POLITECNICO DI MILANO

TC24 MEETING

ADVANCES IN: "AXLE DURABILITY ANALYSIS AND MAINTENANCE"

POLITECNICO DI MILANO 1-2 OCTOBER 2014

ESIS

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Acceptance of defects at press-fits

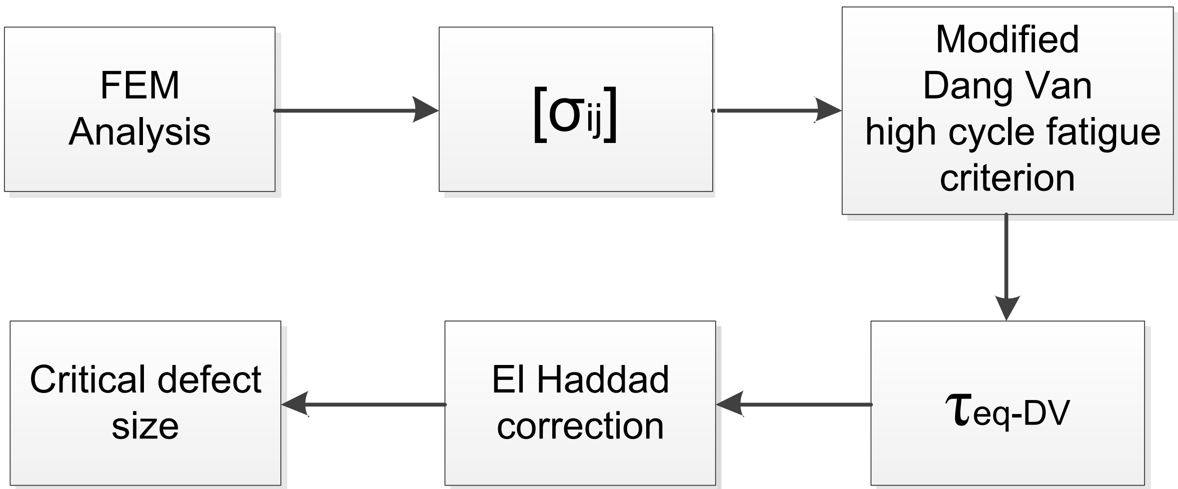
Stefano Foletti, Stefano Beretta, Gurer Goksu, Stefano Accarino

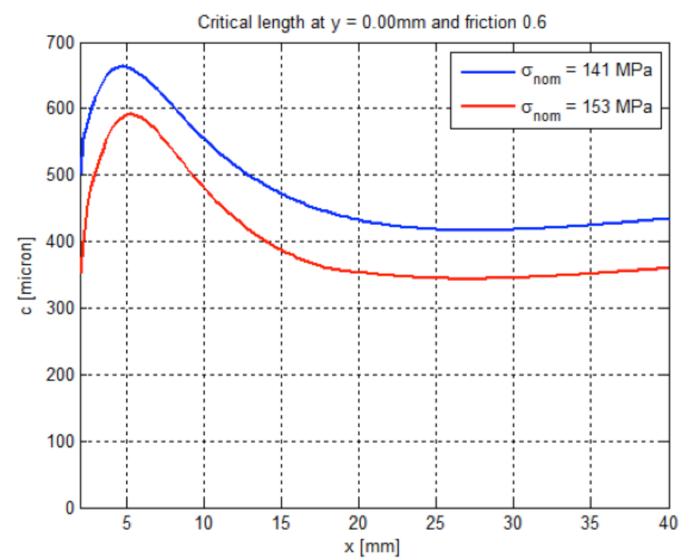
Department of Mechanical Engineering, Politecnico di Milano, Italy

Motivation and proposed model

Evaluation of defect acceptability under fretting fatigue on railway axles

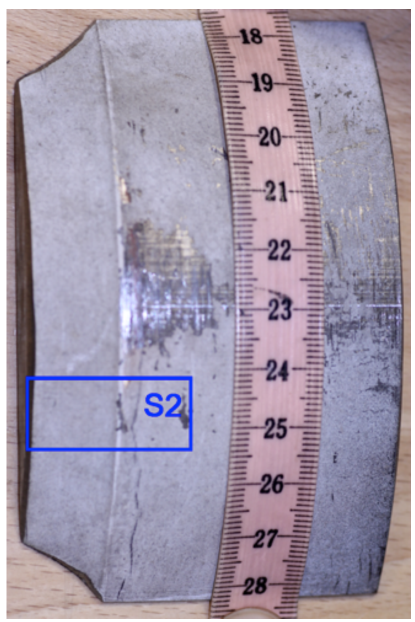
1. FEA to obtain the stress path
2. Application of a multiaxial HCF criterion to obtain an equivalent stress
3. Application of El Haddad correction to obtain the critical size of a prospective defect

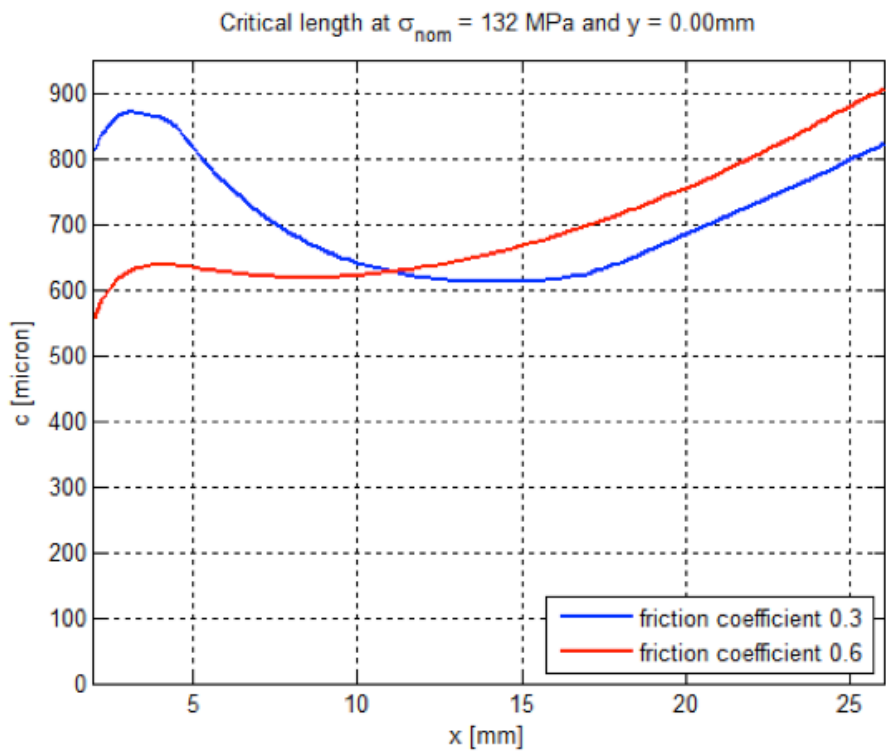




Contents

- Experimental Results of fretting fatigue tests
- FE model
- Modified Dang Van criterion
- Prediction of critical defect size
- Comparison with experimental results





Experimental Results

Four different axles geometries have been considered in Euraxle project:

- F1 Geometry with D/d = 1.19 tested by Polimi on Vitry type test rig
- F4 Geometry with D/d = 1.12 tested by SNCF on Vitry type test rig
- F4 Geometry with D/d = 1.08 tested by CAF on Minden type test rig
- F4 Geometry with D/d = 1.12 tested by Deutsche Bahn on Minden type test rig

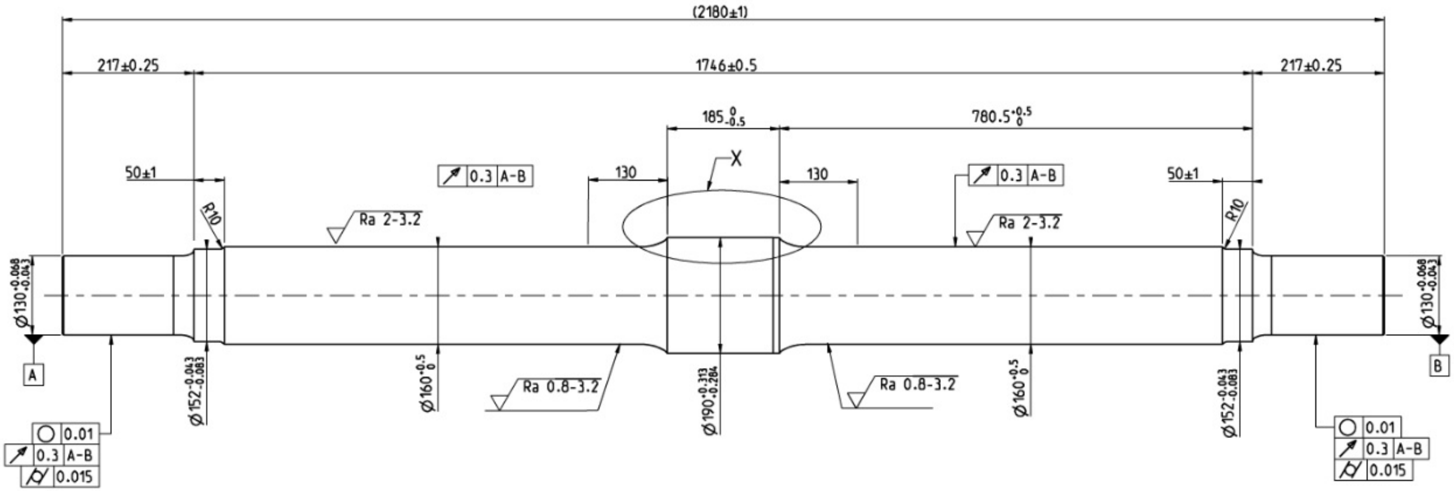
Minden type test rig

Vitry type test rig

Experimental Results

F1 axle D/d = 1.19 (1)

3-point rotating bending tests have been applied on the full scale F1 geometry manufactured from A4T grade steel.



The failure is obtained with a nominal bending stress at the axle's max diameter of 153 MPa. The failure occurred on press-fit seat (ring-axle interface) after $1.6x10^6$ cycles.

