MiiRA

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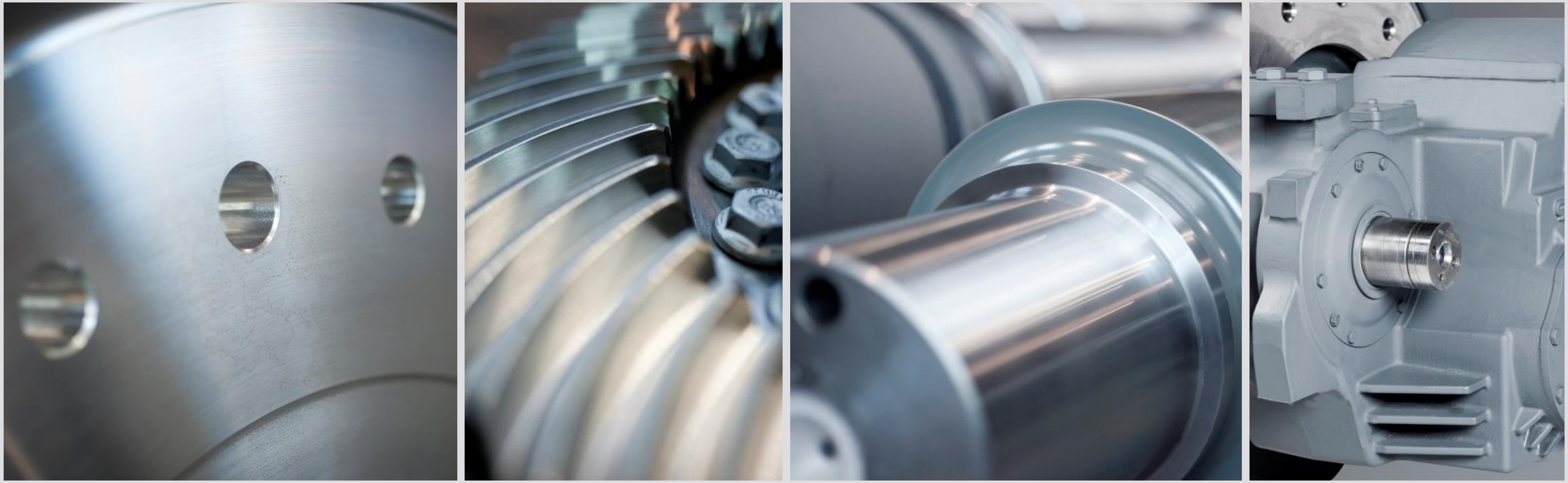

Modeling and calculation of axles

ESIS TC24 Workshop

24-25 October 2016, MCL, Leoben

Aitor Landaberea

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1. Introduction

Review of current EN design standards

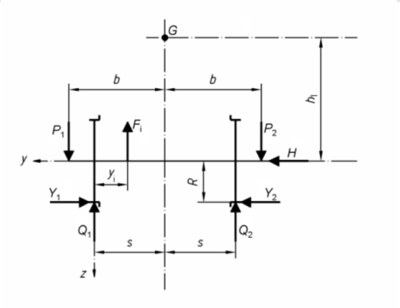
- History of EN 13103/4:
    - Kammerer (1964)
    - ERRI B136/RP11 (1979)
    - NF F 01-118 (1989)
    - UIC 515-3 (1994)
- Methodology:
    - Method to calculate forces acting on the axle
    - Method to calculate stresses in different sections of the axle
        - Beam calculations for axle design
    - Definition of allowable stresses

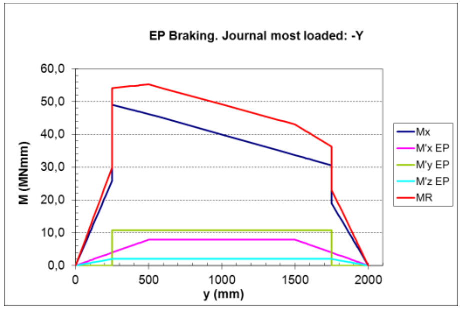
1. Introduction

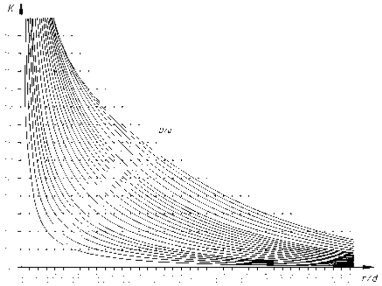
- **General criteria:** For each section of interest: $\sigma_d < \sigma_f$
  - σ_d = Calculated dynamic stress
    $$\sigma_d = K \frac{32 \cdot MR}{\pi d^3}$$
    - MR : Resultant bending moment
    - d : Diameter of the section
    - K : Stress concentration (notch) factor (SCF)

$$K = \frac{\sigma}{\sigma_n} = \frac{\text{Peak stress}}{\text{Nominal stress}}$$

  - σ_f = Allowable stress $\sigma_f = \frac{F}{SF}$
    - F : Fatigue strength (material, zone)
    - SF : Safety factor (type of axle, position, material)
  - K, F obtained from tests of Kammerer (1/3 scale, d = 60 mm, r = 2, 5, 6, 10, 15, 25 mm)



