Implementation of a continuum creep damage model for POM in Abaqus©

J. Strauch[1], Dr. M. De Monte[1], V. Le Baube[1], E. Moosbrugger[1]

[1] Robert Bosch GmbH, Corporate Sector Research and Advance Engineering – Advance Production Technology 1 – Plastics Engineering, Waiblingen (Germany)

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Outline

1. **Introduction**
2. Constitutive equations
3. Implementation
4. Calibration and validation
5. Application
6. Summary and outlook

Motivation

Goal

- Lifetime prediction for plastic parts under long-term static load (creep)

Requirements on material modeling

- All stages of creep behavior have to be represented.

Proceeding

- Standard Abaqus creep models are not sufficient.
- A suitable material model has to be implemented.

Characteristic stages of creep

I. Primary or reduced creep

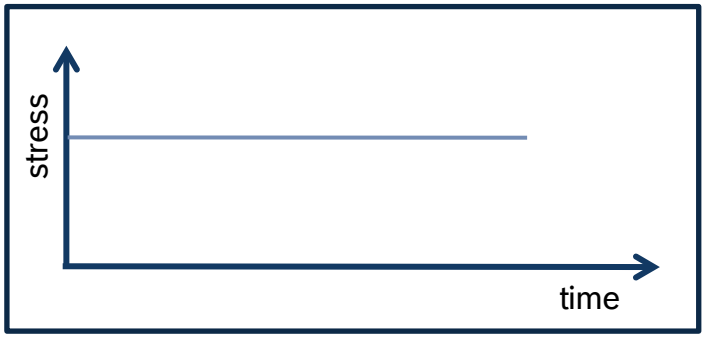
- Hardening dominating
- $d^2\varepsilon_{cr} / dt^2 < 0$

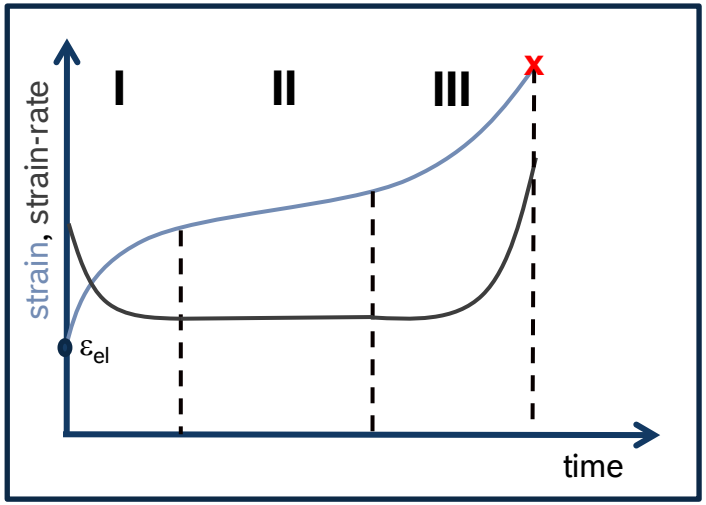
II. Secondary or stationary creep

- Equilibrium between hardening and softening effects
- $d^2\varepsilon_{cr} / dt^2 = 0$

III. Tertiary or accelerated creep

- Softening due to <u>damage</u> (crazing, micro cracks, ...)
- $d^2\varepsilon_{cr} / dt^2 > 0$

