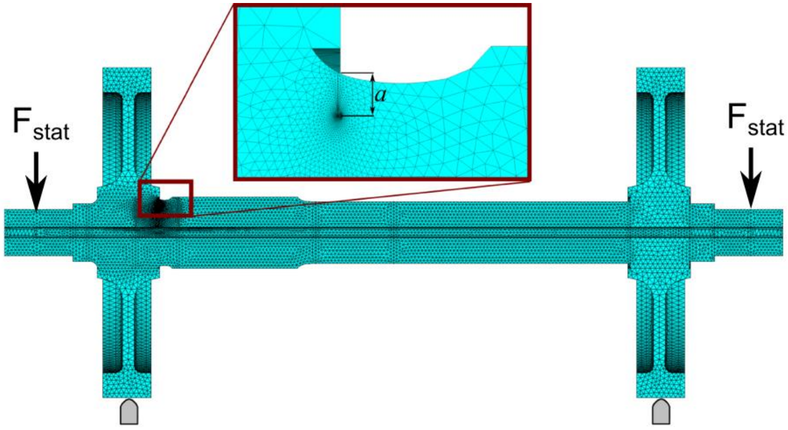


SIF for bending load

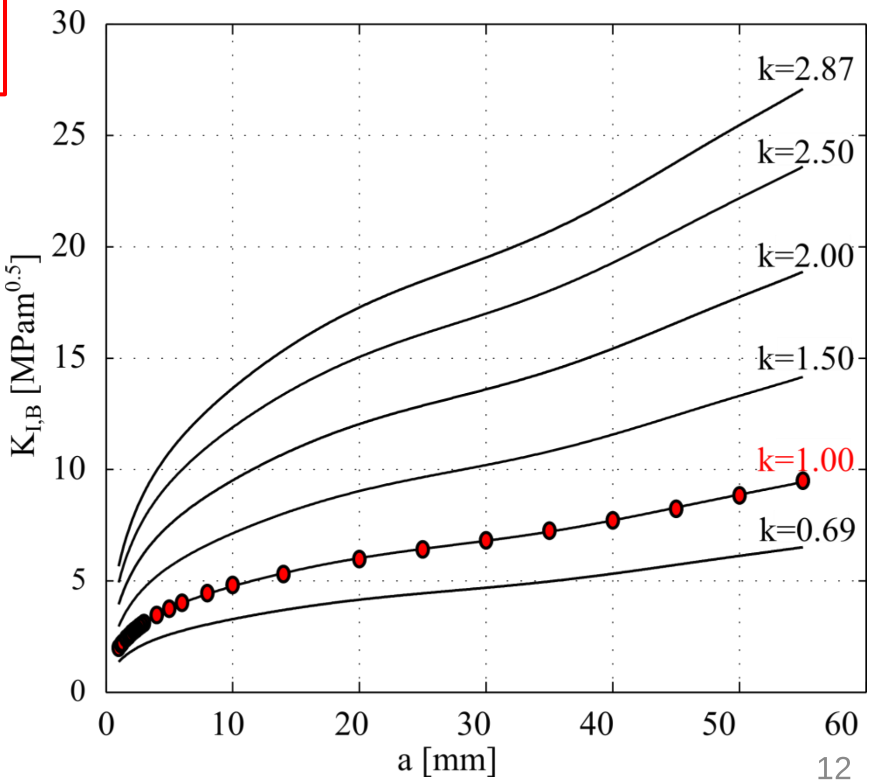
SIF caused by weight of a train (static case)

$$K_{I,total} = \boxed{K_{I,bending}(a,t)} + K_{I,press-fit}(a) + K_{I,residual\_stress}(a)$$

$$\boxed{K_{I,bending} = k.K_{I,bending,static}}$$



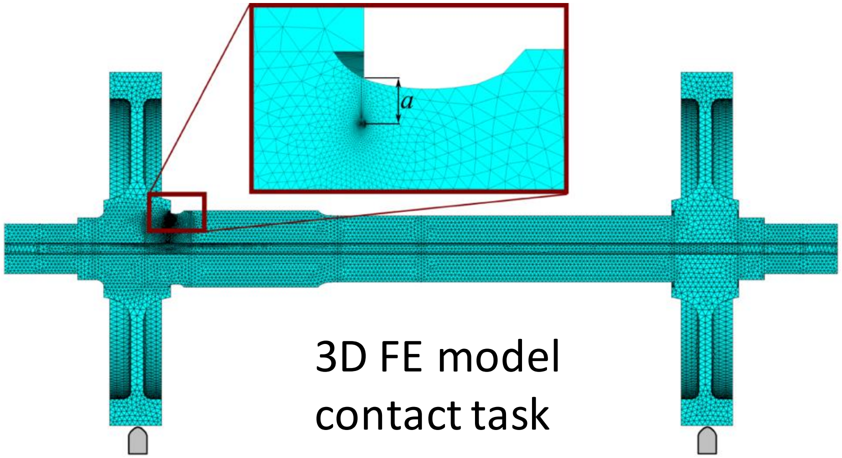
SIF caused by bending load for various k



