

Faculty of Mechanical Engineering Department of Materials Test Engineering (WPT)

Prof. Dr.-Ing. Frank Walther

***Modellierung des Poreneinflusses auf das
Verformungsverhalten von Polyurethan***

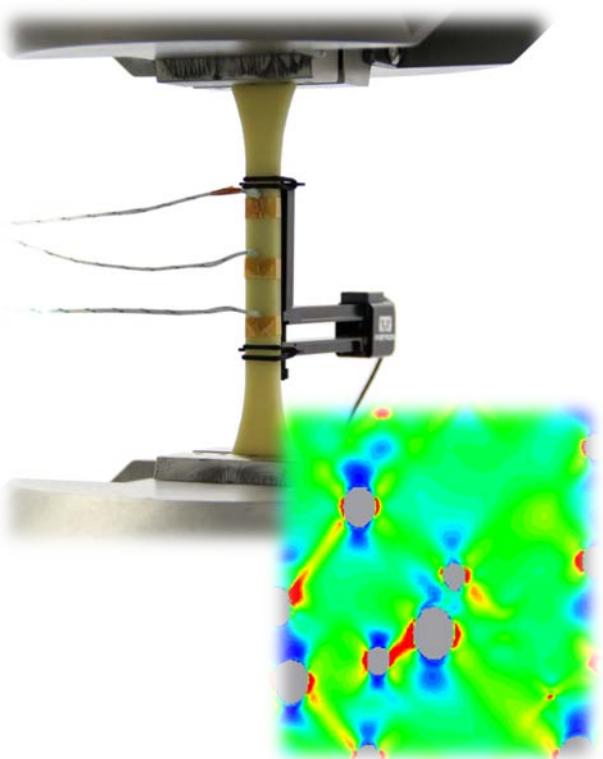
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Chapter

- 1 Motivation
- 2 Structure investigations
- 3 Modeling elasto-plastic behavior
- 4 Modeling damage behavior
- 5 Conclusions and outlook