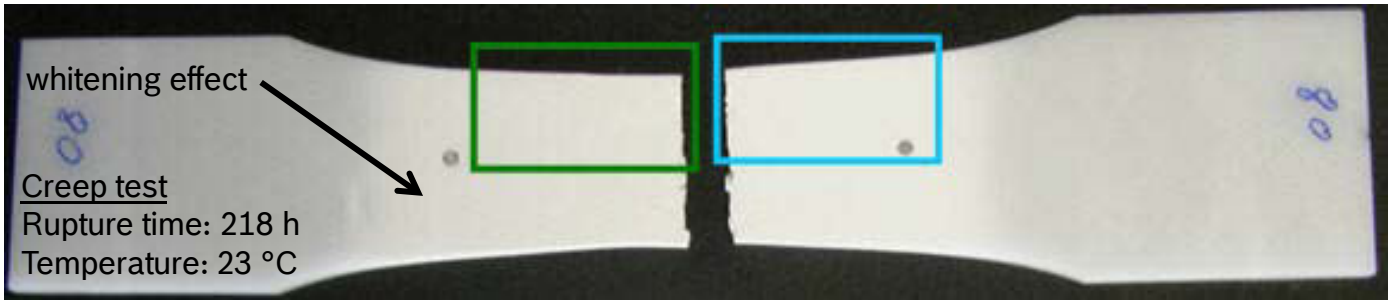


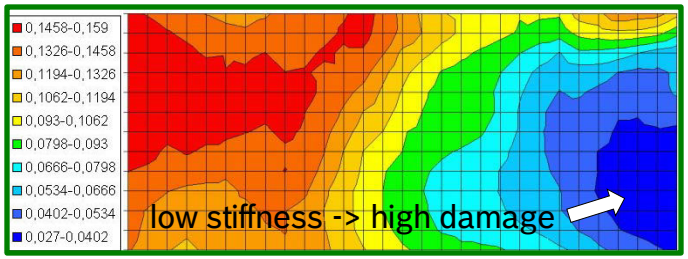


x = failure

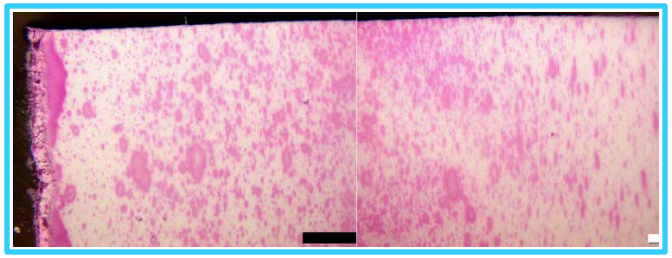
Deformation and damage mechanism

- Investigations on proven POM specimen [Hepp2011]:





Stiffness distribution, measured with a micro hardness tester. Unit [mN/nm]



Microvoids, visualized by a color dye test (cutting plane = 0.5 * thickness)

- The appearance of local damage effects in POM could be confirmed.

[Hepp2011]: Bernhard Hepp, "Analyse und Bewertung von Schädigungs- und Schädigungsmechanismen an POM, Diplomarbeit, Robert Bosch GmbH / Fachhochschule Würzburg-Schweinfurt, 2011

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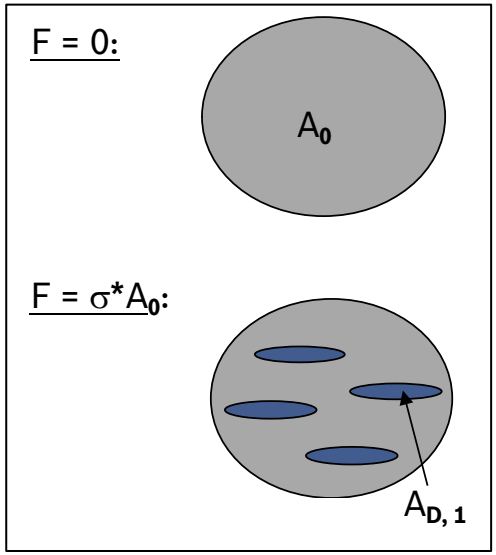
Introduction of a damage variable

- To consider material damage, the definition of a phenomenological scalar damage variable ω was proposed by Kachanov (1958).
- The damage variable describes the area fraction of cracks in a cutting plane:

$$\omega = \frac{\sum_i A_{D,i}}{A_0} \quad \text{with} \quad \omega(t_0) = 0$$

- Originally developed for use with metals
- Here, use of Kachanov's approach to model the damage evolution (e.g. crazes, voids) in POM



Creep damage model (Kachanov-Rabotnov-Hayhurst)

- Coupled differential equation system
  - Constitutive creep equation

$$\dot{\varepsilon}_{cr}(\sigma,\omega,T) = A(T)\cdot H(\varepsilon_{cr})\cdot\left(\frac{\sigma}{1-\omega}\right)^{n}$$

  - Damage evolution equation

$$\dot{\omega}(\sigma,\omega,T) = B(T)\cdot\frac{\sigma^{m}}{(1-\omega)^{l}} \quad \text{with } \omega(t_0)=0 \text{ and } \omega(t_{\text{fail}})=\omega^{*}$$

