Analysis of local stress concentration at transitions

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Contents

Introduction
Objective

- To develop numerical axle modelling using the finite element method
- To analyse the main existing fatigue criteria which can be used to design axles
- To define general recommendations on the generation of numerical models
- To develop a commonly accepted numerical validation process

Contents

Axle calculations - Current status
Introduction

- Actual EN 1310X standards apply beam calculations for axle design
- References:
  - ERRI B136/RP11 (1979)
  - Kammerer (1964)
  - …
- Methodology:
  - Method to calculate forces acting on the axle
  - Method to calculate stresses in different sections of the axle
  - Definition of allowable stresses

Axle calculations - Current status

ERRI B136/RP11 – Calculation of stresses on the axle

- General criteria: $\sigma_d < \sigma_f$
  - σ_d = Dynamic stress
  - σ_f = Allowable stress

$$\sigma_d = K_f \frac{32 \cdot MR}{\pi d^3}$$

- K_f = Fatigue SCF (material dependent)

$$K_f = \frac{S_e\ (unnotched)}{S_e\ (notched)}$$

  - K_f in EN 1310X derived from tests performed by Kammerer

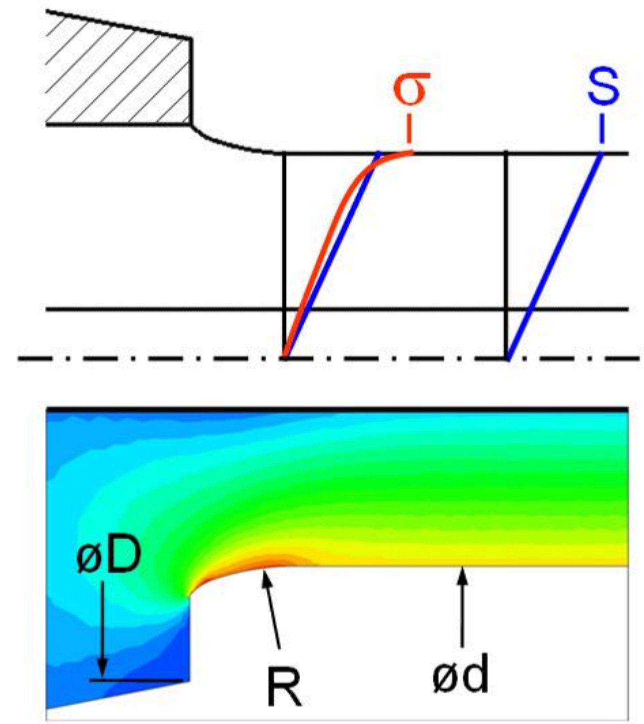
- σ_f = Allowable stresses (EA1N)

	Fatigue strength (MPa)	SF	$\boldsymbol{\sigma_f}$ (MPa)
Body	200	1.2	166
Seat	120	1.2	100

Axle calculations - Current status

Stress concentration factors

- Stress concentration factor, K_t: Relation between the local stress σ and the nominal stress S.
- In bending: $$S = \frac{32 \cdot M \cdot d}{\pi (d^4 - d'^4)}$$
- In the transition there is a biaxial stress state.
- Uniaxial Hooke's law not applicable to strain and stress in longitudinal direction.
- From elasticity theory:
  - Local 1. principal stresses: $K_{t,\sigma 1} = \sigma 1 / S$
  - Local longitudinal strains: $K_{t,\varepsilon} = \varepsilon \times E / S$
  - Local equivalent stresses: $K_{t,\sigma eqv} = \sigma_{eqv} / S$



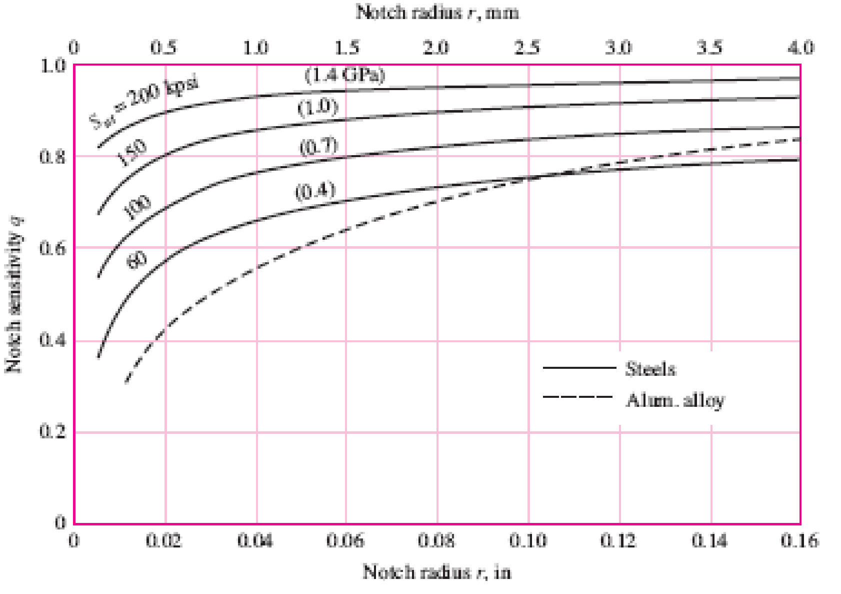
Axle calculations - Current status

Stress concentration factors

- K_f = Fatigue SCF

$$K_f = 1 + q(K_t - 1)$$

  - q: notch sensitivity



- Railway axles:
  - Rm > 550 MPa
  - R = 75 mm

$q \approx 0.95$

$K_f \approx K_t$ (confirmed by experiments)

SEVENTH FRAMEWORK PROGRAMME

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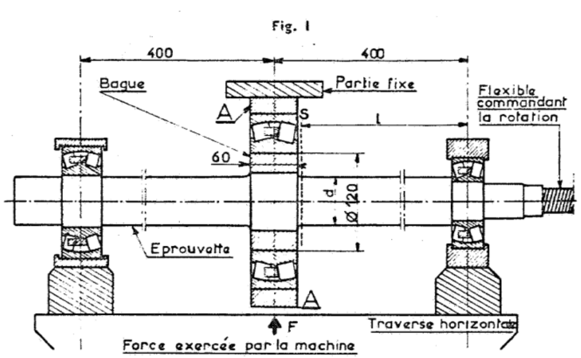
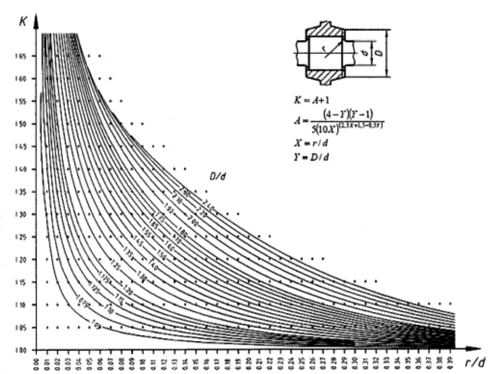
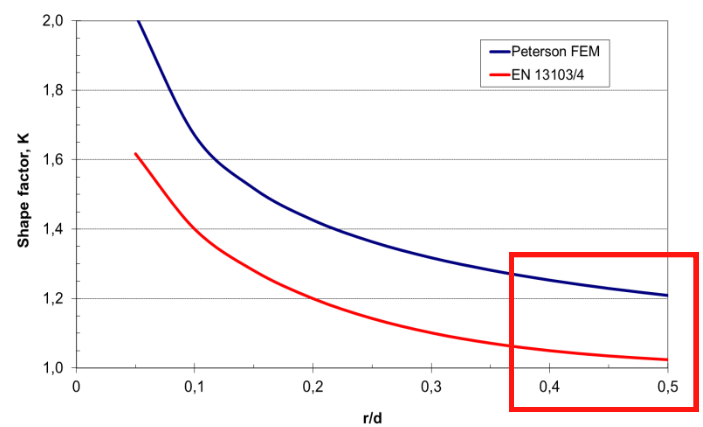
WP2 - New axle fatigue design method

Stress concentration factors

- Kammerer (SNCF) fatigue tests of axles (1/3 scale, d = 60 mm, r = 2, 5, 6, 10, 15, 25 mm) in 1960s
- Nominal stresses calculated by beam theory – No strain gauges applied
- Tests results used to define fatigue limits and shape factors (K_f) introduced in EN 13103/4
- Shape factors of Kammerer/EN standards are ≈ 20% lower than those obtained by measurements, literature or FEA



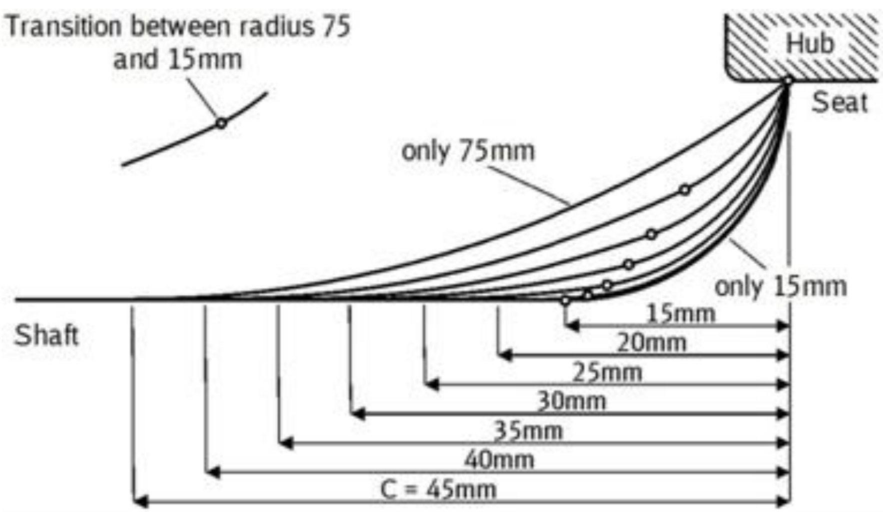


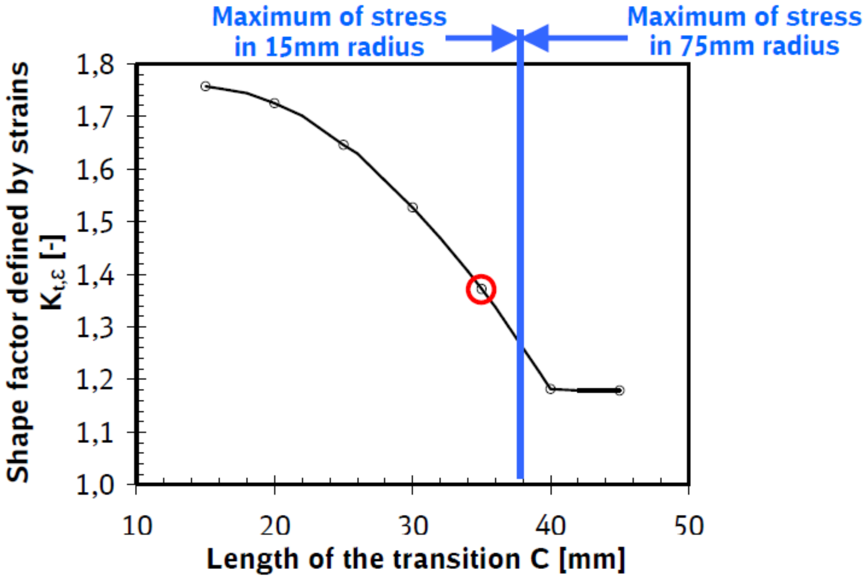


Axle calculations – Current status

Design of the transition – Influence of C on the maximum strain/stress

- For a given set of geometrical parameters, a short transition increases the maximum stress
- **Design criteria**: C > Cmin. Transition length big enough to ensure that the peak stress is at the big radius near to the end of the transition





Axle calculations - Current status

Stress concentration factors

- 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.

