A VIRTUAL TEST RIG FOR BRAKE DISCS BY ADOPTING A THERMO-FLEXIBLE MULTI-BODY APPROACH

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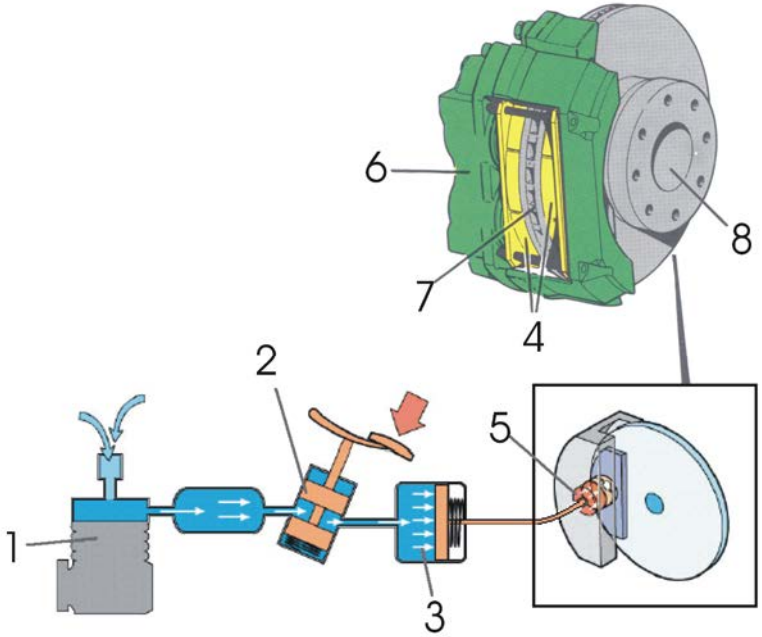
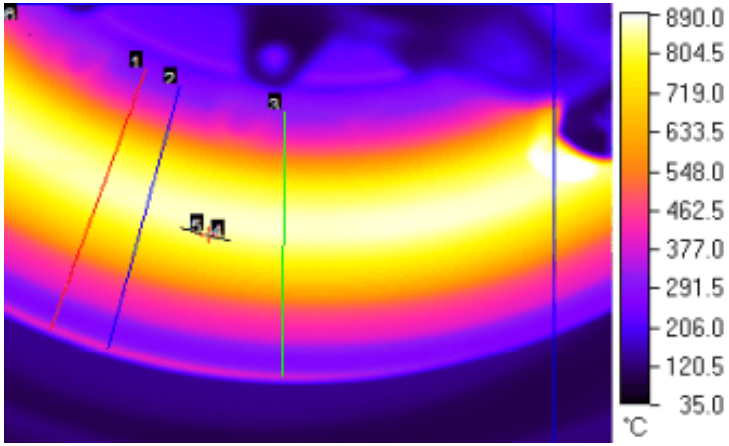
Outline

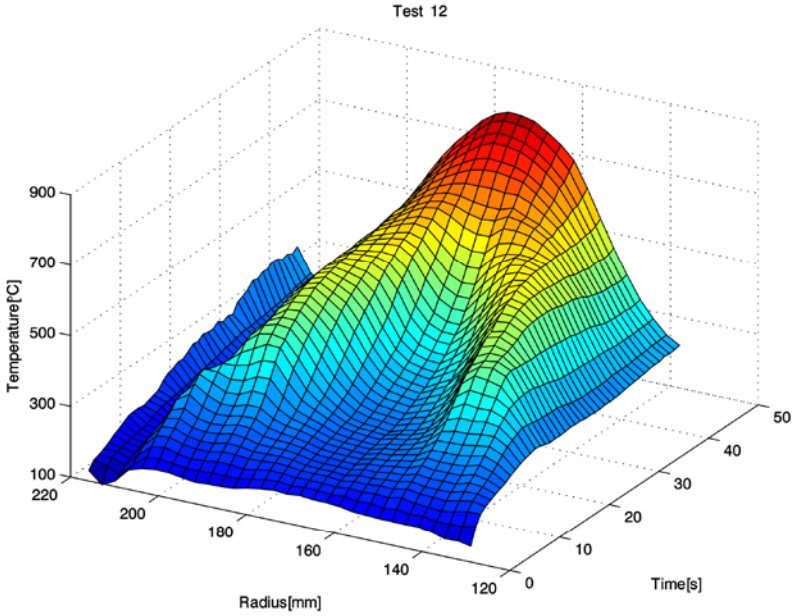
- Background
- New computational approach
- Governing equations
- Algorithm
- Simulation of heat bands in brake discs
- Temperature history, contact pressure, wear
- Simulation of thermal stresses
- Performance
- Test rig - dynamometer
- Virtual test rig - dynamometer
- Temperature dependent friction
- Design optimization
- Concluding remarks

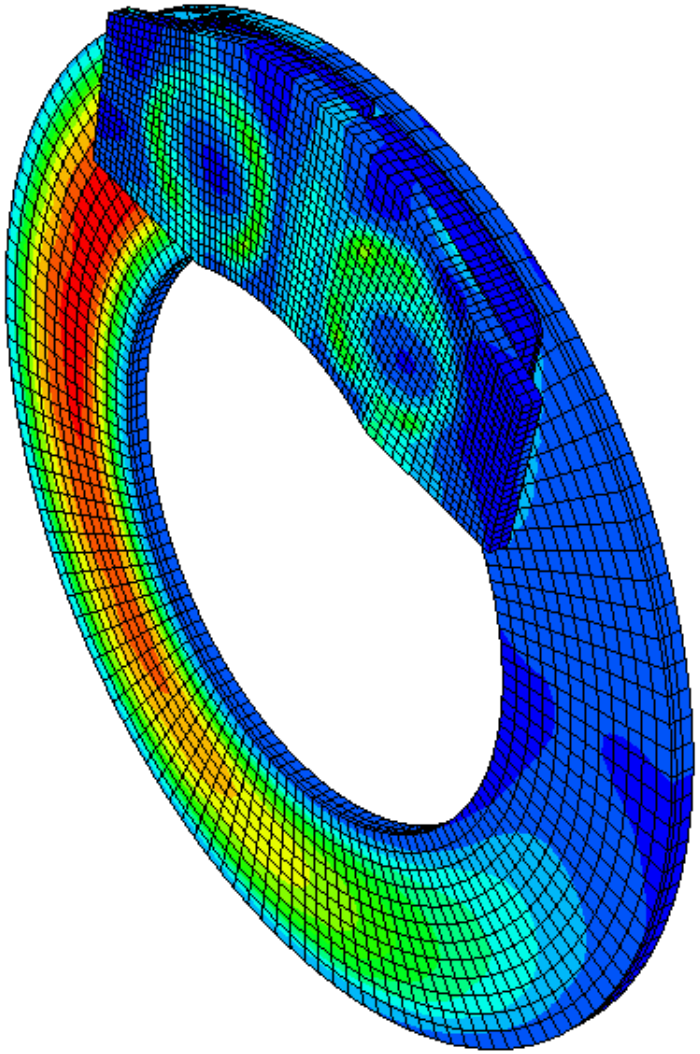
Background



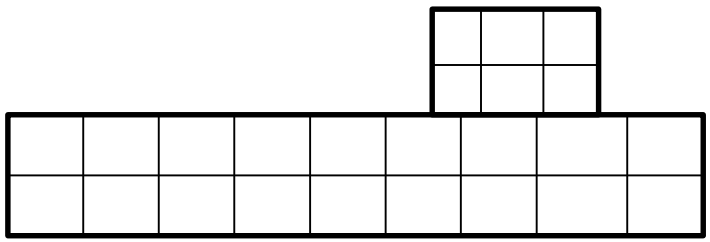
Background

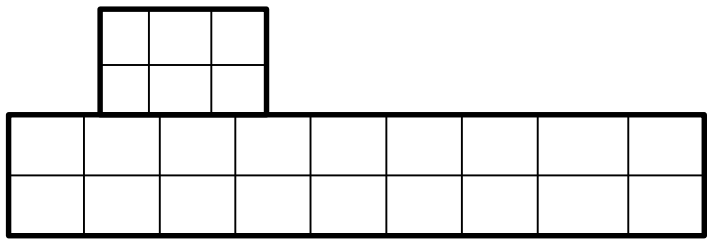

890.0
804.5
719.0
633.5
548.0
462.5
377.0
291.5
206.0
120.5
35.0
°C


Test 12
Temperature[°C]
900
700
500
300
100
220
200
180
160
140
120
Radius[mm]
0
10
20
30
40
50
Time[s]



Traditional approach - Lagrangian



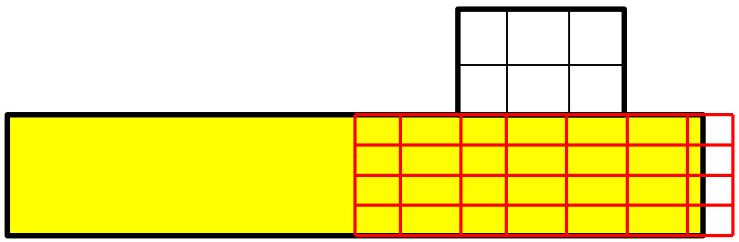


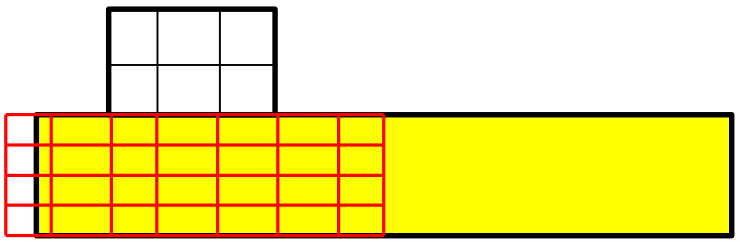
Lagrangian formulation

+ Established approach that can be found in many comercial softwares

- Very long CPU-times

New suggested approach - Eulerian

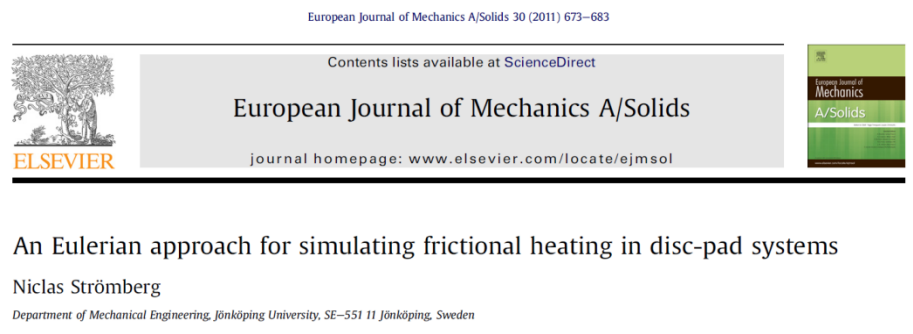




Eulerian formulation

- Not availible on comercial softwares

+Node-to-node contact
+Fine mesh locally at the contact between disc and pad
+Much shorter CPU times



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An Eulerian approach for simulating frictional heating in disc-pad systems