  - with strain hardening function *H* and Arrhenius functions *A* and *B*

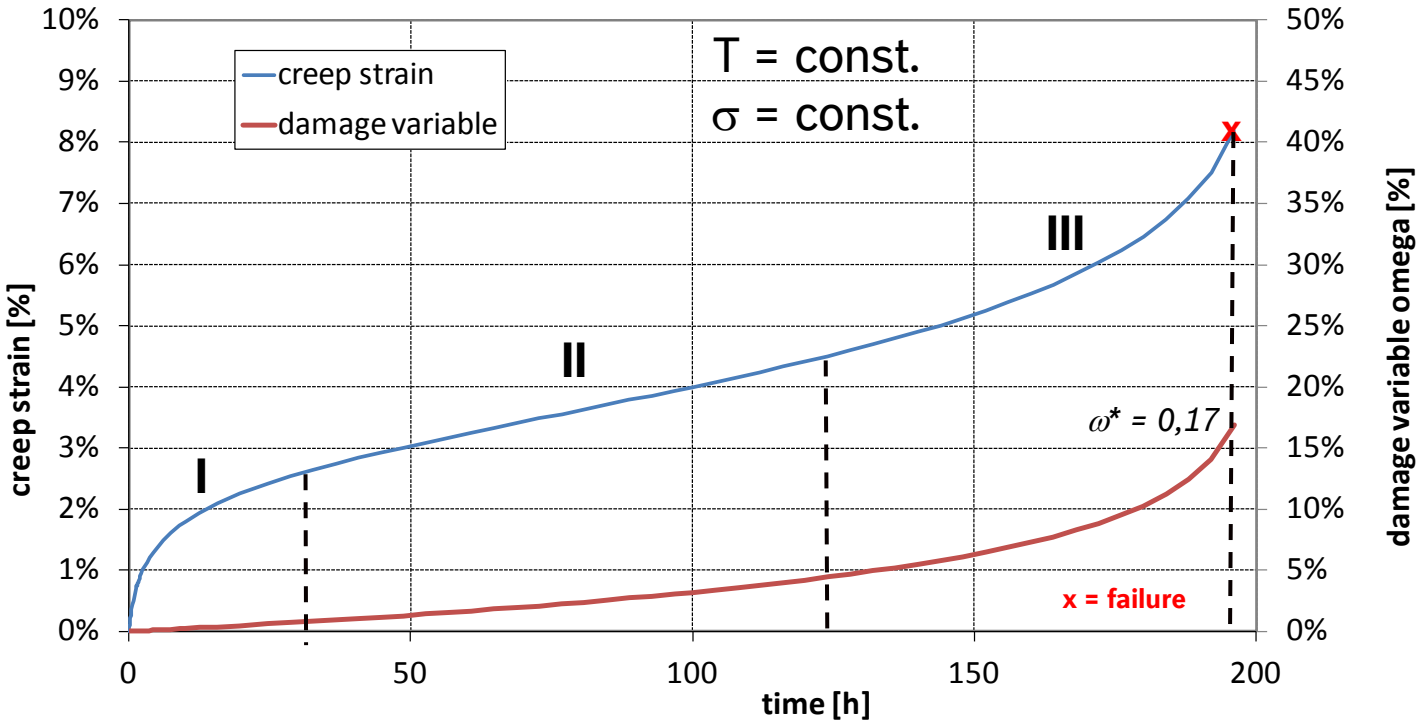
$$H(\varepsilon_{cr}) = 1 + C\cdot e^{-\frac{\varepsilon_{cr}}{k}} \quad ; \quad A(T) = A_0\cdot e^{-\frac{h}{T}} \quad ; \quad B(T) = B_0\cdot e^{-\frac{p}{T}}$$

- Nine model parameter: $C, k, A_0, h, B_0, p, n, m, l$

σ = von Mises equivalent stress
ε_{cr} = plastic equivalent strain (creep strain)
$\dot{\varepsilon}_{cr}$ = plastic strain rate (creep rate)

Example

- Numerical integration of coupled differential equation system



- The model is able to reproduce all three creep stages including failure.

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Abaqus user subroutine “creep.f ”

3D approach follows from the plastic flow rule:

$$\Delta\varepsilon_{ij}^{pl} = \Delta\lambda \frac{\partial g}{\partial \sigma_{ij}} = \Delta\lambda \left(\frac{\partial g}{\partial p}\frac{\partial p}{\partial \sigma_{ij}} + \frac{\partial g}{\partial q}\frac{\partial q}{\partial \sigma_{ij}} \right) = \frac{1}{3}\underbrace{\boxed{\Delta\varepsilon_{sw}}}_{\text{DESWA(1)}}\delta_{ij} + \underbrace{\boxed{\Delta\varepsilon_{cr}}}_{\text{DECRA(1)}}\frac{3s_{ij}}{2q}$$

$\Delta\lambda$ = plastic (Lagrange) multiplier
q = von Mises stress
p = hydrostatic pressure
g = plastic potential
σ_{ij} = Cauchy stress tensor
$\Delta\varepsilon_{ij}^{pl}$ = tensor of plastic increment
$\Delta\varepsilon_{cr}$ = equivalent creep strain increment (deviatoric)
$\Delta\varepsilon_{sw}$ = equivalent swelling strain increment (volumetric)

Coding:

```
SUBROUTINE CREEP(DECRA,DESWA,STATEV,SERD,EC,ESW,P,QTILD,
    1 TEMP,DTEMP,PREDEF,DPRED,TIME,DTIME,CMNAME,LEXIMP,LEND,
    2 COORDS,NSTATV,NOEL,NPT,LAYER,KSPT,KSTEP,KINC)
C
    INCLUDE 'ABA_PARAM.INC'
C
    CHARACTER*80 CMNAME
C
    DIMENSION DECRA(5),DESWA(5),STATEV(*),PREDEF(*),DPRED(*),
    1 TIME(2),EC(2),ESW(2),COORDS(*)

    user coding to define DECRA, DESWA

RETURN
END
```

Not considered here!