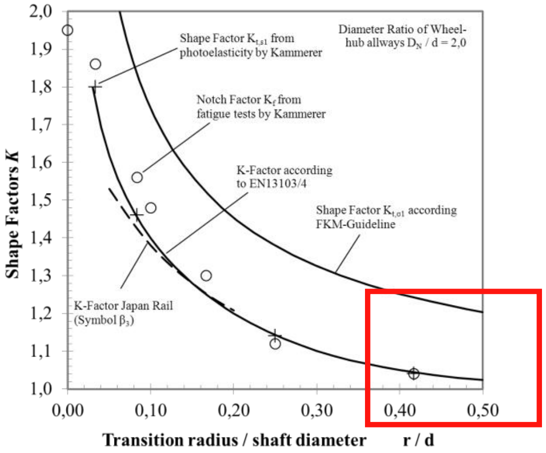




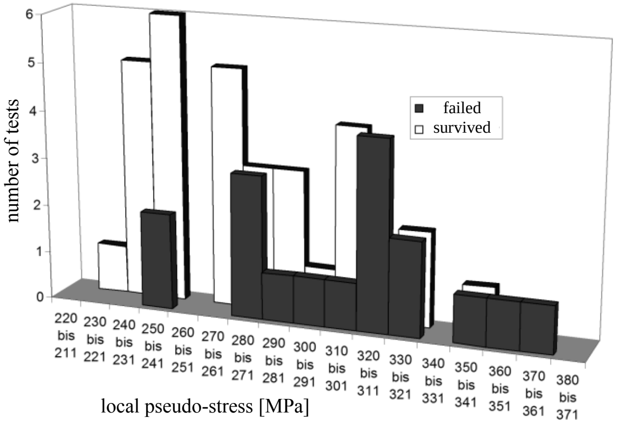
1. Introduction

- Notch factors of Kammerer/EN standards are ≈ 20% lower than those obtained by measurements, literature or FEA
- Local stresses acting on the transitions of the axles are higher than those calculated according to EN 13103/4
- EXPERIENCE shows that the fatigue limits of the axles based on local stresses are higher than those established in the current standards.
- Product qualification according to current EN standards should be conducted on the basis of nominal stresses.

CURRENT DESIGN PROCEDURE LEADS TO RELIABLE RESULTS



(Traupe et al., 2004)



(Schikora et al., 2008)

1. Introduction

Need for numerical modeling of axles

- State of the art: Calculation of axles according to EN 13103/4
- Analysis based on local stresses should be adopted for better control of the acting stresses
  - Direct correspondence with local stresses in full fatigue tests
- Application:
  - Analysis of complex geometries (e.g. powered axles) non-standard transitions are needed due to design constraints
  - Optimization of axles

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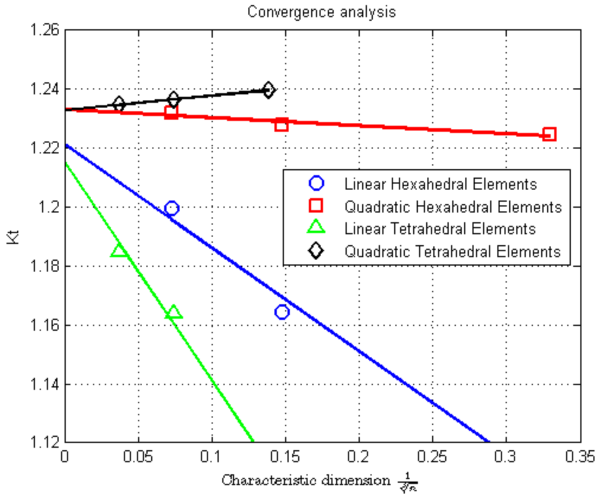
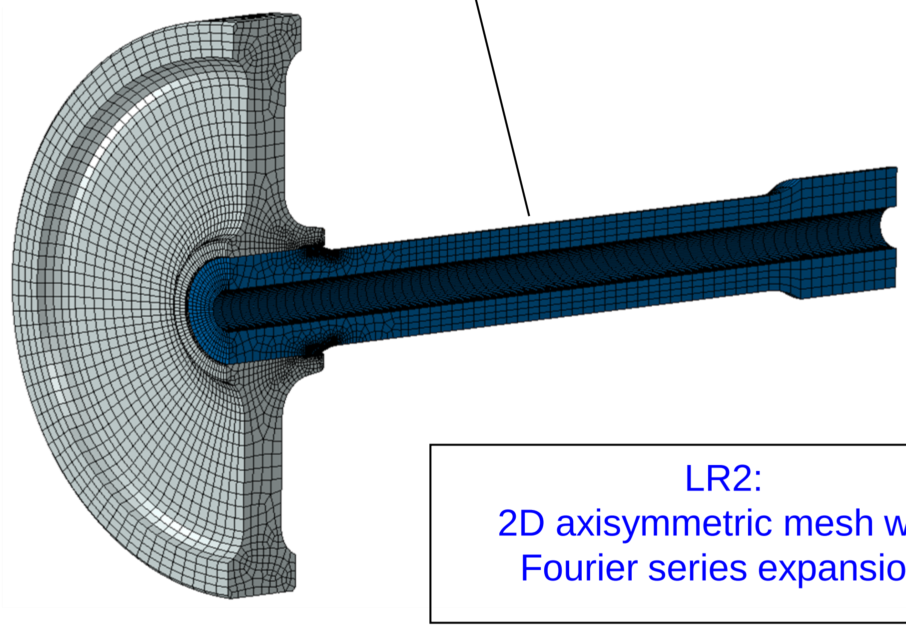
2. Numerical models

Model generation

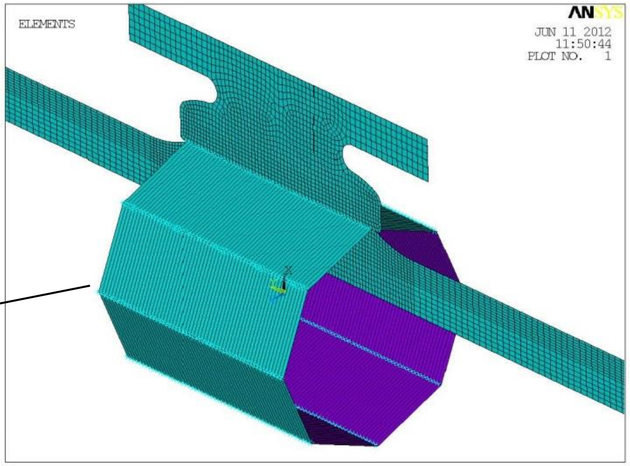
- FE models of full scale fatigue test samples
- Convergence analysis for element type and size performed
- Model validation: Comparison with tests measurements