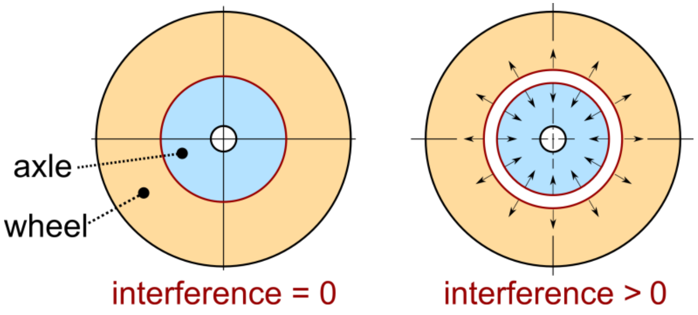
SIF for press-fit load

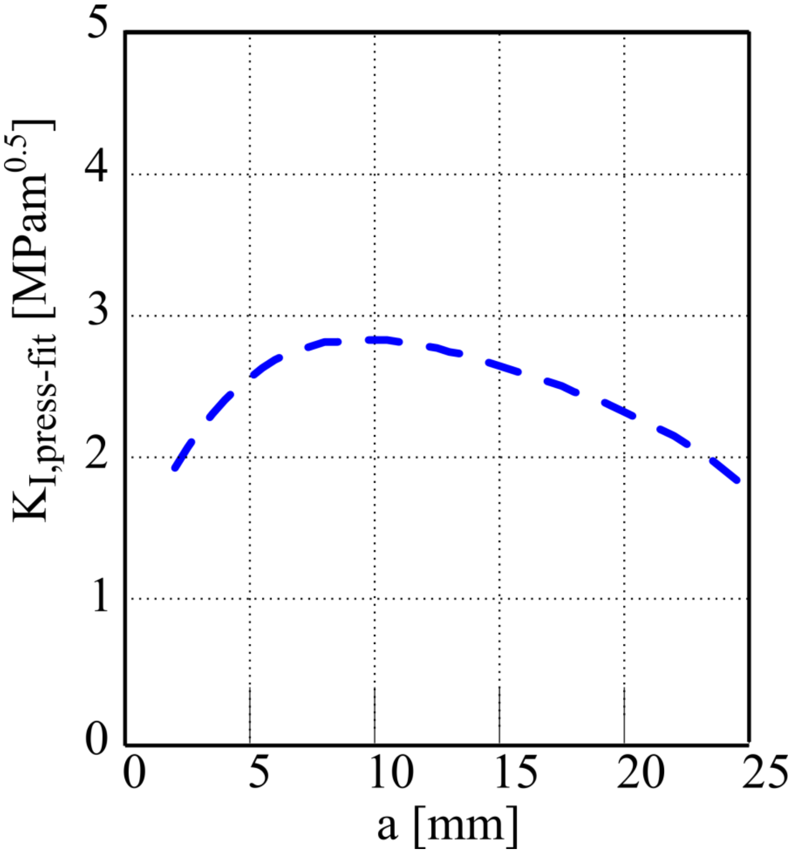
SIF caused by press-fitted wheel

$$K_{I,total} = K_{I,bending}(a,t) + \boxed{K_{I,press-fit}(a)} + K_{I,residual\_stress}(a)$$