Implementation of creep equation

- Differential equation for creep behaviour

$$\dot{\varepsilon}_{cr}(\sigma,\omega,T) = A_0 \cdot e^{-\frac{h}{T}} \cdot \left(1 + C \cdot e^{-\frac{\varepsilon_{Cr}}{k}}\right) \cdot \left(\frac{\sigma}{1-\omega}\right)^n$$

$$= A(T) \cdot H(\varepsilon_{cr}) \cdot F(\sigma,\omega)$$

- Variables to be defined for implicit/explicit time integration

$$\mathrm{DECRA}(1) = \Delta\varepsilon_{cr} = A(T) \cdot H(\varepsilon_{cr}) \cdot F(\sigma,\omega) \cdot \Delta t$$

$$\mathrm{DECRA}(2) = \frac{\partial \Delta\varepsilon_{cr}}{\partial \varepsilon_{cr}} = A(T) \cdot \frac{\partial}{\partial \varepsilon_{cr}} H(\varepsilon_{cr}) \cdot F(\sigma,\omega) \cdot \Delta t$$

$$\mathrm{DECRA}(5) = \frac{\partial \Delta\varepsilon_{cr}}{\partial \sigma} = A(T) \cdot H(\varepsilon_{cr}) \cdot \frac{\partial}{\partial \sigma} F(\sigma,\omega) \cdot \Delta t$$

definition necessary only for implicit time integration

Implementation of damage evolution equation

- Differential equation for damage evolution

$$\dot{\omega}(\sigma,\omega,T) = B_0 \cdot e^{-\frac{p}{T}} \cdot \frac{\sigma^m}{(1-\omega)^l}$$

- User coding: Explicit time integration of damage evolution equation
  - First order ordinary differential equation (initial value problem)

$$\dot{\omega} = f(\omega(t)), \qquad \omega(t_0) = \omega_0$$

$$\dot{\omega} \approx \frac{\omega(t+\Delta t) - \omega(t)}{\Delta t}$$

$$\omega(t+\Delta t) \approx \omega(t) + \Delta t \cdot \dot{\omega}$$

$$\approx \omega(t) + \Delta t \cdot f(\omega(t))$$

  - Finite difference approximation by Euler Forward method

$$\omega|^{t+\Delta t} = \omega|^{t} + \dot{\omega}|^{t} \cdot \Delta t$$ ➡ Storage as SDV*

*SDV: **S**olution **D**ependent state **V**ariable

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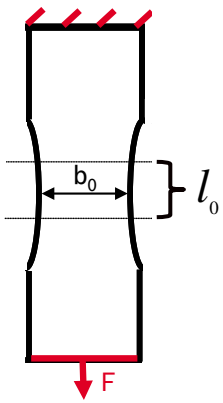
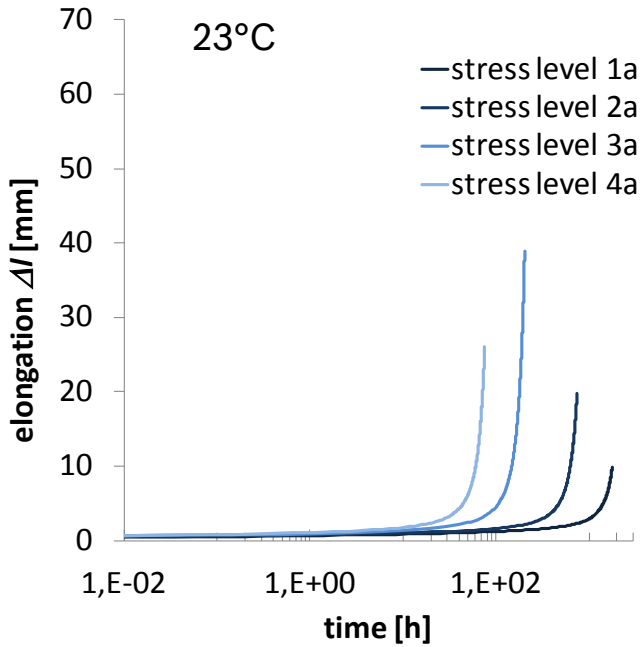
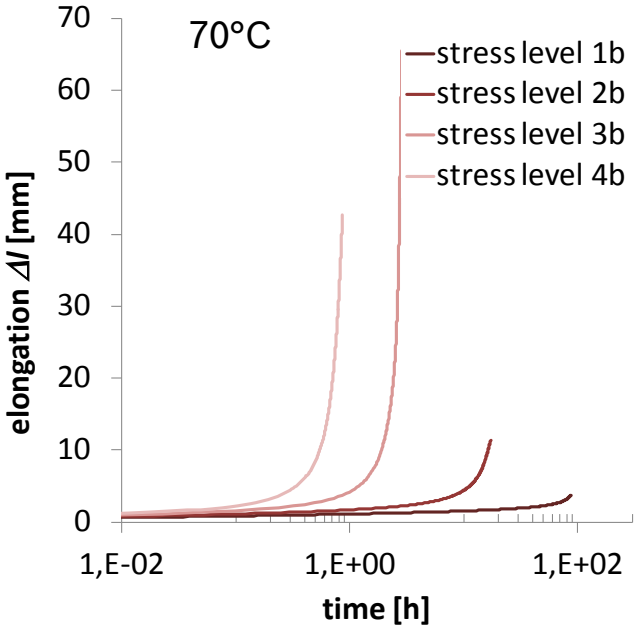
Material characterization and calibration