Source: faz.net



Source: aerospace-technology.com



Source: FACC

- ◆ PU - RTM Resin
- ◆ EP - RTM Resin

Damage tolerance

Better performance

Curing time

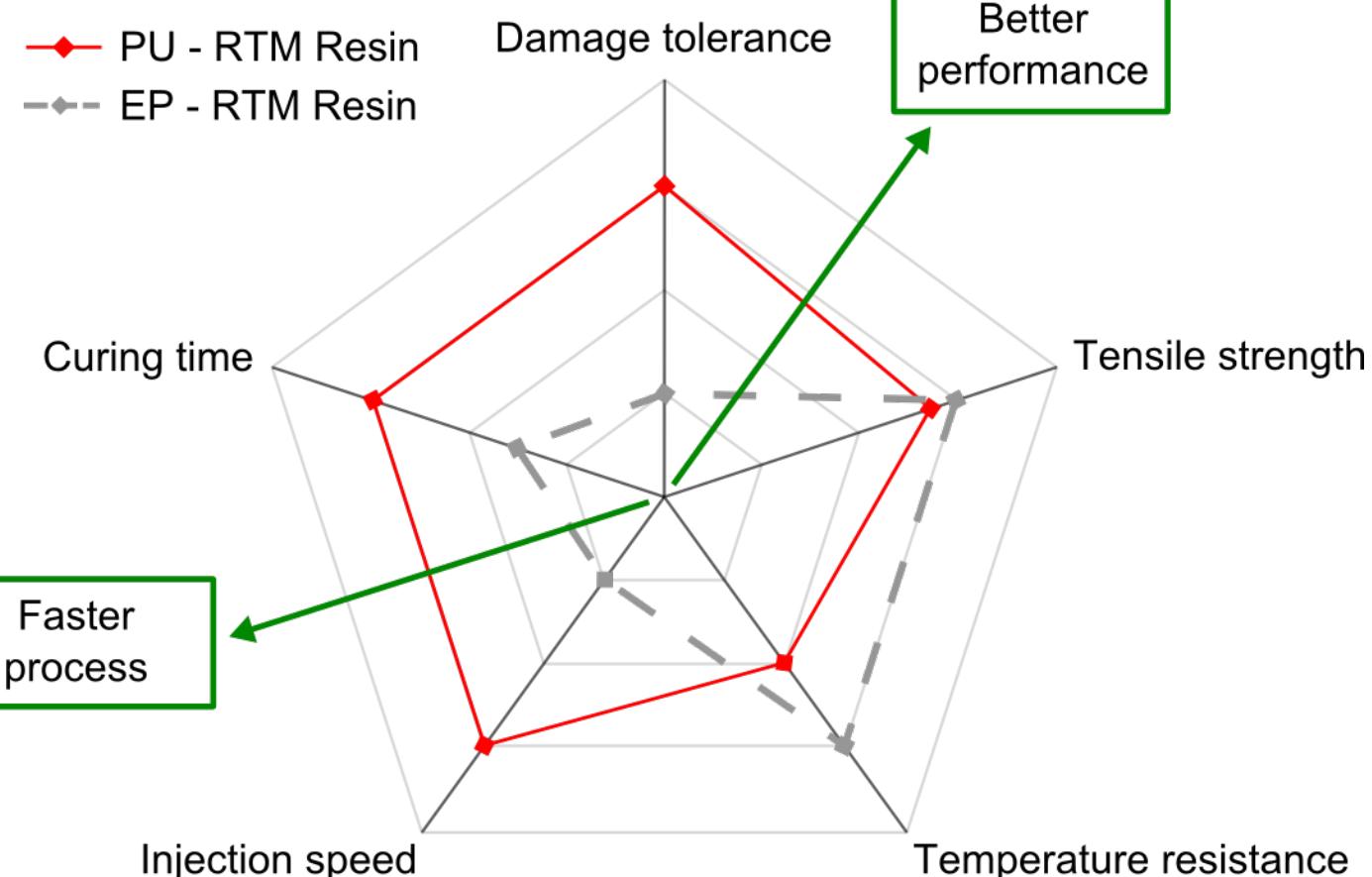
Tensile strength

Injection speed

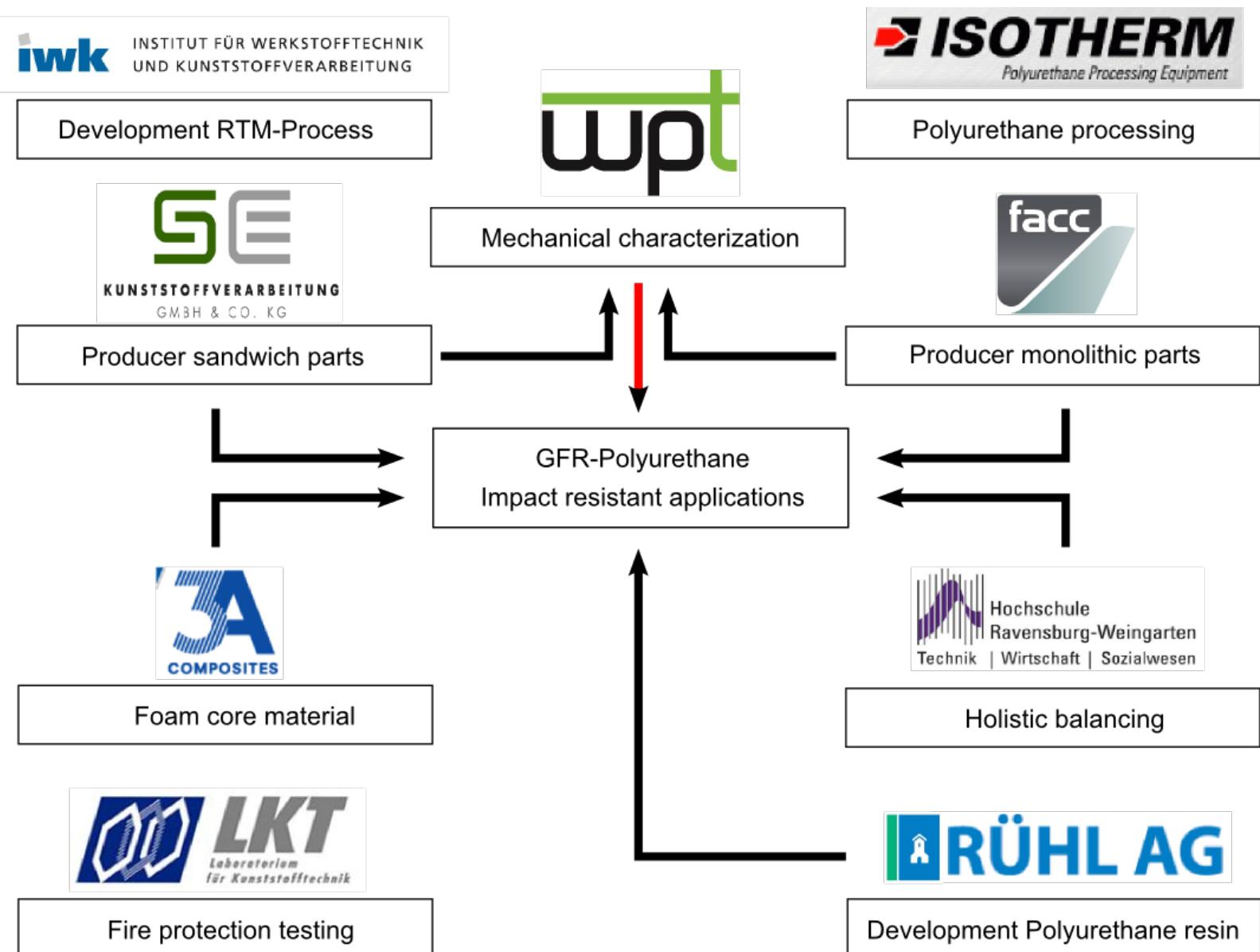
Temperature resistance

Faster process

Source: Henkel

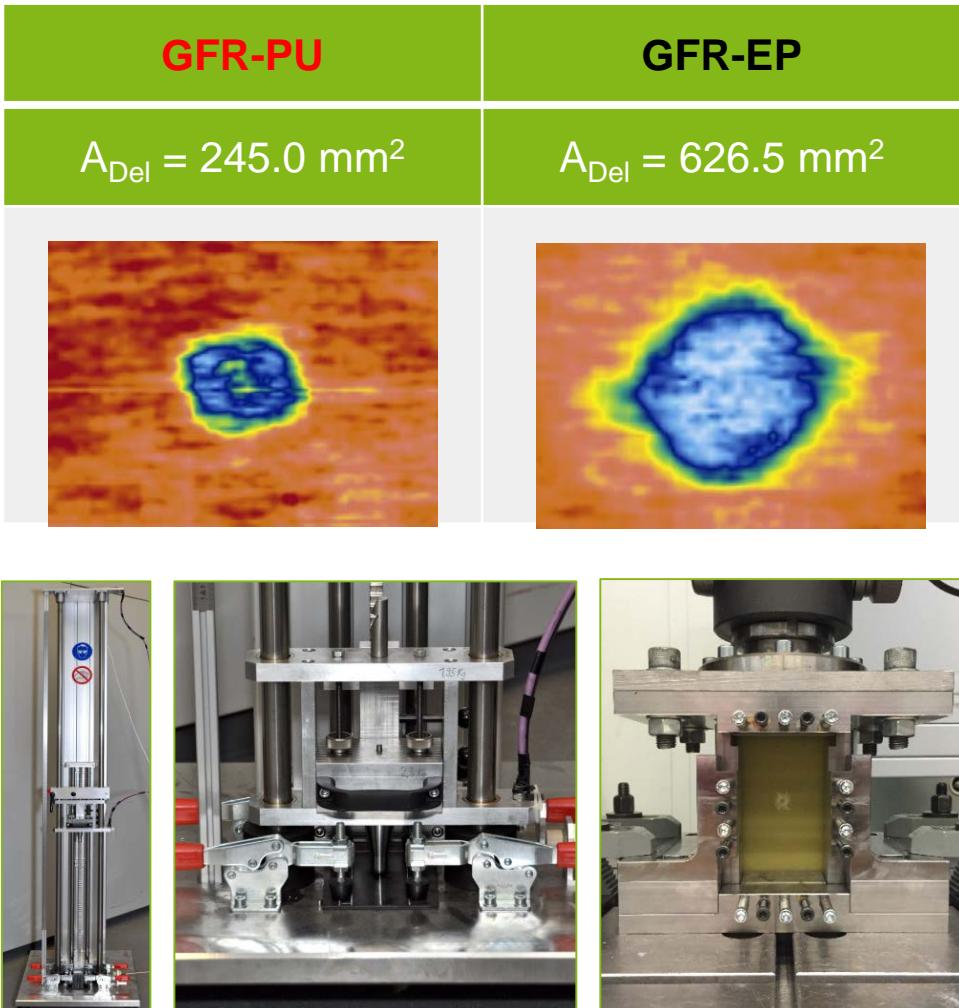