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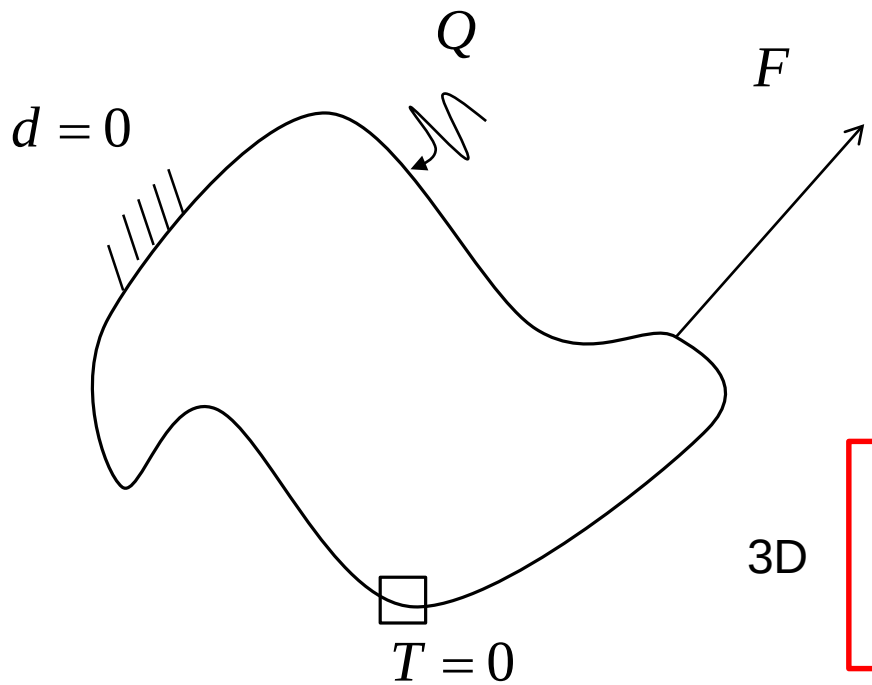
Governing equations, disc and pad – linear thermoelasticity



1D

$$\epsilon = \frac{\sigma}{E} + \alpha \Delta T$$

$$\frac{\partial \sigma}{\partial x} = 0 \qquad \text{+B.C.}$$

3D

$$\sigma_{ij} = \lambda \epsilon_{kk} \delta_{ij} + 2G\epsilon_{ij} - (3\lambda + 2G)\alpha T \delta_{ij}$$

$$\frac{\partial \sigma_{ij}}{\partial x_j} = 0 \qquad \text{+B.C.}$$

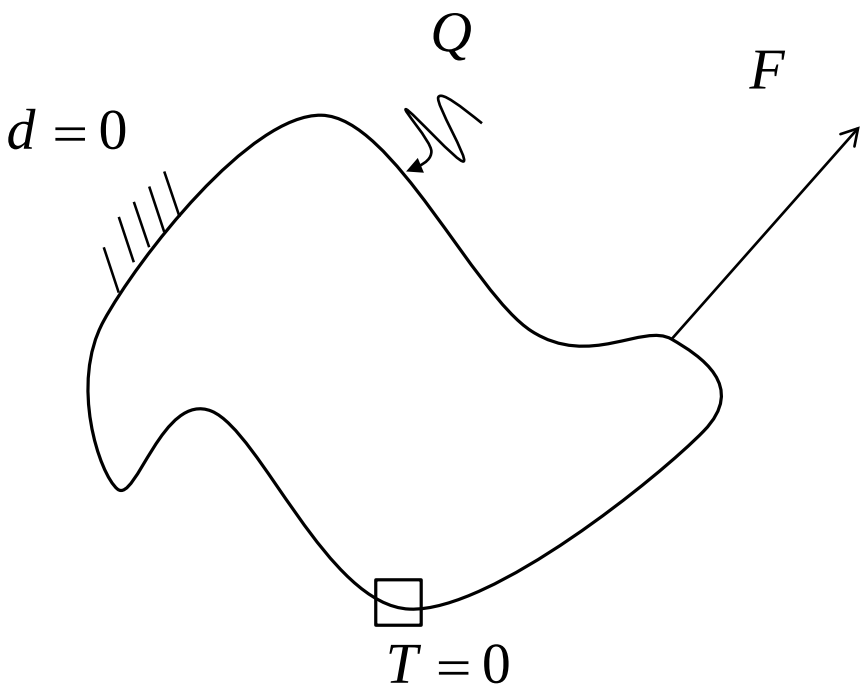
$$K_{ik}^{BA} = \int_{\Omega^m} E_{ijkl} \frac{\partial N^A}{\partial x_l} \frac{\partial N^B}{\partial x_j} \, \mathrm{d}V,$$

$$\hat{K}_i^{BA} = \int_{\Omega^m} \alpha(3\lambda + 2G) N^A \frac{\partial N^B}{\partial x_i} \, \mathrm{d}V,$$

FEM

$$\boldsymbol{K}\boldsymbol{d} - \hat{\boldsymbol{K}}\boldsymbol{T} = \boldsymbol{F}$$

Governing equations, pad – heat balance, Lagrangian formulation



3D

$$\rho c \dot{T} = k \sum_{i=1}^{3} \frac{\partial^2 T}{\partial x_i^2}$$

+B.C. +I.C.

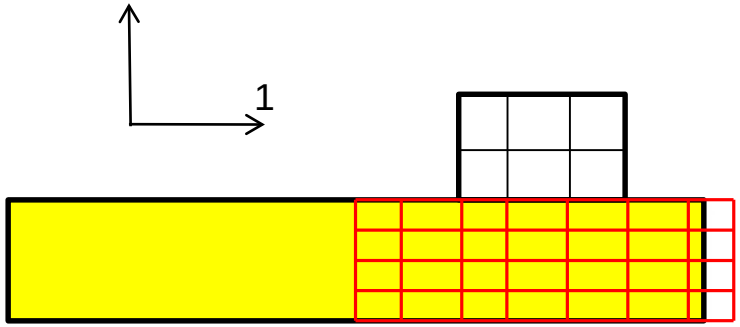
FEM

$$\boldsymbol{M}\dot{\boldsymbol{T}} + \boldsymbol{O}\boldsymbol{T} = \boldsymbol{Q}$$

$$M^{BA} = \int_{\Omega^m} \rho c N^A N^B \, \mathrm{d}V,$$

$$O^{BA} = \int_{\Omega^m} k \frac{\partial N^A}{\partial x_i} \frac{\partial N^B}{\partial x_i} \, \mathrm{d}V,$$

Background, disc – heat balance, Eulerian formulation



$$\dot{T} = \frac{\partial T}{\partial x_i}\frac{\partial x_i}{\partial t} + \frac{\partial T}{\partial t} = v_i \frac{\partial T}{\partial x_i} + \frac{\partial T}{\partial t}$$

3D

$$\rho c \frac{\partial T}{\partial t} + \rho c v \frac{\partial T}{\partial x_1} = T \sum_{k=1}^{3} \frac{\partial^2 T}{\partial x_i^2}$$

+B.C. +I.C.

$$x_i = x_i(\boldsymbol{X}, t)$$

or

$$X_i = X_i(\boldsymbol{x}, t)$$

FEM

$$\boldsymbol{M}\dot{\boldsymbol{T}} + \boldsymbol{O}\boldsymbol{T} + \boldsymbol{N}\boldsymbol{T} = \boldsymbol{Q}$$

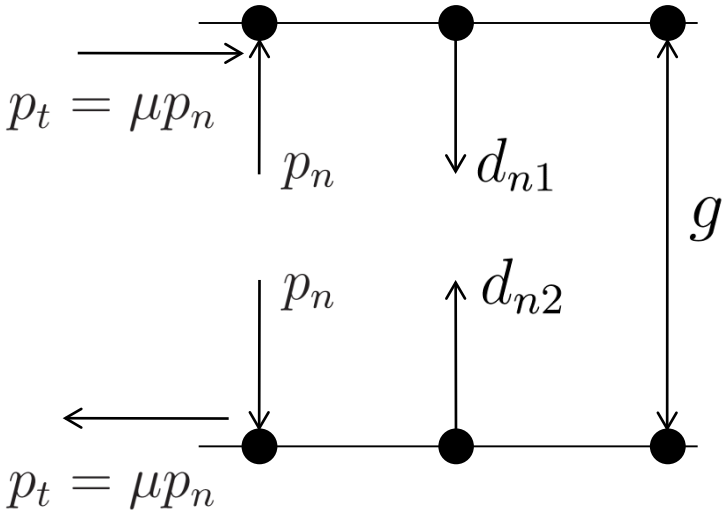
SU-FEM

$$\boldsymbol{M}\dot{\boldsymbol{T}} + \boldsymbol{O}\boldsymbol{T} + \boldsymbol{N}\boldsymbol{T} + \boldsymbol{R}\boldsymbol{T} = \boldsymbol{Q}$$

$$T = T(\boldsymbol{x}, t)$$

$$N^{BA} = \int_{\Omega^1} \rho c v_i \frac{\partial N^A}{\partial x_i} N^B \, \mathrm{d}V. \qquad R^{BA} = \bar{k} \int_{\Omega^1} v_i \frac{\partial N^A}{\partial x_i} v_j \frac{\partial N^B}{\partial x_j} \, \mathrm{d}V$$

Governing equations, contact interface – equilibrium



$$p_n \geq 0, \quad \delta_n \leq 0, \quad p_n \delta_n = 0$$

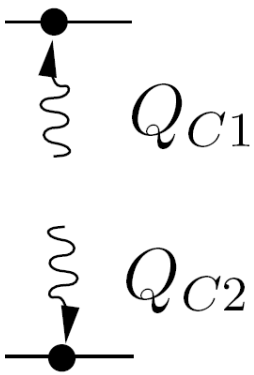
$$p_n = \frac{p_n + r\delta_n + |p_n + r\delta_n|}{2}$$

$$\delta_n = d_{n1} + d_{n2} - g$$

$$\boldsymbol{K}_1 \boldsymbol{d}_1 - \hat{\boldsymbol{K}}_1 \boldsymbol{T}_1 = \boldsymbol{F} + \boldsymbol{F}_{N1} + \boldsymbol{F}_{T1}$$

$$\boldsymbol{K}_2 \boldsymbol{d}_2 - \hat{\boldsymbol{K}}_2 \boldsymbol{T}_2 = \boldsymbol{F}_{N2} + \boldsymbol{F}_{T2}$$

Governing equations, contact interface – heat balance



$$Q_{C1} = \varphi^0 p_n (T^2 - T^1) + \xi \mu p_n v$$
$$Q_{C2} = \varphi^0 p_n (T^1 - T^2) + (1 - \xi) \mu p_n v$$