3D FE model
contact task



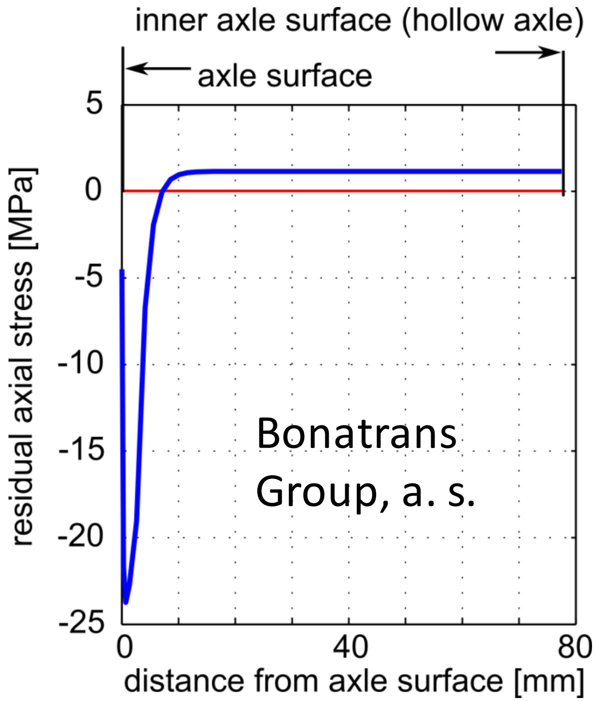


SIF due to residual stress

SIF caused by residual stress field close to the axle surface

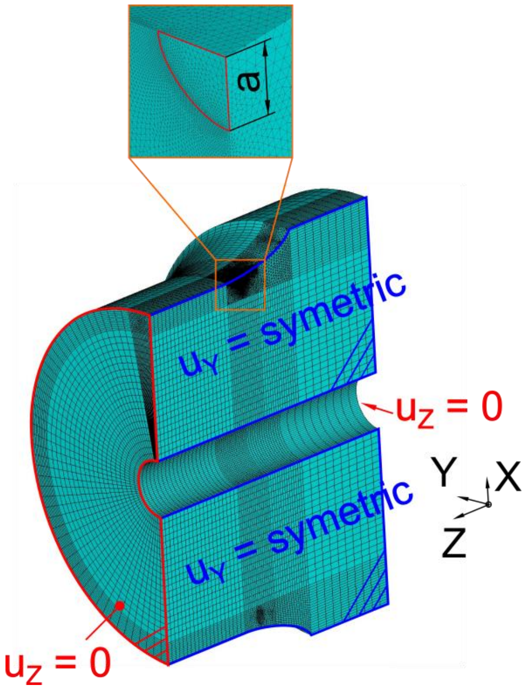
$$K_{I,total} = K_{I,bending}(a,t) + K_{I,press-fit}(a) + \boxed{K_{I,residual\_stress}(a)}$$

experimentally measured
(drilled out + strain gauges)

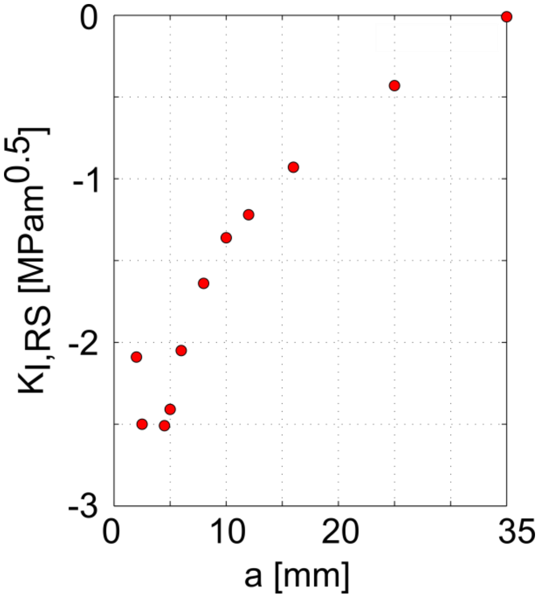


Bonatrans Group, a. s.

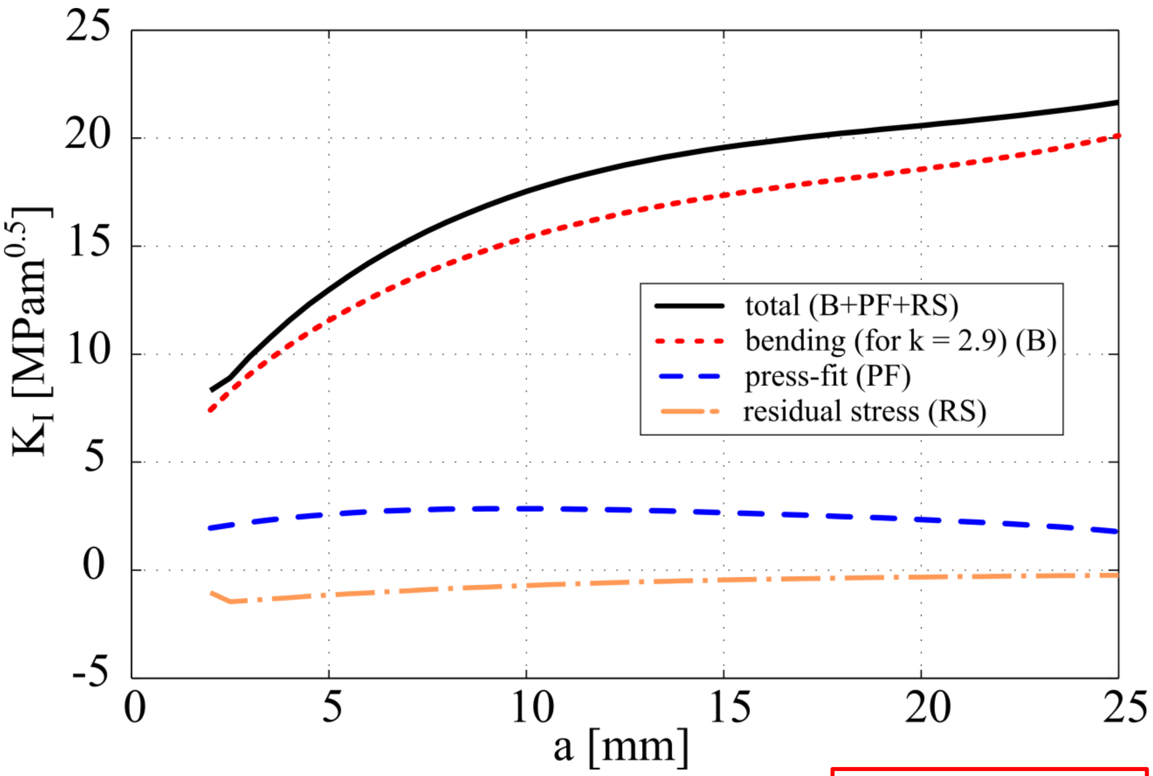
stress distribution serves as input to numerical model