Axle #	σmax [MPa]	σnom [MPa]	Number of Cycles	Failure location
1	310	153	1688594	Failed at press-fit seat
2	285	141	1.00E+07	run-out
3	310	153	1467172	Failed at press-fit seat

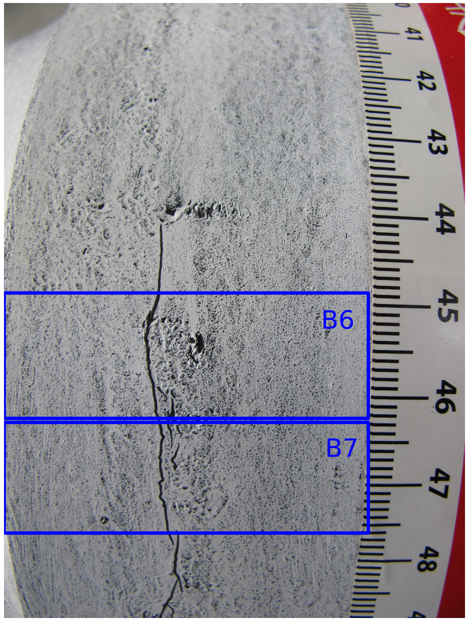
Experimental Results

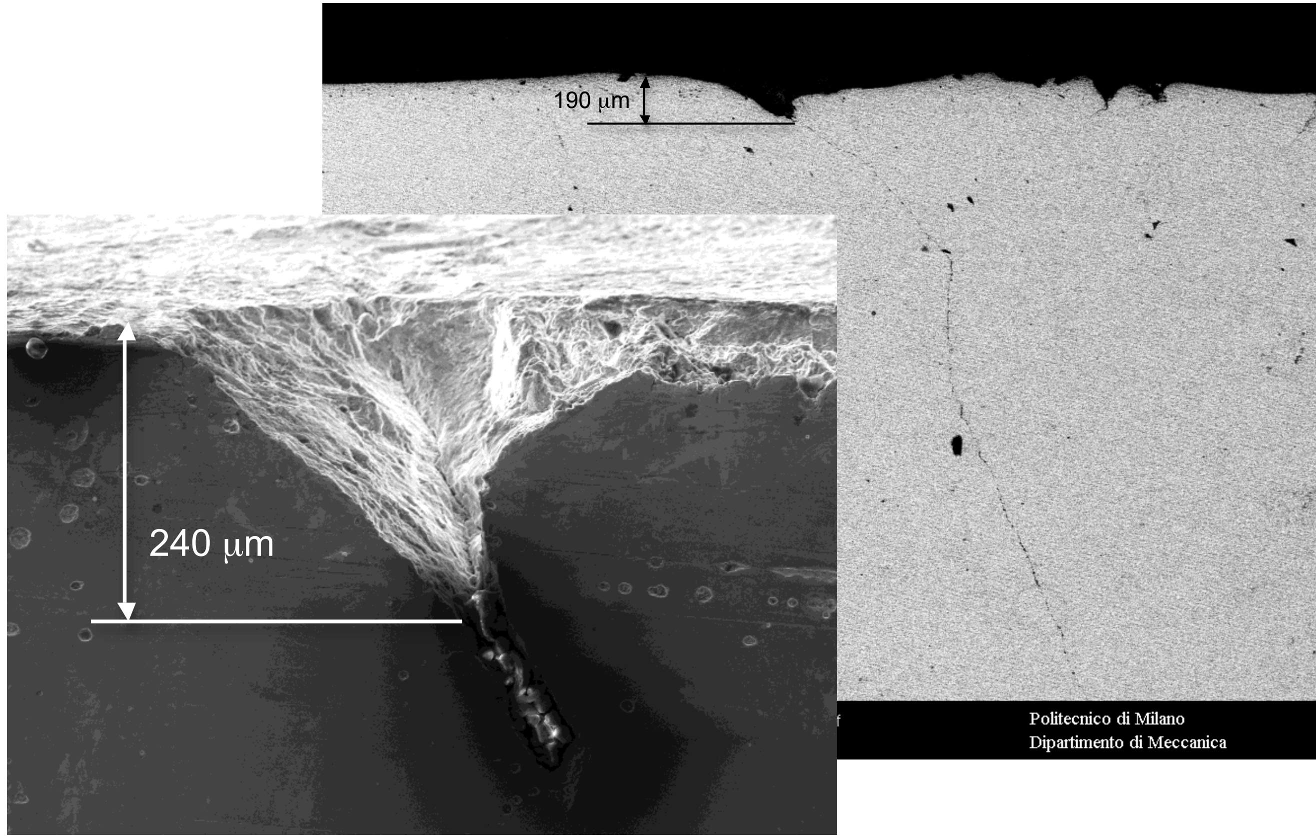
F1 axle D/d = 1.19 (2)

Visual inspection Axle #1, F1 geometry Vitry test type, σ_{nom} = 153 MPa.

- Presence of a big crack through the whole thickness, at about 20 mm from the border.
- A lot of smaller cracks are evident in the seat, at about 10mm from both the corners

Experimental Results
F1 axle D/d = 1.19 (3)

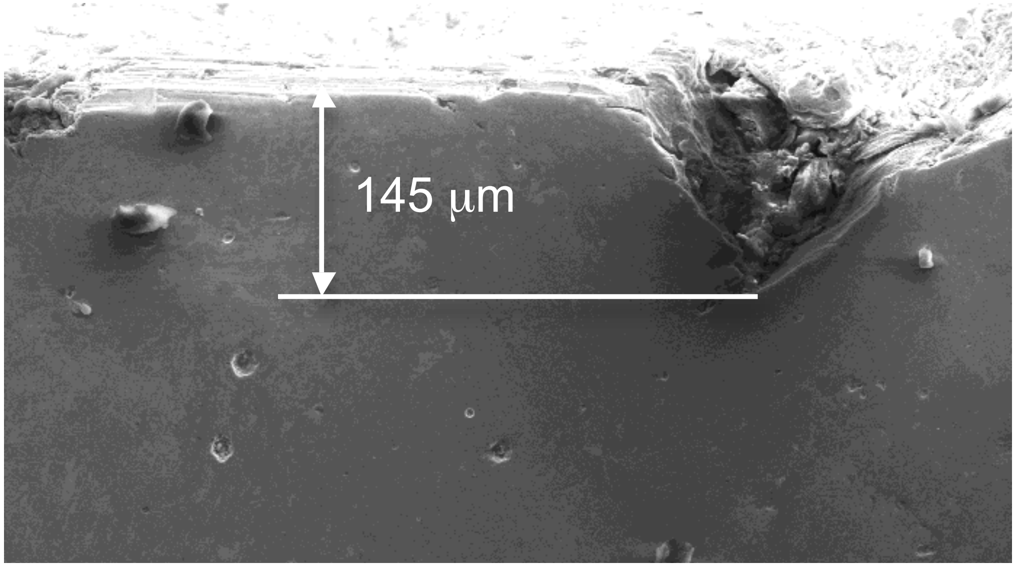




- Fretting damage on material surface has been observed from SEM observation.
- In many cases crack propagation originated from a surface defect has been observed.
- The defect size from which the crack propagates is in the order of 200-250 μm

Experimental Results

F1 axle D/d = 1.19 (4)

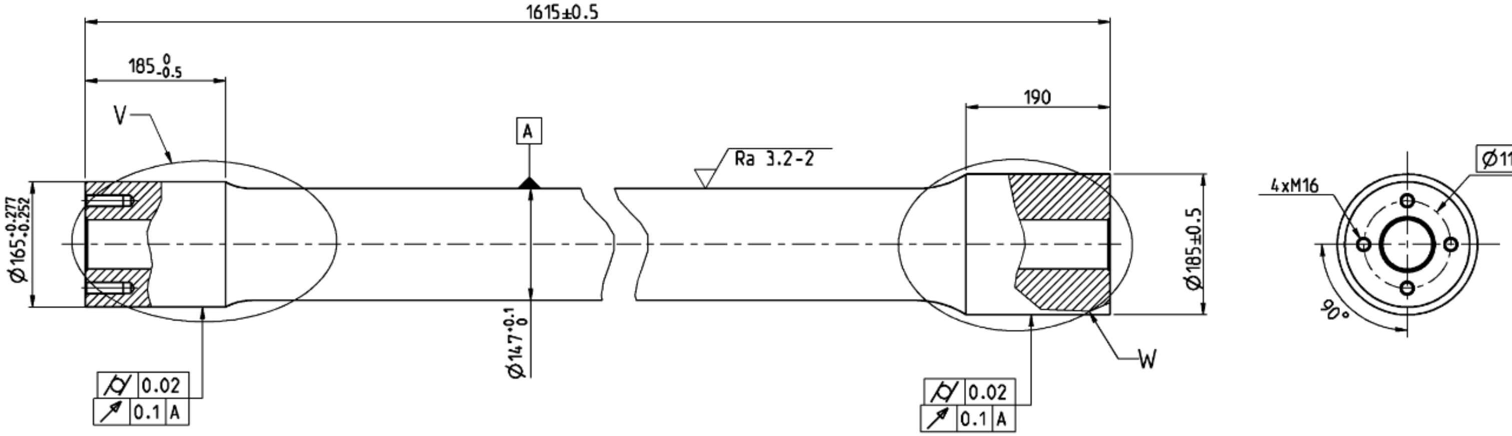


Surface defect with non-propagating cracks

- A lot of non-propagating cracks have been observed. The observed defect depth is in the order of 100-150 μm

Experimental Results

F4 axle D/d = 1.12 (1)



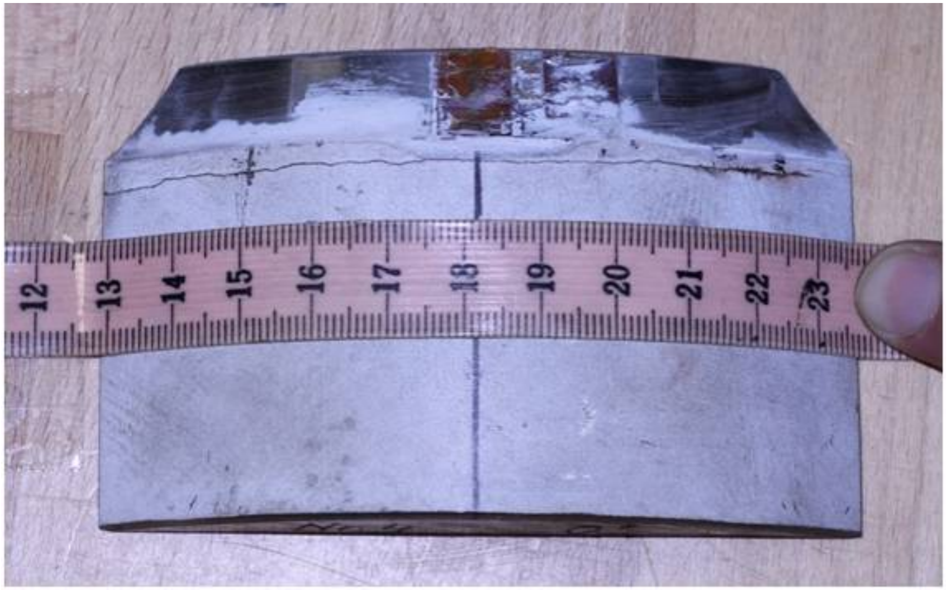
F4 geometry, D/d = 1.12, Minden type test rig

The nominal stress, σ_{nom}, is the nominal bending stress at the axle's maximum diameter.