- Tensile creep tests at different stress levels and temperatures



$$\Delta l = l(t) - l_0$$





- Stepwise regression method used for parameter fitting, see [Gorash2008]

[Gorash2008]: Yevgen Gorash,'Development of a creep-damage model for non-isothermal long-term strength analysis of high-temperature components operating in a wide stress range' , PhD-thesis, Martin-Luther-Universität Halle-Wittenberg, 2008

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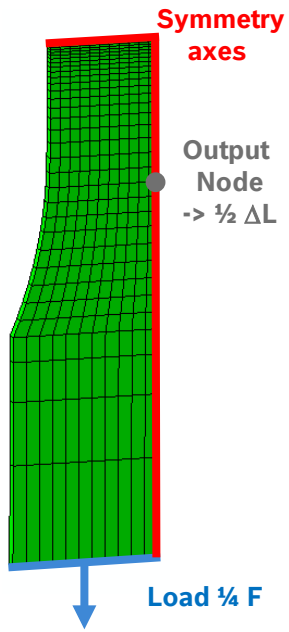
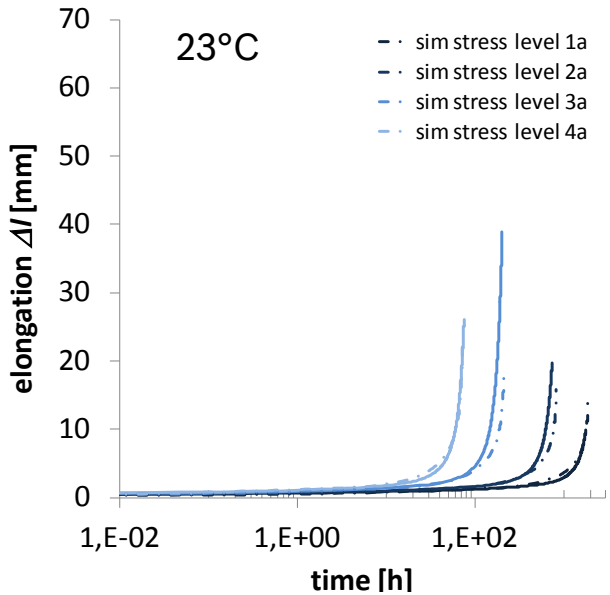
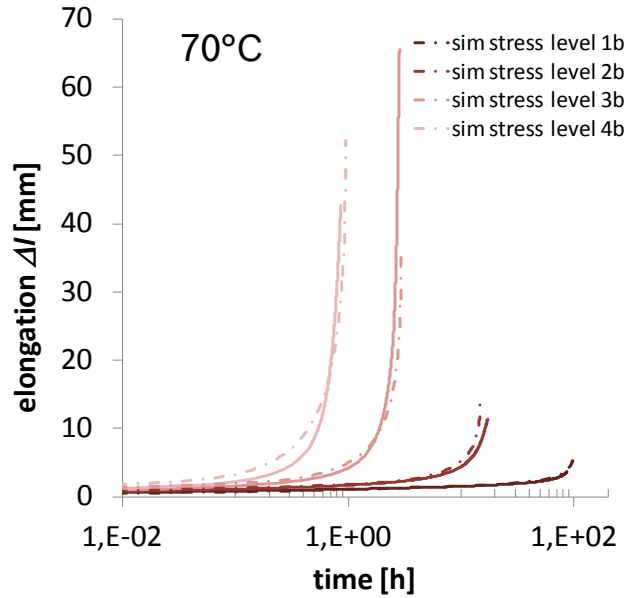
Tensile creep test (1)

➔ Simulation vs. experiment



FE Model (1/8)





stress level	Failure Time (MW) Experiment [h]	Predicted Failure Time [h]	Difference Sim-Exp [%]
1a	1774,8	1878,8	5,9%
2a	743,7	821,4	10,4%
3a	203,6	211,7	4,0%
4a	75,6	72,3	-4,3%