ACTUAL DESIGN PROCEDURE IS SAFE

- Numerical methods needed:
  - Optimization of the design of axles
  - Clarifications to avoid misunderstandings.
- Real local fatigue limits needed (WP3)

Contents

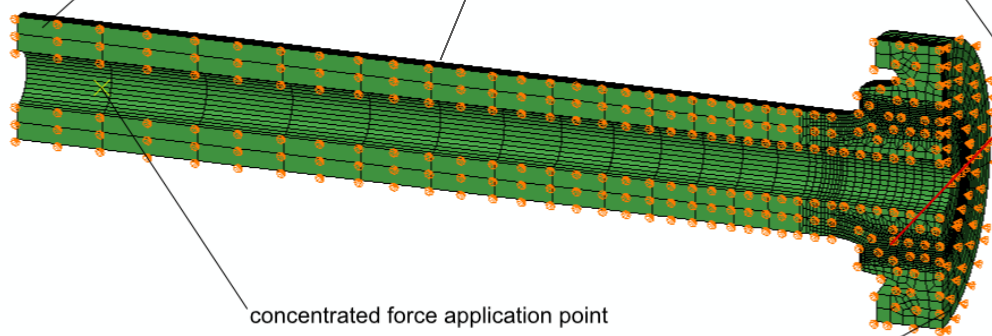
Development of numerical models
Introduction

- Finite element softwares:
  - Abaqus, Ansys
  - Others (Cosmos, I-deas NX, CATIA)
- Development of models
  - Convergence analysis
- Model validation: Comparison with experiments

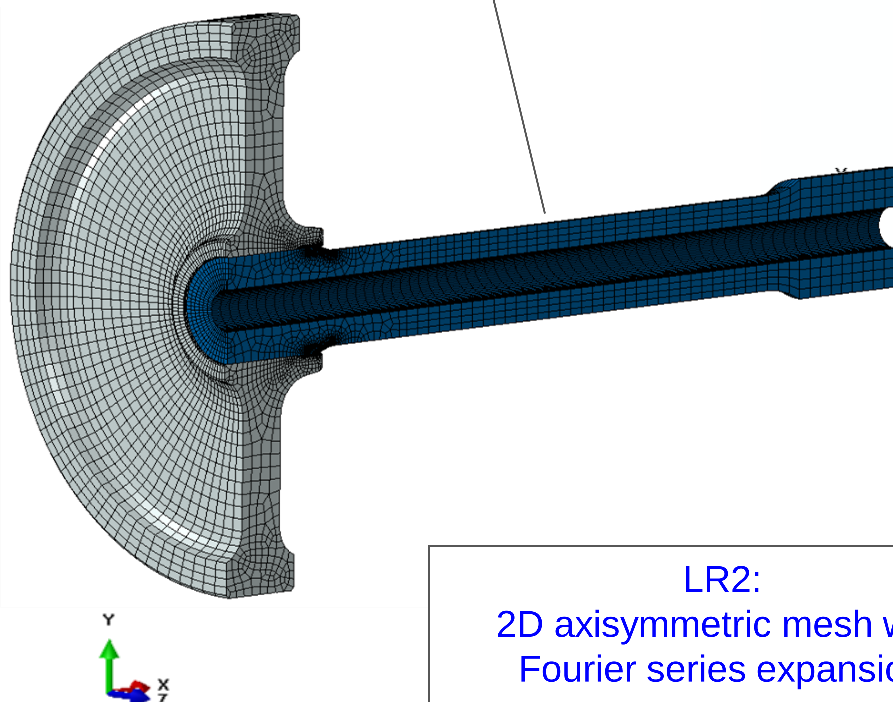
Development of numerical models

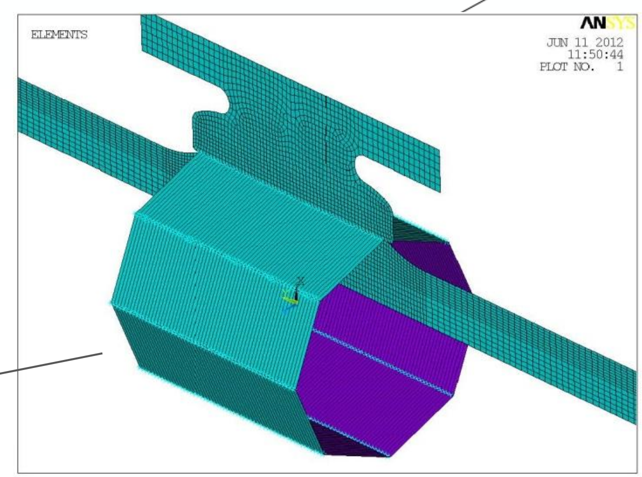
Models

LR2:
3D mesh



LR1:
3D mesh





LR2:
2D axisymmetric mesh with
Fourier series expansion

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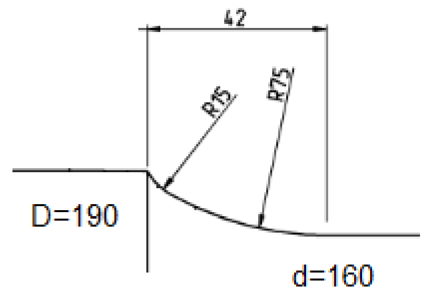
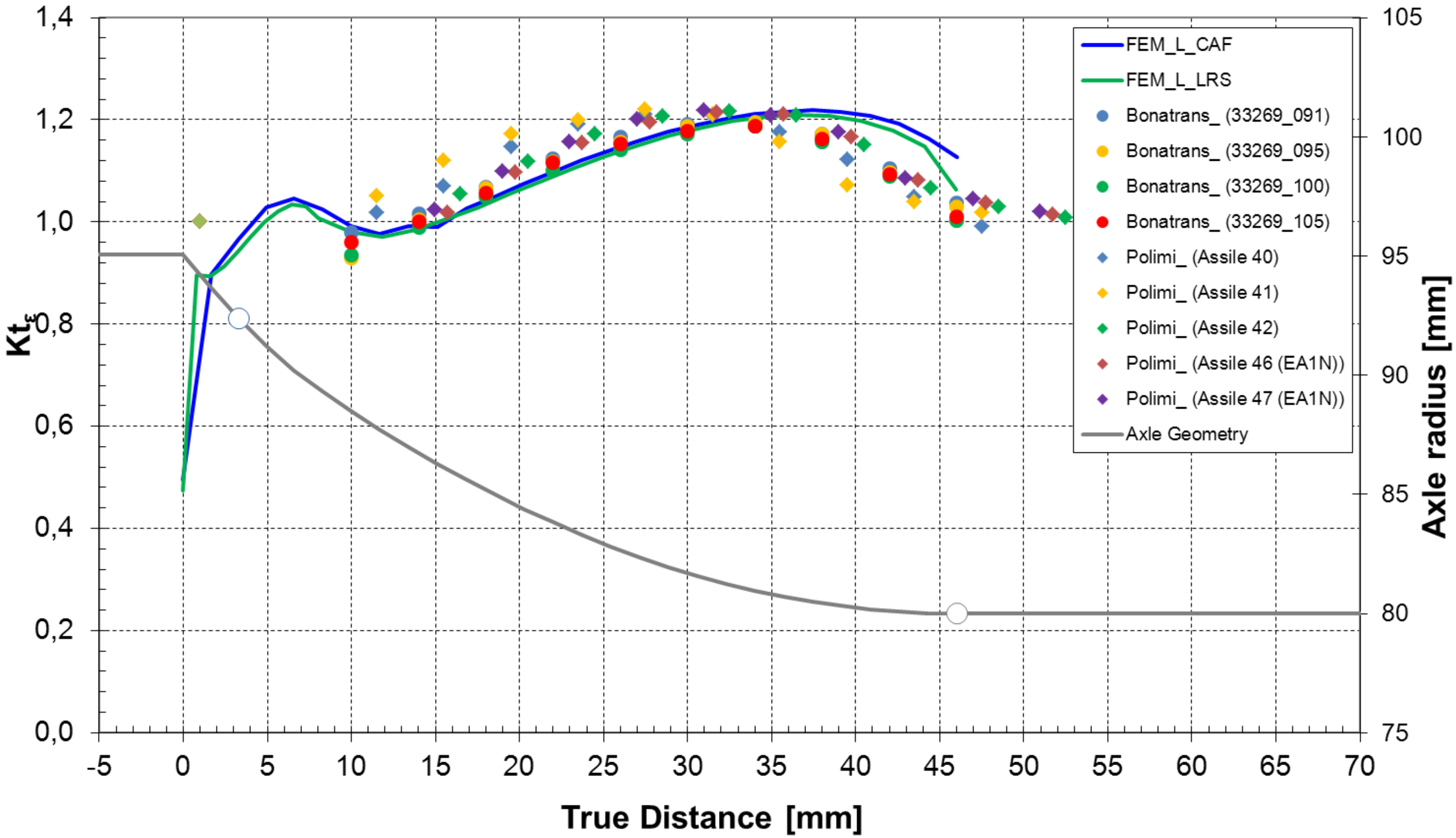
Model validation