Axle #	σnom [MPa]	Number of Cycles	Failure	Failure Location
1	132	10000000	yes	crack on press-fit seat
2	126	10000000	yes	crack on press-fit seat
3	120	10000000	run-out	no crack
4	126	10000000	yes	crack on press-fit seat

Experimental Results

F4 axle D/d = 1.12 (2)

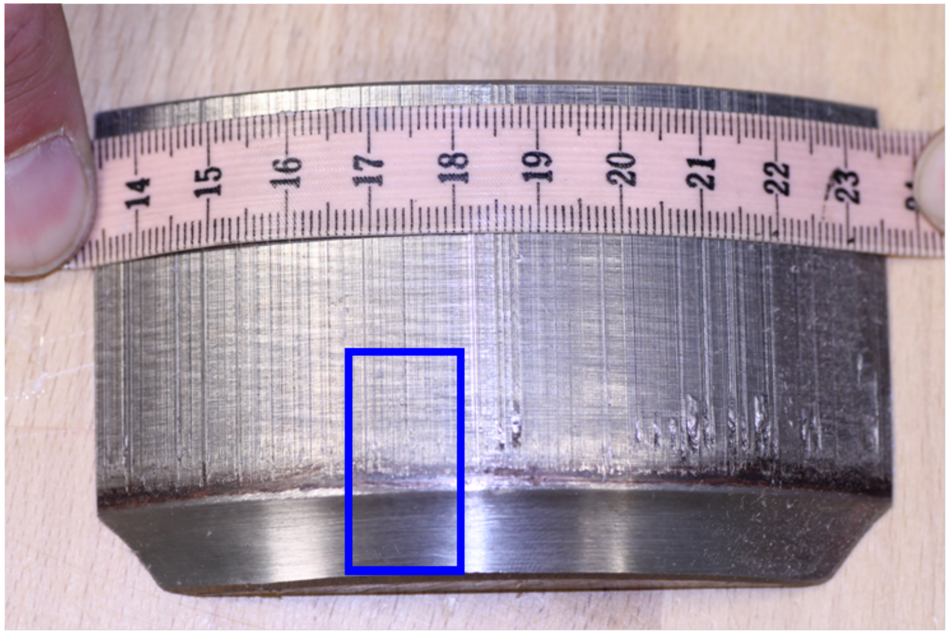


Visual inspection Axle #4, F4 geometry D/d = 1.12 Minden test type, σ_{nom} = 126 MPa.

- The visual inspection revealed the presence of a big crack through the whole thickness, at about 5 mm from the border.
- Some smaller cracks are evident in the seat, at about 2 mm from the fillet

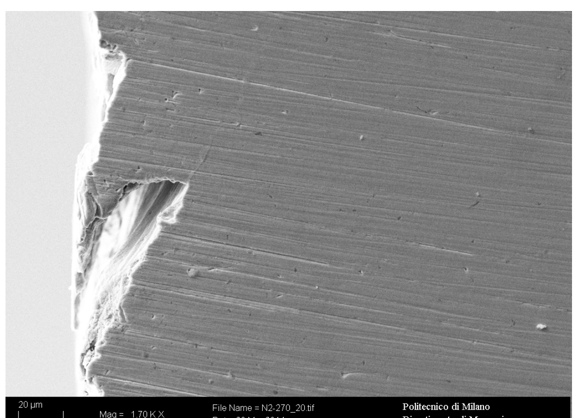
Experimental Results

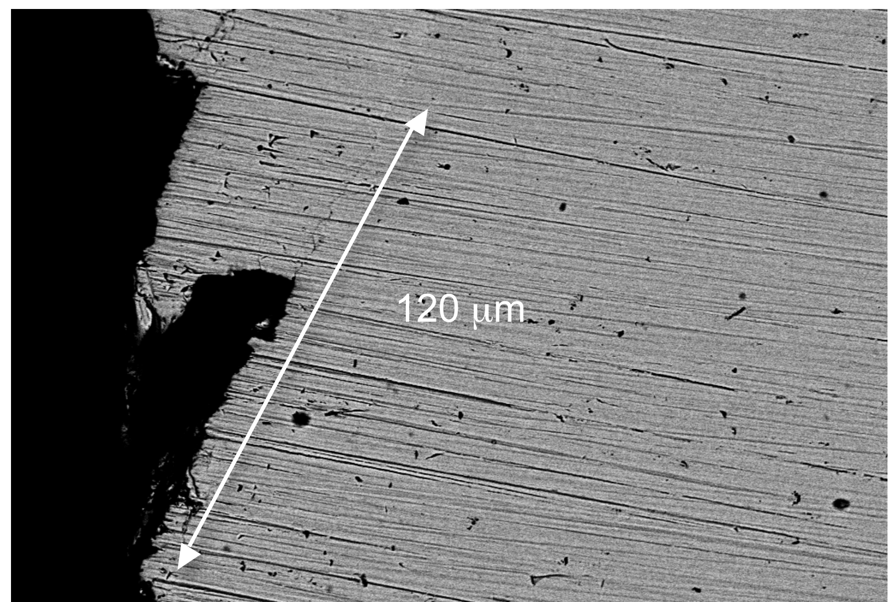
F4 axle D/d = 1.12 (3)



Section detail Axle #3, F4 geometry Minden test type, σ_{nom} = 120 MPa

- The run-out axle, Axle #3 tested at σ_{nom} = 120 MPa, has been sectioned in order to observe the presence of non-propagating cracks
- The non-propagating cracks are in order of 100-150 μm





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- FE model
- Modified Dang Van criterion
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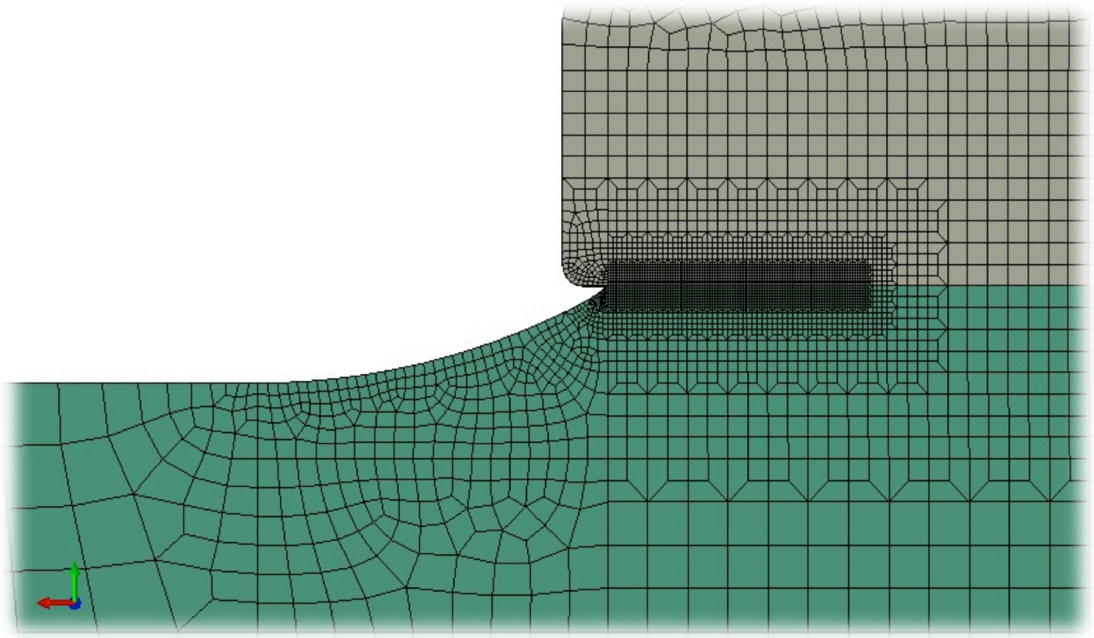
FEM model (1)

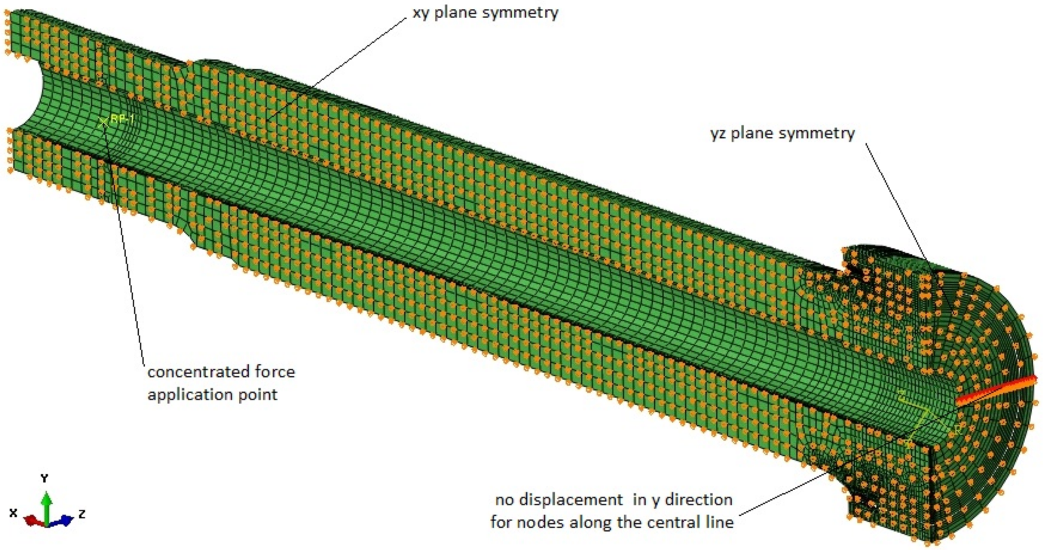
Different FEM analyses have been carried out to simulate experimental tests and obtain the stress path in the critical regions of the shaft.