LR1:
3D mesh



LR2:
2D axisymmetric mesh with
Fourier series expansion

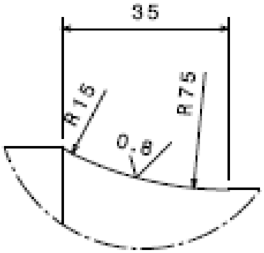


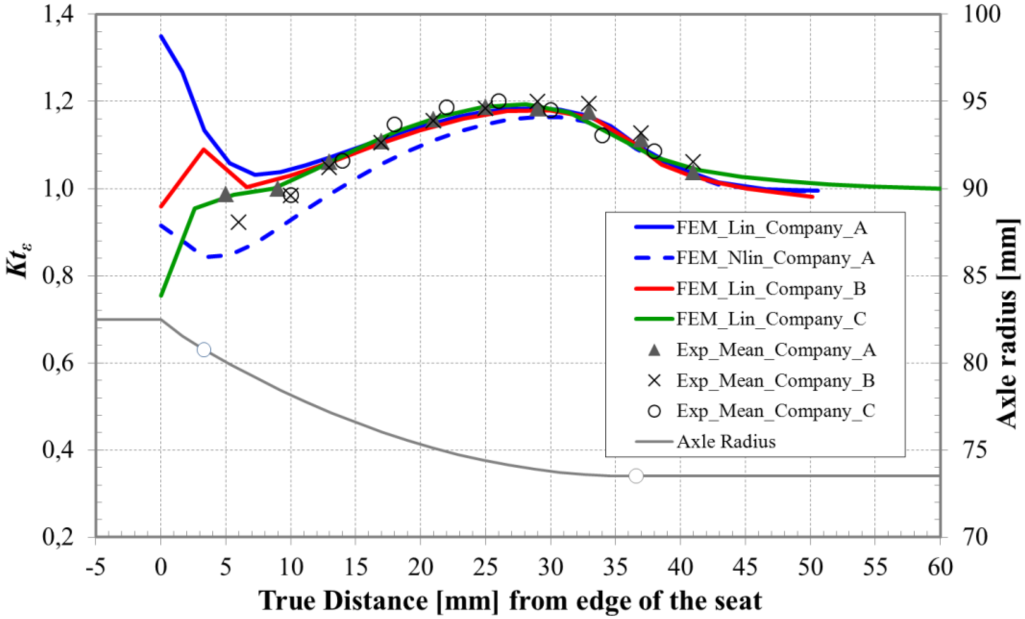
2. Numerical models

Model validation

- F4, D/d = 1,12

Kt,ε1 max = 1,21





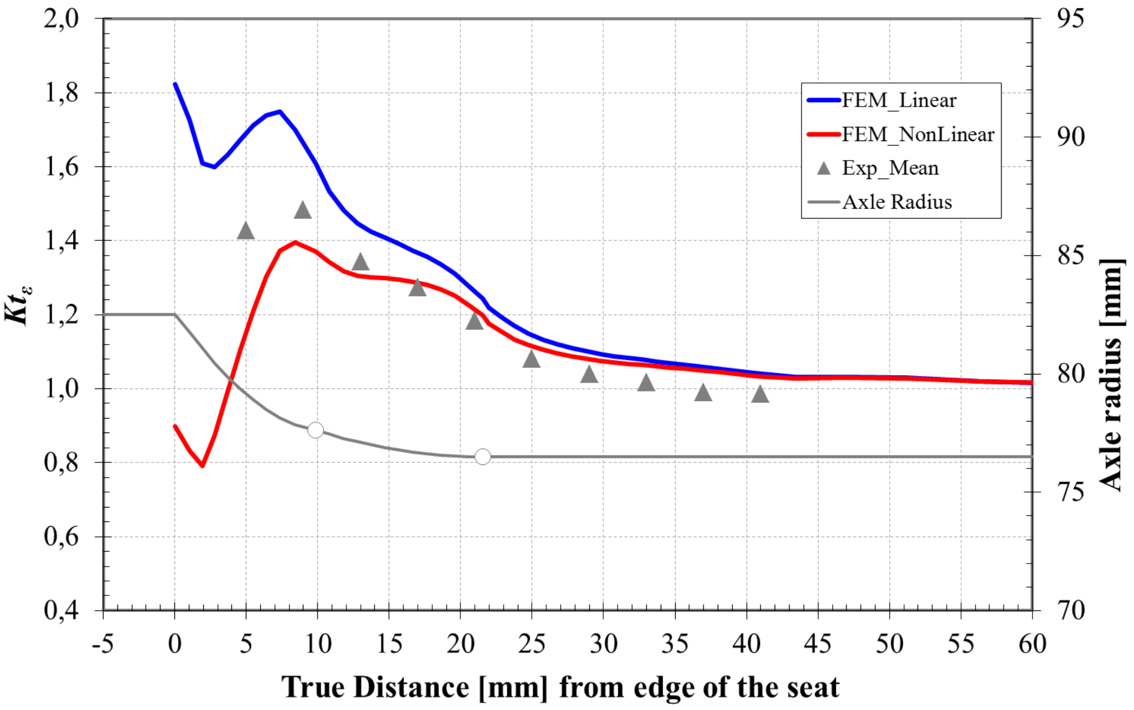
- Good adjustment (linearised models better)
- Peak stress at the end of the transition
- Some diferences near the seat due to different averaging of nodal results