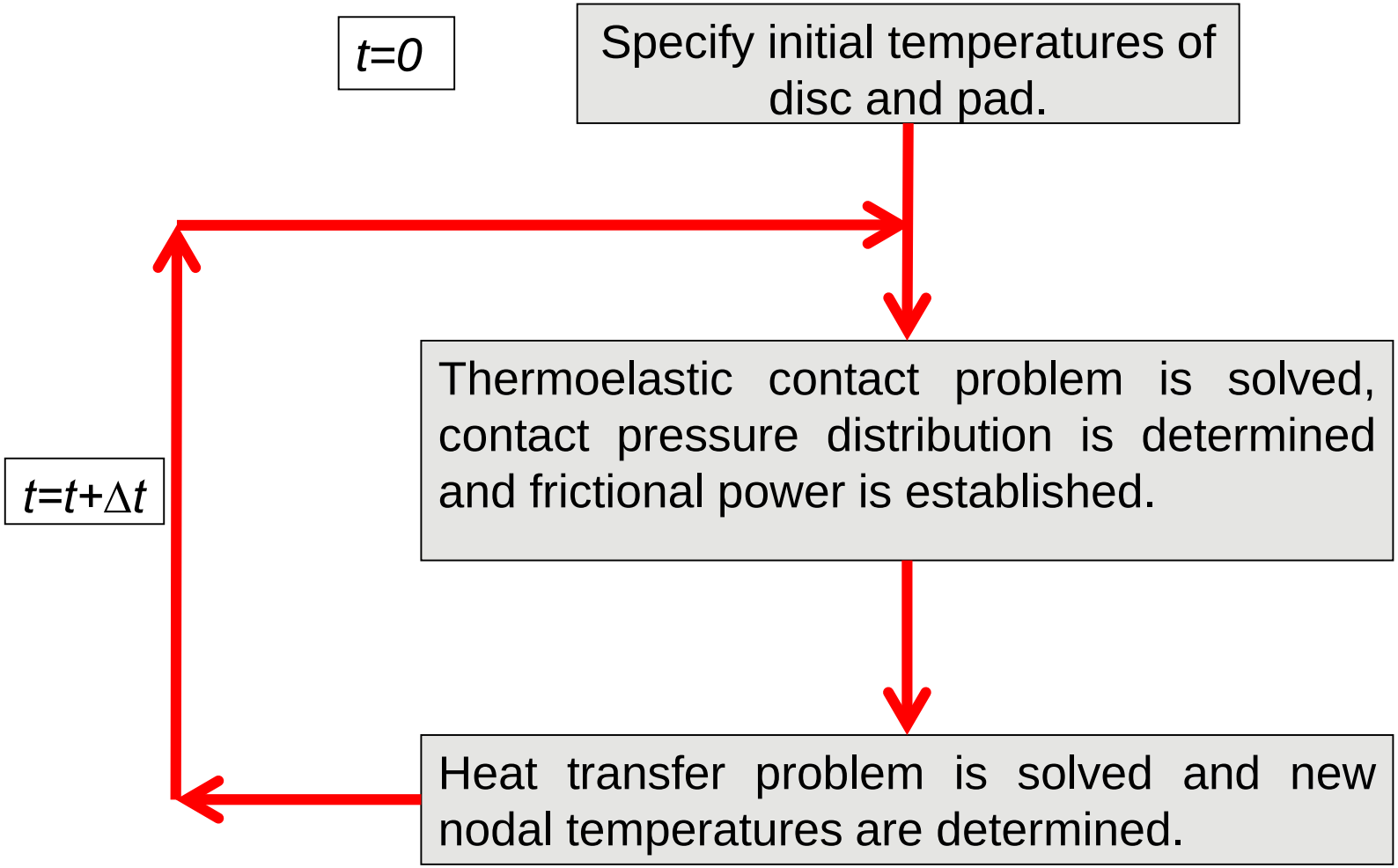
$$\boldsymbol{M}_1 \dot{\boldsymbol{T}}_1 + \boldsymbol{O}_1 \boldsymbol{T}_1 = \boldsymbol{Q} + \boldsymbol{Q}_{C1}(\boldsymbol{T}, \boldsymbol{P}_n)$$

$$\boldsymbol{M}_2 \dot{\boldsymbol{T}}_2 + (\boldsymbol{N} + \boldsymbol{R} + \boldsymbol{O}_2) \boldsymbol{T}_2 = \boldsymbol{Q}_{C2}(\boldsymbol{T}, \boldsymbol{P}_n)$$

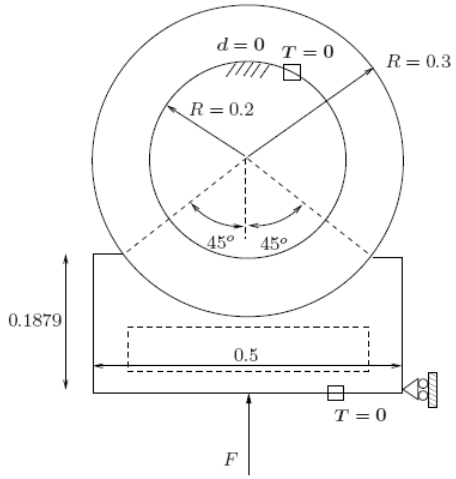
$$\boldsymbol{Q}_{c1}(\boldsymbol{T}, \boldsymbol{P}_n) = \boldsymbol{S}_{P2}(\boldsymbol{P}_n) \boldsymbol{T}_2 - \boldsymbol{S}_{P1}(\boldsymbol{P}_n) \boldsymbol{T}_1 + \boldsymbol{Q}_\mu^1(\boldsymbol{P}_n)$$
$$\boldsymbol{Q}_{c2}(\boldsymbol{T}, \boldsymbol{P}_n) = \boldsymbol{S}_{P1}(\boldsymbol{P}_n) \boldsymbol{T}_1 - \boldsymbol{S}_{P2}(\boldsymbol{P}_n) \boldsymbol{T}_2 + \boldsymbol{Q}_\mu^2(\boldsymbol{P}_n)$$

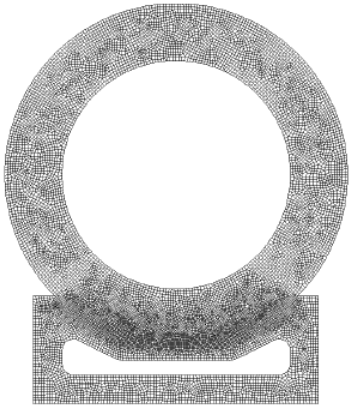
$$\boldsymbol{S}_{Pm}^A = \left[\boldsymbol{0} \left[\varphi^0 P_n^A\right] \boldsymbol{0}\right]$$