results of $K_{I,RS}$



Total SIF, determination of operation stress ratio



$$K_{I,\max} = K_{I,bending} + K_{I,press-fit} + K_{I,residual\ stress}$$

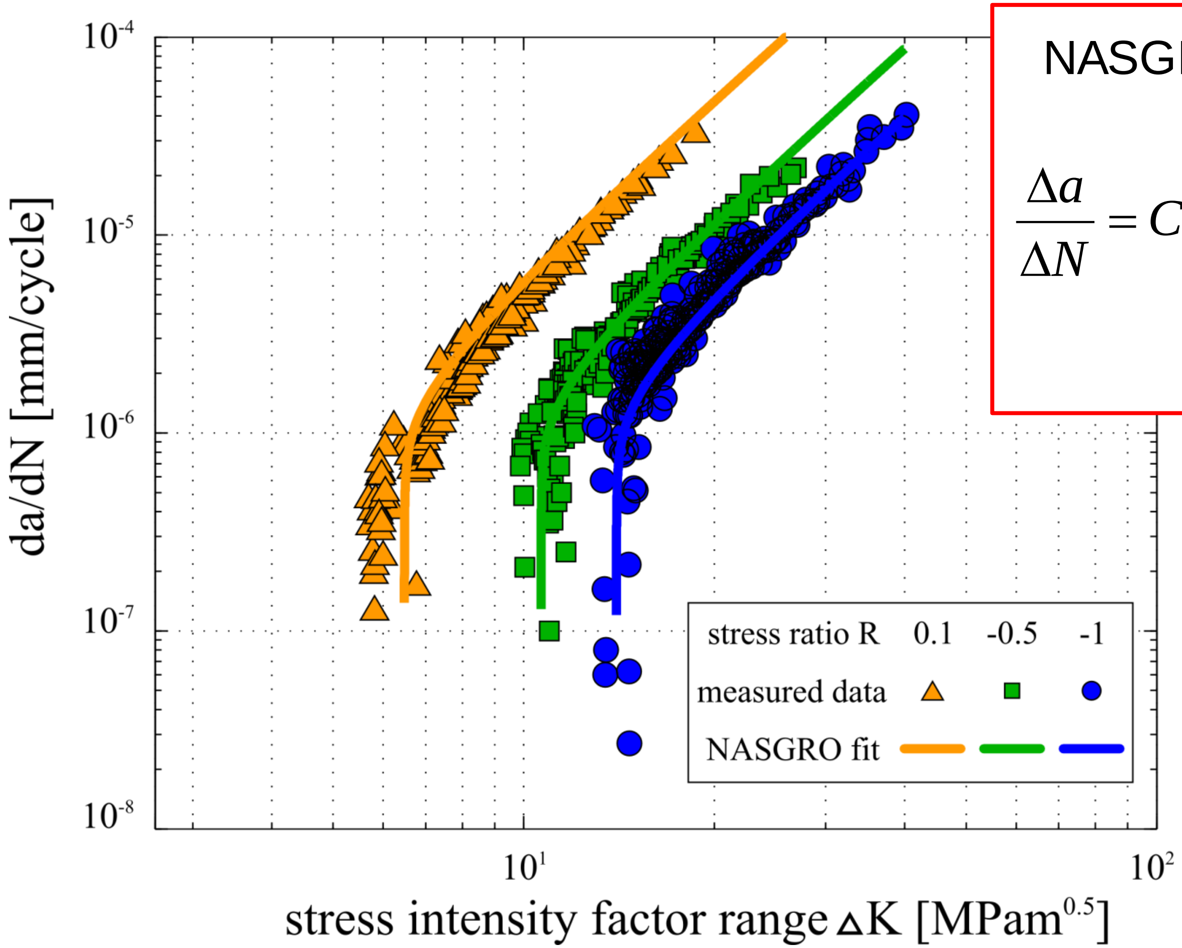
$$K_{I,\min} = -K_{I,bending} + K_{I,press-fit} + K_{I,residual\ stress}$$

$$\boxed{R = \frac{K_{I,\min}}{K_{I,\max}}}$$

$R \in (-1; -0.3)$ **considering of PF + RS**

$R \in (-1; 0.2)$ only considering of PF

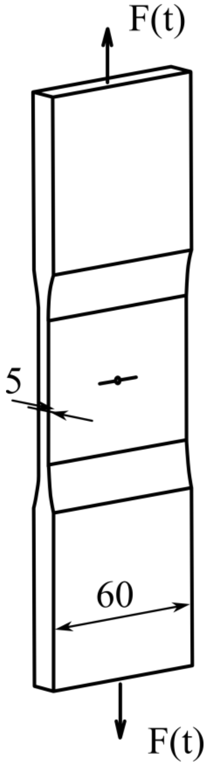
v-K curves of EA4T steel (*IPM data*)