F1 D/d=1.187

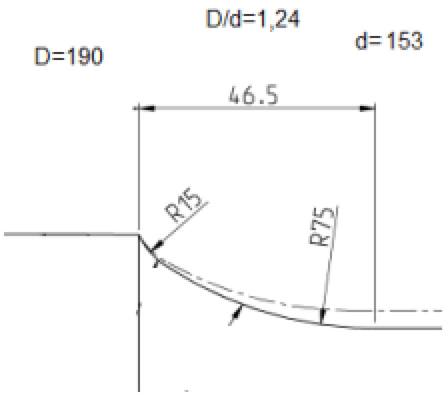


Kt,ε max = 1,20

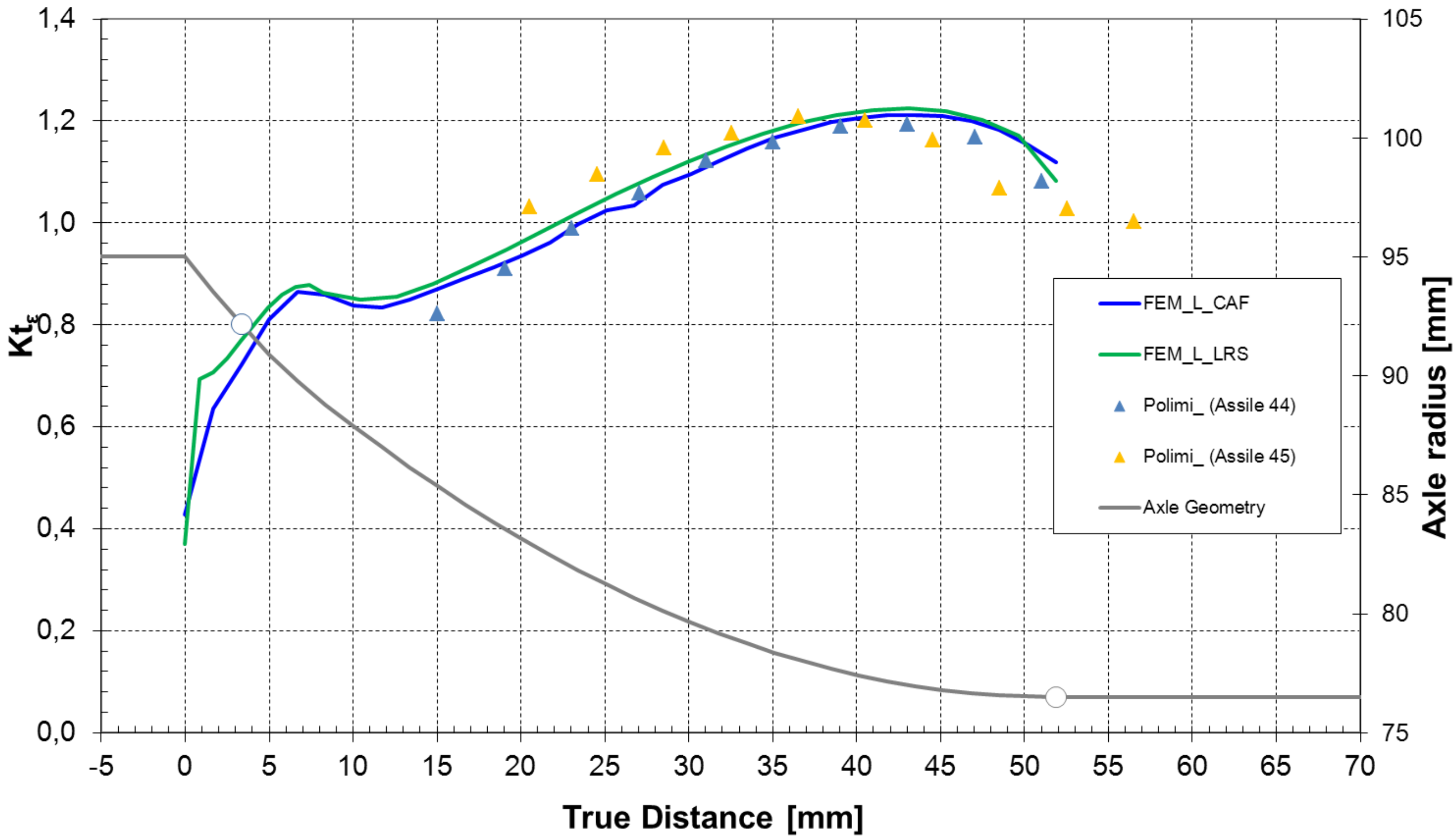


Model validation

F1 D/d=1.24

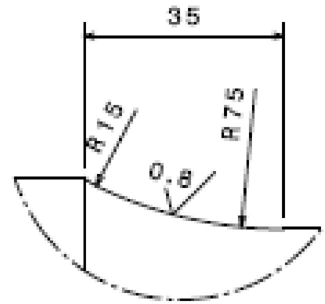


Kt,ε max = 1,20

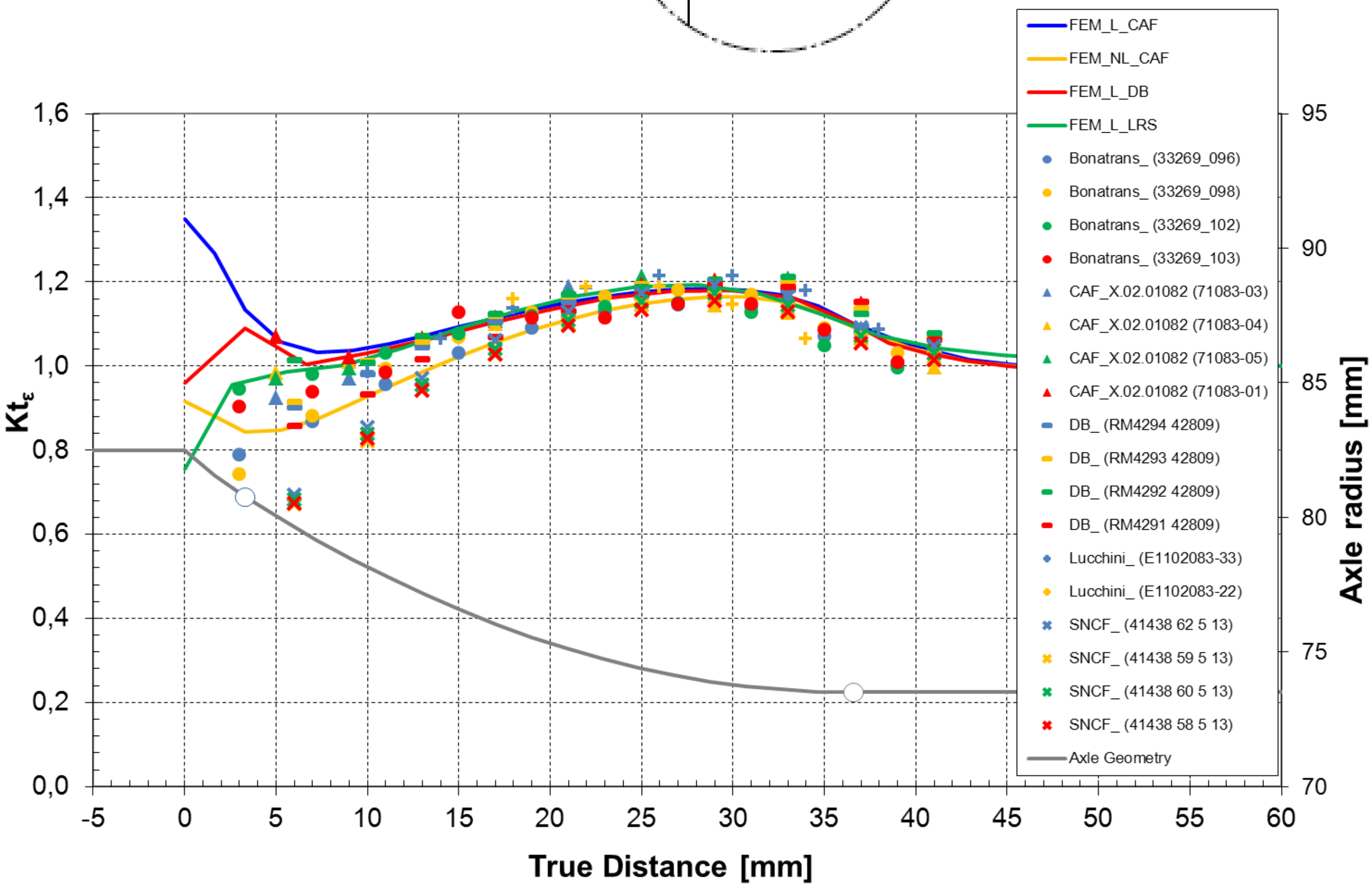


Model validation

F4 D/d=1.12

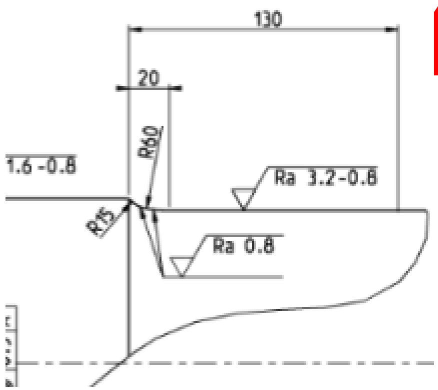


Kt,ε max = 1,21

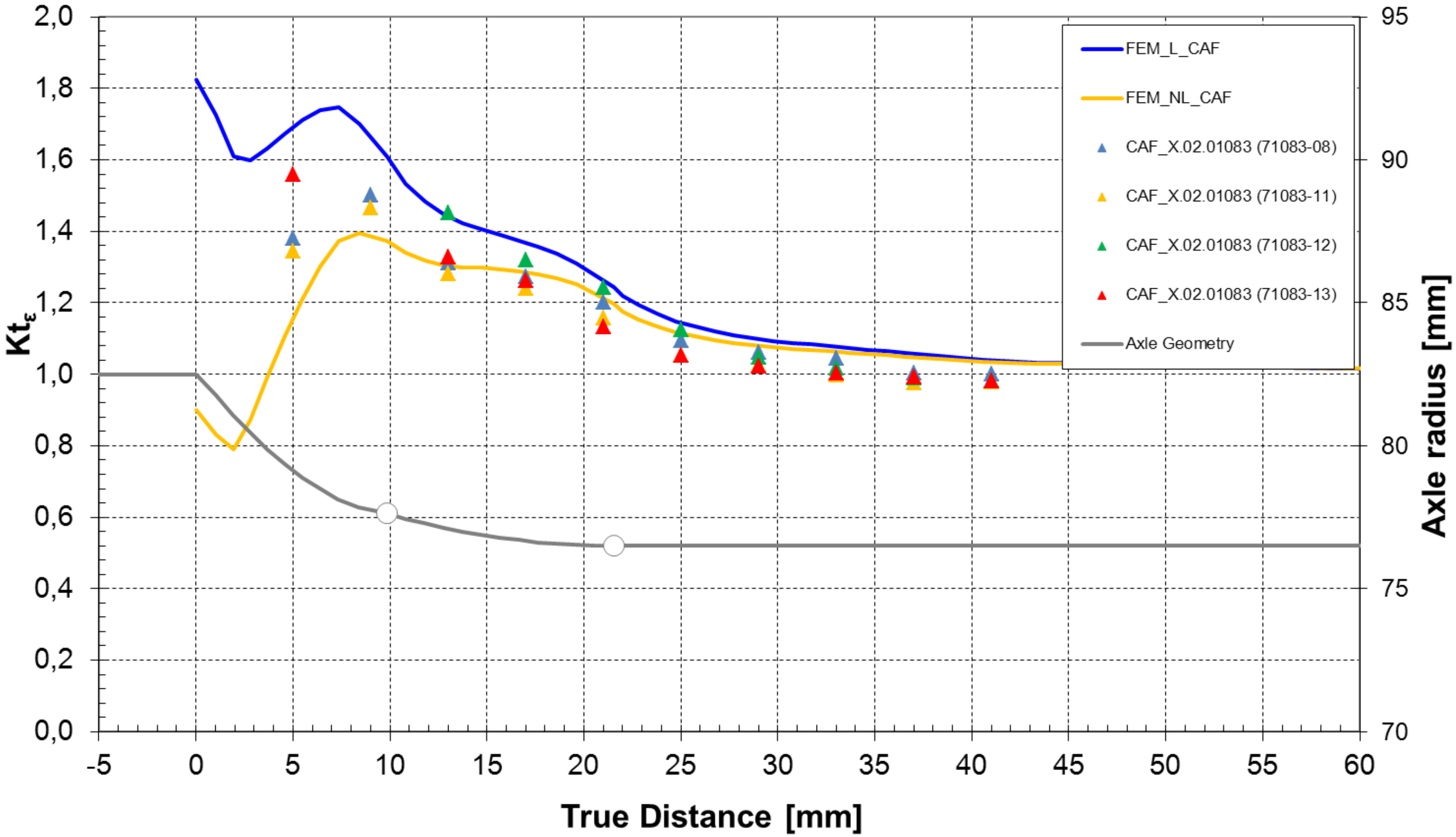


Model validation

F4 D/d=1.08

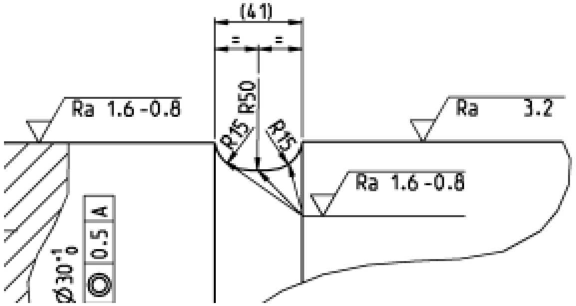


Kt,ε max = 1,56

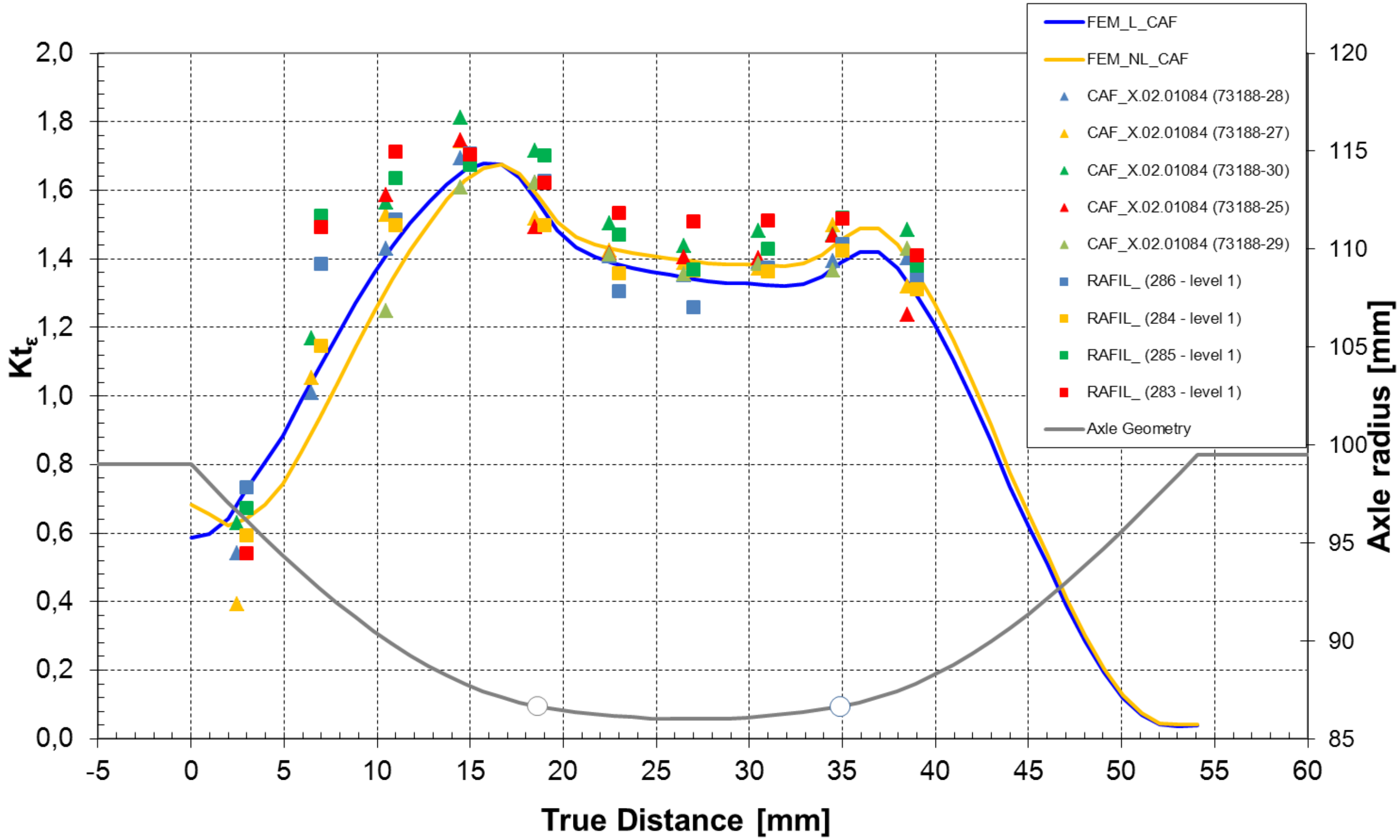


Model validation

Motor axle F1 D/d=1.15



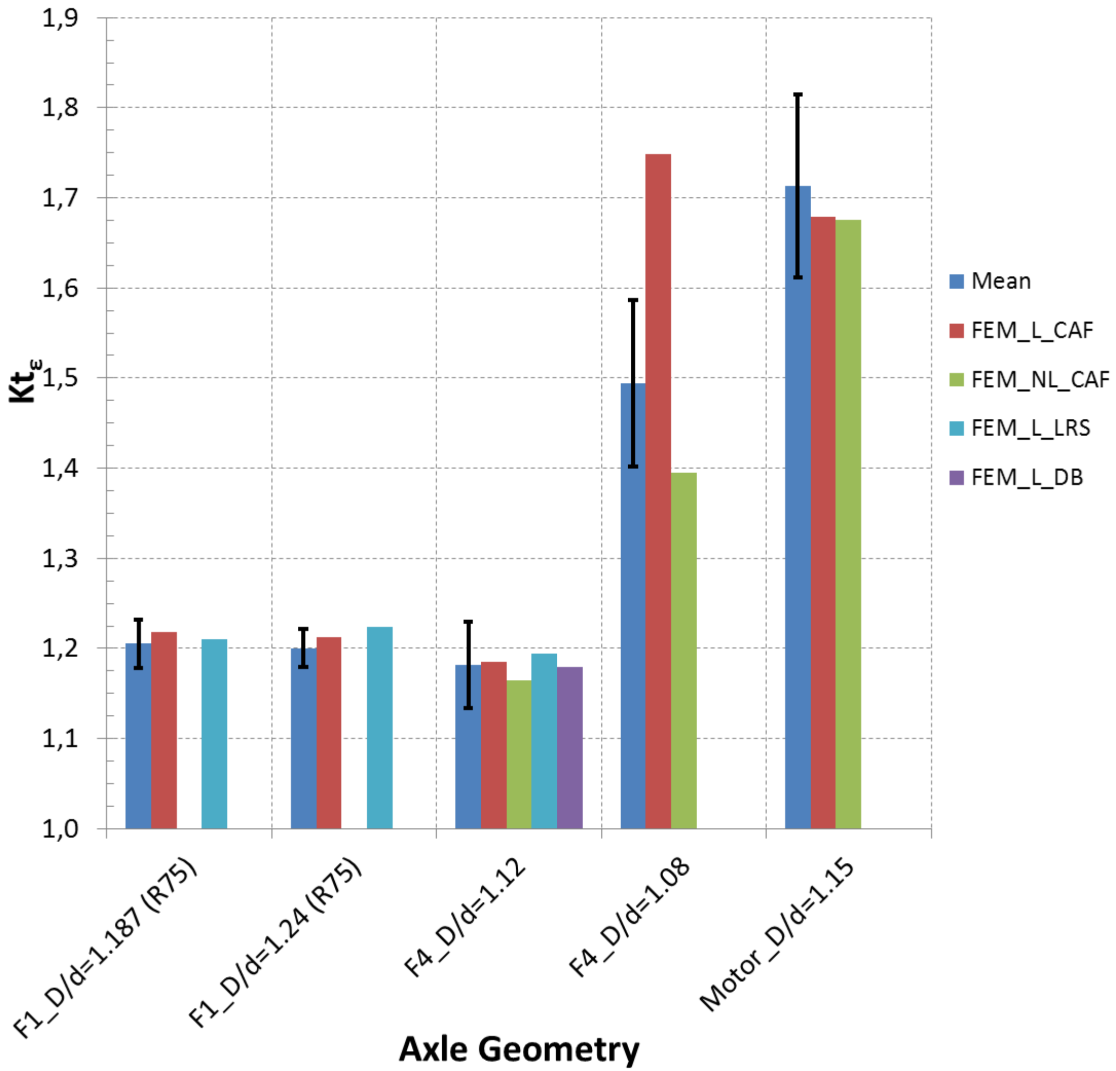