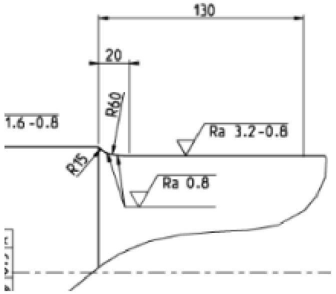
2. Numerical models

Model validation

$Kt,\varepsilon 1$ max = 1,56

- F4, D/d = 1,08



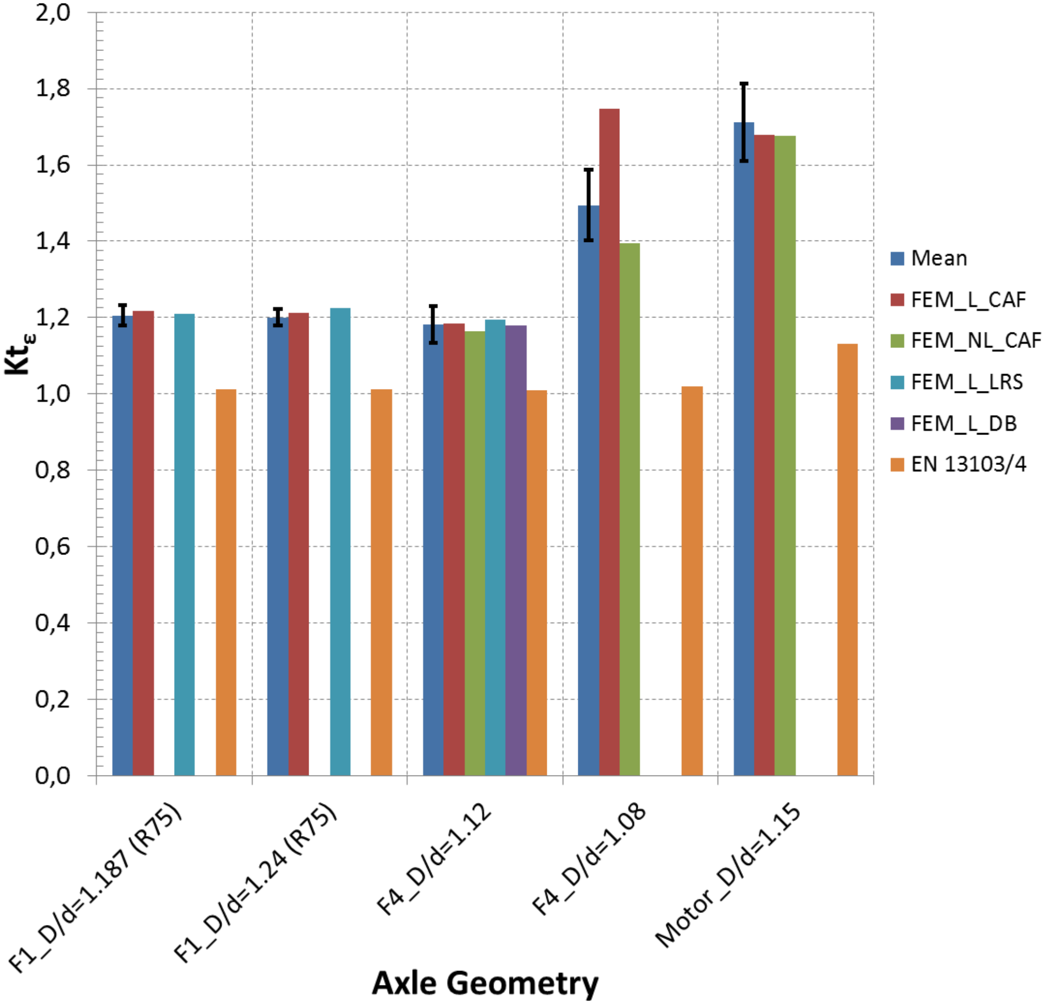


- Good adjustment up to the small radius *r* (linearised models better)
- Peak stress at the small radius
- Linearised model more conservative

2. Numerical models

Model validation – Kt Summary

- Good adjustment of models
- In general, linearised models give better adjustment than non-linear models
- *K* **(Notch factor)** acc. to EN 13103/4 values lower than FE
- EN 13103/4, F4, D/d=1,08, r=15 mm
    - $K_{t,\varepsilon 1}$ = 1,49



2. Numerical models

Model - Recommendations

- 3D or 2D with Fourier series expansion finite element models can be applied.
- Element type: linear hexahedral elements are accepted assuming that mesh convergence is verified.
- Element size: convergence analyses should be performed to check the validity of the models.
  - If the peak stress is located at the big radius of the transition, the typical element size in this zone should be approximately 4 mm.
  - If the peak stress is located at the small radius of the transition, the typical element size in this zone should be approximately 1 mm.
- For post-processing, unaveraged results are recommended to check convergence and the effect of singularities

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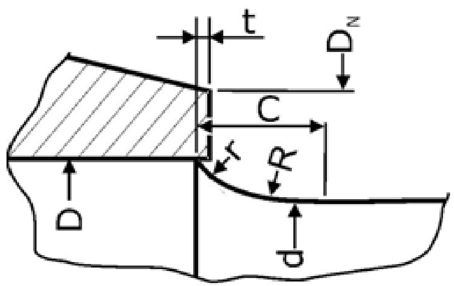
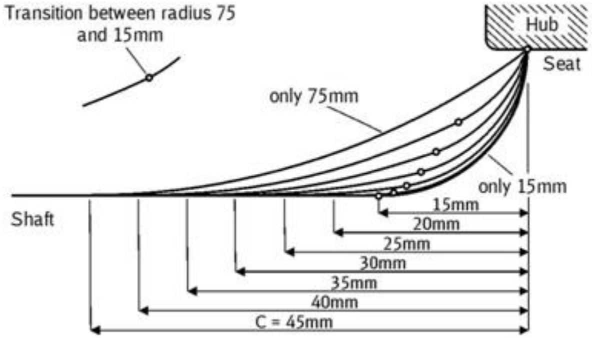
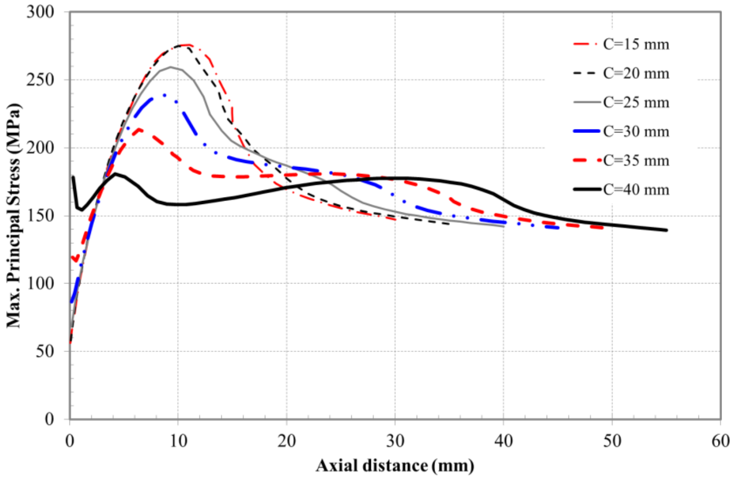
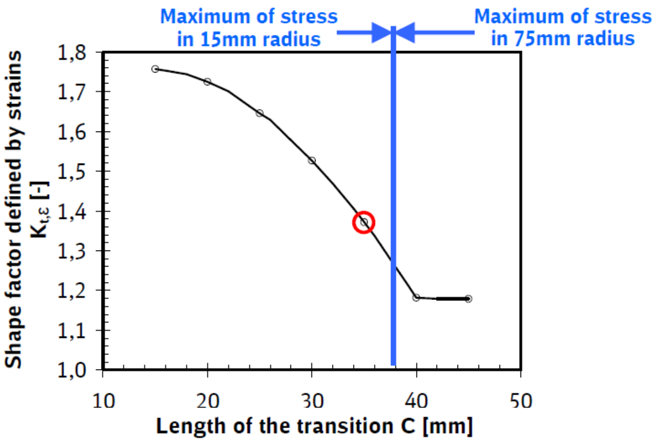
3. Design of the transition