- The A4T steel has been modelled as linear-elastic using E=206000 MPa and v=0.3
- C3D8R elements (8-node linear brick), reduced integration, hourglass control
- In the press fit seat, the element dimension is 0.25x0.25 mm
- The interference fit has been applied in the first step, with the use of the maximum value supplied by technical drawings. Tangential behaviour is described with two different friction coefficient: 0.3 and 0.6 respectively

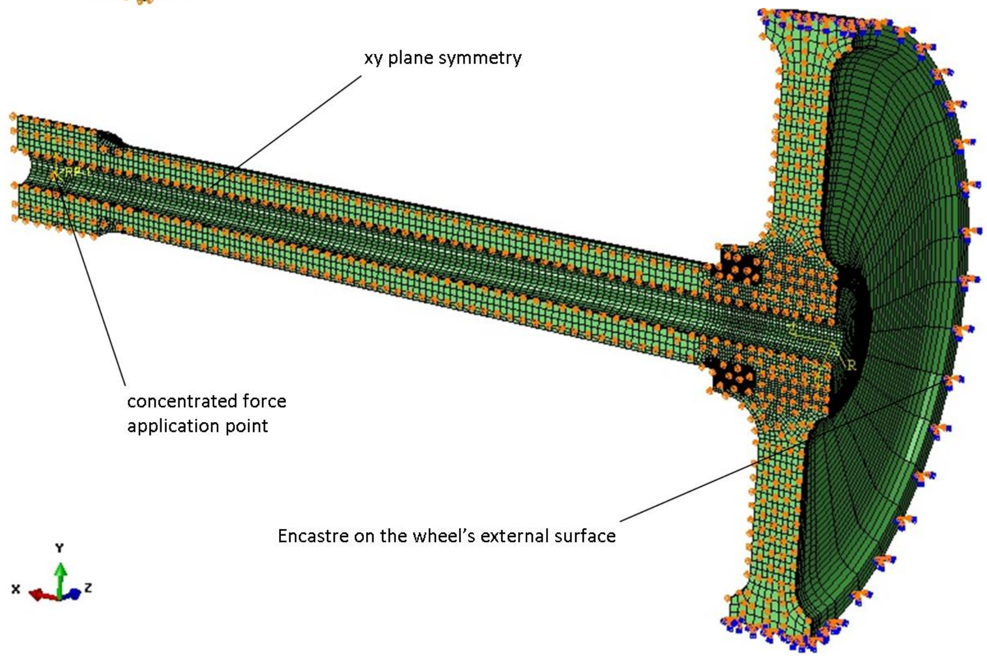
F1 (D/d =1.18)	-0.313 mm
F4 (D/d = 1.12)	-0.277 mm
F4 (D/d = 1.08)	-0.277 mm

FEM model (2)

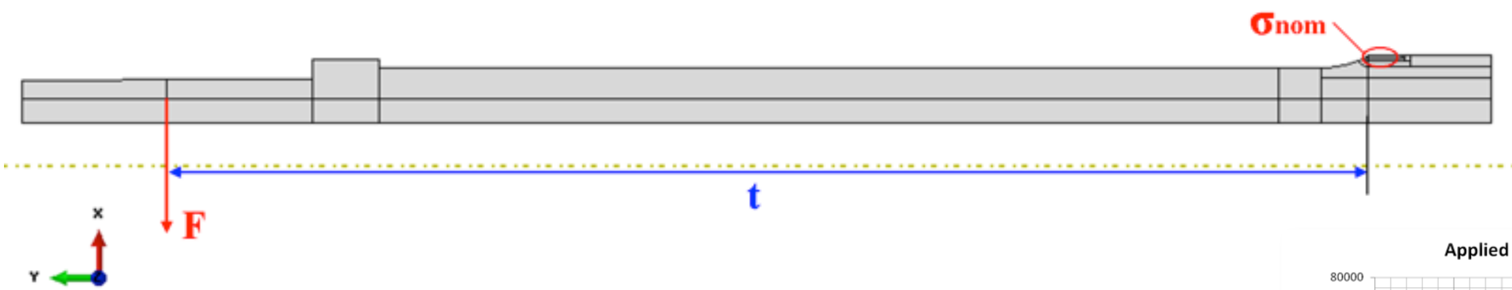


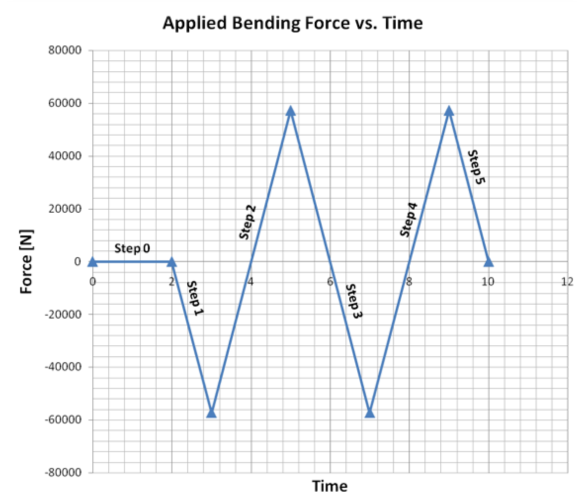
FE model: boundary conditions (Vitry test type)

FE model: Boundary conditions (Minden test type)



FE analyses



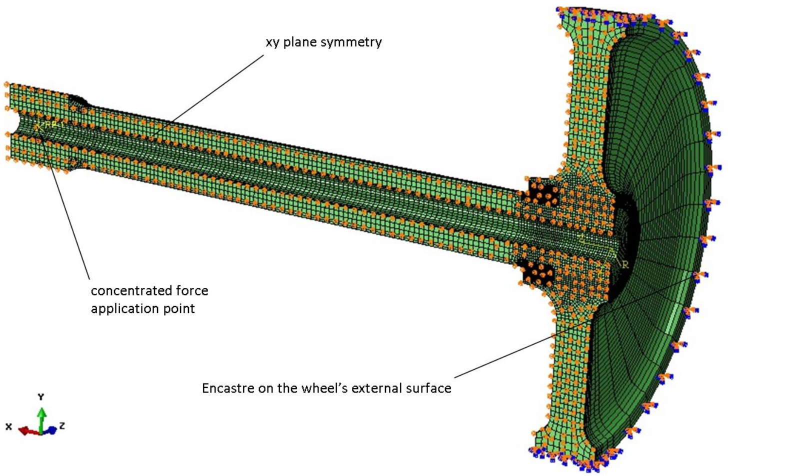


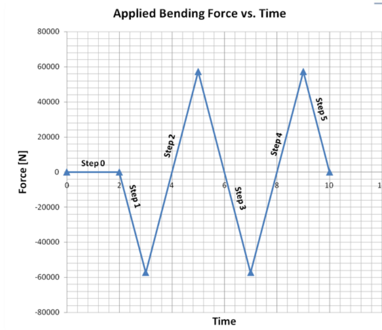
For each axle two different analyses have been carried out, using two different nominal stresses as experimentally tested. The first one leading to a failure condition, the second one to run out condition.

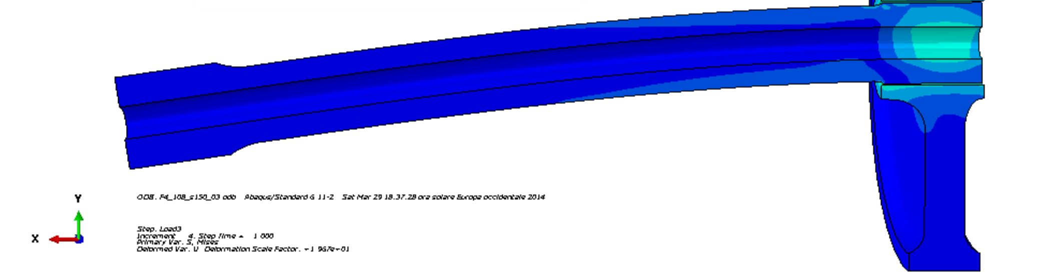
F1 (D/d = 1.19)	Vitry test type	t = 889 mm	F = 52721 N	σnom = 141 MPa	Run out
			F = 57346 N	σnom = 153 MPa	Failure
F4 (D/d = 1.12)	Vitry test type	t = 899 mm	F = 28725 N	σnom = 120 MPa	Run out / Failure
			F = 31597 N	σnom = 132 MPa	Failure
F4 (D/d = 1.08)	Minden test type	t = 1520 mm	F = 19820 N	σnom = 140 Mpa	Run out
			F = 21236 N	σnom = 150 MPa	Failure
F4 (D/d = 1.12)	Minden test type	t = 1520 mm	F = 16989 N	σnom = 120 MPa	Run out
			F = 18688 N	σnom = 132 MPa	Failure

FE results

F4 axle, D/d = 1.08, Minden Type test rig

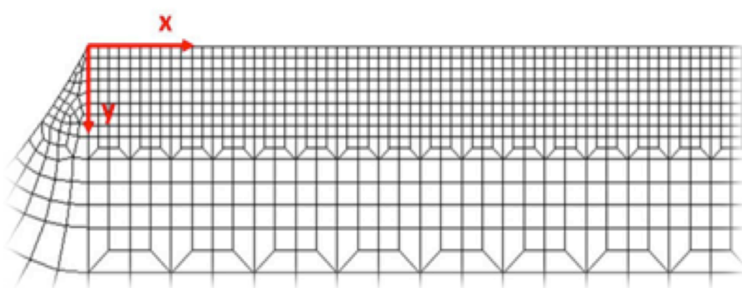


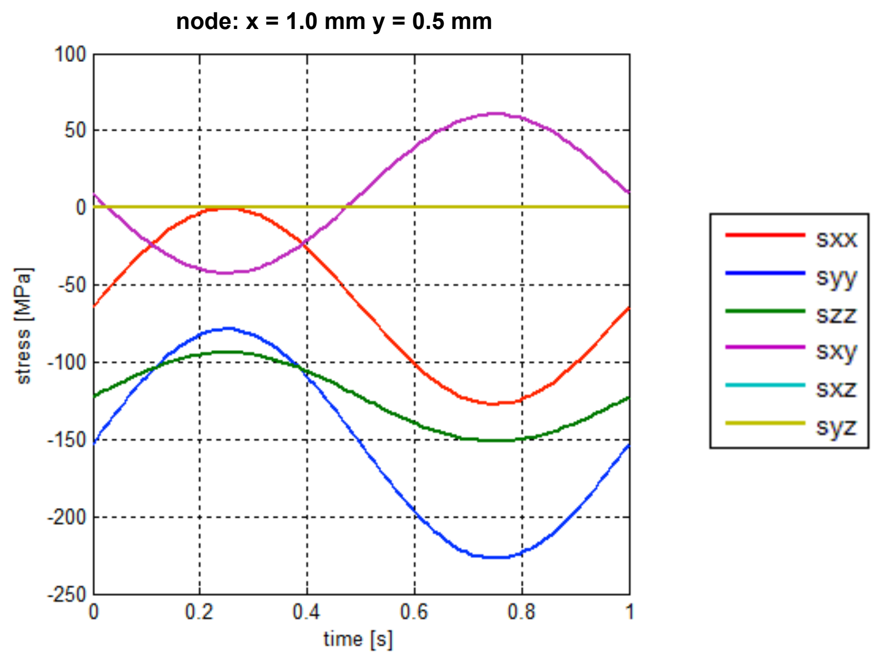




In order to obtain a stabilized numerical result different steps were processed, carrying out two complete cycles.