Kt,ε max = 1,81



Model validation

Kt - Summary

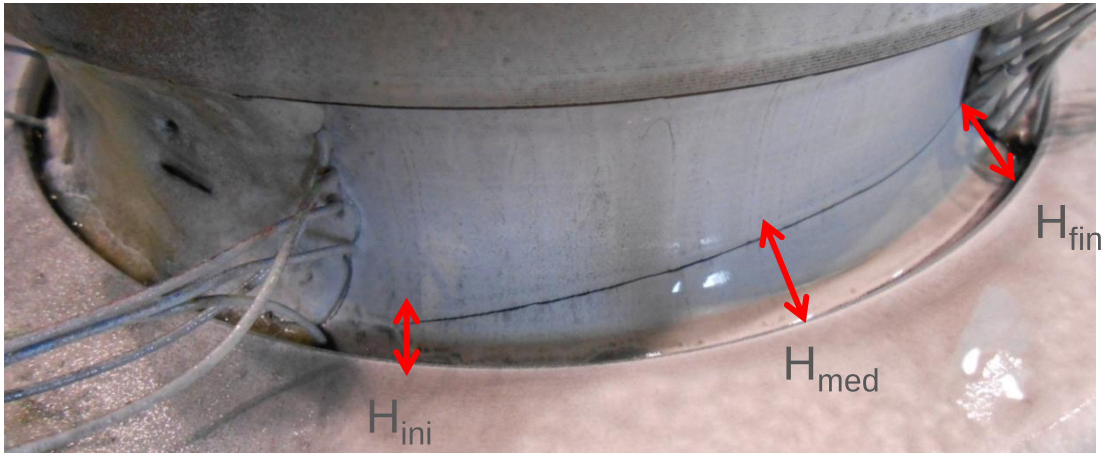
- Good adjustment of models
- Linear models give better adjustment than non-linear models (generally applicable to high interference areas, e.g. wheels and pinions)



Model validation

Fatigue analysis - Motor axle F1 D/d=1.15

- Test results
  - H_{med} is the point of crack initiation

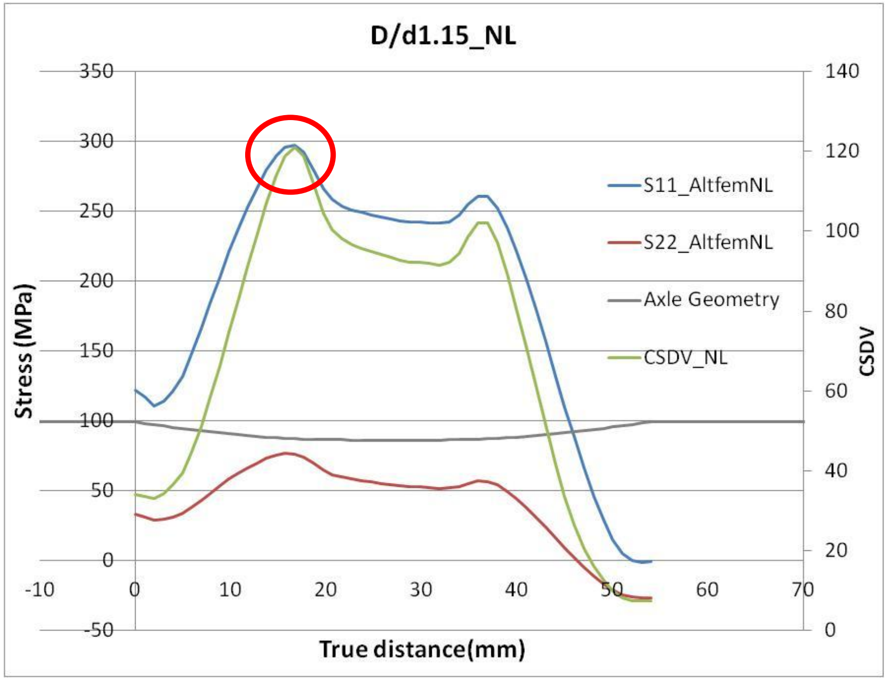


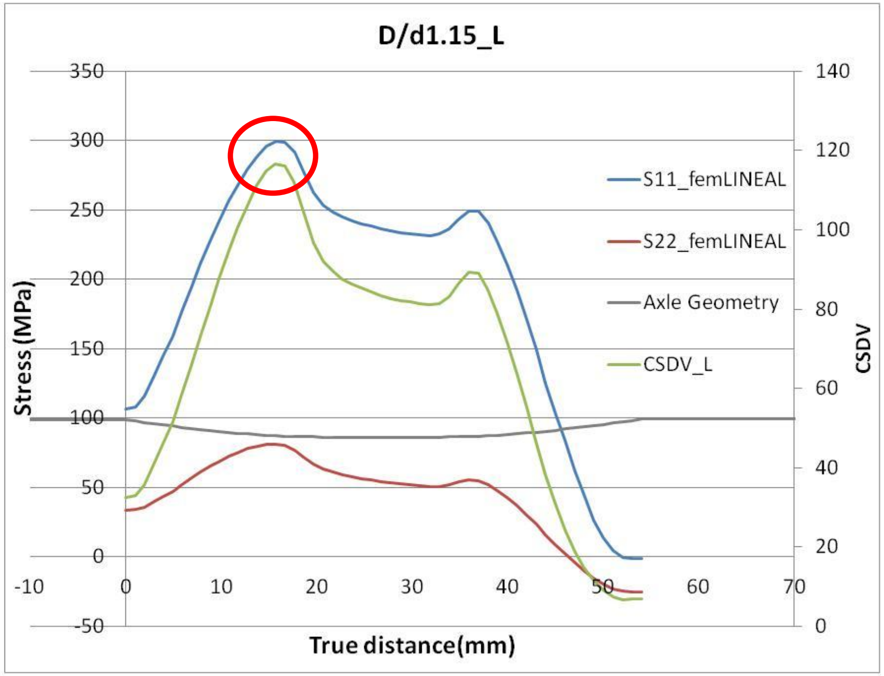
Serial nº	Crack extension(mm)	H ini(mm)	H fin(mm)	H med(mm)
73188-27	115	13	21	16
73188-25	120	9	24	17
73188-28	120	8	22	16
73188-30	120	10	23	16