Project consortium

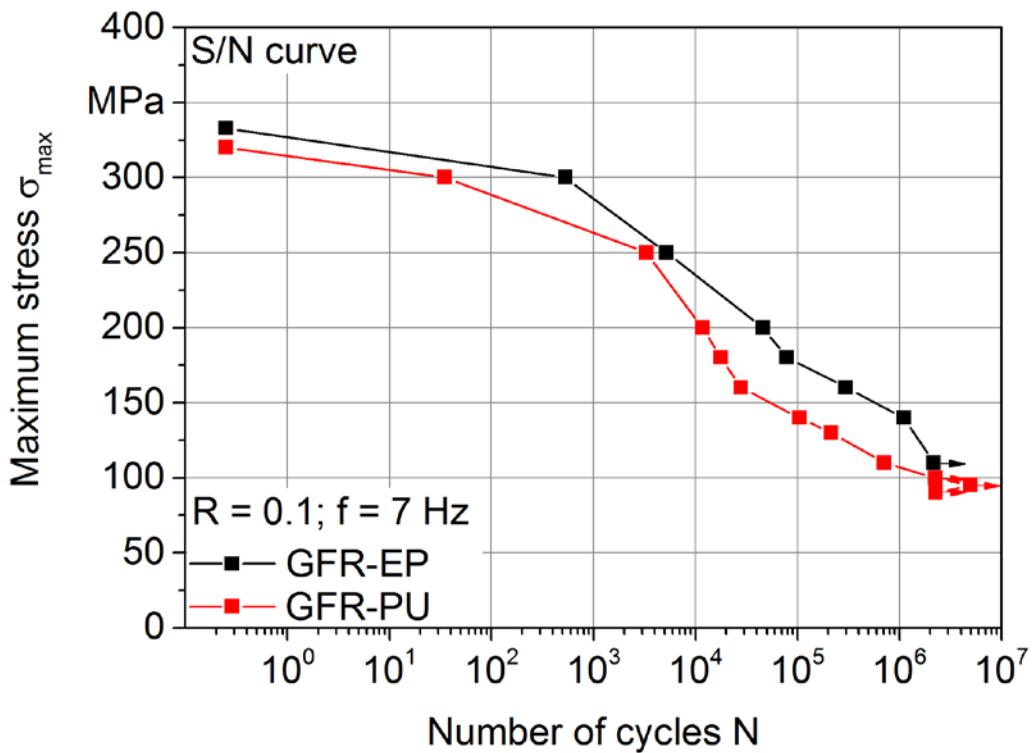


Comparison of GFR-PU and -EP

Impact investigations



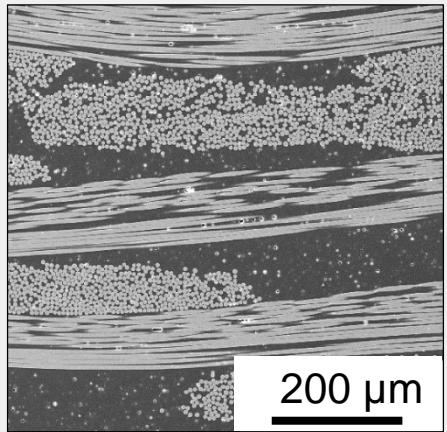