The stress path has been extracted from the last cycle in a local reference system





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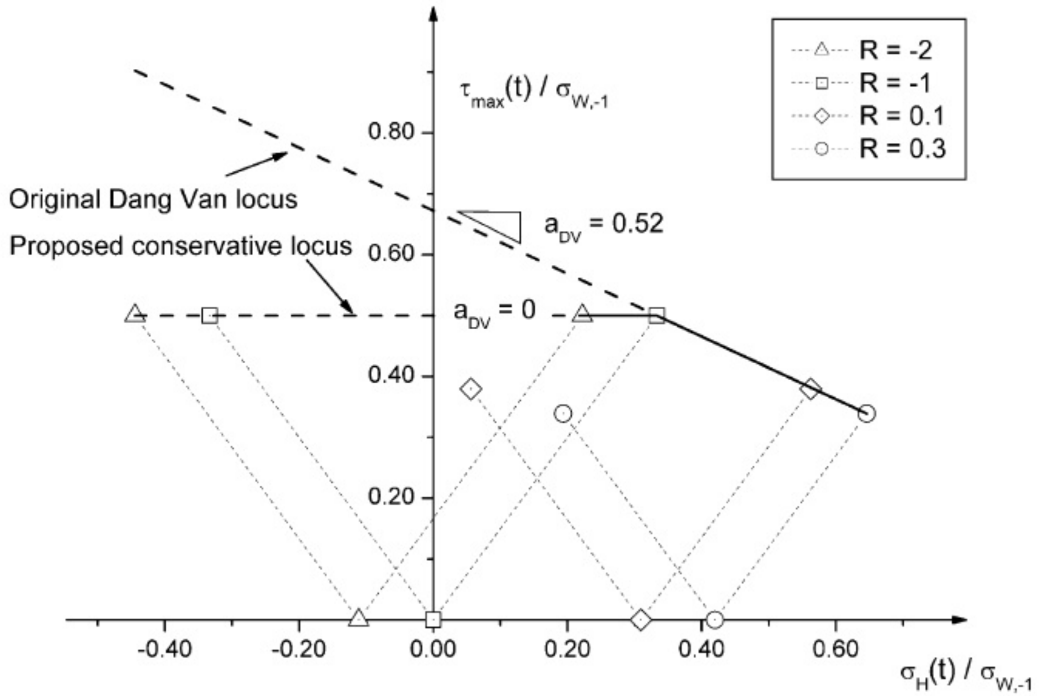
Modified Dang Van Criterion (1)

Dang Van criterion is a mutiaxial high cycle fatigue criterion based on the application of the elastic shakedown principles at the mesoscopic scale. Dang Van criterion can be expressed by:

$$\tau_{\mathrm{DV}}(t) + \alpha_{\mathrm{DV}}\sigma_{\mathrm{h}}(t) \leqslant \tau_{\mathrm{W}}$$

Where τ_W is the fatigue limit in reversed torsion, $\sigma_h(t)$ is the instantaneous hydrostatic component of the stress tensor, $\tau_{DV}(t)$ is the instantaneous value of Tresca shear stress and α_{DV} is a material constant.



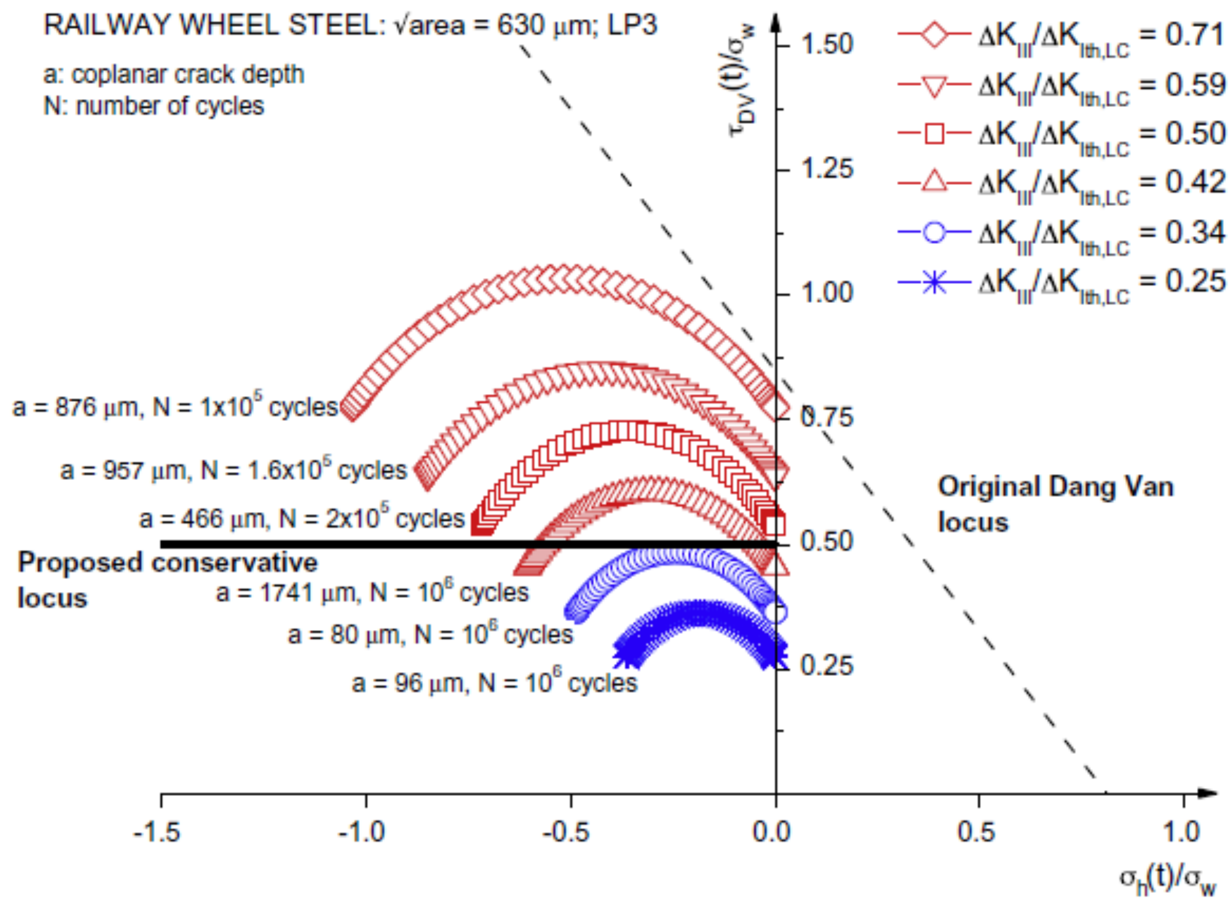
Modified Dang Van Criterion (2)

Experimental fatigue tests for a gear steel and a mild railway wheel steel, that have been subjected to out-of-phase multiaxial fatigue loading, have demonstrated that the multiaxial fatigue limit does not depend on hydrostatic stress if $\sigma_h < 0$

For $\sigma_h < 0$ a conservative locus has been proposed:

$$\max(\tau_{DV}(t)) \leq s_W/2$$

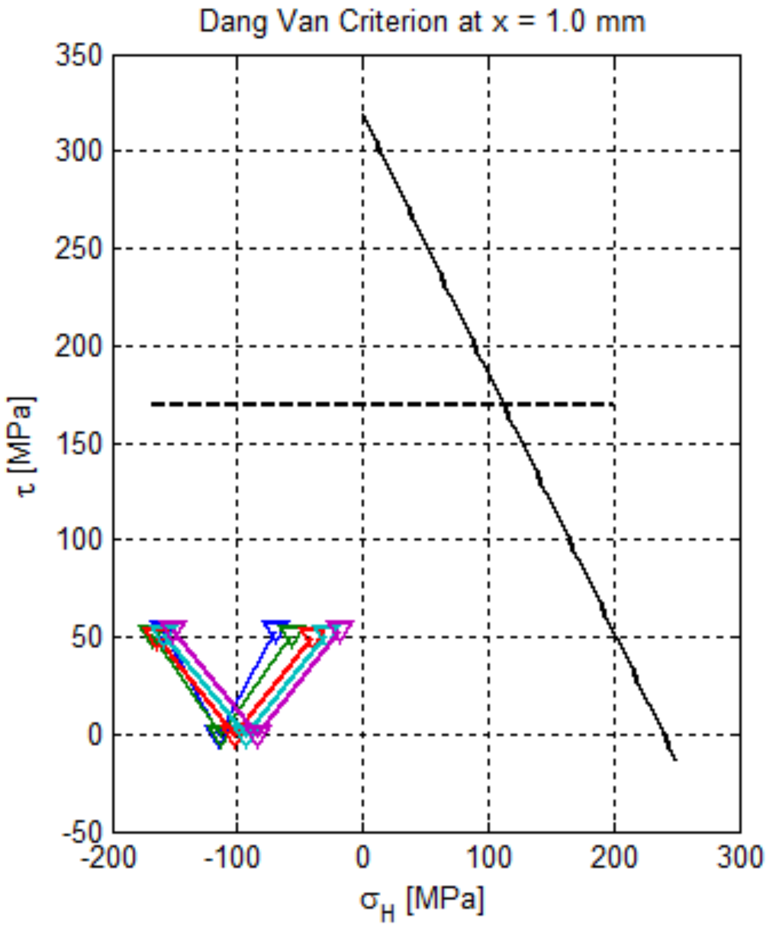
As reported in Figure the Dang Van criterion with the original locus gives a very non-conservative prediction

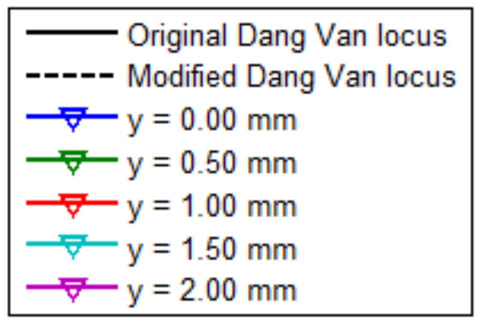


Modified Dang Van Criterion (3)

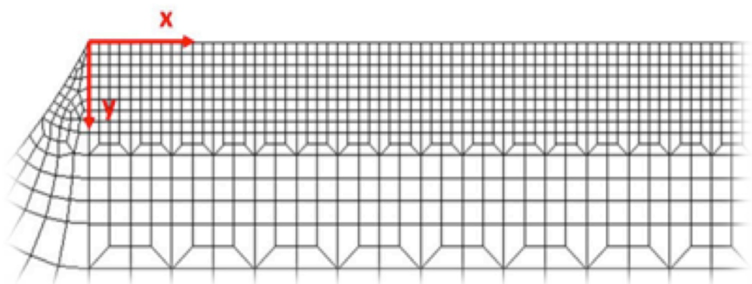
Axial and torsional fatigue limit for A4T steel, obtained on smooth specimen

Ultimate Tensile Strength = 1100 MPa
Axial Fatigue Limit (R=-1) = 338 MPa*
Torsional Fatigue Limit (R=-1) = 319 MPa





- Hydrostatic vs. Shear stress path for a specific test (F4 Minden test type, D/d = 1.08 σ_{nom} = 150 MPa, friction coefficient 0.3)
- **No failure is expected if the fatigue limit of material without defects is considered**



Modified Dang Van Criterion (4)

El Haddad correction

In order to predict the critical size of a prospective defect a relationship between the material fatigue limit and the defect size has to be introduced.