- Seat-body transitions generally designed as Basket archs (multiple radii)
- For a given set of geometrical parameters, a short transition increases the peak stress
- Design criteria: C > Cmin: Transition long enough to ensure that the peak stress is at the big radius near to the end of the transition, that is, lowest peak stress



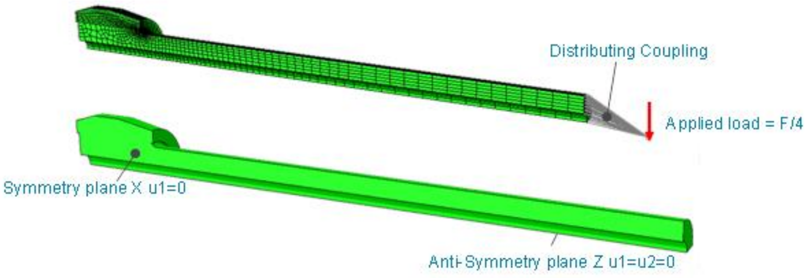






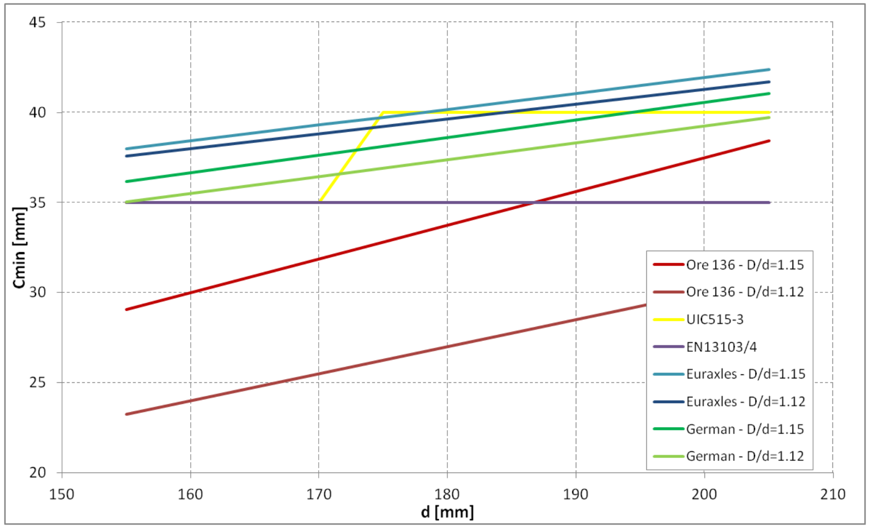
3. Design of the transition

- Parametric analysis (DOE) based on FE performed (for simple transitions)
- Outputs:
  - Peak stress along the transition
  - Position of the peak stress
  - Stress concentration factors
  - Cmin: minimum transition length



Source	Cmin [mm]
Ore 136	$1{,}25 \cdot d \cdot \left(\frac{D}{d} - 1\right)$
UIC515-3	$35 \text{ if } d \in (155{,}170)$ $40 \text{ if } d \in (175{,}205)$
EN13103/4	e.g. 35
EIBFW-I	$C \geq (0{,}0952 \cdot d + 20{,}6) \frac{\left(\frac{D}{d} - 0{,}2113\right)}{0{,}9351} \cdot \frac{\left(\frac{D_N}{D} + 5{,}192\right)}{6{,}468}$
Euraxles	-3,8 + 0,035·d + 0,381·rmax + 0,0279·D

Included in prEN 13103-1:2014



Current EN 13103/4 not conservative

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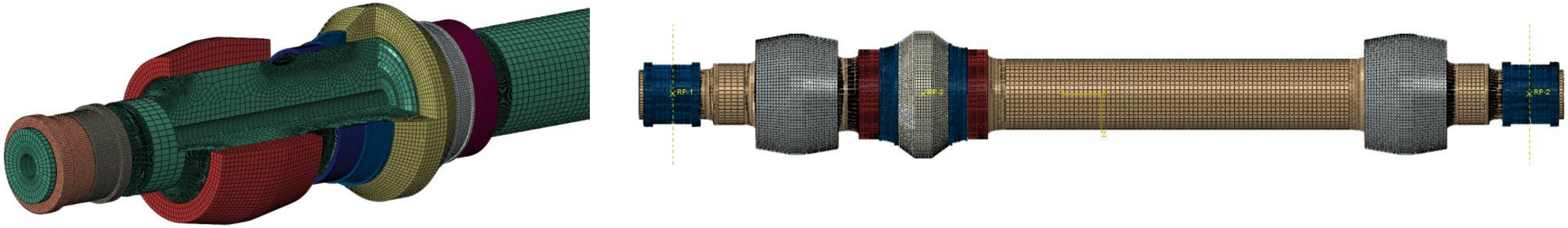
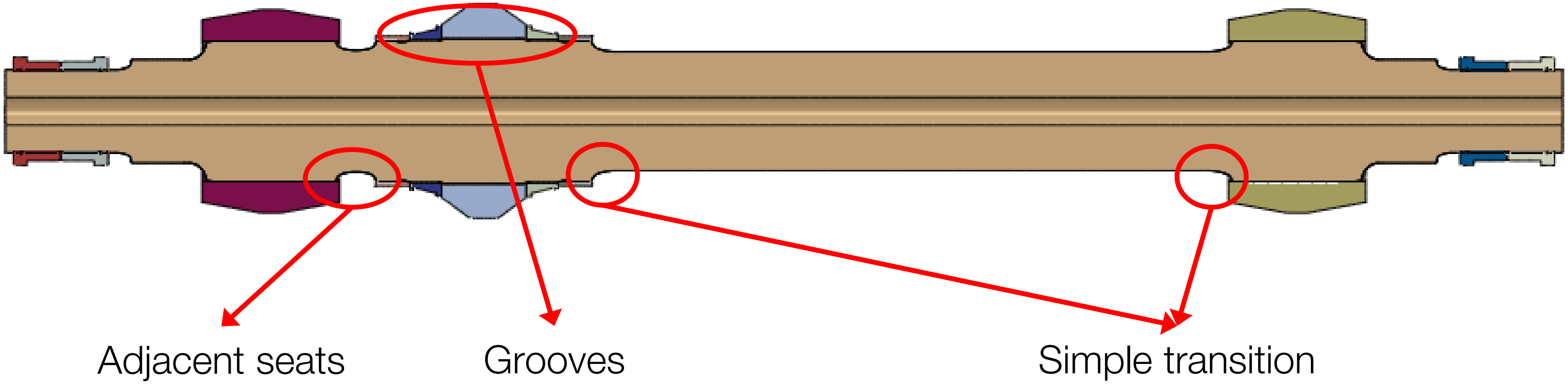
4. Assessment of mounted components