Model validation

Fatigue analysis - Motor axle F1 D/d=1.15

- Principal Stresses and Dang Van Multiaxial fatigue coefficient along the transition
  - CSDV non linear model > linear model (influence of mean stresses)
  - CSDV non linear/ CSDV linear = 1.04
- Failure (and position) well predicted by both models



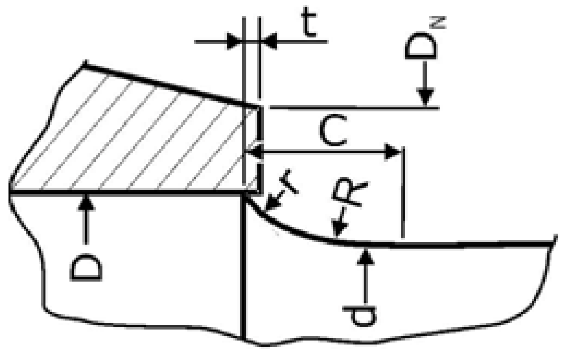


Contents

Parametric analysis of stress concentration factor

Motivation

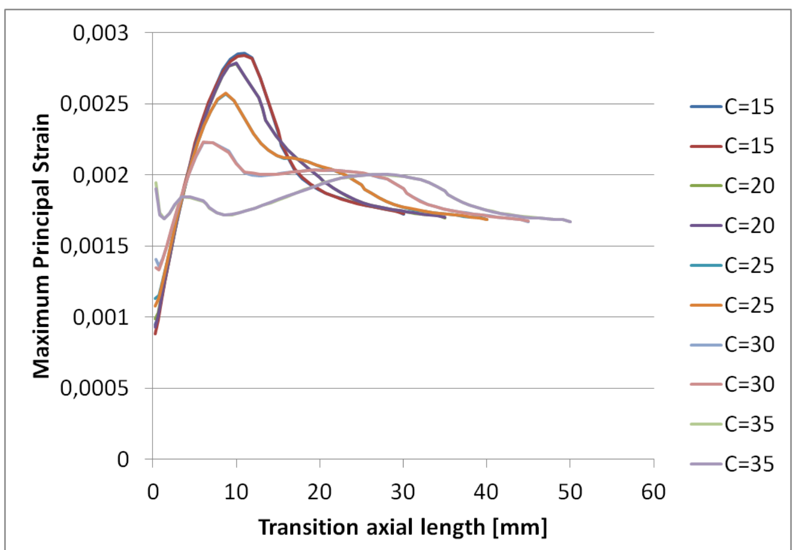
- K factors of EN 13103/4 should be reviewed.
- Multiple radii in typical axle transitions.
  - Position of the peak stress can be in small radius
  - Peak stress (and consequently Kt) may differ from bibliography data
- Objective: To derive mathematical expresions for Kt in typical simple transitions of railway axles.
- Parametric analysis based on DOE (Design of Experiments) has been performed.
- Geometrical constraints to avoid unfeasible combinations - final number of combinations = 8.880

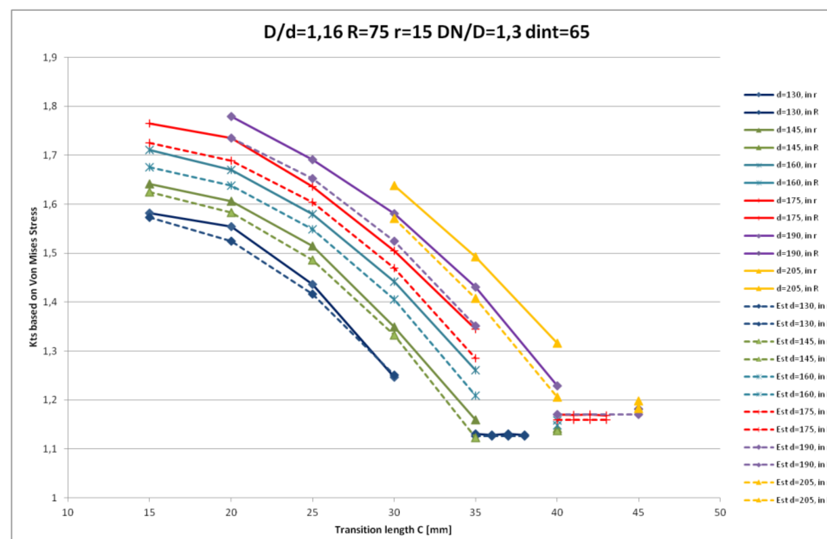


Parametric analysis of stress concentration factor

Results

- Output:
  - Maximum values along the transition area in terms of von Mises stress, maximum principal stress and maximum principal strain.
  - Location in axial coordinates of the aforementioned variables.
  - Values of the maximum stress/strain concentration factor Kt.





Parametric analysis of stress concentration factor

Results

- Numerical adjustment:
  - Minimum transition length C:

$$C_{min} = -8.3257 - 0.1845 \cdot d + 0.6364 \cdot R + 7.0194 \cdot \frac{D_n}{D} + 0.0007342 \cdot d \cdot R + 0.2166 \cdot d \cdot \frac{D}{d} - 0.002060 \cdot d \cdot r - 0.3632 \cdot R \cdot \frac{D}{d} + 0.004535 \cdot R \cdot r + 0.4270 \cdot \frac{D}{d} \cdot r - 0.2936 \cdot \frac{D_n}{D} \cdot r$$

  - Kt when peak stress at R:

$$K_{t,VM} = 1.2045 + 0.002535 \cdot d - 0.007553 \cdot R + 0.03702 \cdot \frac{D_n}{D}$$ if C<25 mm

$$K_{t,VM} = 1.2453 + 0.001278 \cdot d - 0.003258 \cdot R - 0.001209 \cdot C$$ if C ≥ 25 mm

Parametric analysis of stress concentration factor

Assessment of Cmin

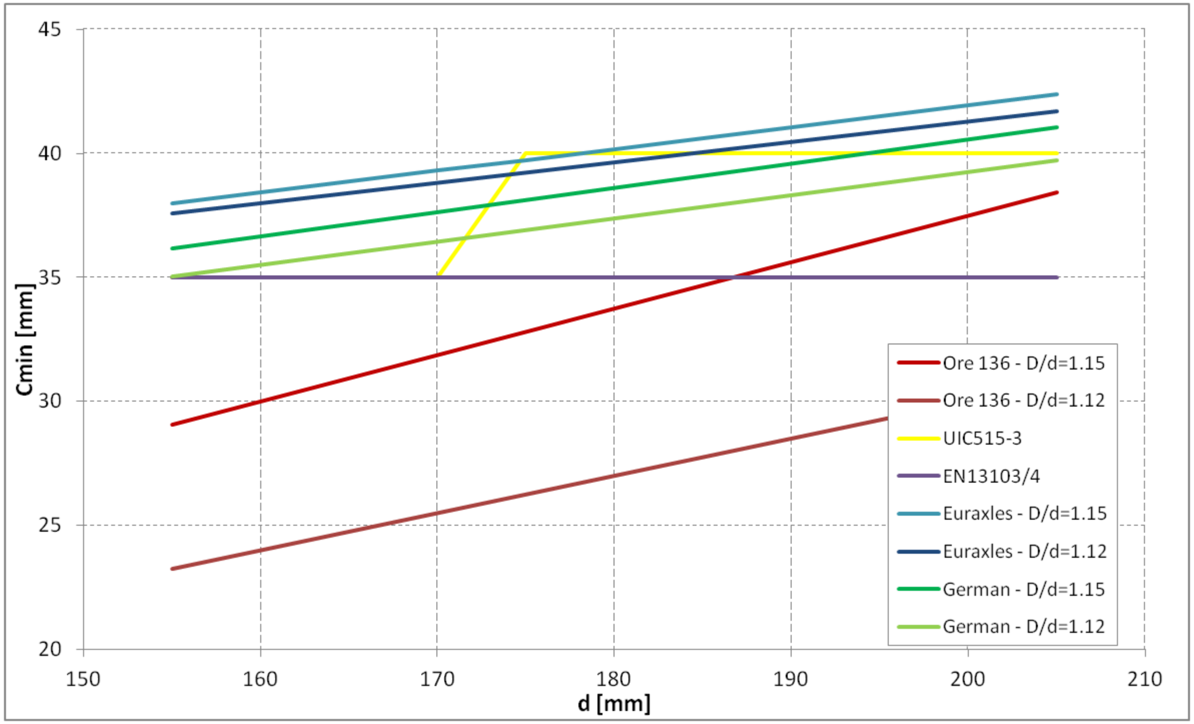
- Equations:

	Cmin [mm]
Ore 136	$1.25 \cdot d \cdot \left(\frac{D}{d} - 1 \right)$
UIC515-3	35 if $d \in (155,170)$ 40 if $d \in (175,205)$
EN13103/4	e.g. 35
EIBFW-I Project	$C \geq (0{,}0952 \cdot d + 20{,}6) \frac{\left(\frac{D}{d} - 0{,}2113\right)}{0{,}9351} \cdot \frac{\left(\frac{D_N}{D} + 5{,}192\right)}{6{,}468}$
Euraxles	$C_{min} = -8.3257 - 0.1845 \cdot d + 0.6364 \cdot R + 7.0194 \cdot \frac{D_n}{D} + 0.0007342 \cdot d \cdot R + 0.2166 \cdot d \cdot \frac{D}{d} - 0.002060 \cdot d \cdot r - 0.3632 \cdot R \cdot \frac{D}{d} + 0.004535 \cdot R \cdot r + 0.4270 \cdot \frac{D}{d} \cdot r - 0.2936 \cdot \frac{D_n}{D} \cdot r$
	$C_{min} = -3.79336 + 0.0384789 \cdot d + 0.381324 \cdot R + 0.0279497 \cdot D_N$