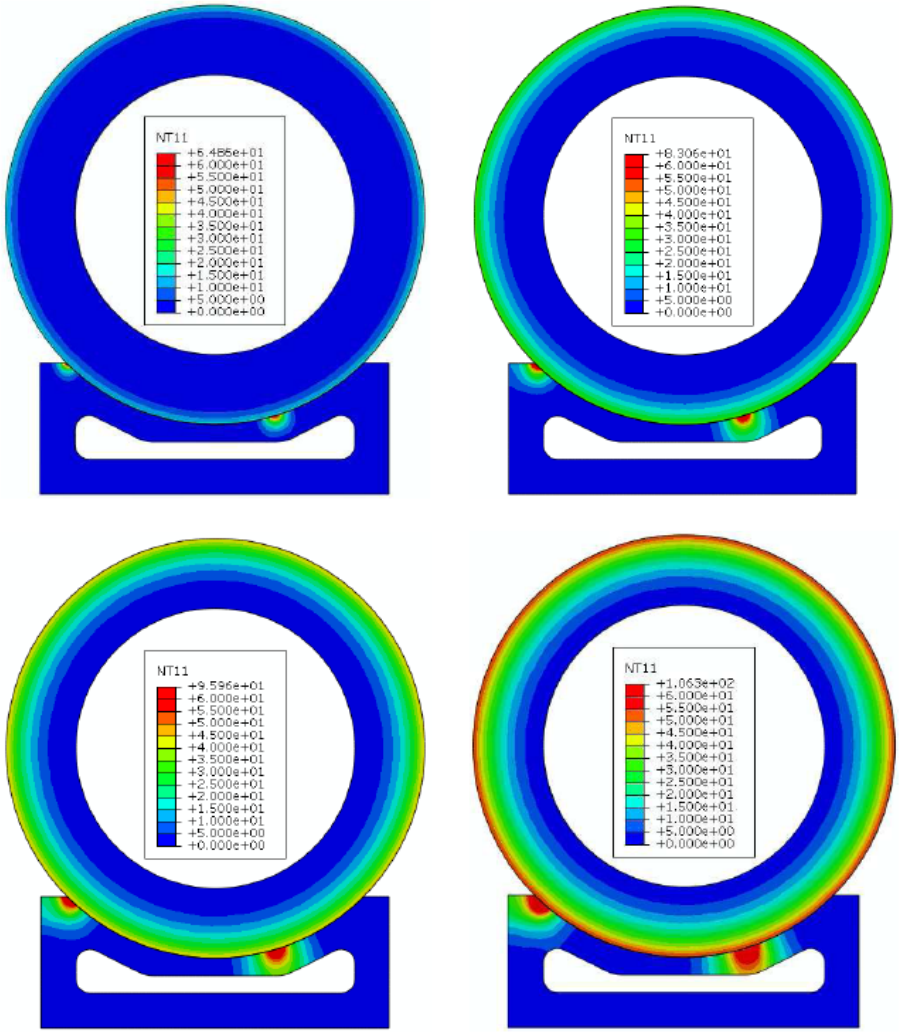
Algorithm - sequential



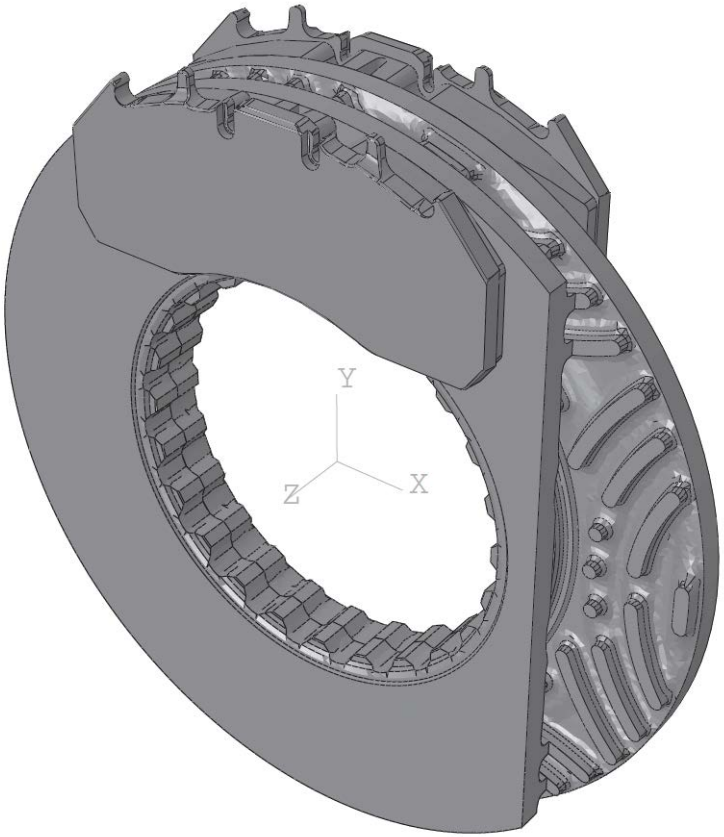
Benchmark 2D

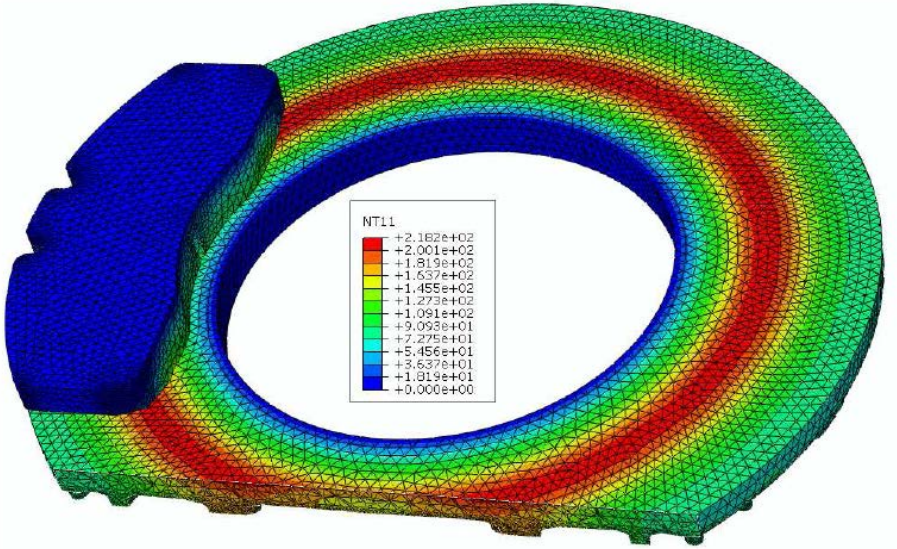






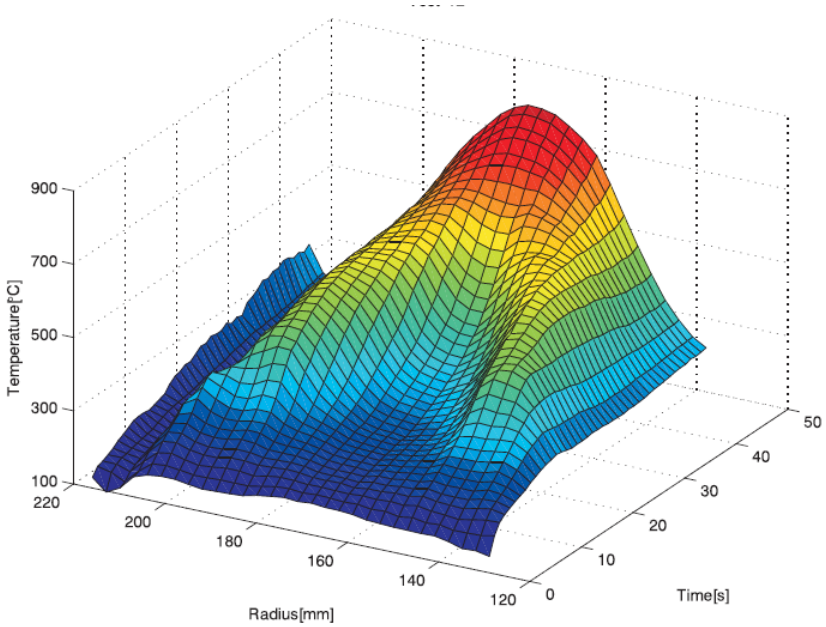
Simulation of heat bands in disc brakes



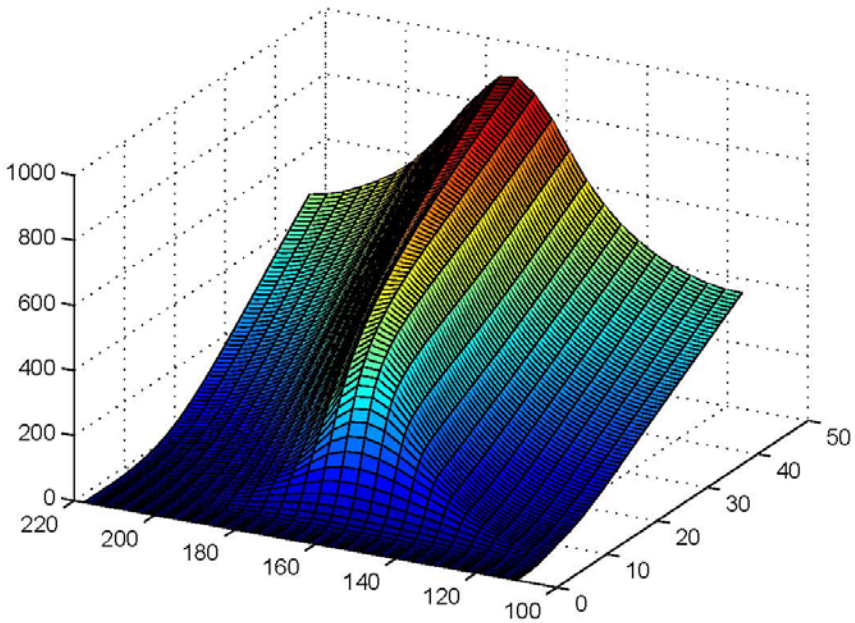


Temperature history – no wear

Test 12-Thermography camera

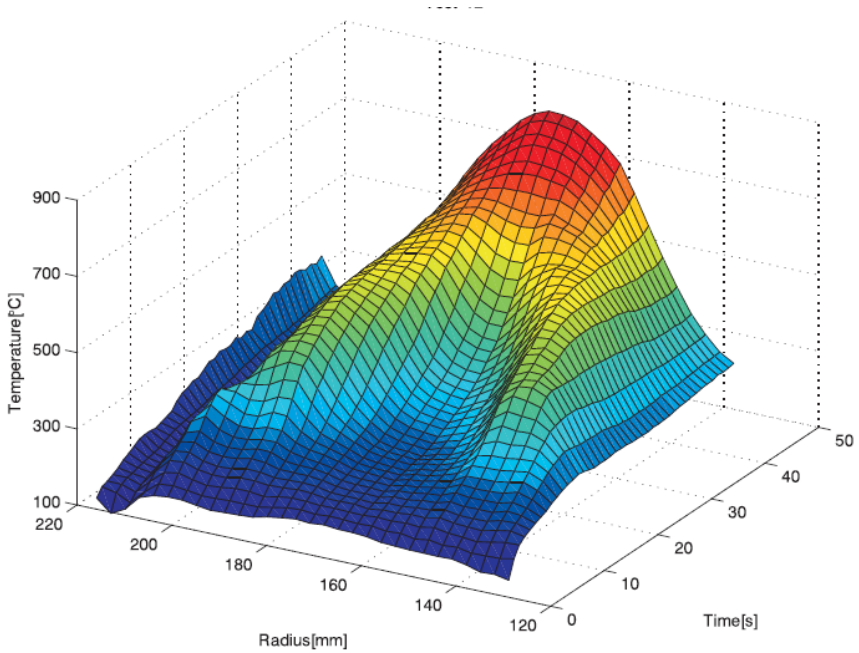


In-house software

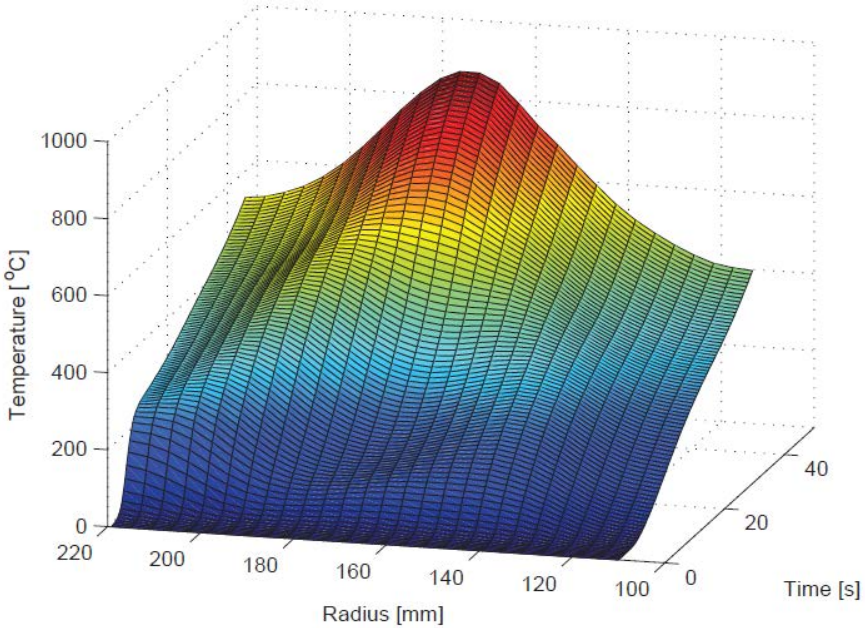


Temperature history – including wear

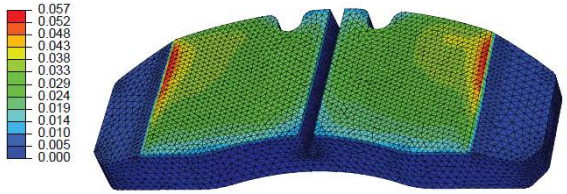
Test 12-Thermography camera



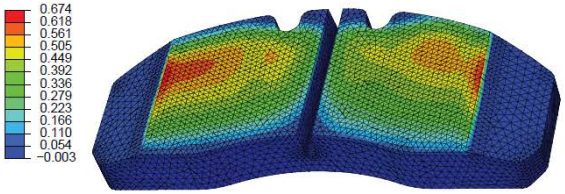
In-house software



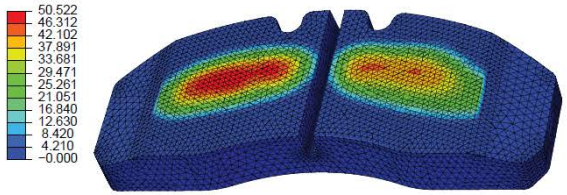
Contact pressure



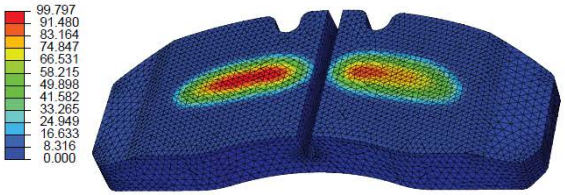
(a) t = 0.5 s



(b) t = 2.5 s

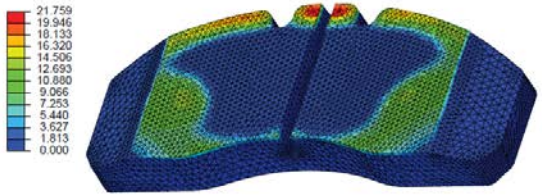


(c) t = 7.5 s

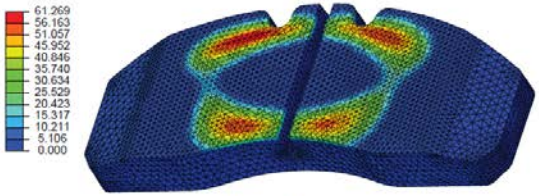


(d) t = 10 s

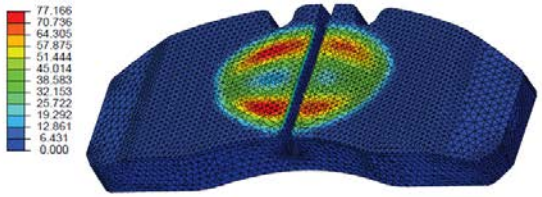
First cycle



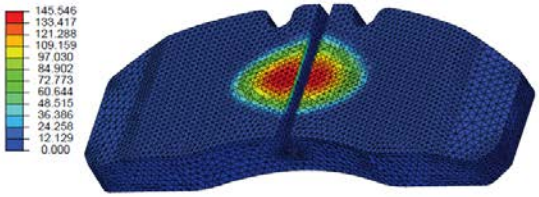
(a) t = 5 s



(b) t = 15 s



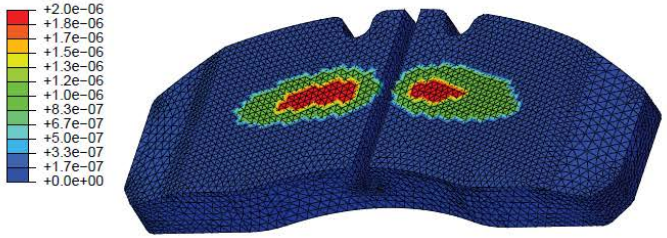
(c) t = 30 s



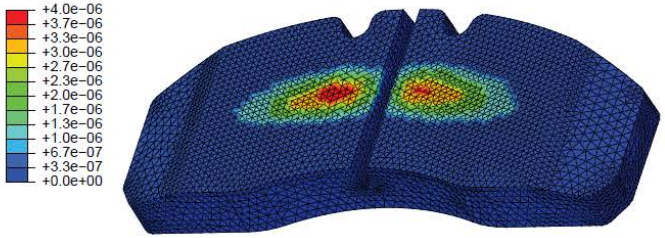
(d) t = 45 s

After a period of running in.