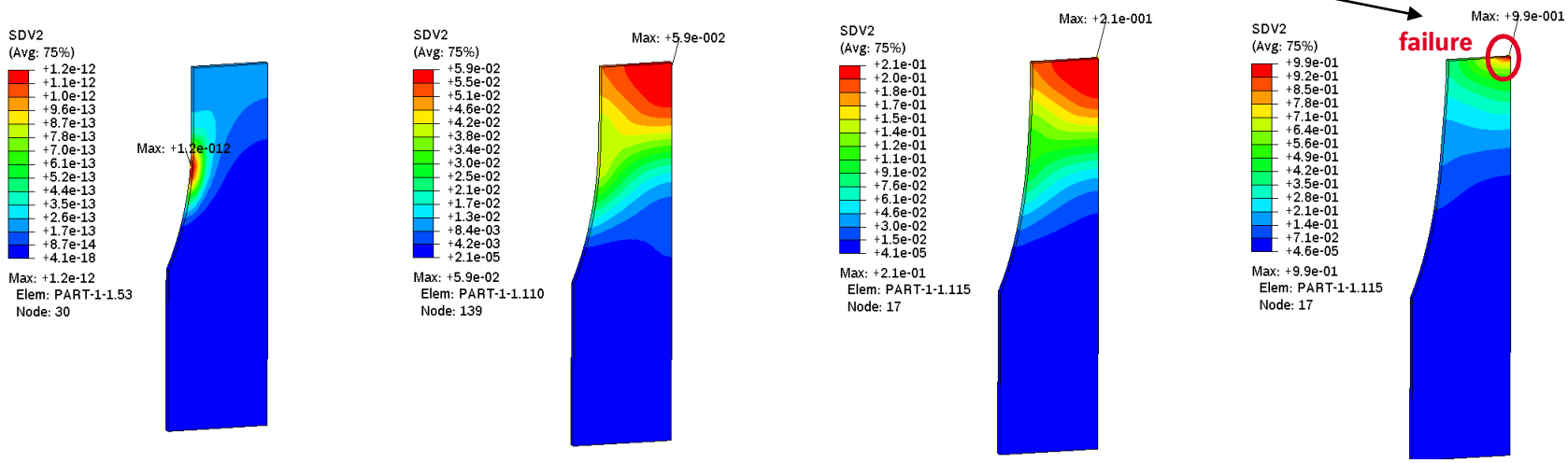
stress level	Failure Time (MW) Experiment [h]	Predicted Failure Time [h]	Difference Sim-Exp [%]
1b	97,91	85,76	-12,41%
2b	14,80	17,22	16,32%
3b	2,94	2,85	-3,04%
4b	0,94	0,85	-9,82%

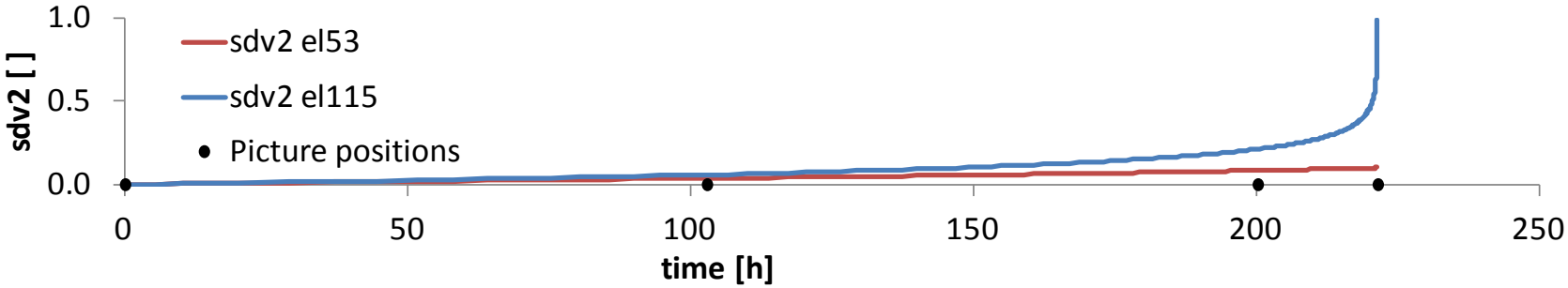
Tensile creep test (2)

➔ Damage evolution (stress level 3a at 23 °C)