NASGRO:

$$\frac{\Delta a}{\Delta N} = C\left[\left(\frac{1-f}{1-R}\right)\Delta K\right]^{n} \frac{\left(1-\frac{\Delta K_{th}}{\Delta K}\right)^{p}}{\left(1-\frac{K_{\max}}{K_{c}}\right)^{q}}$$

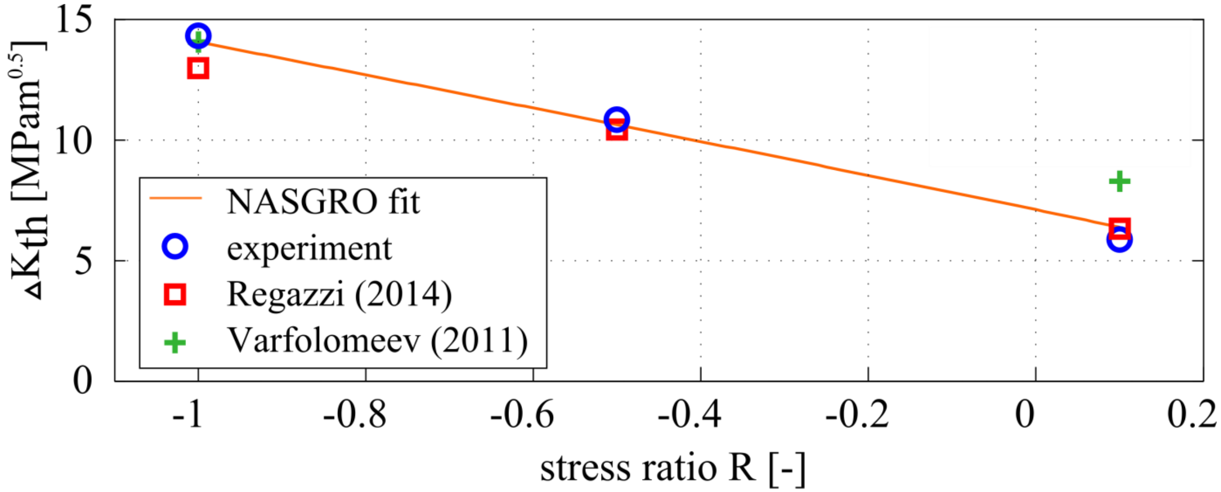
$$R \in (-1;-0.3)$$



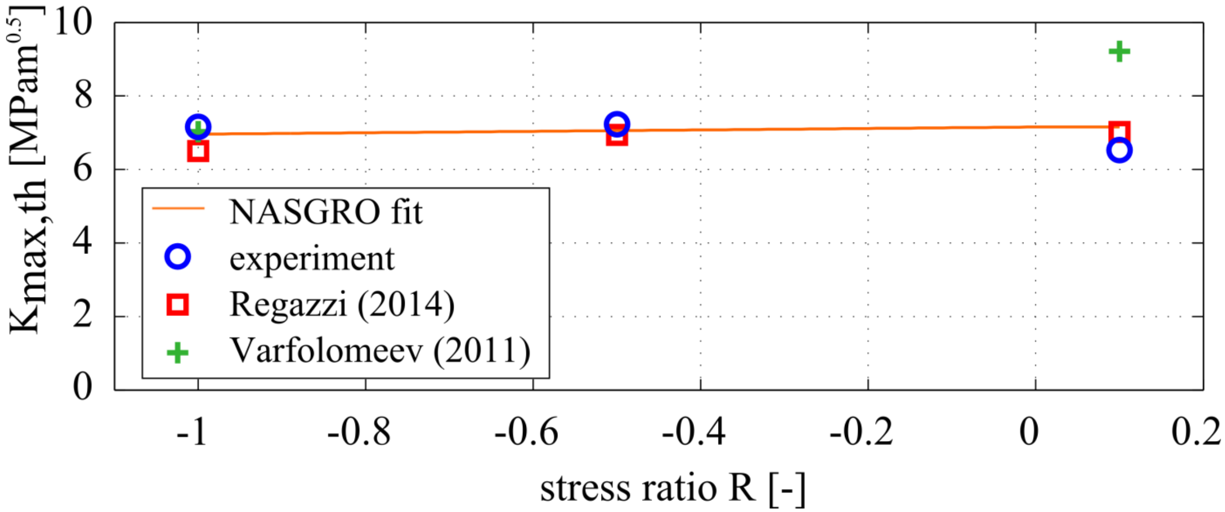
used M(T) specimen

Threshold of EA4T steel as a function of R

ΔK
expression

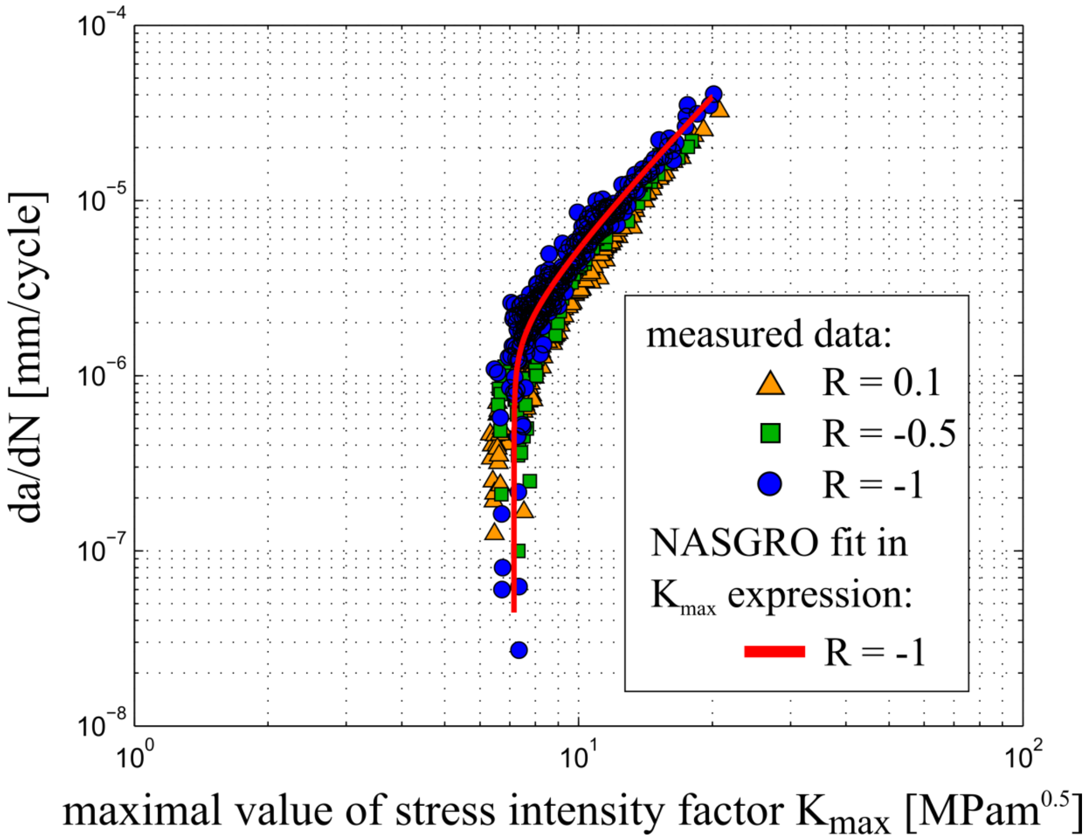


$K_{\max}$
expression



** Regazzi et al. 2014, Engineering Fracture Mech. 131, **Varfolomeev et al. 2011, Engineering Fracture Mech. 78*

NASGRO (K_{max} expression – only positive part of ΔK is considered)



$$\frac{\Delta a}{\Delta N} = C^{*}\left[K_{I,\max}\right]^{n^{*}}\left(1-\frac{K_{\max,th}}{K_{I,\max}}\right)^{p^{*}}$$