- Finite element models of complete wheelsets can be very complex
- Is it possible to simplify the models for the analysis?
  - Linear/Non-linear
  - Removal of components

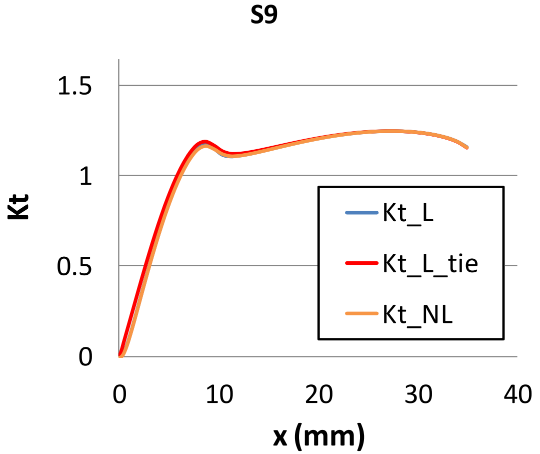


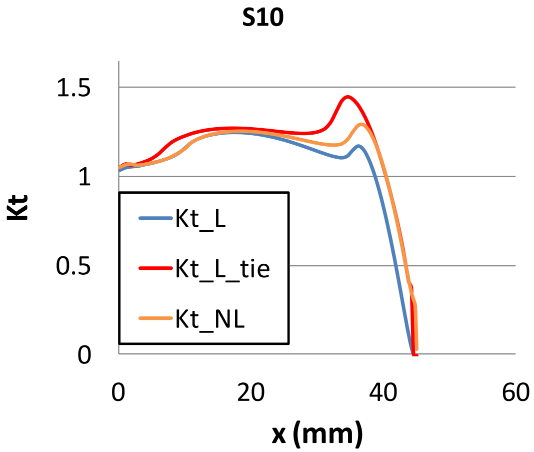


4. Assessment of mounted components

Simple transitions

Section	Part	Interference	Stiffness	Comments
9	Labyrinth	Low	Low	Part can be removed from the model
10	Wheel	High	High	Part cannot be removed Linear + tie model more conservative (better adjustment to experimental results)

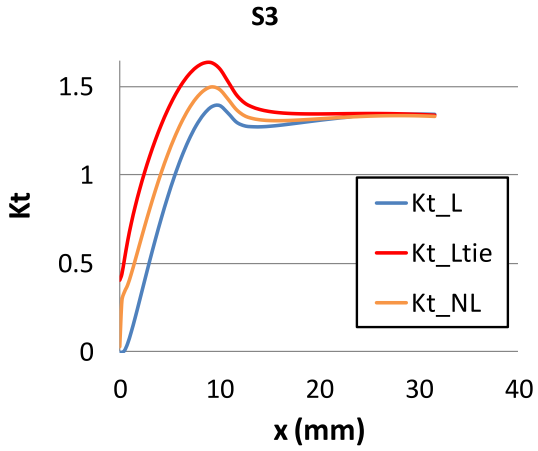


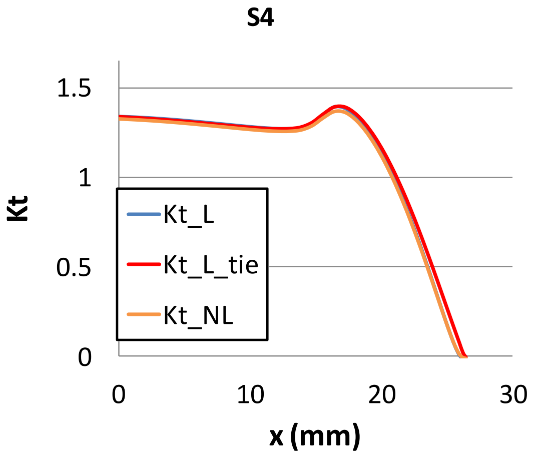


4. Assessment of mounted components

Adjacent seats

Section	Part	Interference	Stiffness	Comments
3	Wheel	High	High	Part cannot be removed Linear + tie model more conservative
4	Labyrinth	Low	Low	Part can be removed from the model