Parametric analysis of stress concentration factor

Assessment of Cmin

- Graphical comparison:
  - EN1310X not conservative

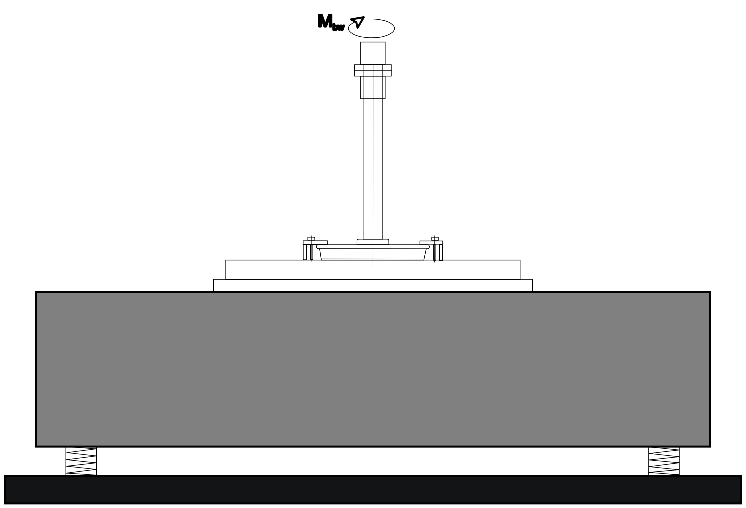


Contents

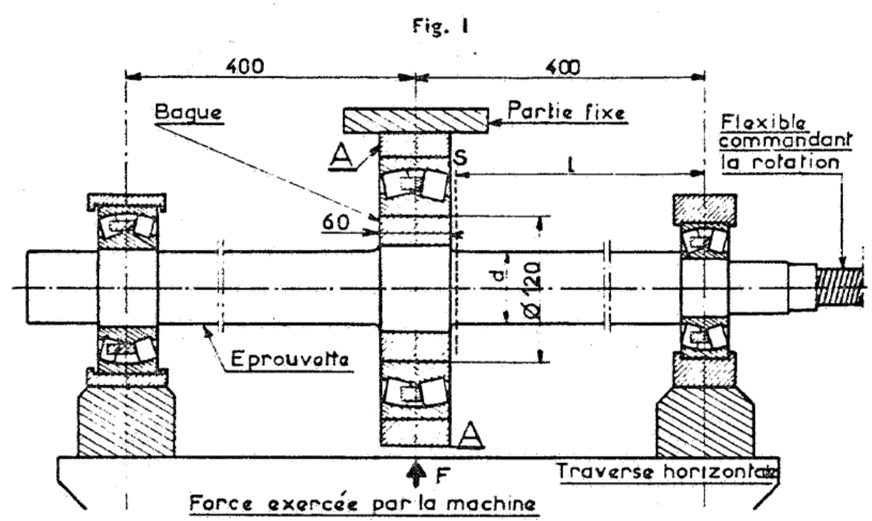
Simulation of axle testing

Fatigue test rigs

- LR1: “Minden” type. A resonant rotating fatigue test system with an unbalanced mass rotating at the top of the axle which generates the desired bending moment at the section of interest.
- LR2: “Vitry” type. Three point bending with a load applied at the centre of the axles by an hydraulic actuator.



LR1: “Minden”

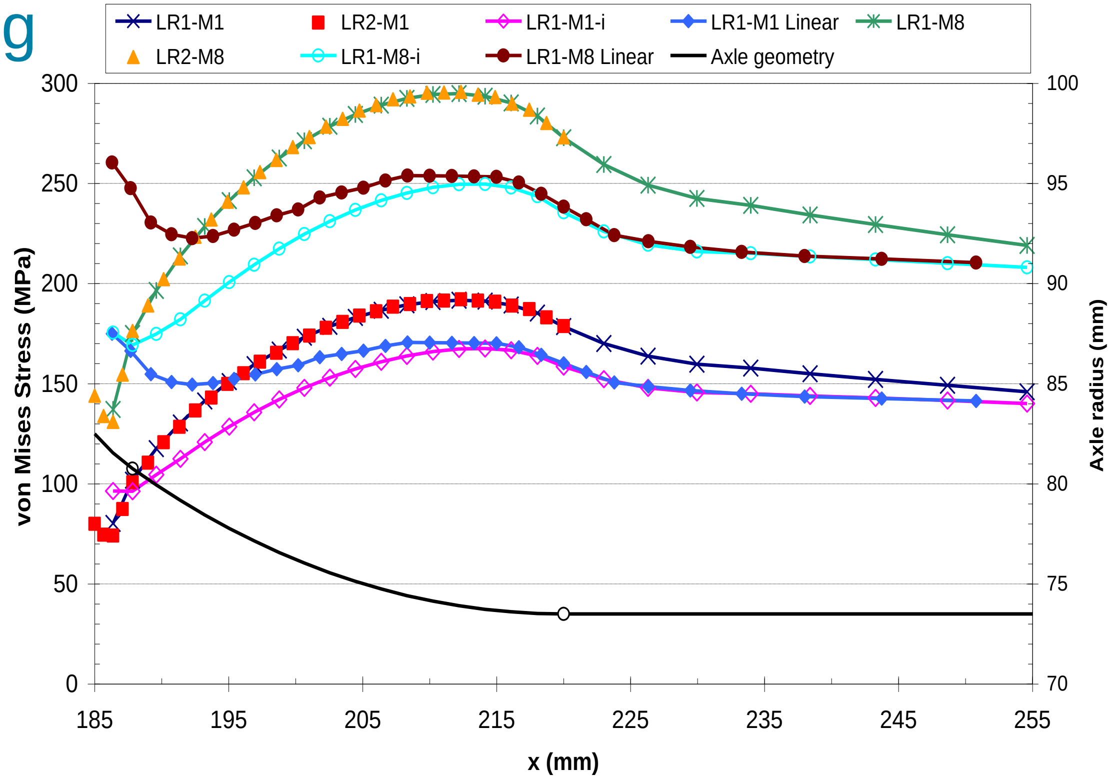


LR2: “Vitry”

Simulation of axle testing

Results – Transition

- Analysis:
  - 2 test rigs
  - Cases: M1 & M8
  - Linear & Non-linear models
  - Stress due to interference (constant load)
- Same results for both test rigs.
- Linear models: Good prediction of value and position of the peak stress.
- Kt factors similar in all cases.



Maximum friction coefficent: 0.3

	45 KNm	56 KNm	67 KNm
i = 0.308 mm	1.2485	1.2464	1.2422
I = 0.165 mm	1.2359	1.2286	1.2222

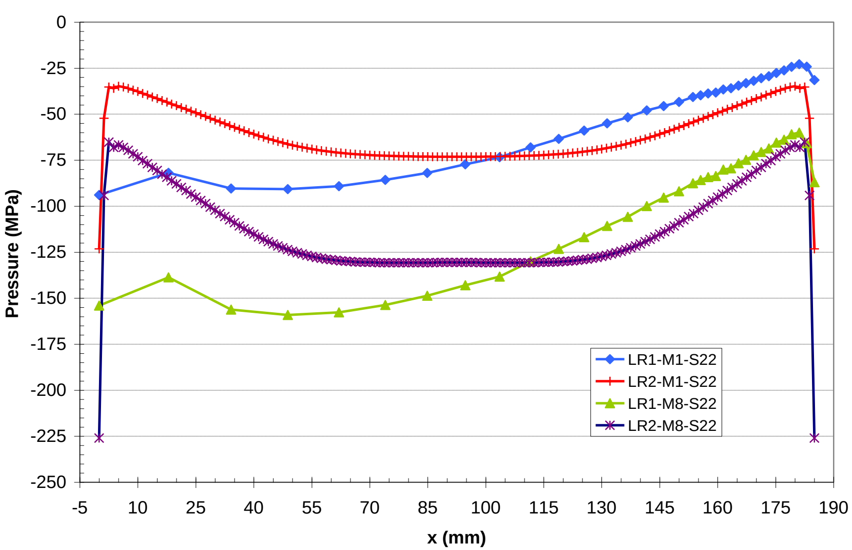
Minimum friction coefficent: 0.05

	45 KNm	56 KNm	67 KNm
i = 0.308 mm	1.2328	1.2304	1.2288
I = 0.165 mm	1.2295	1.2282	1.2275

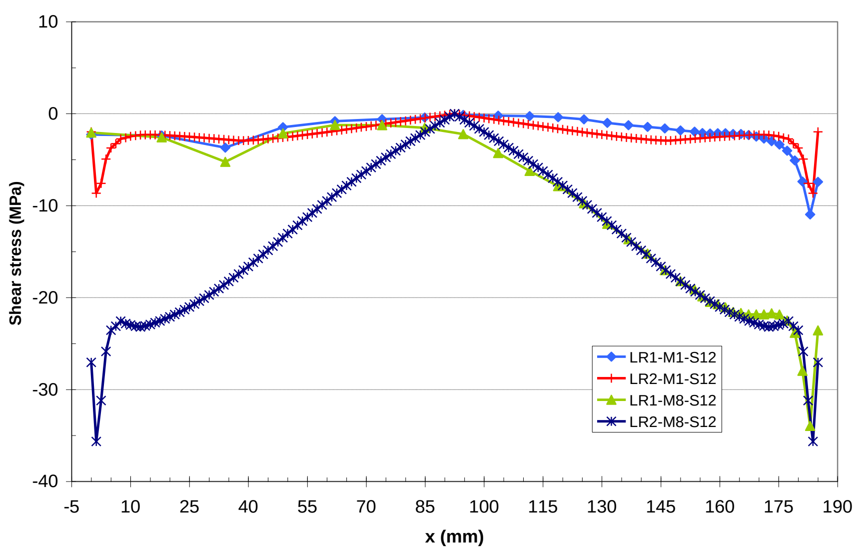
Simulation of axle testing

Results – Seat

- Similar stress distributions in LR1 and LR2 near the axle body transition.
- LR2, symmetrical distributions theoretically predicted (conical entrance not considered in the models)



Pressure



Shear stress

Contents

Complete wheelset simulation

Introduction

- Analysis of complete wheelsets
  - Motor
  - Trailer
- 3D and 2D Axisymmetric with Fourier's series expansion
- Comparison with EN 1310X

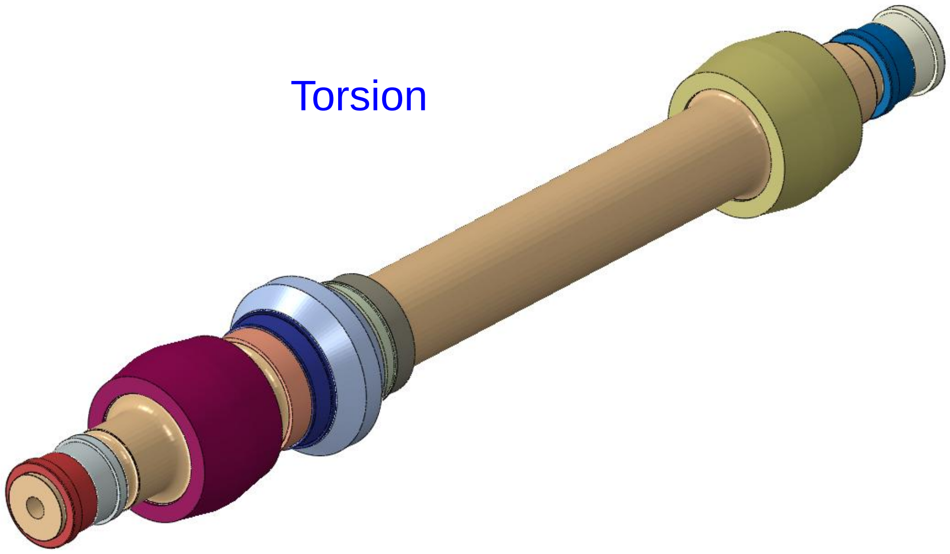
Complete wheelset simulation

EMU Motor wheelset - Model

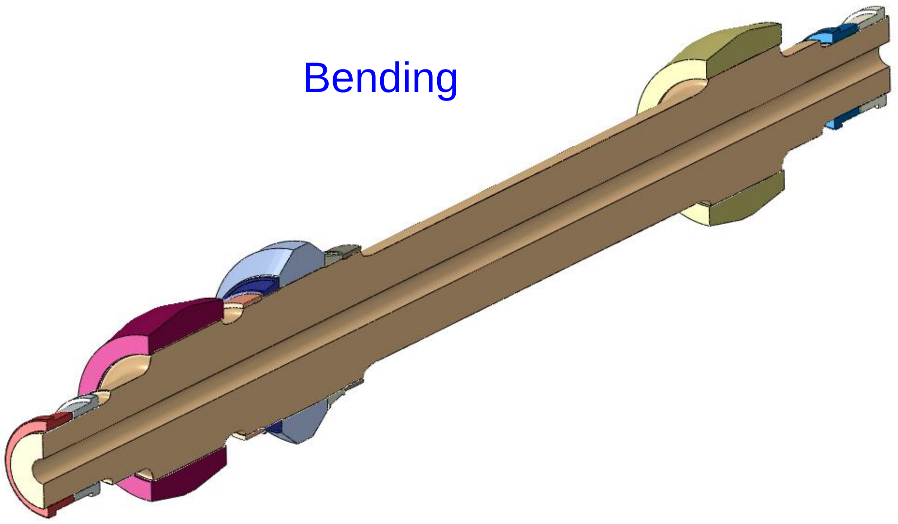
- Non-linear and linear models
- Skin of shell elements for post-processing
- Calculation times high