Fatigue investigations



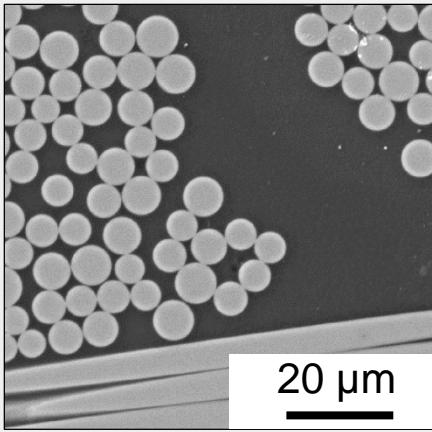
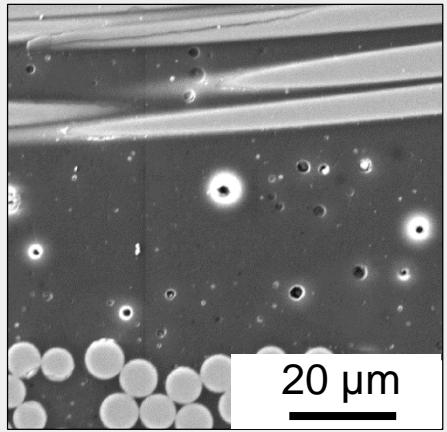
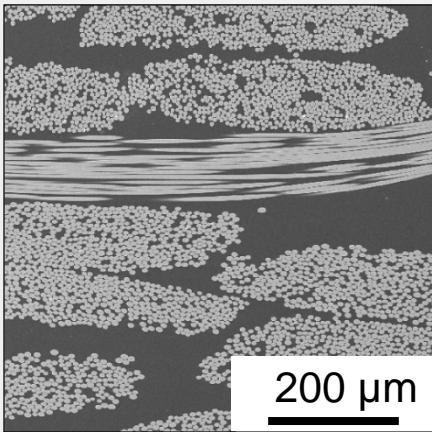
Comparison of GFR-PU and -EP