$$\Delta a = C^{*}\left[K_{I,\max}\right]^{n^{*}}\left(1-\frac{K_{\max,th}}{K_{I,\max}}\right)^{p^{*}}\Delta N$$

Fatigue crack propagation software

In the case of NASGRO equation the discretized fatigue crack increment could be determined:

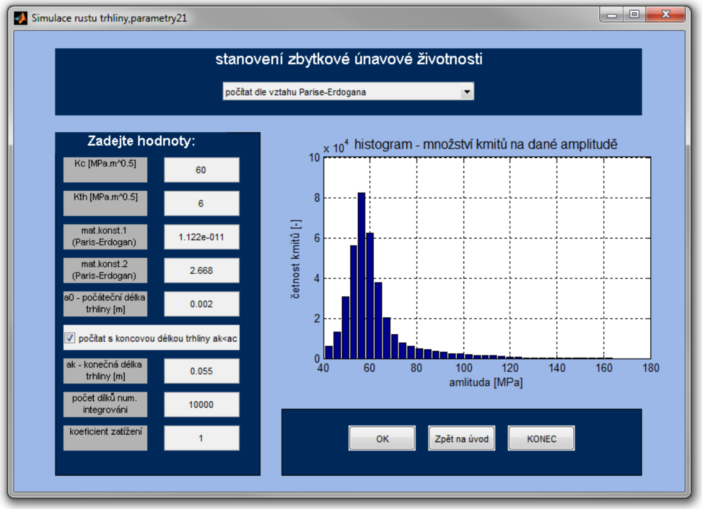
$$\Delta a = C\left[K_{\max}\right]^{n}\left(1-\frac{\Delta K_{th}}{\Delta K}\right)^{p}\Delta N$$

Computation runs in a loop (until crack length a<a_c) :

$$a_i = a_{i-1} + \Delta a$$

For this purpose we developed our own software written in MATLAB.

This software can calculate increments „block by block“ or „cycle by cycle“. There is a possibility to take into account retardation effects (implementation of Generalized Willenborg model).