	Full model	Half model
Nodes	1261532	792680
Elements	1233132	764852

Torsion



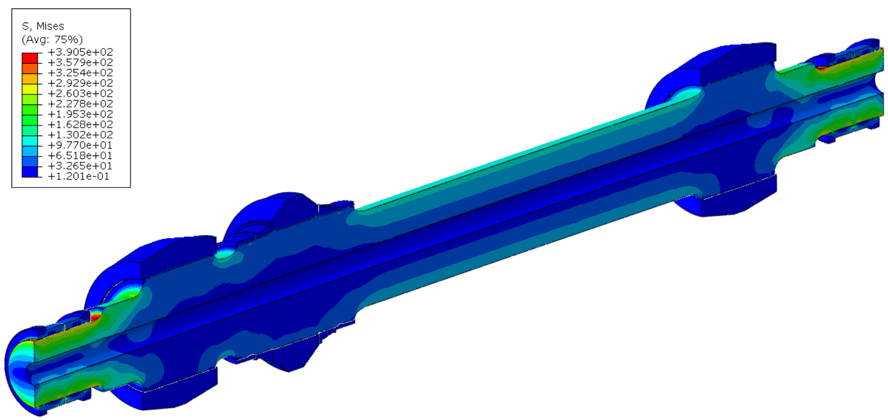
Bending

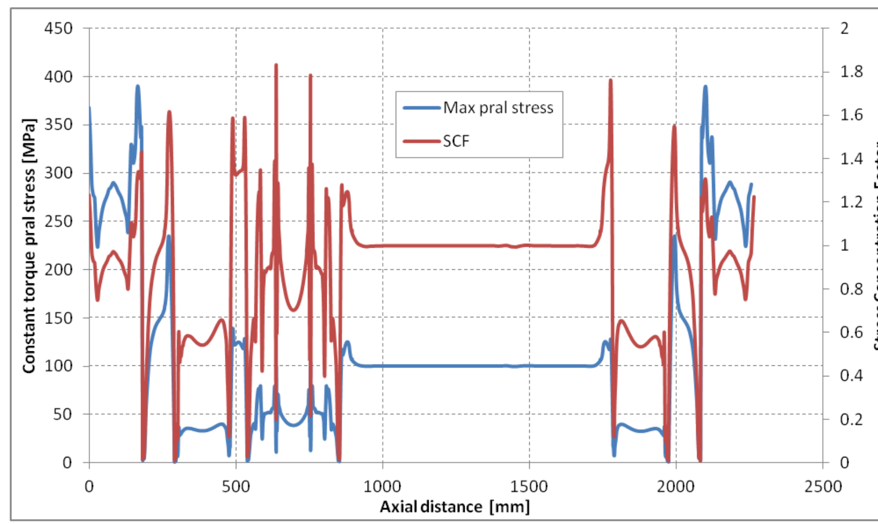


Complete wheelset simulation

EMU Motor wheelset – Results example

- Stress distribution along the surface of the axle.
- SCF calculation. Can be applied for beam analysis (as EN 1310X)





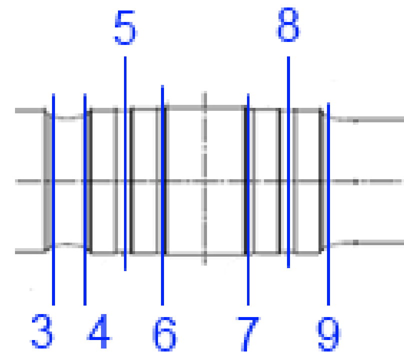
Complete wheelset simulation

EMU Motor wheelset – Analysis methods

- Method 1:
  - Constant bending moment and torque applied to the FEM model (linear and non linear)
  - Calculation of Kt,ε in different sections
  - Application of beam theory (as current EN 1310X)
- Method 2:
  - Application of EN 1310X loads to the model
  - Calculation of stress distributions in the different sections
  - Fatigue criteria (Tresca) directly from post-processed results

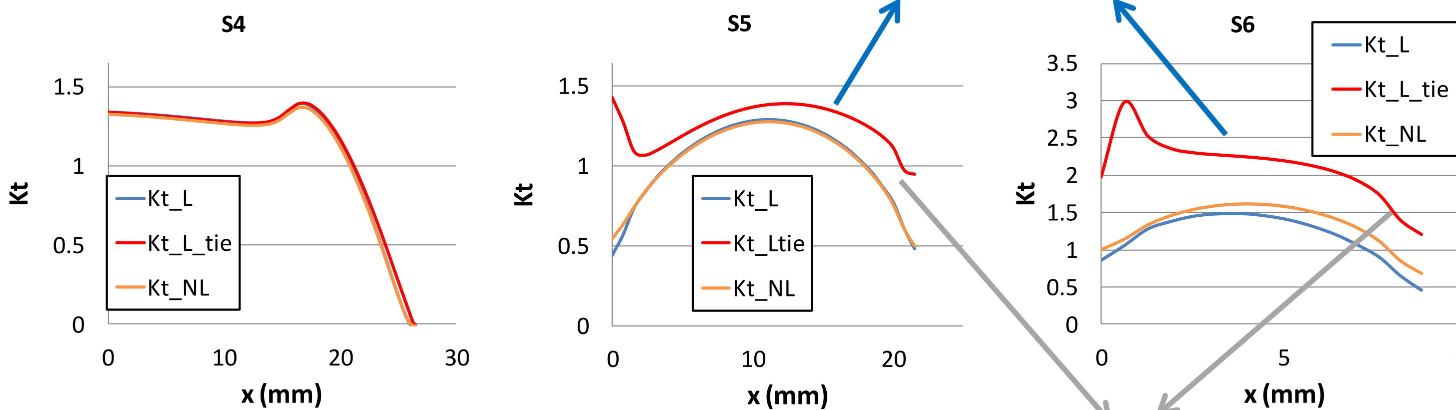
Complete wheelset simulation

EMU Motor wheelset – Results



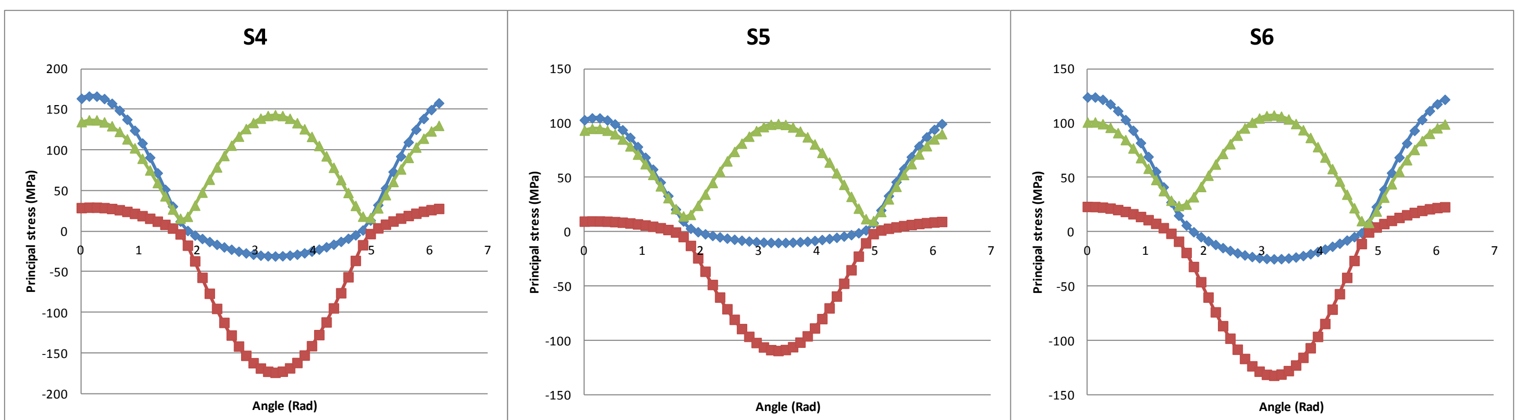
Linear models with mounted components too conservative

- Method 1



Conical entrance

- Method 2



Complete wheelset simulation

EMU Motor wheelset – Results: Method 1

$$\sigma = \sigma_1 - \sigma_2 = \sqrt{\sigma_n^2 + 4\sigma_t^2} = \sqrt{(K_\sigma \cdot \sigma_{ba})^2 + 4(K_\tau \cdot \tau_{ta})^2}$$

$$\sigma_{allow} = E \cdot \varepsilon_1$$

$$SF = \frac{\sigma_{allow}}{\sigma}$$

	Nominal stresses		FE values Strain-based		Methodology 1						EN 13104				
Section	σ_{ba}	τ_{ta}	$\kappa_{\varepsilon EF.}$	$\kappa_{\gamma EF.}$	σ_1	σ_2	$\sigma 2/\sigma 1$	$\sigma=\sigma_1-\sigma_2$	σ_{allow}	SF	K	σ	σ_{allow}	SF	SF_1/SF_{EN}
1	65.08	0.00	1.26	1.15	82.02	0.00	0.00	82.02	285	**3.47**	1.012	65.88	240	**3.64**	0.95
2	77.19	0.00	1.47	1.26	113.44	0.00	0.00	113.44	285	**2.51**	1.05	81	240	**2.96**	0.85
3	125.17	5.23	1.52	1.29	190.18	-0.24	0.00	190.42	285	**1.50**	1.056	132.63	240	**1.81**	0.83
4	125.17	5.23	1.32	1.17	165.80	-0.23	0.00	166.03	285	**1.72**	1.056	132.63	240	**1.81**	0.95
5	85.22	3.53	1.26	1.17	107.78	-0.16	0.00	107.93	285	**2.64**	1.295	110.73	240	**2.17**	1.22
6	79.23	3.27	1.54	1.38	121.92	-0.17	0.00	122.09	285	**2.33**	1.678	133.4	240	**1.80**	1.30
7	78.02	-3.27	1.54	1.38	120.30	-0.17	0.00	120.46	285	**2.37**	1.678	131.37	240	**1.83**	1.30
8	82.75	-3.53	1.26	1.16	104.35	-0.16	0.00	104.51	285	**2.73**	1.295	107.55	240	**2.23**	1.22
9	127.39	-5.60	1.21	1.12	153.98	-0.25	0.00	154.23	285	**1.85**	1.018	130.25	240	**1.84**	1.00
10	88.29	-5.60	1.35	1.16	119.29	-0.35	0.00	119.64	285	**2.38**	1.018	90.61	240	**2.65**	0.90
11	53.41	0.00	1.47	1.26	78.52	0.00	0.00	78.52	285	**3.63**	1.05	56.05	240	**4.28**	0.85
12	45.06	0.00	1.26	1.15	56.79	0.00	0.00	56.79	285	**5.02**	1.012	45.59	240	**5.26**	0.95