Structure investigations

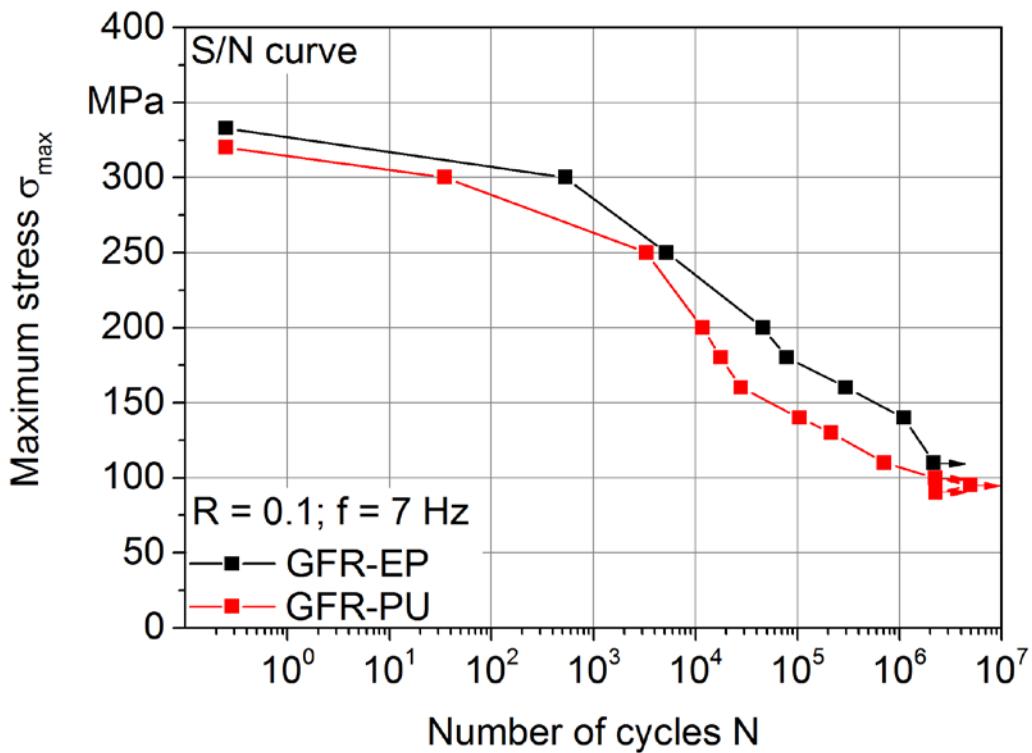
GFR-PU

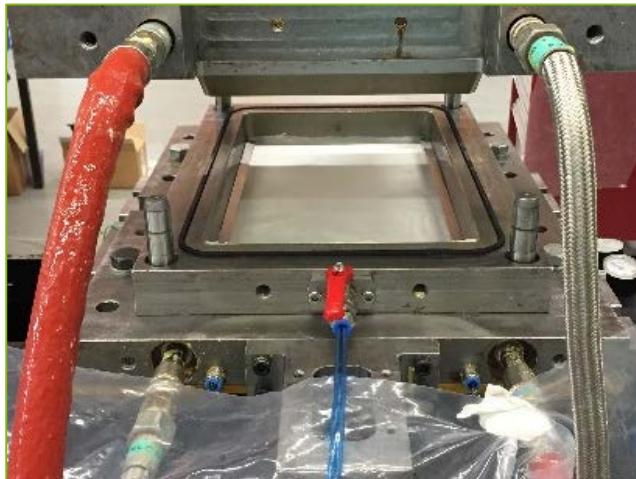
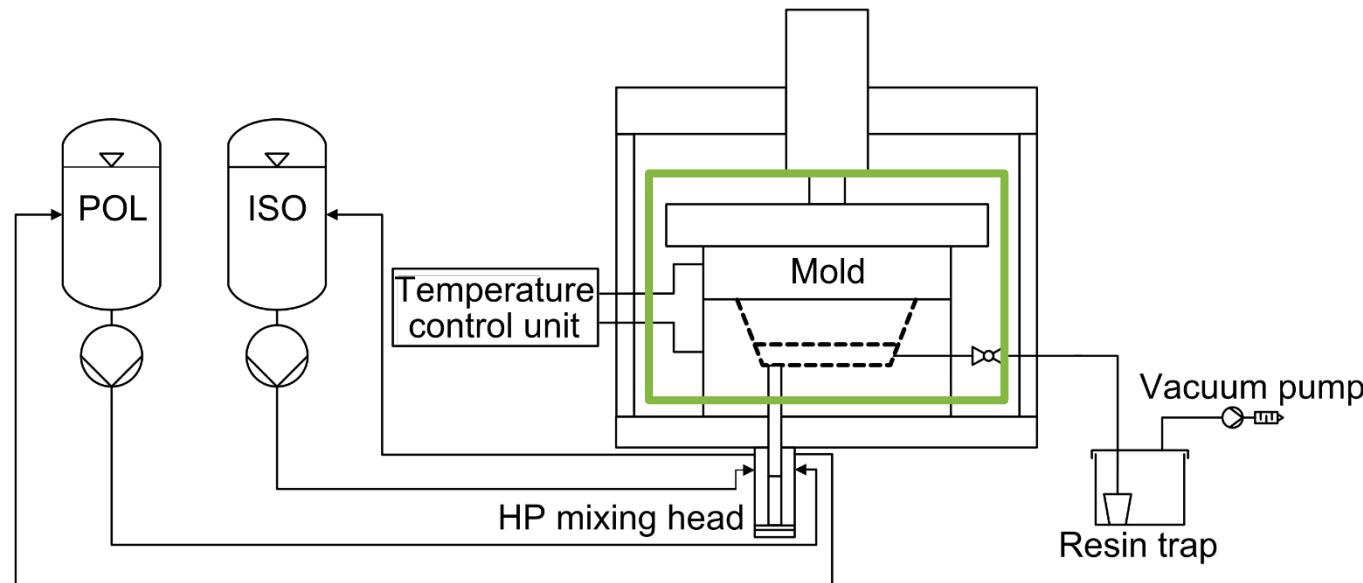