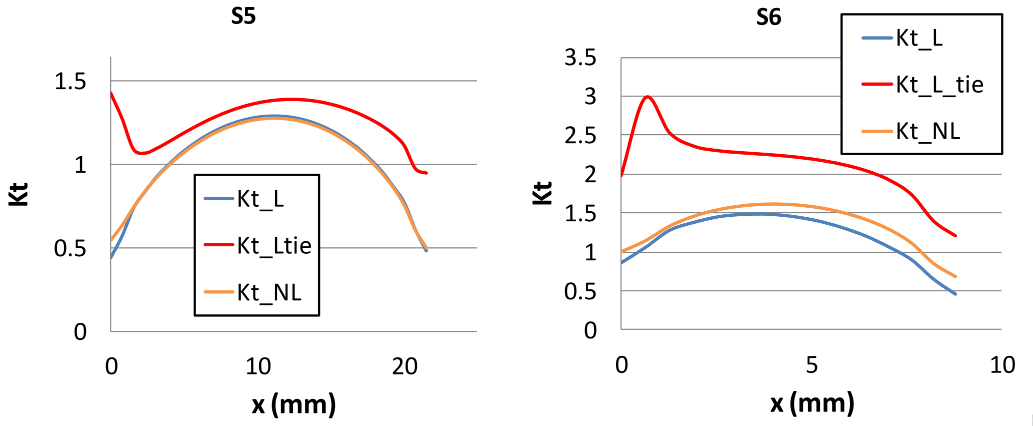




4. Assessment of mounted components

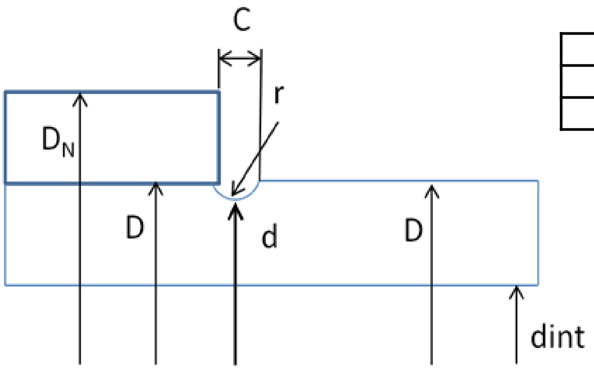
Grooves

Section	Part	Interference	Stiffness	Comments
5,8	Labyrinth-Bearing	Low-Low	Low-Low	Linear + tie model more conservative Small difference with non-linear model and linear w/o part
6,7	Bearing-Gear	Low-High	Low-High	Linear + tie model too conservative High difference with non-linear model and linear w/o part Non-linear model more realistic