Complete wheelset simulation

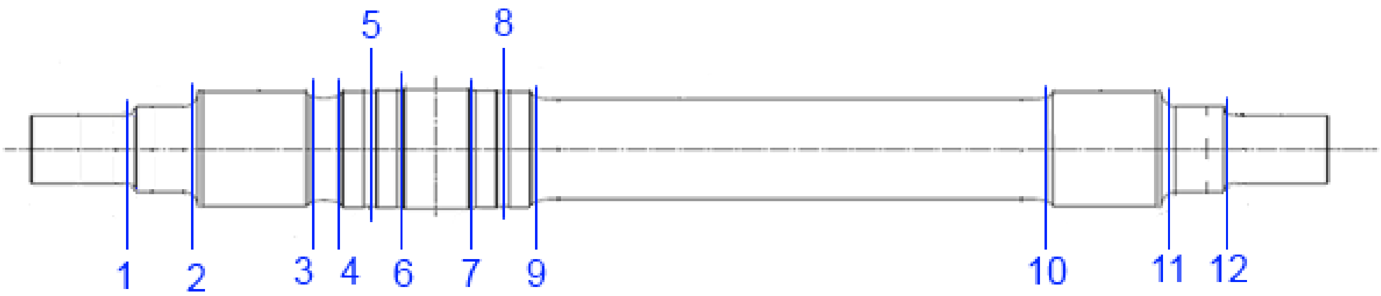
EMU Motor wheelset – Results: Method 2

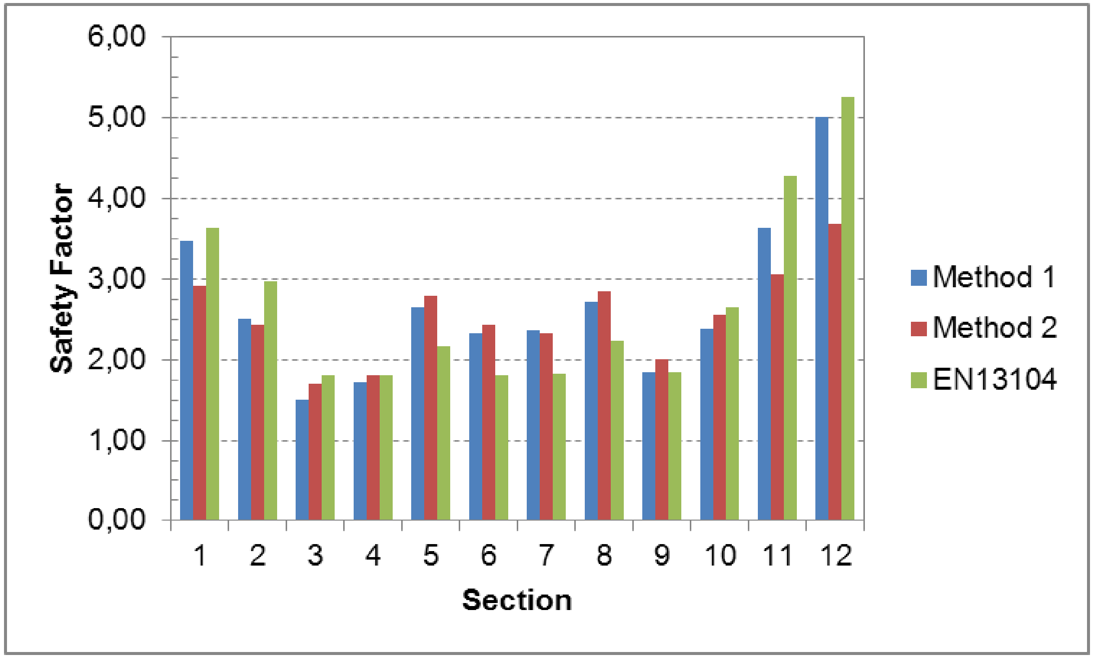
σ_{allow}: Corrected value for E·ε1 = 285 MPa

	Nominal stresses		FE values Strain-based		Methodology 1						Methodology 2							
Section	σ_{ba}	τ_{ta}	$K_{\varepsilon EF.}$	$K_{\gamma EF.}$	σ_1	σ_2	$\sigma 2/\sigma 1$	$\sigma=\sigma_1-\sigma_2$	σ_{allow}	SF	σ_1	σ_2	$\varepsilon 1*E$	$\sigma 2/\sigma 1$	$\sigma=\sigma_1-\sigma_2$	σ_{allow}	SF	SF_1/SF_2
1	65.08	0.00	1.26	1.15	82.02	0.00	0.00	82.02	285.00	**3.47**	102.32	14.81	97.87	0.14	87.51	254.8	**2.91**	1.19
2	77.19	0.00	1.47	1.26	113.44	0.00	0.00	113.44	285.00	**2.51**	124.96	26.12	117.12	0.21	98.84	240.5	**2.43**	1.03
3	125.17	5.23	1.52	1.29	190.18	-0.24	0.00	190.42	285.00	**1.50**	179.40	39.18	167.64	0.22	140.21	238.4	**1.70**	0.88
4	125.17	5.23	1.32	1.17	165.80	-0.23	0.00	166.03	285.00	**1.72**	166.27	29.29	157.48	0.18	136.97	247.9	**1.81**	0.95
5	85.22	3.53	1.26	1.17	107.78	-0.16	0.00	107.93	285.00	**2.64**	104.67	9.69	101.76	0.09	94.98	266.0	**2.80**	0.94
6	79.23	3.27	1.54	1.38	121.92	-0.17	0.00	122.09	285.00	**2.33**	123.89	23.08	116.96	0.19	100.81	245.6	**2.44**	0.96
7	78.02	-3.27	1.54	1.38	120.30	-0.17	0.00	120.46	285.00	**2.37**	130.25	25.12	122.72	0.19	105.14	244.2	**2.32**	1.02
8	82.75	-3.53	1.26	1.16	104.35	-0.16	0.00	104.51	285.00	**2.73**	102.65	8.29	100.16	0.08	94.35	268.5	**2.85**	0.96
9	127.39	-5.60	1.21	1.12	153.98	-0.25	0.00	154.23	285.00	**1.85**	148.37	19.97	142.37	0.13	128.39	257.0	**2.00**	0.92
10	88.29	-5.60	1.35	1.16	119.29	-0.35	0.00	119.64	285.00	**2.38**	118.44	23.10	111.51	0.20	95.34	243.7	**2.56**	0.93
11	53.41	0.00	1.47	1.26	78.52	0.00	0.00	78.52	285.00	**3.63**	99.27	21.10	92.94	0.21	78.17	239.7	**3.07**	1.18
12	45.06	0.00	1.26	1.15	56.79	0.00	0.00	56.79	285.00	**5.02**	80.87	11.80	77.33	0.15	69.06	254.5	**3.69**	1.36

Complete wheelset simulation

EMU Motor wheelset – Results: Comparison



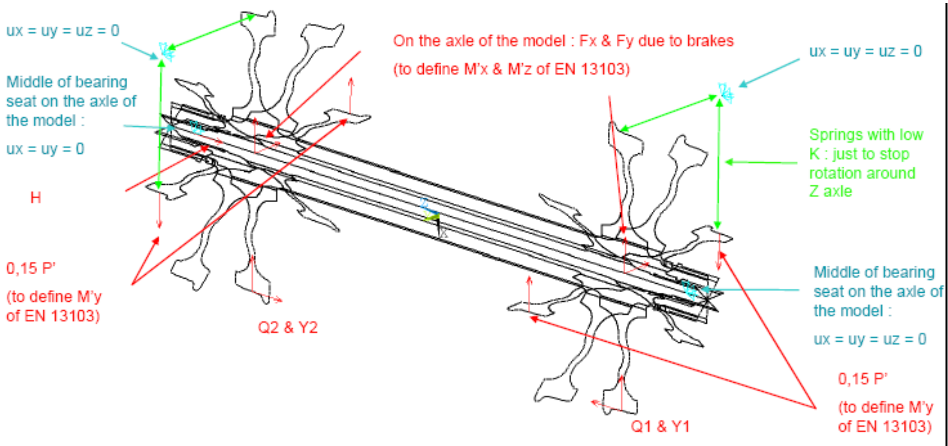


- All methods give similar SFs in relevant sections
- Method 1 tends to be more conservative in simple transitions
- EN 13104 more conservative in grooves
- Method 1 requires lower pre- and post-processing time than Method 2.
- Further analysis (fatigue limits) needed

Complete wheelset simulation

Trailer wheelset UIC type B 22,5 t - Model

- Models: 3D and 2D axisymmetric with Fourier series expansions (Ansys)



- Stress distribution along the transitions similar in both models
- Calculation time 2D models << 3D models.
- Calculation time non-linear models >> linear, merged models

9054	3D	2D	2D refine
Merged nodes	3h 13min 11s	7min 4s	24min 31s
Constraint equations	/	15min 0s	/
Contacts Node-to-Node	2d 20h 53min 55s	1d 11h 25min 32s	2d 19h 24min 45s
Contacts Surf-to-Surf	1d 20h	/	/

Contents

Conclusions
General

- Finite element modelling has been demonstrated to accurately reproduce the stress fields acting on railway axles.
- Local stresses estimated by finite element modelling and correlated by experimental measurements are higher than the stresses calculated according to the actual EN 1310X standards (K_t higher than K_f defined in EN 1310X)
- At the same time, the fatigue strength in terms of local strains and stresses is higher than considered by the standards.
- Experience shows that the actual design procedure of axles is safe.
- Complete wheelset models require large computational times, especially if non linear conditions are introduced.
  - 2D axisymmetric models with Fourier expansions reduce time

Conclusions

General - Modelling

- 3D or 2D with Fourier expansion can be applied
- Element type: linear elements OK
- Element size: convergence analysis should be performed to check the validity of the models
  - If peak stress at R: typical size ≈ 4 mm
  - If peak stress at r: typical size ≈ 1 mm
- Post-processing
  - Unaveraged results recommended to check convergence and effect of singularities
  - A skin of membrane elements can be used to facilitate the analysis
- General design recommendation: peak stress at the end of the transition (R)
  - Transition length C > Cmin

Conclusions

General - Transitions

- Transitions:
  - Simple and adjacent transitions (wheel and brake disc seats) can be modelled using tied non coincident meshes (linearised models)
  - For simple and sufficiently long transitions, analytical Kt values can be applied.
- Grooves
  - Contact interaction (non linear behaviour) is recommended to model the wheels, gears and brake discs with adjacent grooves
  - Recommended friction coefficient = 0.6
  - Components with low interference and DN/D (bearings, labyrinths) can be removed from the models

Conclusions

Proposal to complement EN 1310X

- Forces: Current EN 1310X
- Stresses:
  - Applying beam theory in the different sections

$$\sigma_d = K_t \frac{32 \cdot MR}{\pi d^3}$$

  - K_t
    - $K_{t,\varepsilon}$
    - Analytical expressions derived in EURAXLES for simple transitions
    - FEA following recommendations derived in EURAXLES
- Allowable values
  - F1, F3/F4: From WP3
  - Safety factors: additional investigation needed

Thank you for your attention