Wear on pad surface

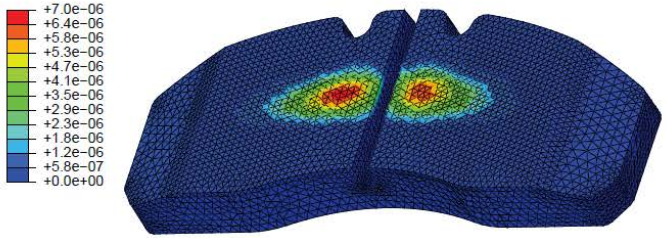


(a) t = 17.5 s

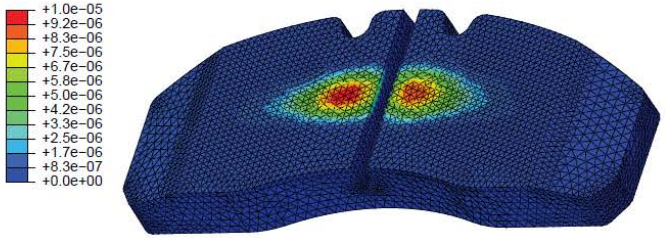


(b) t = 25 s

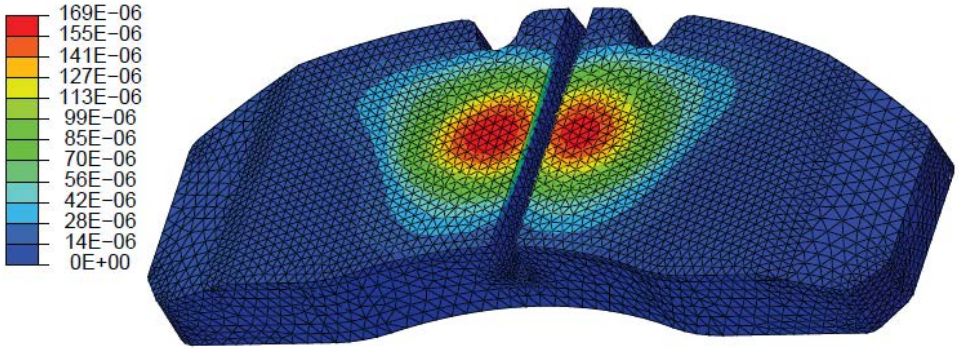
First cycle



(c) t = 35 s

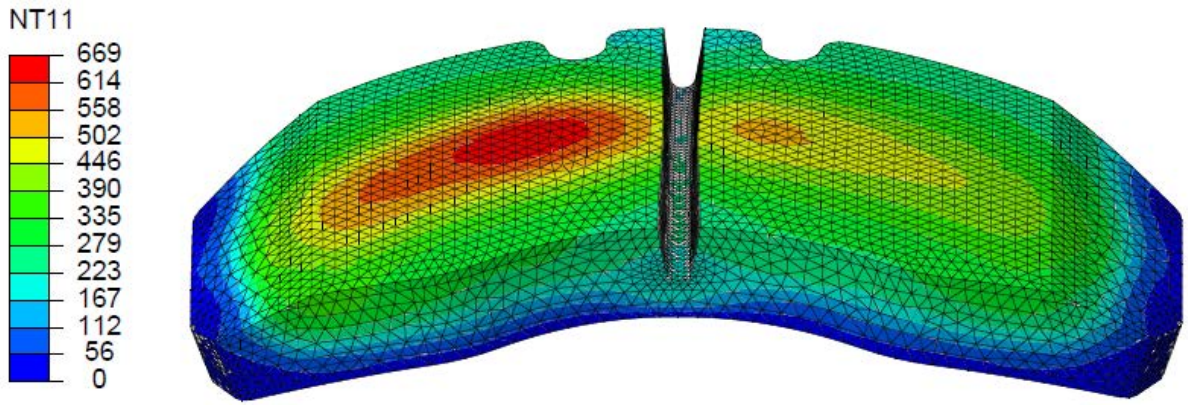


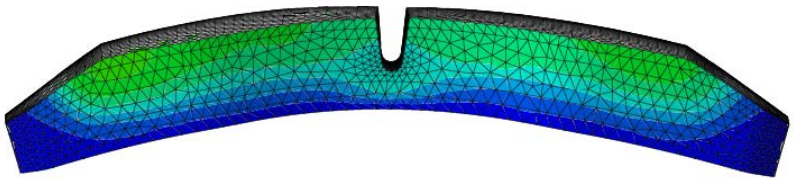
(d) t = 45 s

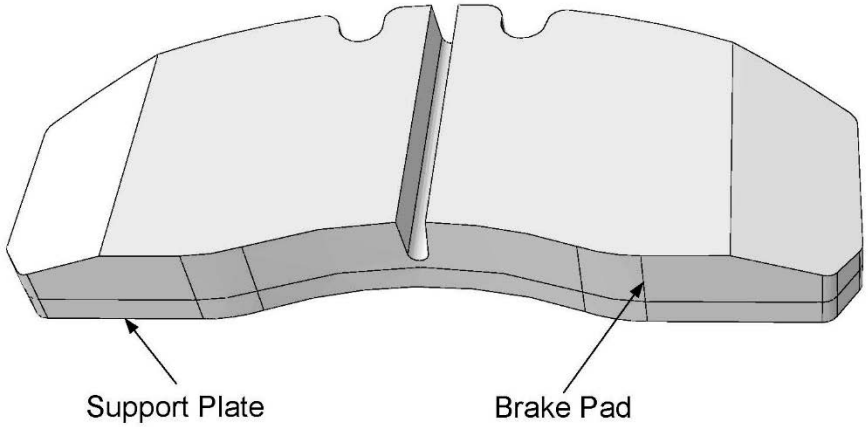


After a period of running in.