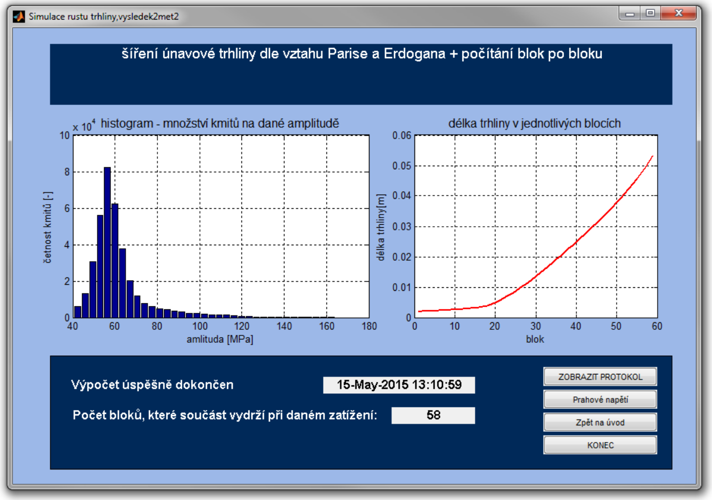

Simulace rustu trhliny,parametry21

stanovení zbytkové únavové životnosti

počítat dle vztahu Parise-Erdogana

Zadejte hodnoty:

Kc [MPa.m^0.5]	60
Kth [MPa.m^0.5]	6
mat.konst.1 (Paris-Erdogan)	1.122e-011
mat.konst.2 (Paris-Erdogan)	2.668
a0 - počáteční délka trhliny [m]	0.002
☑ počítat s koncovou délkou trhliny ak<ac	
ak - konečná délka trhliny [m]	0.055
počet dílků num. integrování	10000
koeficient zatížení	1


Simulace rustu trhliny,vysledek2met2

šíření únavové trhliny dle vztahu Parise a Erdogana + počítání blok po bloku

Výpočet úspěšně dokončen 15-May-2015 13:10:59

Počet bloků, které součást vydrží při daném zatížení: 58

Residual fatigue lifetime - results

$$\Delta a = C^{*}\left[K_{I,\max}\right]^{n*}\left(1-\frac{K_{\max,th}}{K_{I,\max}}\right)^{p*}\Delta N \qquad a_i = a_{i-1} + \Delta a$$

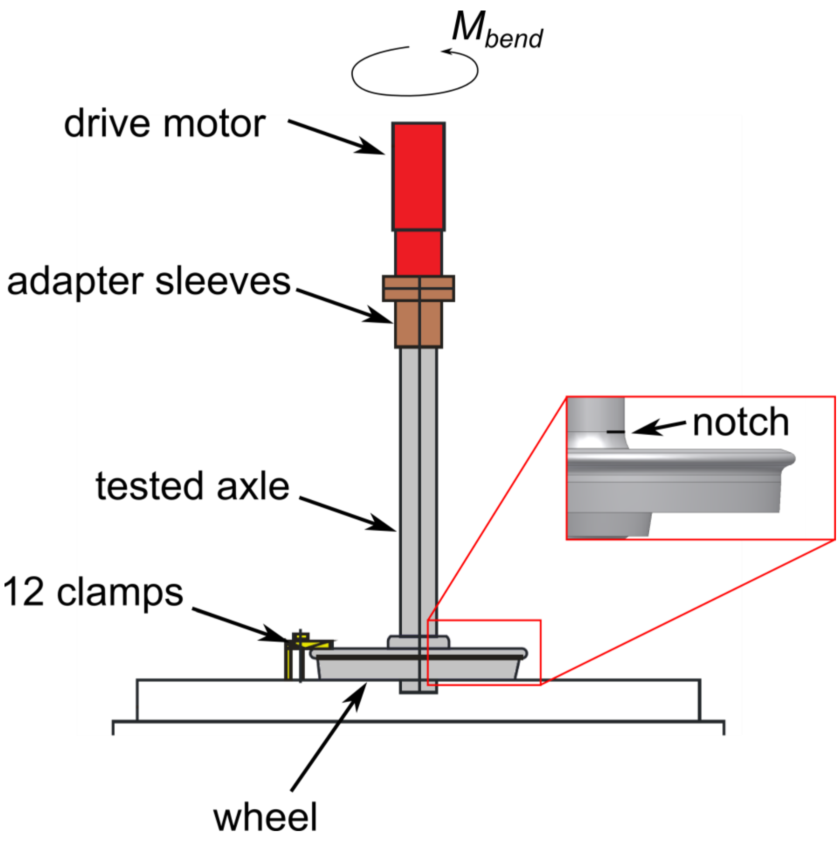
$$K_{I,\max} = K_{I,bending} + K_{I,press-fit} + K_{I,residual\ stress}$$

calculated residual fatigue lifetime in load blocks ($a_f = 35$ mm):