Abaqus message in *.dat file

```
**********************************
** Failed Element :          115
** Failed IntPunkt:            1
** Failure Time[h]:    221.283600524118
** Omega_norm[ ]  :    1.00618977452506
**********************************
```





sdv2 = ω/ω* = standardized damage variable

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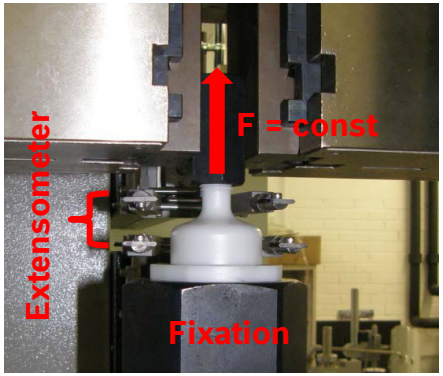
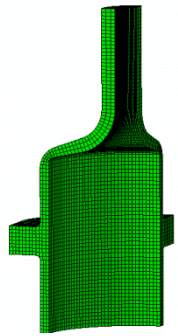
Tensile creep test on bottle specimen (1)

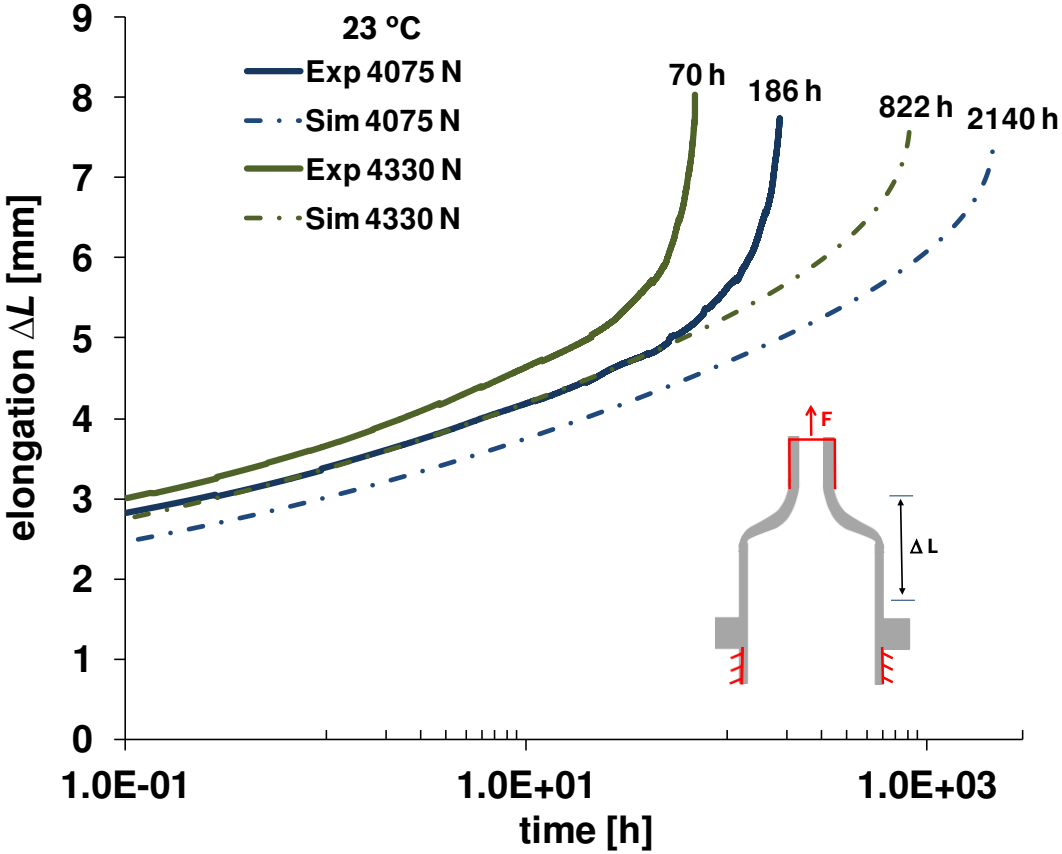
- Simulation vs. experiment



Experimental setup

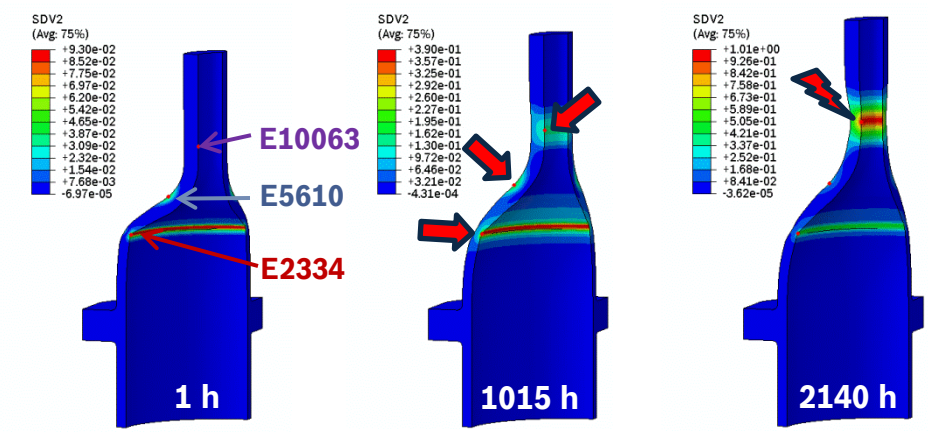


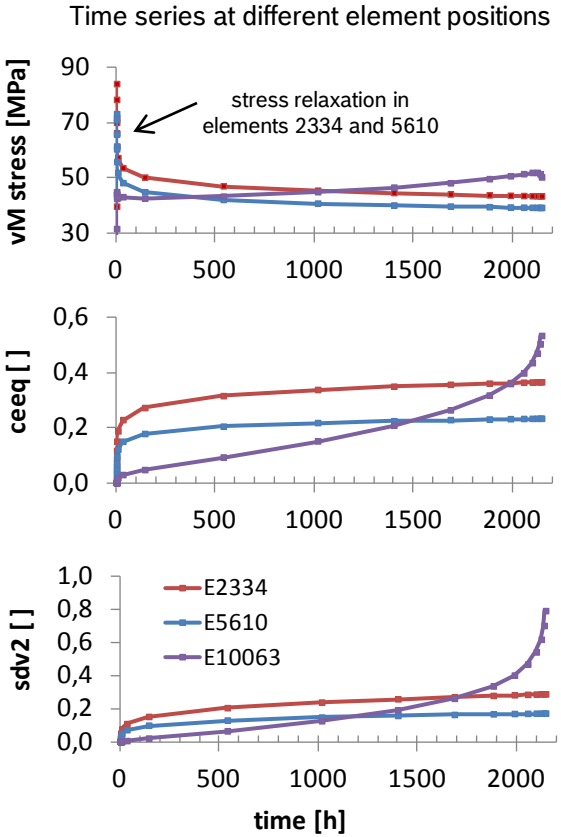
FE Model (1/4)



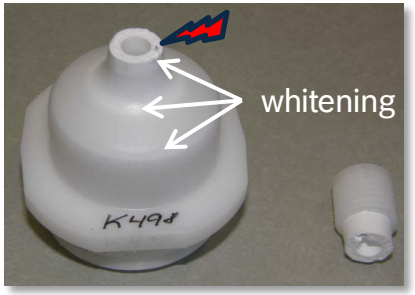
Tensile creep test on bottle specimen (2)

- Damage evolution and prediction of failure position (4075 N)





- 3 competing positions of high damage ( )
- 1 failure position ( )