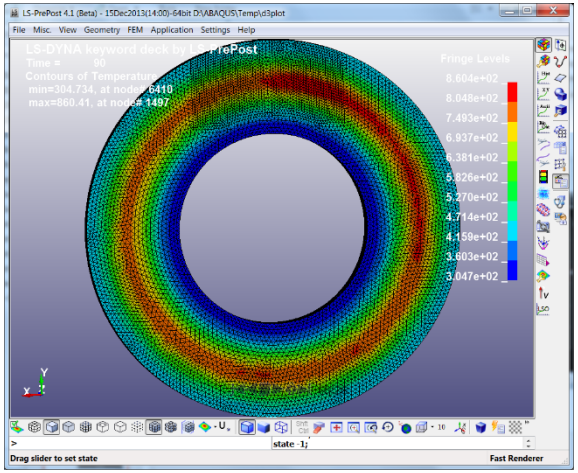
Convex bending

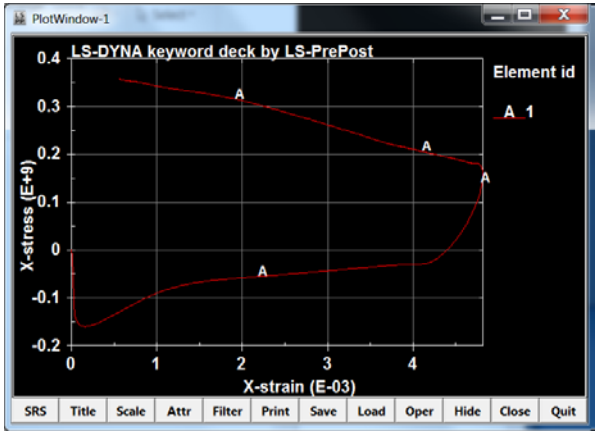


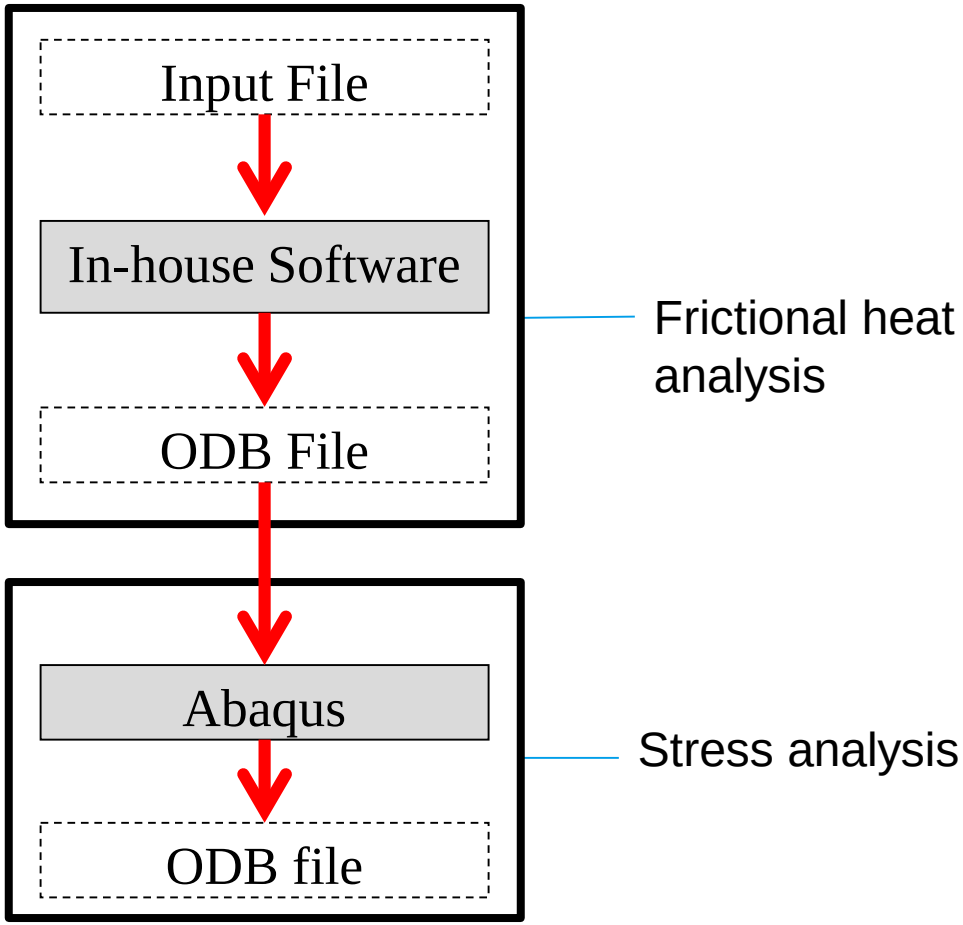




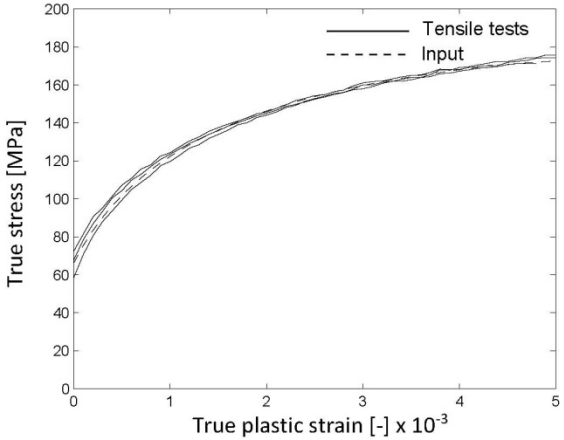
Stress analysis – decoupled approach



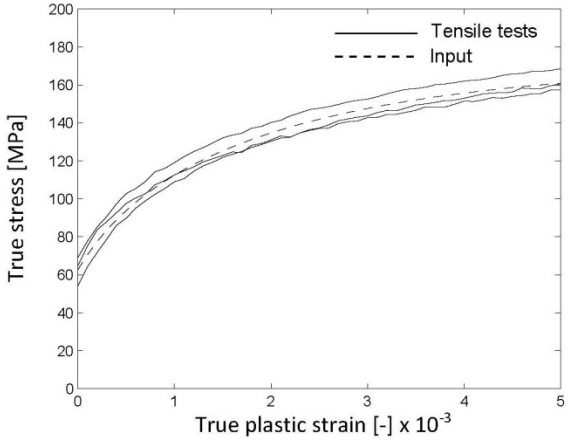




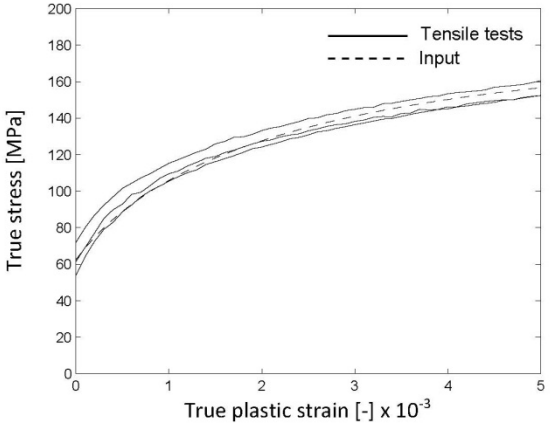
Temperature dependent material data



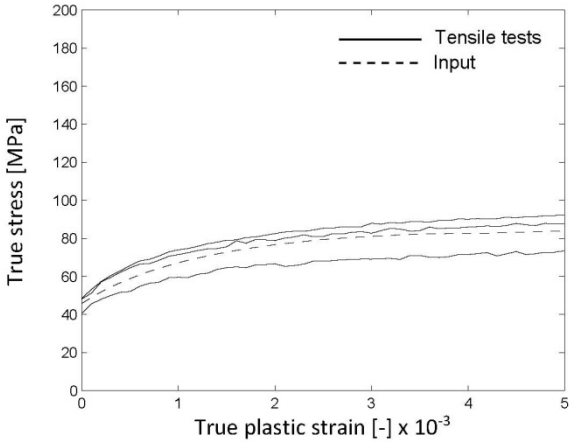
20°C



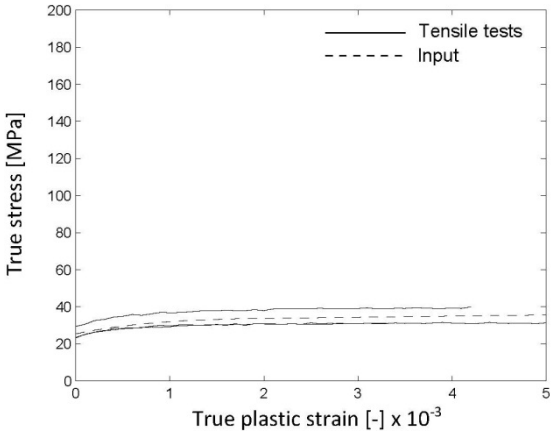
200°C



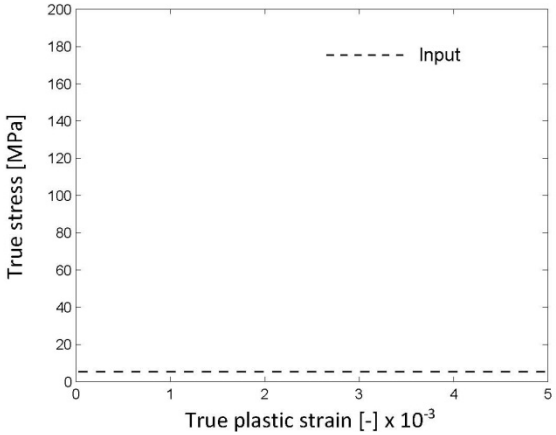
400°C



600°C

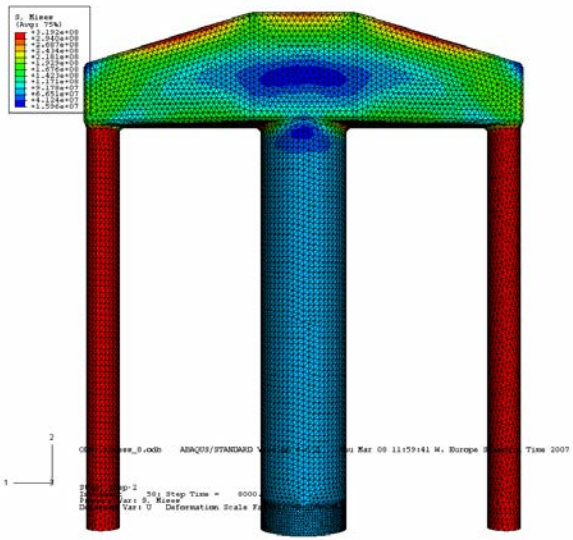


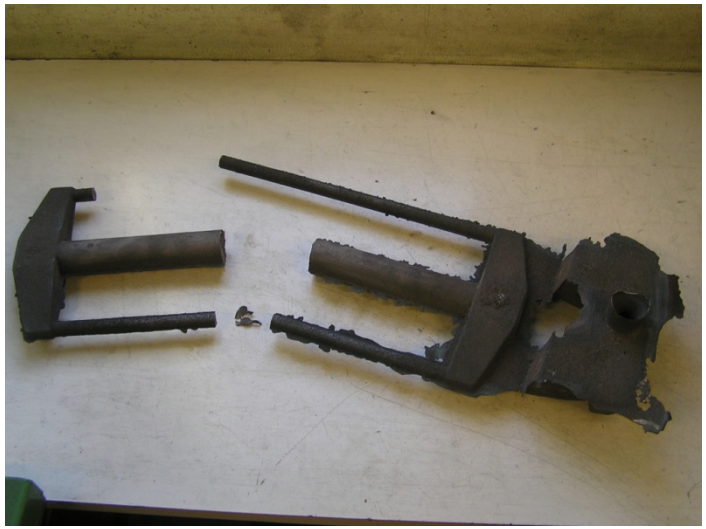