Introducing the El Haddad correction in the Dang Van criterion it is possible to obtain the critical defect size of a non-propagationg crack:

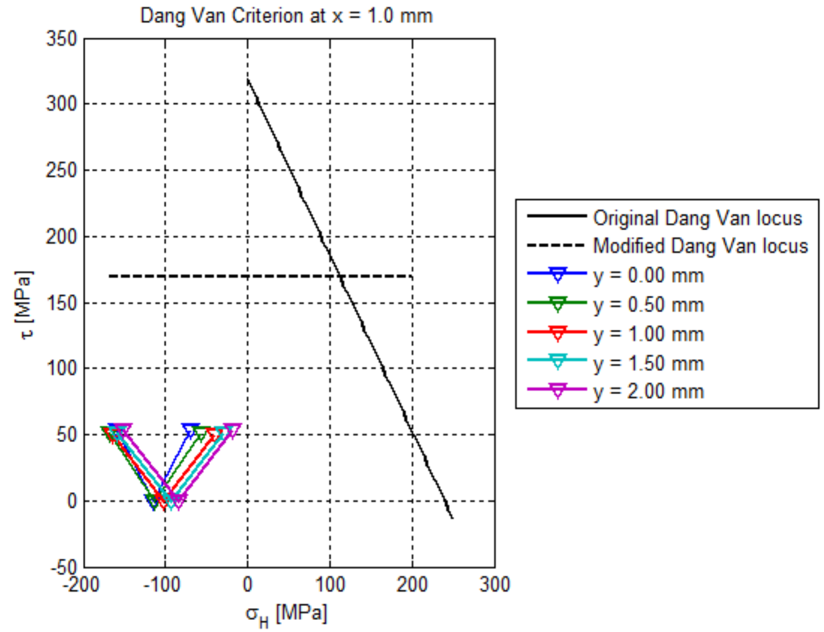
$$max(\tau_{DV}(t)) = \frac{\sigma_w}{2} = \frac{\sigma_{W0}}{2}\sqrt{\frac{\sqrt{area_0}}{\sqrt{area}+\sqrt{area_0}}} \quad \Rightarrow \quad \sqrt{area}$$

being σ_{w0}= 338 MPa the material fatigue limit without defects and $\sqrt{(area_0)}$= 127.66 μm

Finally, to obtain the crack depth of a very shallow surface crack it is possible to use the following relationship:

$$\sqrt{area} = c \cdot \sqrt{10}$$

being c the crack depth.



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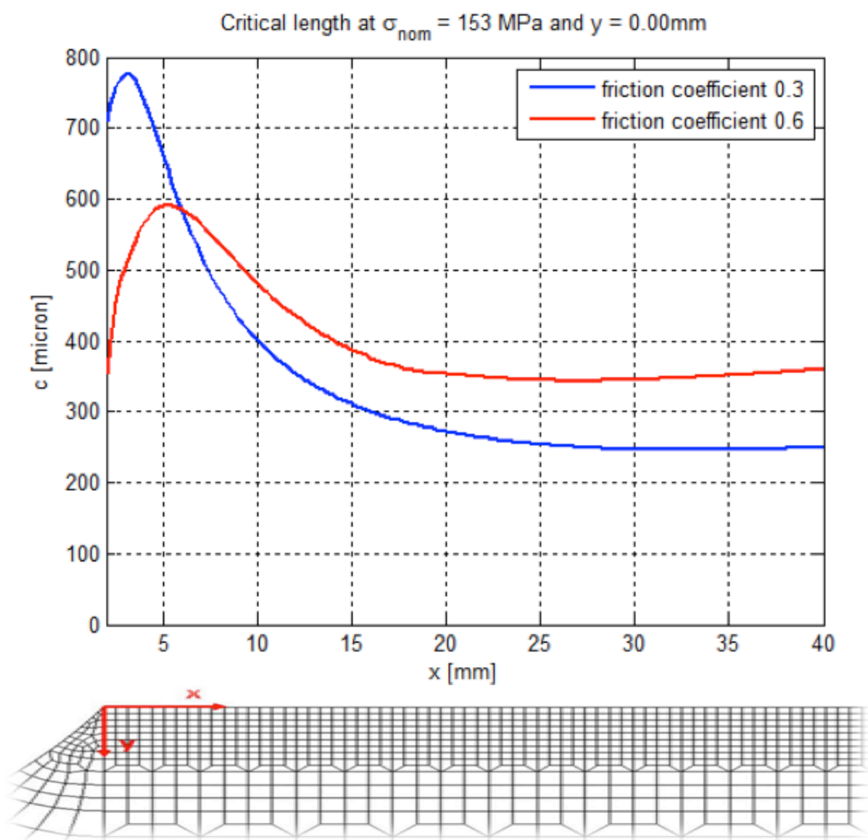
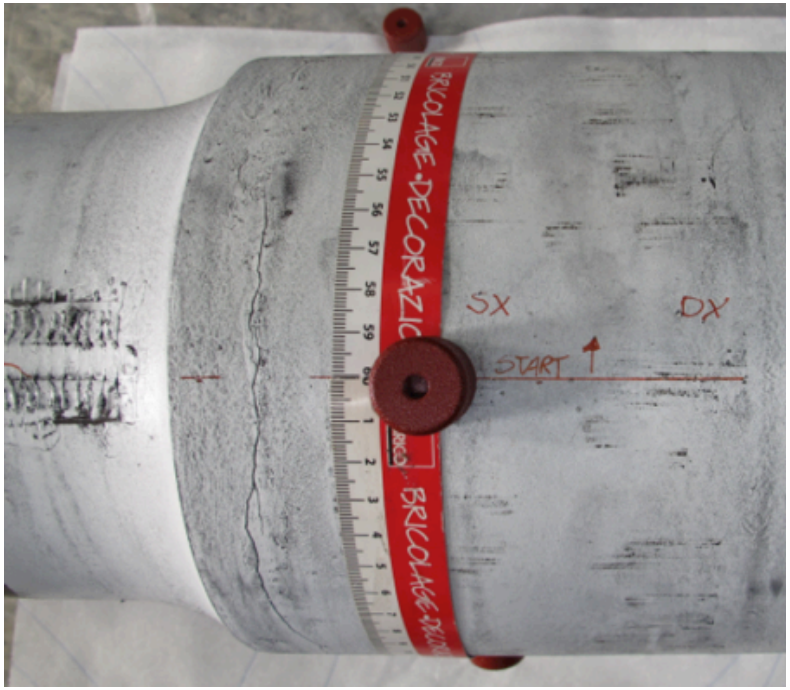
Prediction of critical defect size

F1 axle - Vitry test (1)

F1 (D/d = 1.19) Vitry test	σnom = 153 MPa (failure)	Critical position along x
Analytical results	friction coefficient = 0.3	25 - 35 mm
	friction coefficient = 0.6	20 - 30 mm
Experimental results		20 mm

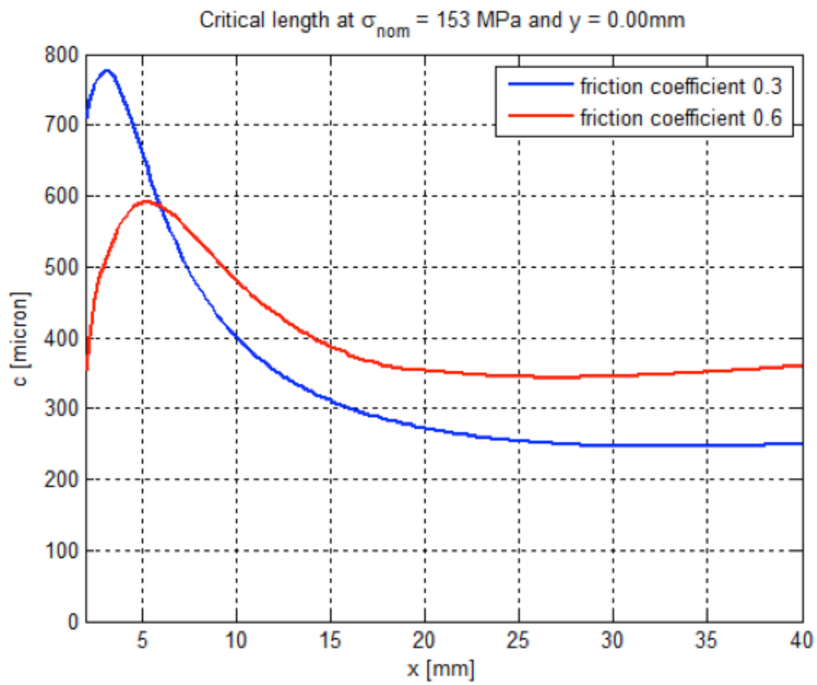


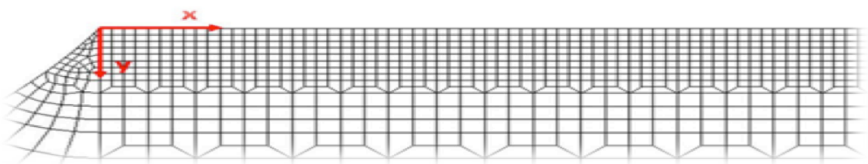


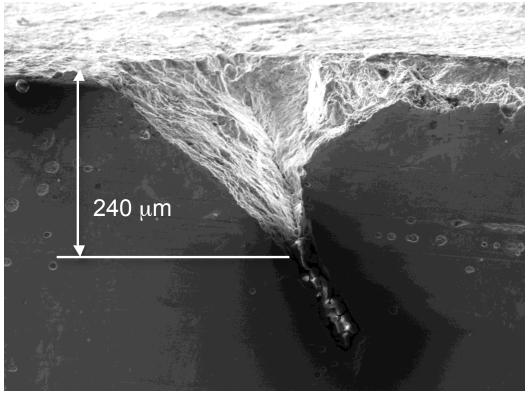
Failure location
x = 20-25 mm

Prediction of critical defect size

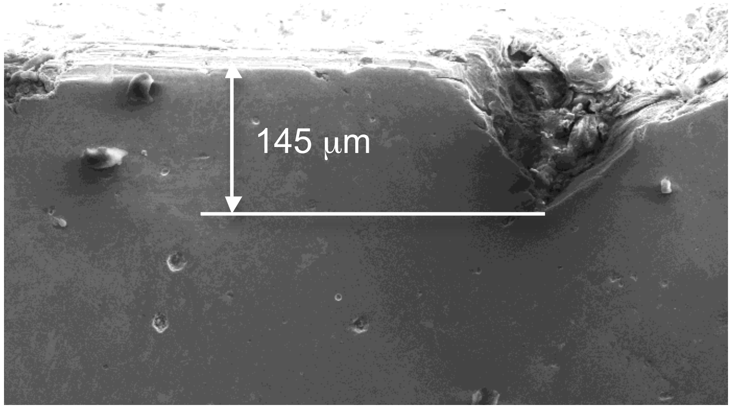
F1 axle - Vitry test (2)