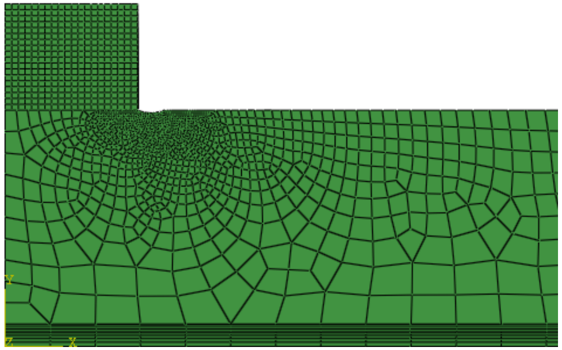


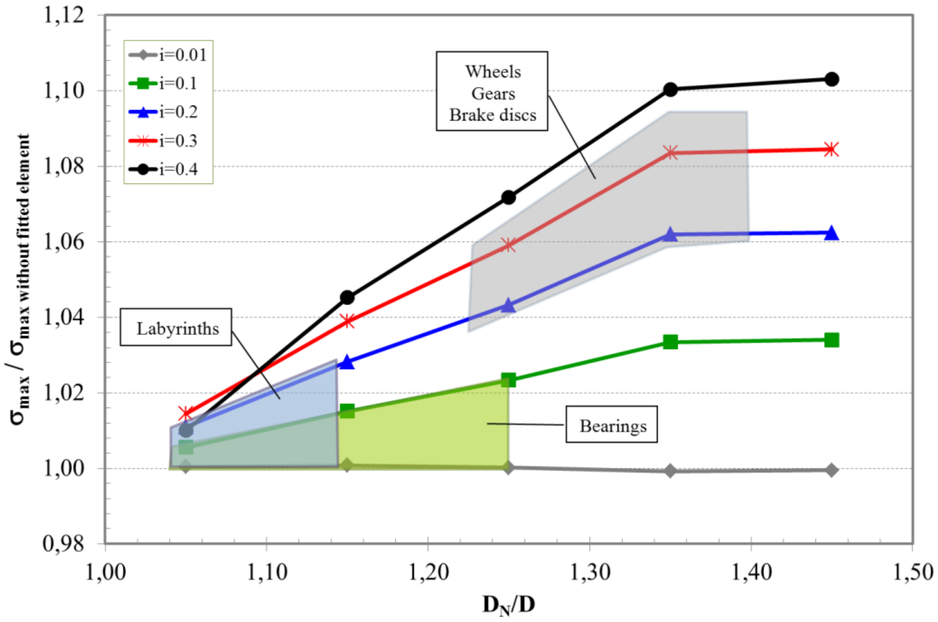
4. Assessment of mounted components

- Parametric analysis performed for simple transitions and grooves



r	16 mm
D	210 mm
C	12 mm

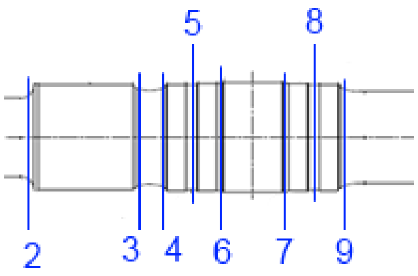


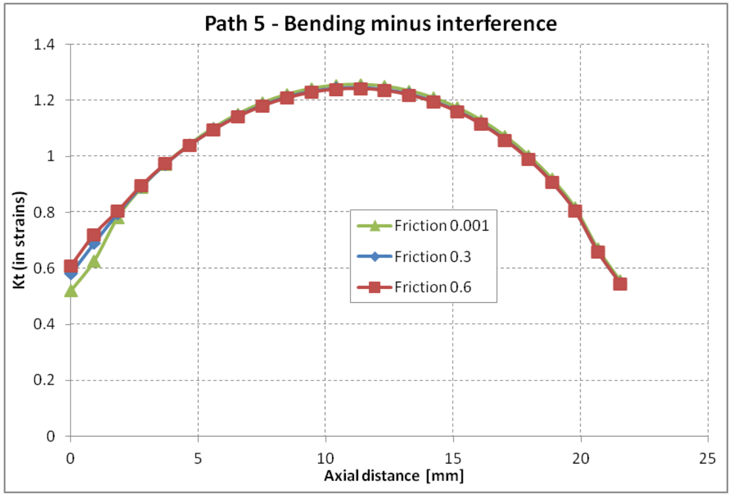


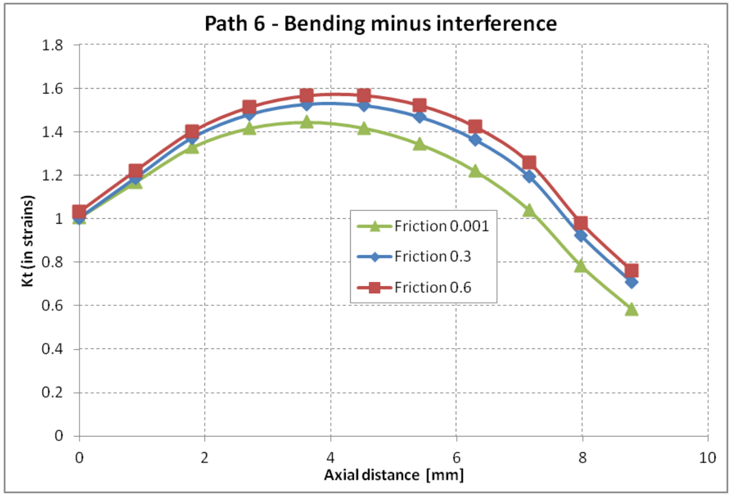
4. Assessment of mounted components

Model - Recommendations

- High stiffness-high interference elements (wheels, brake discs, gears)
  - Simple transitions: Linearised + tie models
  - Adjacent seats: Linearised + tie models
  - Grooves: Non-linear contact interaction (μ = 0,6)
- Low stiffness-low interference elements (bearings, labyrinths)
  - Remove from the models







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5. Axle calculation method

Motivation

- Current EN13103/4 represent the SoA and lead to reliable components
- Main limitations have been identified
  - e.g. complex structures like powered axles with non-standard transitions due to design constraints
- Different modelling and analysis methods of axles have been evaluated in the EURAXLES project
- A practical approach has been defined:
  - Balance between complexity (modelling and calculation) and results
  - Combination of current calculation standards and a local stress approach

5. Axle calculation method

- Local stress approach
  - Fatigue limit in terms of local stress or strain is less variable than nominal values (influenced by the geometry of the transitions)
  - Common practice in full scale fatigue tests of axles: uniaxial strain gauges - $\varepsilon 1$
  - Pseudo-stress $\sigma = E \cdot \varepsilon 1$ and $K_{t,\varepsilon 1}$ should be used

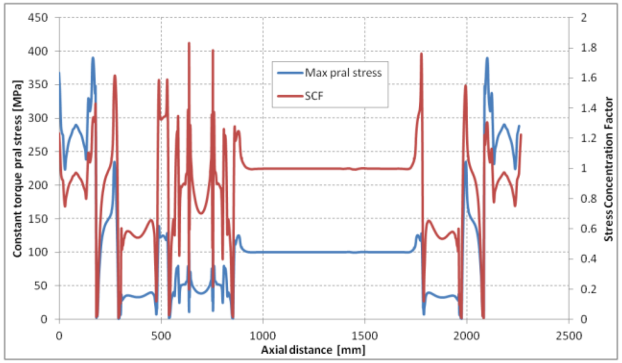
5. Axle calculation method

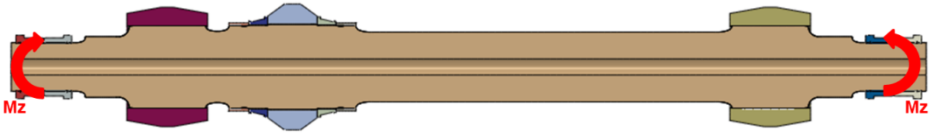
Calculation method

1. Appy forces as per current EN 13103/4 standards
2. Calculation of bending moments and nominal stresses σ_n in the different sections of interest by applying beam theory:

   (solid axle) $$\sigma_n = \frac{32 \cdot MR}{\pi d^3}$$

   - Transitions: calculate σ_n at the end of the transition on the free surface of the axle
3. Calculation of $K_{t,\varepsilon 1}$ in transitions
   - Recommendation: Transition length C ≥ Cmin
   - Use finite element models of the axle following recommendations derived in the project
     - 3D half model using symmetry/2D model with Fourier series expansion
     - Simply supported at the center of both journals
     - Constant bending moment applied at both ends





5. Axle calculation method

4. Calculation of the dynamic local stresses in each section:

(solid axle)

$$\sigma_d = K_{t,\varepsilon 1} \cdot \sigma_n = K_{t,\varepsilon 1} \frac{32 \cdot MR}{\pi d^3}$$

5. Check $\sigma_d < \sigma_f$ for each section. If not, redesign.
   - Need:
     - Fatigue limits
     - Safety factors

5. Axle calculation method

Fatigue limits

- *F*1: Fatigue limits on axle surface as defined in EN 13261
  - Full scale tests:
    - EURAXLES WP3
    - S. Cervello, Int. J. Fatigue 86 (2016), 2-12.

Material	Average fatigue limit (MPa)	Std deviation (MPa)	Fatigue limit 2.5% (MPa)	***F*1 - EN13261 (MPa)**
EA4T	307	18	271	240

- Average fatigue limit from tests > 1,2 · *F*1
- EN standards: no probability of failure is associated to the fatigue limits

5. Axle calculation method

Safety factors

- Analysis of safety factors:
  - Probabilistic analysis
    - EURAXLES WP2
    - S. Beretta, D. Regazzi, Int. J. Fatigue 86 (2016), 13-23.

Material	Constant load - SFmin	Notes	***SF*** **- EN13261**
EA4T	1.15-1.2	Pf = $7 \cdot 10^{-5}$ Strength 2.5% w/o correction for notch sensitivity	1.33

- Similar values both approaches

- Additional studies needed

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6. Conclusions

- Analysis of the current EN 13103/4 standards has been presented
  - Local stresses acting on the transitions of the axles are higher than those calculated according to EN 13103/4
  - Fatigue limits in terms of local stresses are also higher than the values given in EN 13103/4
  - Current procedure leads to reliable results
  - Qualification of the axles according to current standards should be based on nominal stresses
- Recommendations for the numerical modelling of axles have been derived
  - Validation through comparison with experimental tests
- A practical approach for the calculation of axles has been defined
  - Based on local pseudo-stresses to be coherent with the current practice in full scale fatigue tests

6. Conclusions

- EN standards: no probability of failure is associated to the fatigue limits and related safety factors.
    - Comparison with new methods is difficult
- Additional studies should be conducted
    - Load estimation
    - Fatigue limits
    - Definition of safety factors

Acknowledgements

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EURAXLES - Minimizing the risk of fatigue failure of railway axles

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CAF GROUP