800°C

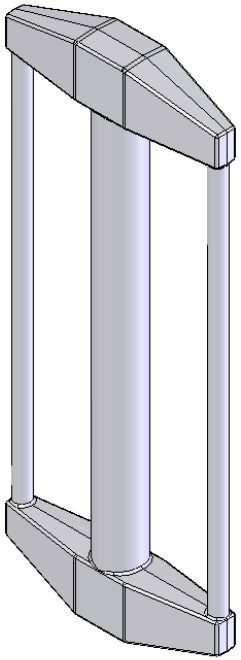


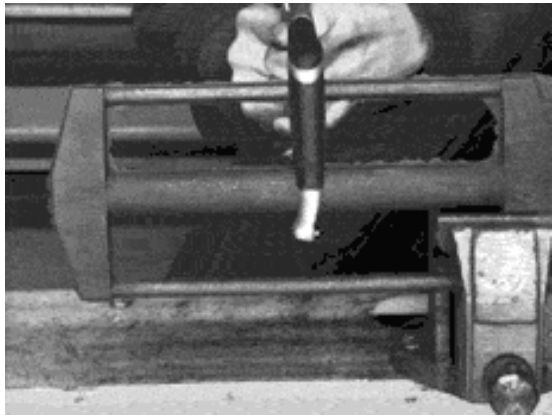
1120°C

Residual stresses – simulation & experiments

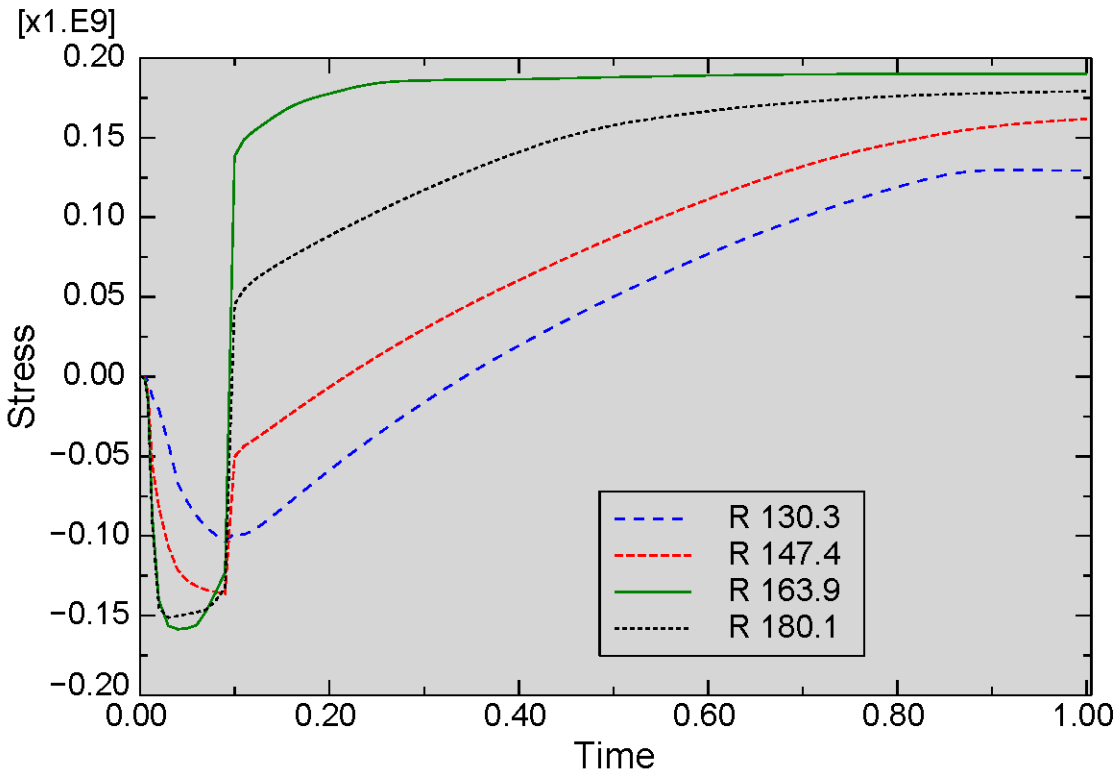


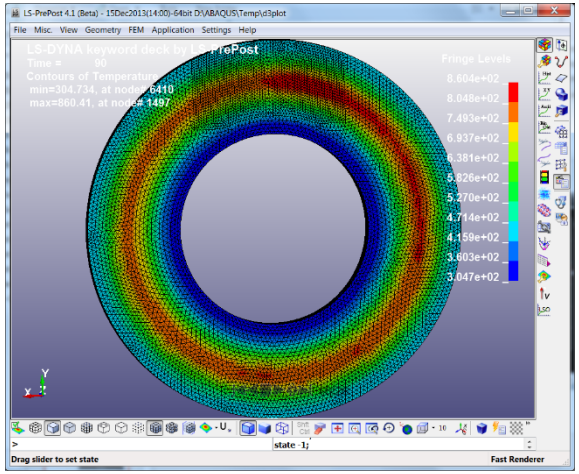




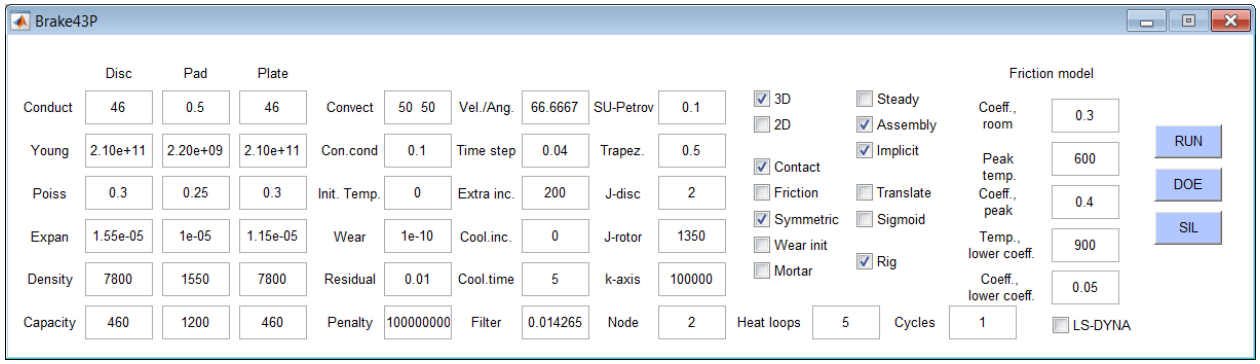


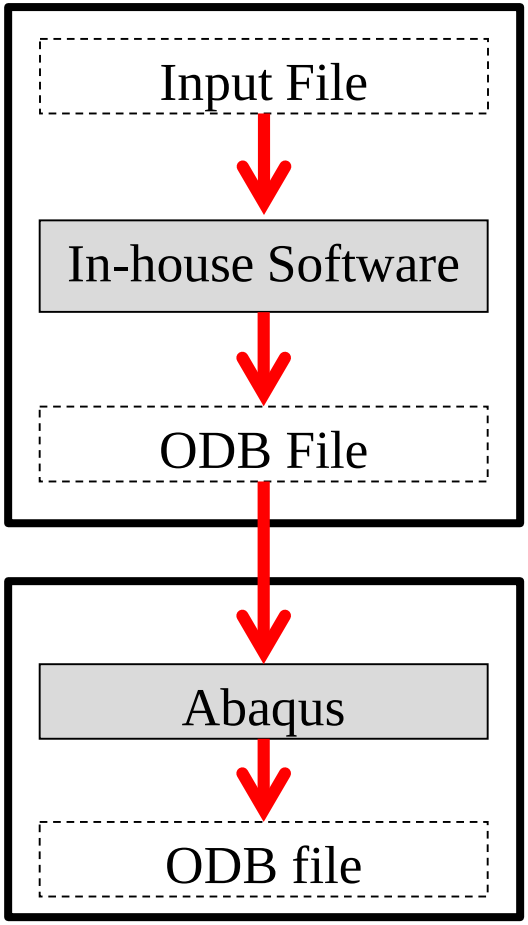
Circumferential stresses





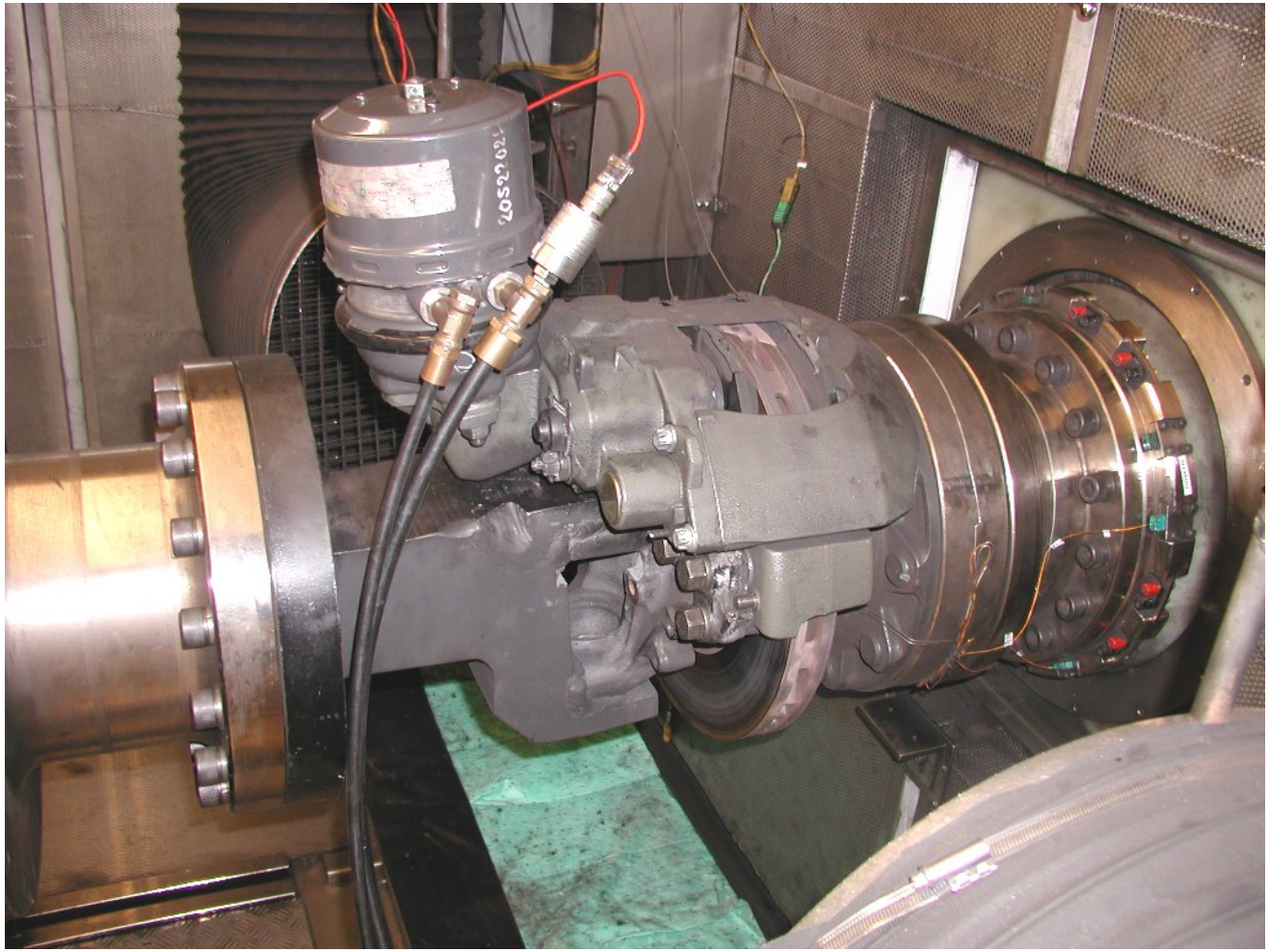
Performance



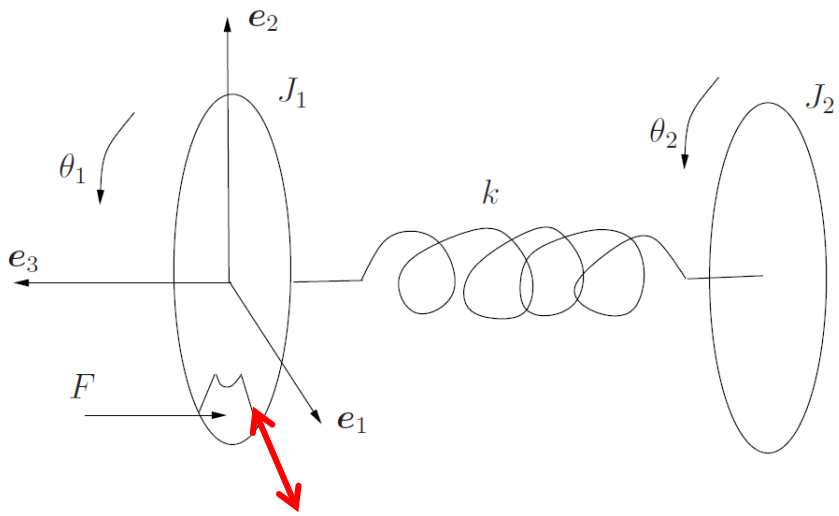


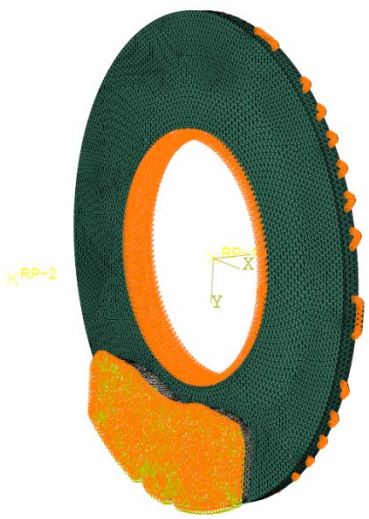
	Run Time (hours)	Brake Time (s)
Sequential Approach	3.8	45
Fully Coupled Approach	480	5