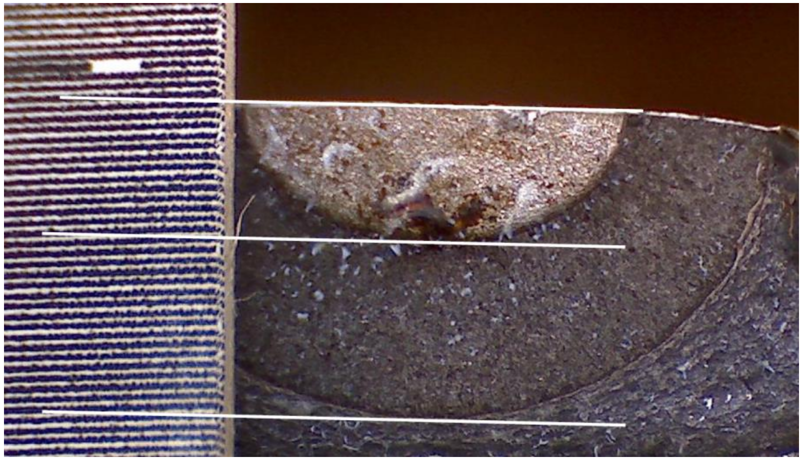
	Initial crack length a_0		
	1 mm	2 mm	5 mm
without consideration of residual stresses	Inf.	128	19
with consideration of residual stresses	Inf.	2696	37

Experiments (*Bonatrans Group*)

Experimental stand
tests 1:1



cross section of axle
(position of electro discharged notch)



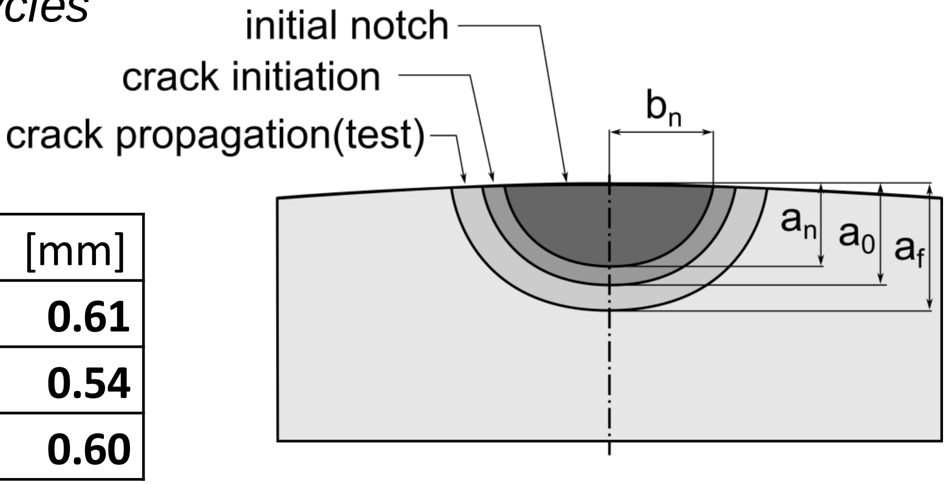
$a_n = 2$ mm, $b_n = 2{,}5$ mm ($a/b = 0{,}8$)

1. electro discharged notch
2. initiation at maximal load in load spectrum, propagation up to a_0
3. fatigue crack growth from a_0 up to a_f (application of load spectrum - corresponding to 500 000 km)

Experimental results

a_n *length of notch*
a_0 *length of initial crack (length of initiated crack)*
a_f *length of crack after applied cycles corresponding to* ***500 000 km***

$a_n = 2$ mm, $b_n = 2{,}5$ mm ($a/b = 0{,}8$)



	a_0 [mm]	a_f [mm]	Δa [mm]
axle 1	2.44	3.05	**0.61**
axle 2	2.16	2.70	**0.54**
axle 3	2.40	3.00	**0.60**

	Δa	calculation without res. stresses	**calculation with res. stresses**	**experimental load**
axle 1	0.61 mm	26 000 km	**354 000 km**	**500 000 km**
axle 2	0.54 mm	42 000 km	**1 104 000 km**	**500 000 km**
axle 3	0.60 mm	27 000 km	**415 000 km**	**500 000 km**

Conclusion

A methodology developed at IPM with co-operation with Bonatrans Group for estimation of residual fatigue lifetime of railway axle was shown. The methodology (in the presented form) takes into account:

- real load spectrum
- bending load
- existence of press-fitted wheel in the vicinity of initial crack
- existence of residual stresses close to axle surface (machining, hardening)
- change R-ratio during train ride (in each cycle)
- change of the threshold value due to change of R-ratio

The methodology uses **numerically calculated stress intensity factors obtained by own procedure simulating fatigue crack propagation through the railway axle**.

Other parameters or effects can be added to the methodology, e.g. **declined crack initiation retardation effects** (both was studied in the past), **influence of plasticity-induced crack closure**, **oxide-induced crack closure** (influence of air humidity), **roughness-induced crack closure** (will be presented tomorrow by P. Pokorný)

Conclusion (cont.)

Own material data of EA4T steel (3 different R-ratio) were used for estimation of residual fatigue lifetime of the railway axle.

Influence of residual stresses close to axle surface on the residual fatigue lifetime **was determined**, experimental data by Bonatrans Group was used.

The comparison of numerically estimated fatigue lifetime (IPM) with 1:1 experimental data obtained on real axle geometry (Bonatrans Group) for crack increment approx. 0.6 mm (a_0 approx. 2.4 mm, a_f approx. 3.0 mm) **was done.** Good agreement between predicted and measured data was found.

Thank you for your attention

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BONATRANS

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