sdv2 = ω/ω^* = standardized damage variable ; ceeq = equivalent creep strain

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Summary

Capability of current creep damage model

- Time dependent deformation and damage evolution
- Considering stress redistribution
- Prediction of time to rupture
- Prediction of failure position

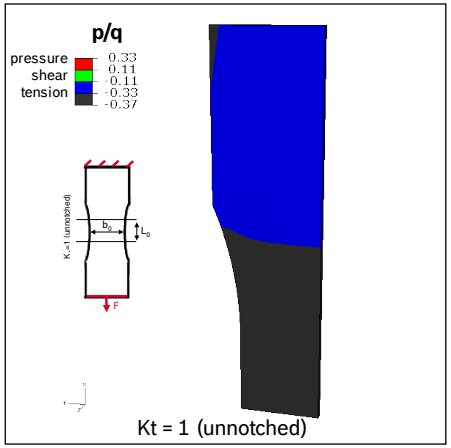
Evaluation

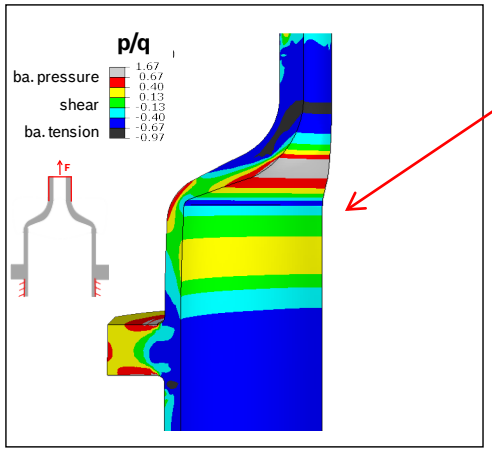
- Validation on tensile specimen successful
- Application on complex part geometry
  - Prediction of failure position successful
  - Prediction of part deformation overestimated

Outlook

Potential for model improvement

- Influence of stress triaxiality on creep behavior not yet investigated





Highly multiaxial stress states in complex part

q = von Mises stress
p = hydrostatic pressure

Further work

- Additional shear and compression creep tests
- Consider pressure dependence in creep damage model