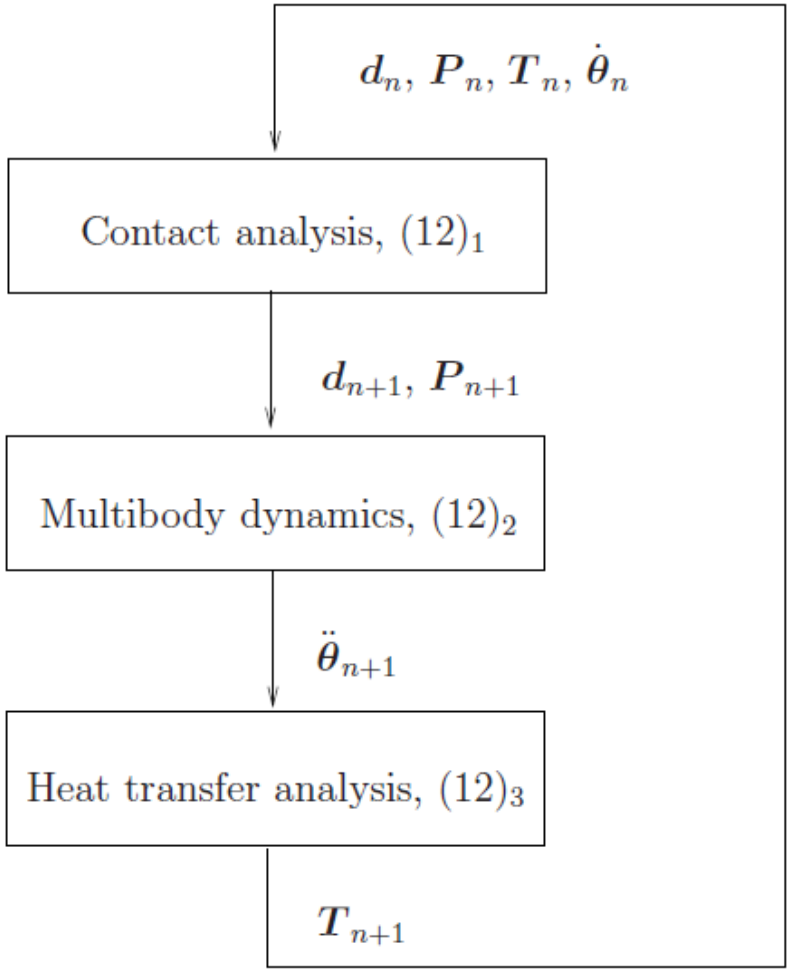
Test rig - dynamometer



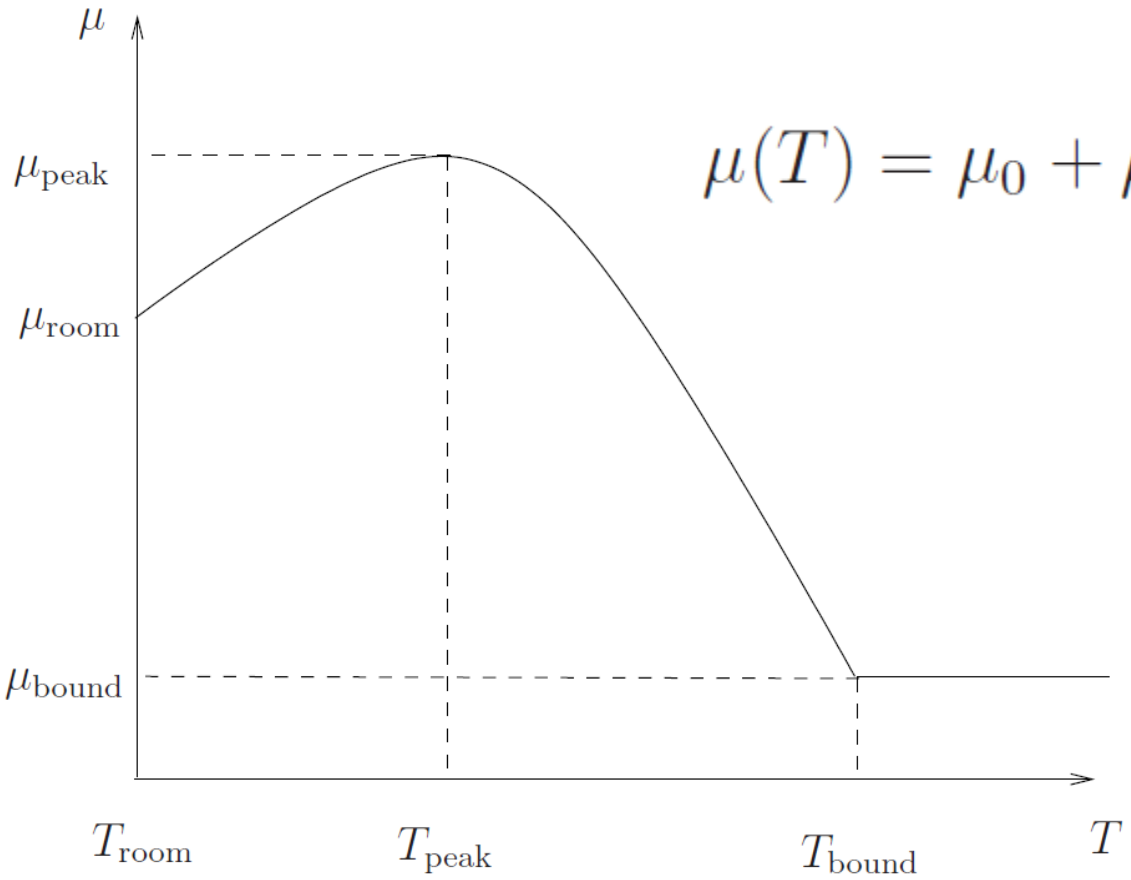
Virtual test rig - dynamometer





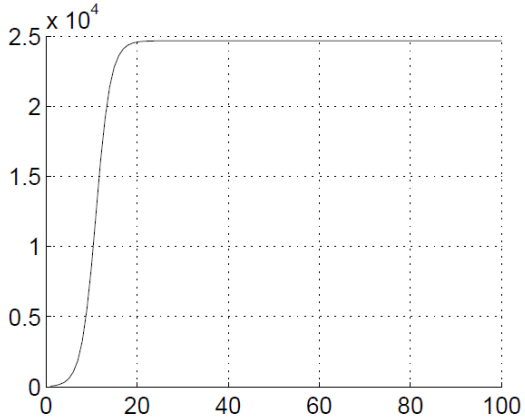


Friction model – temperature dependent

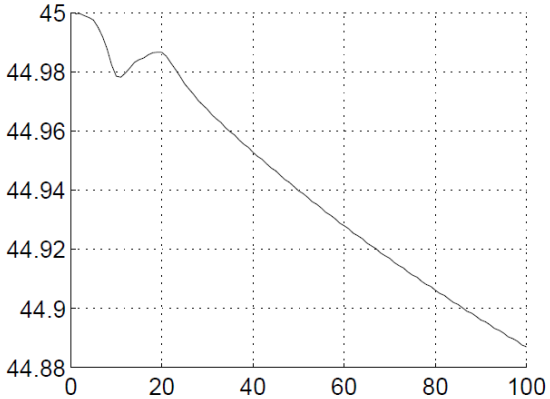


$$\mu(T) = \mu_0 + \mu_1 T + \mu_2 T^2$$

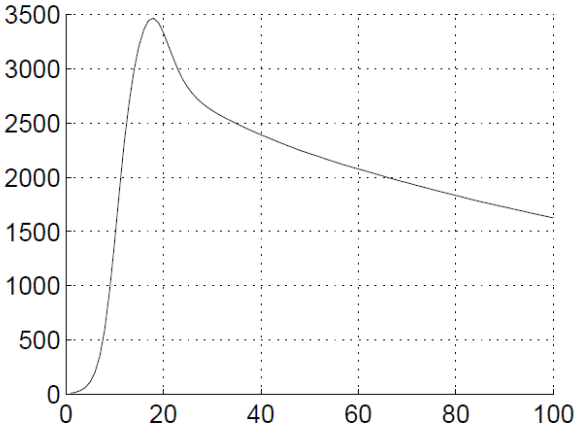
Virtual test data



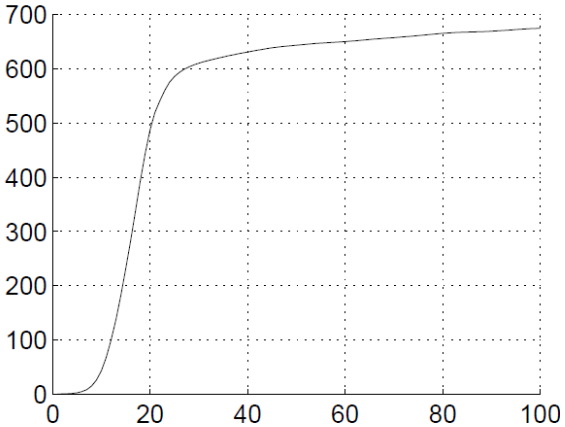
(a) Clamping force



(b) Angular velocity



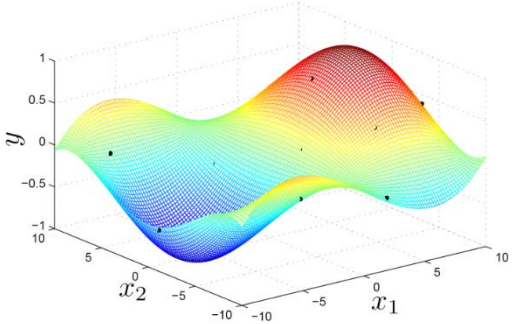
(c) Brake moment

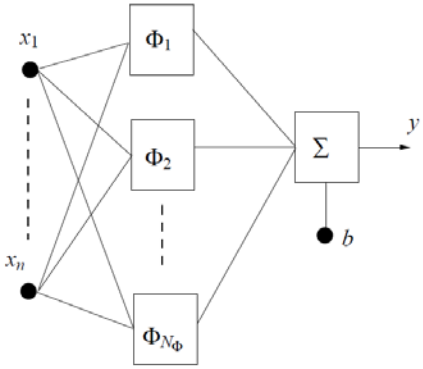


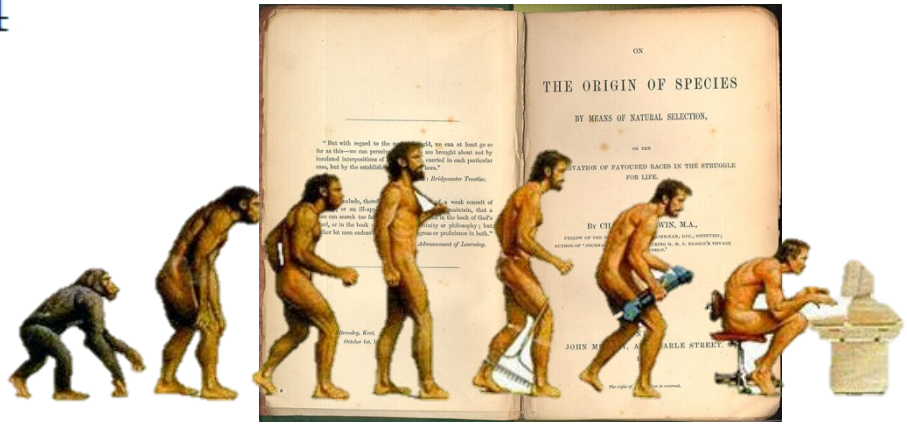
(d) Maximum temperture

Design optimization

$$
\begin{aligned}
\text{Minimize} \quad & T_{max}(\boldsymbol{x}), \\
\text{Maximize} \quad & E_{brake}(\boldsymbol{x}), \\
\text{Minimize} \quad & m(t), \\
& 17.15E + 3 \leq F \leq 24.5E + 3 \\
& 2.2E + 8 \leq E \leq 2.2E + 9 \\
& 5 \leq t \leq 14
\end{aligned}
$$







Concluding remarks

- A new idea for thermomechanical contact problems is suggested, derived and implemented.
- A toolbox for simulating brake disc is developed based on the new approach.
- A thermo-flexible multi-body model is suggested for simulating dynamomters for brake discs.
- A virtual test rig is developed by implementing the thermo-flexible multi-body model in the toolbox
- A decoupled approach for simulating corresponding residual stresses is developed.
- Design optimization of the disc pad system is initiated.

Acknowledgements

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