Propagating cracks from a defect of 240 μm at x = 25 mm

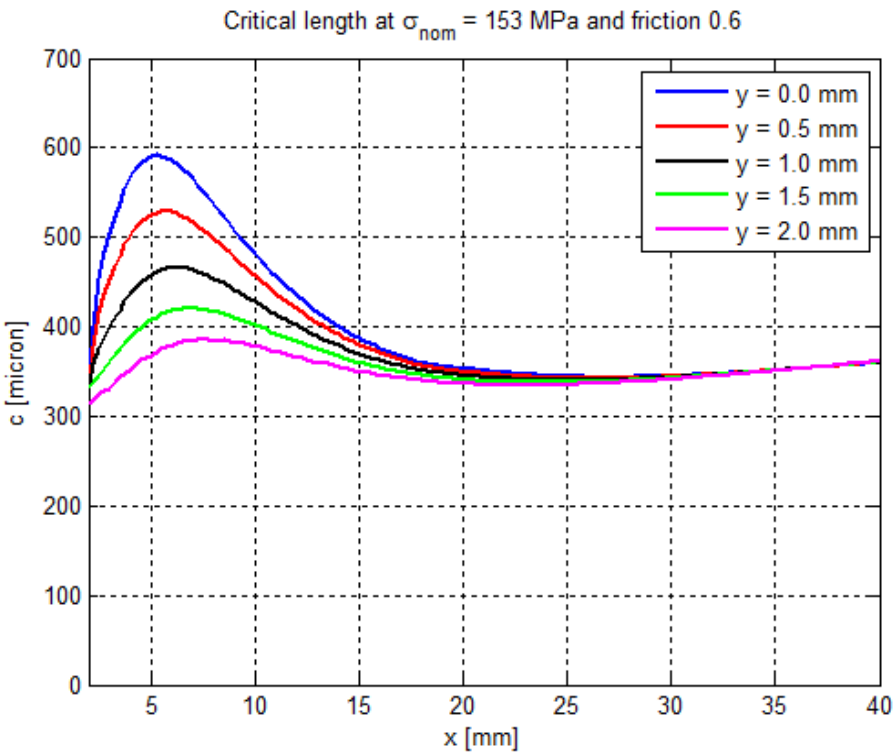


Surface defect with non-propagating cracks

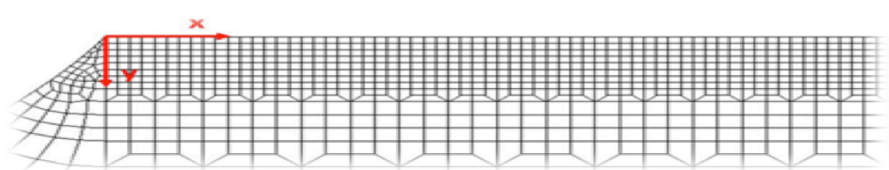
Prediction of critical defect size

F1 axle - Vitry test (3)

The minimum value of defect size is not affected by the position under the contact surface (y coordinate).



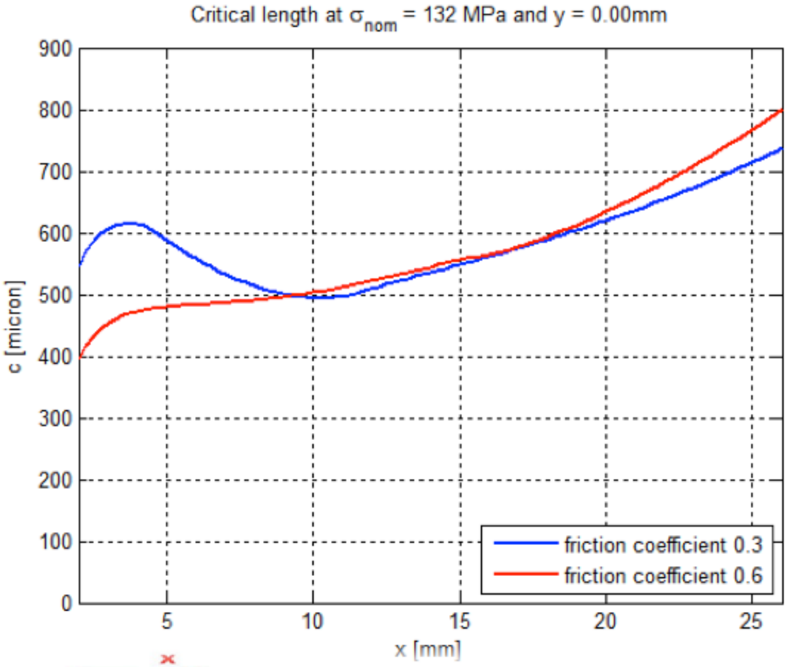
A lot of smaller cracks are evident in the seat, at about 10mm

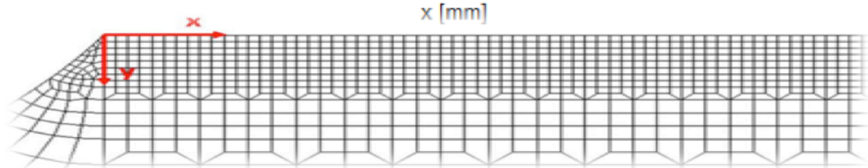


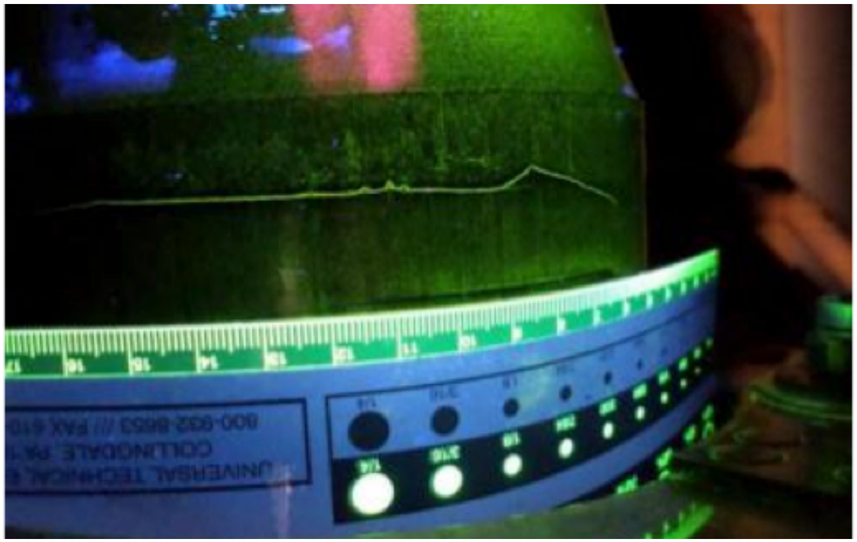
Prediction of critical defect size

F4 axle- Vitry test

F4 (D/d = 1.12) Vitry test			Critical position along x
Analytical results	σnom = 120 MPa	friction coefficient = 0.3	5 - 15 mm
	σnom = 120 Mpa	friction coefficient = 0.6	3 - 8 mm
	σnom = 132 Mpa	friction coefficient = 0.3	7 - 15 mm
	σnom = 132 MPa	friction coefficient = 0.6	3 - 8 mm
Experimental results	σnom = 120 Mpa		10 mm
	σnom = 132 Mpa		15 mm





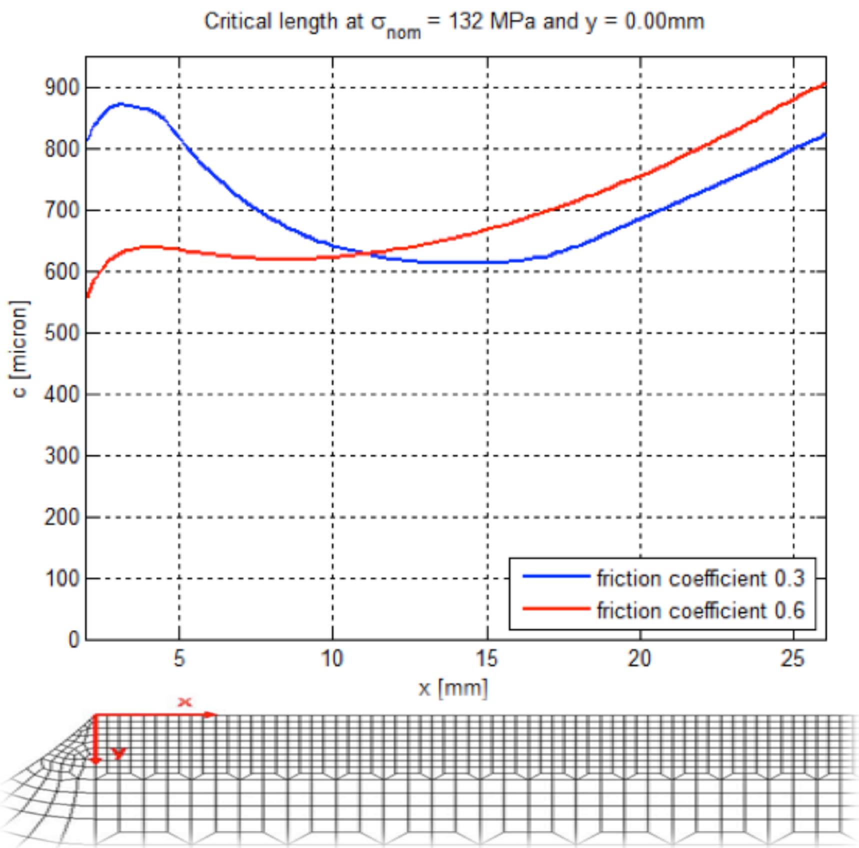


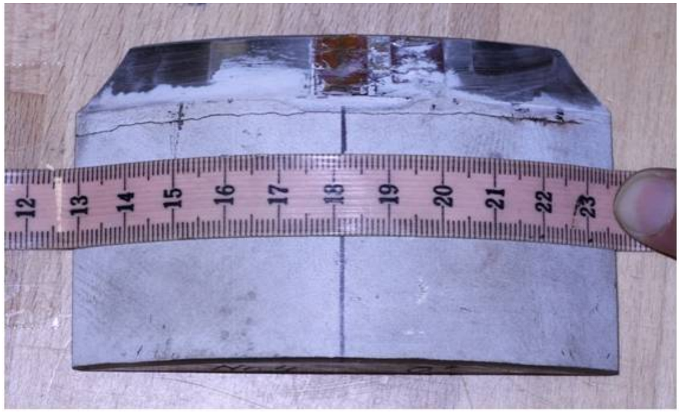
Failure location
x = 10-15 mm

Prediction of critical defect size

F4 axle- Minden test (D/d = 1.12) (1)

F4 (D/d = 1.12) Minden test			Critical position along x
Analytical results	σnom = 132 MPa	friction coefficient = 0.3	12 - 18 mm
	σnom = 132 Mpa	friction coefficient = 0.6	4 - 12 mm
Experimental results	σnom = 126 Mpa		5 mm
	σnom = 132 Mpa		4 mm



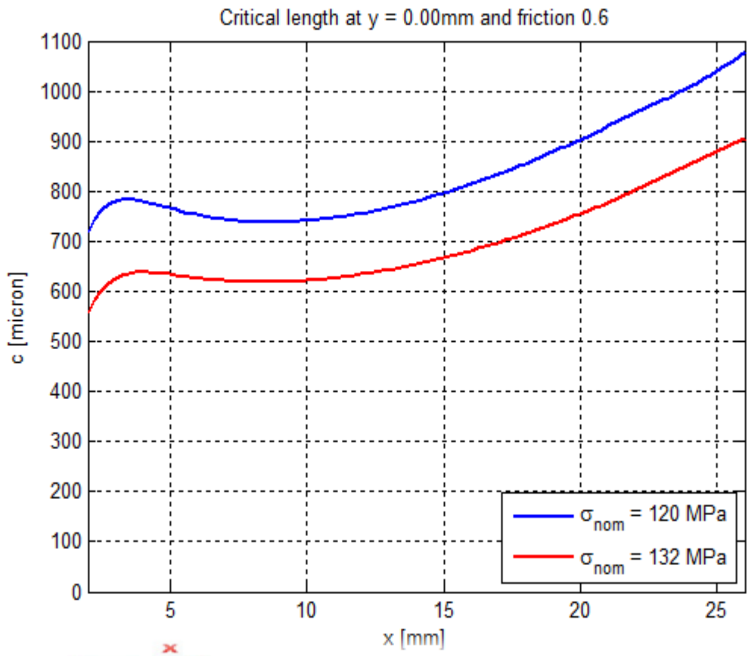


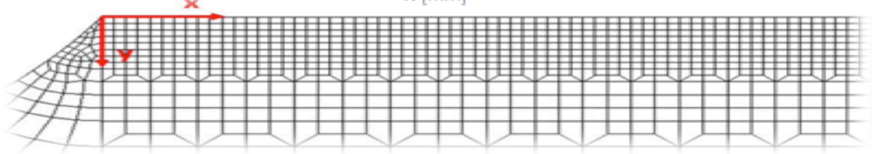
Failure location
x = 5 mm (σ = 132 MPa)

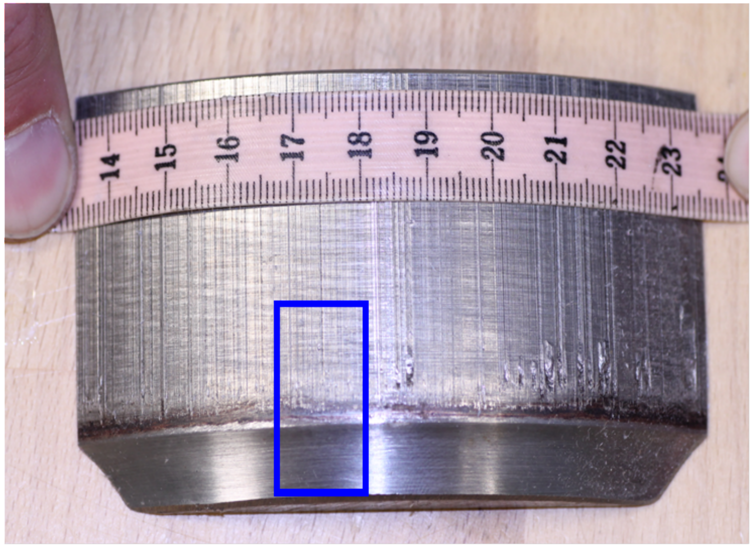
Prediction of critical defect size

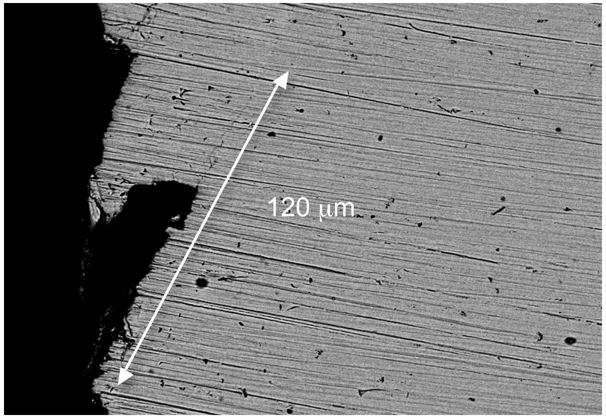
F4 axle- Minden test (D/d = 1.12) (2)

Run-out specimen σ_{nom} = 120 MPa







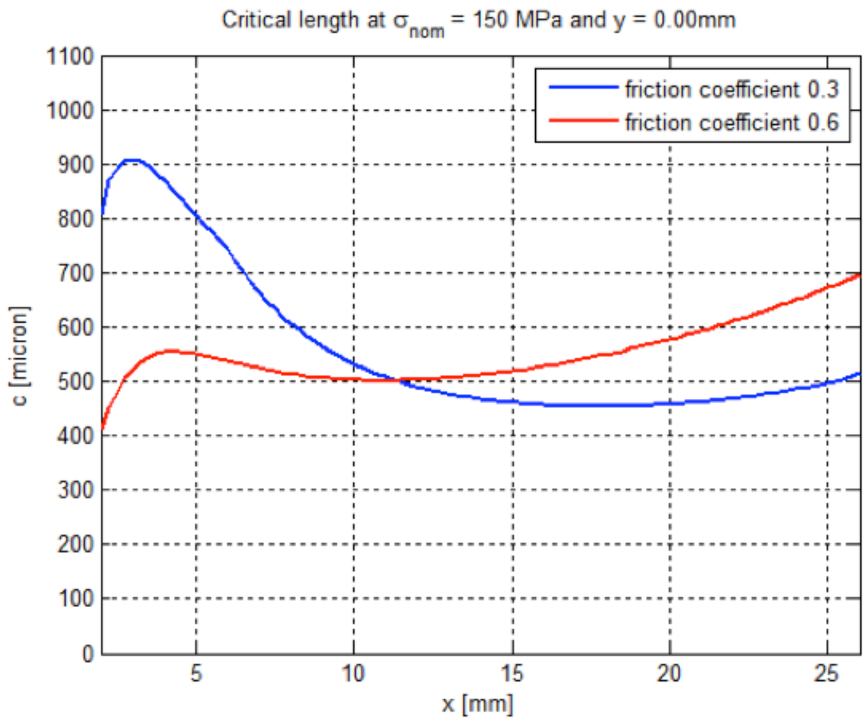


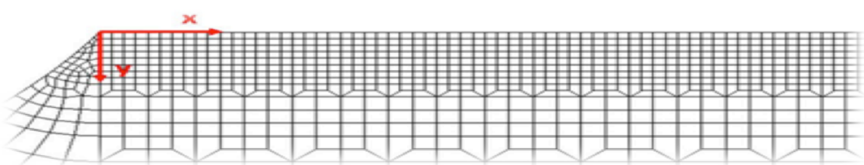
Non propagating cracks on run-out specimen (σ = 120 MPa)

Prediction of critical defect size

F4 axle - Minden test (D/d = 1.08)

F4 (D/d = 1.08) Minden test	σnom (failure)	Critical crack size	Critical position along x
friction coefficient = 0.3	150 Mpa	450 µm	12 - 24 mm
friction coefficient = 0.6	150 MPa	500 µm	6 - 14 mm





No experimental observation of failure location.

Conclusion (1)

- A model based on Dang Van criterion together with El Haddad correction has been developed in order to study defects acceptability at press-fits
- The proposed model is able to correctly predict the failure location for all axle's geometries. The better results can be obtained by the use of a friction coefficient equal to 0.6
- The proposed model is able to predict the critical size of a prospective defect.
- The experimental observations seem to confirm the model prediction.

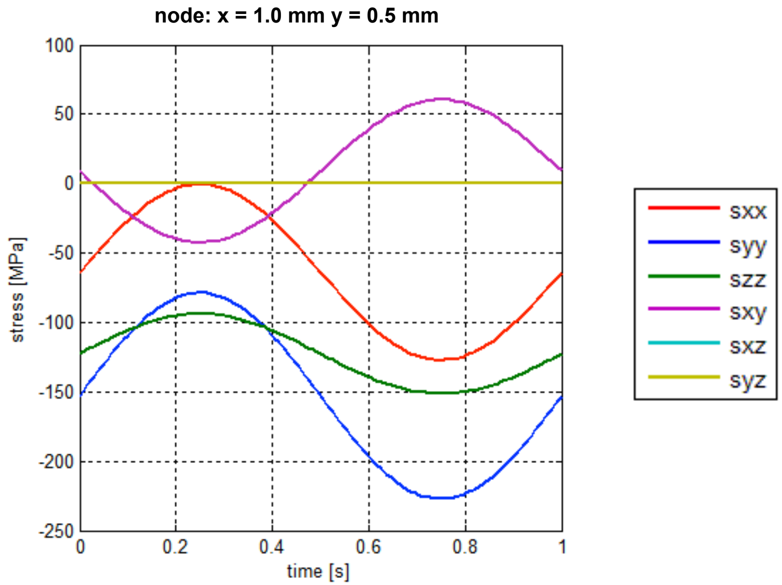
Conclusion (2)

- New research project between Lucchini RS and PoliMi to develop a crack growth model under fretting condition

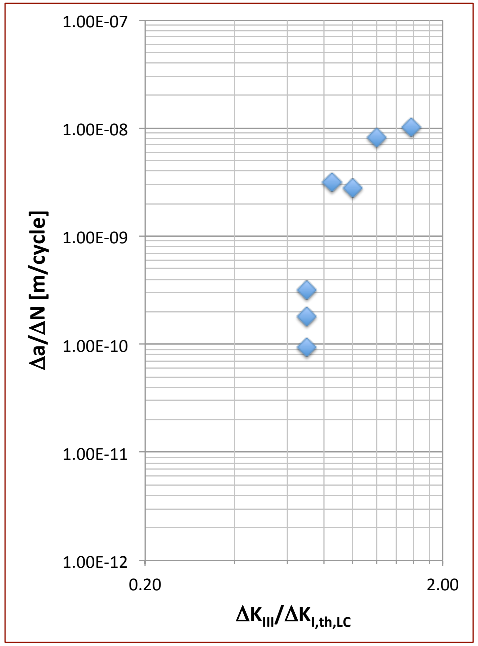
Full scale tests with artificial defects

Conclusion (3)

- New research project between Lucchini RS and PoliMi to develop a crack growth model under fretting condition



MTS 809 Axial-Torsional Test System



Fatigue tests on specimens with artificial defects with a loading path similar to the one experienced by the crack under the press fit

Thank you for your attention