GFR-EP

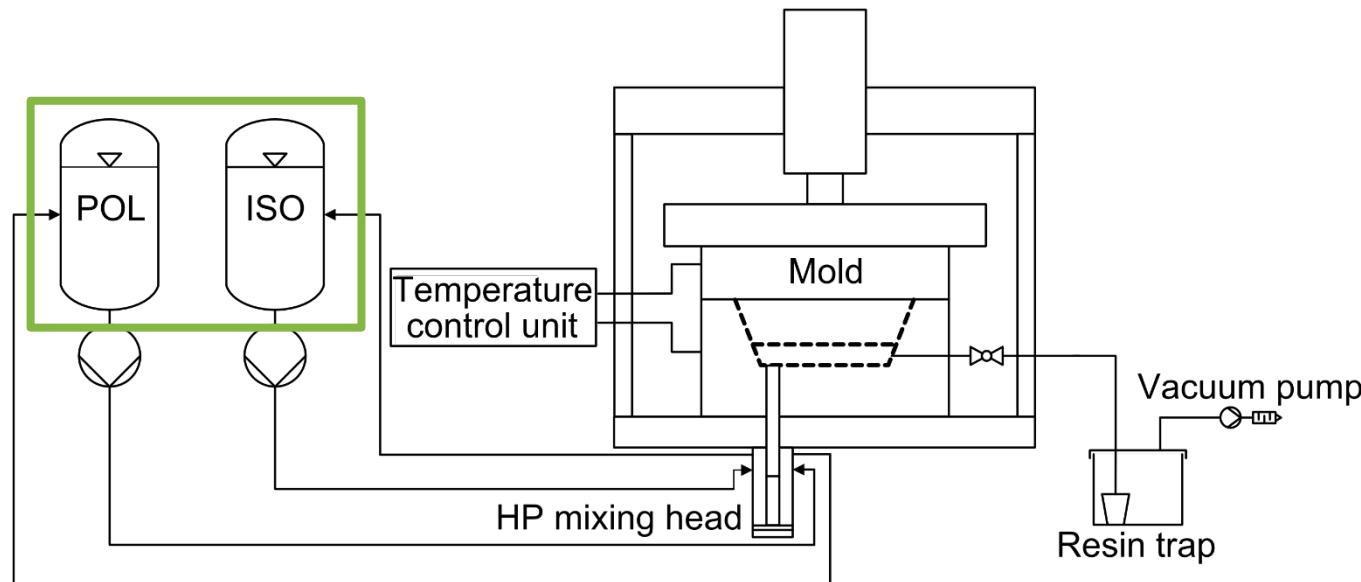


Fatigue investigations

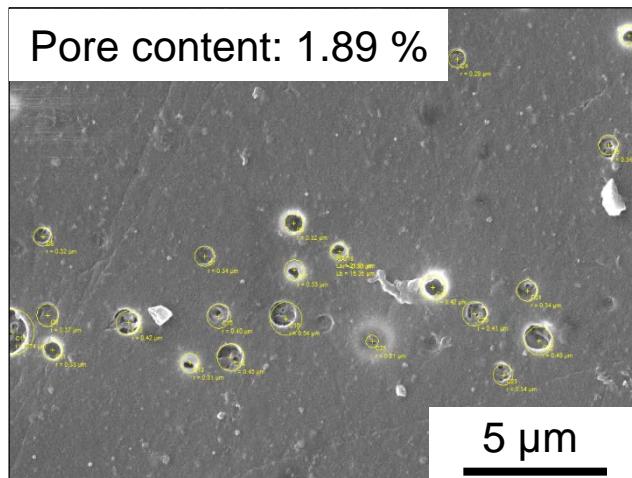




Pore content – PU



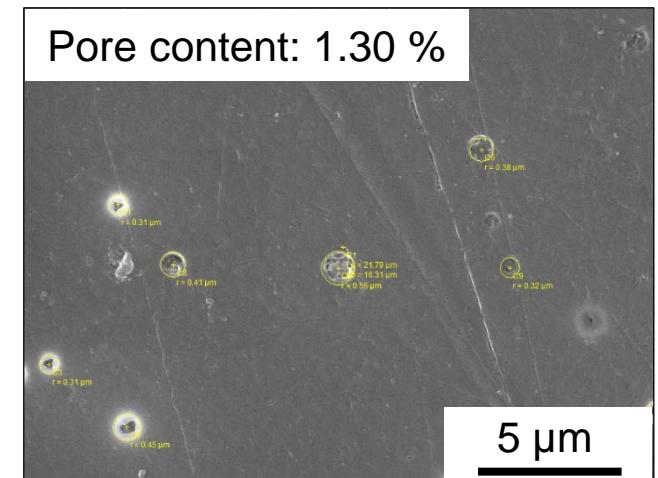
First PU component (PU)



Molecular

filter

Improved PU component (PU)

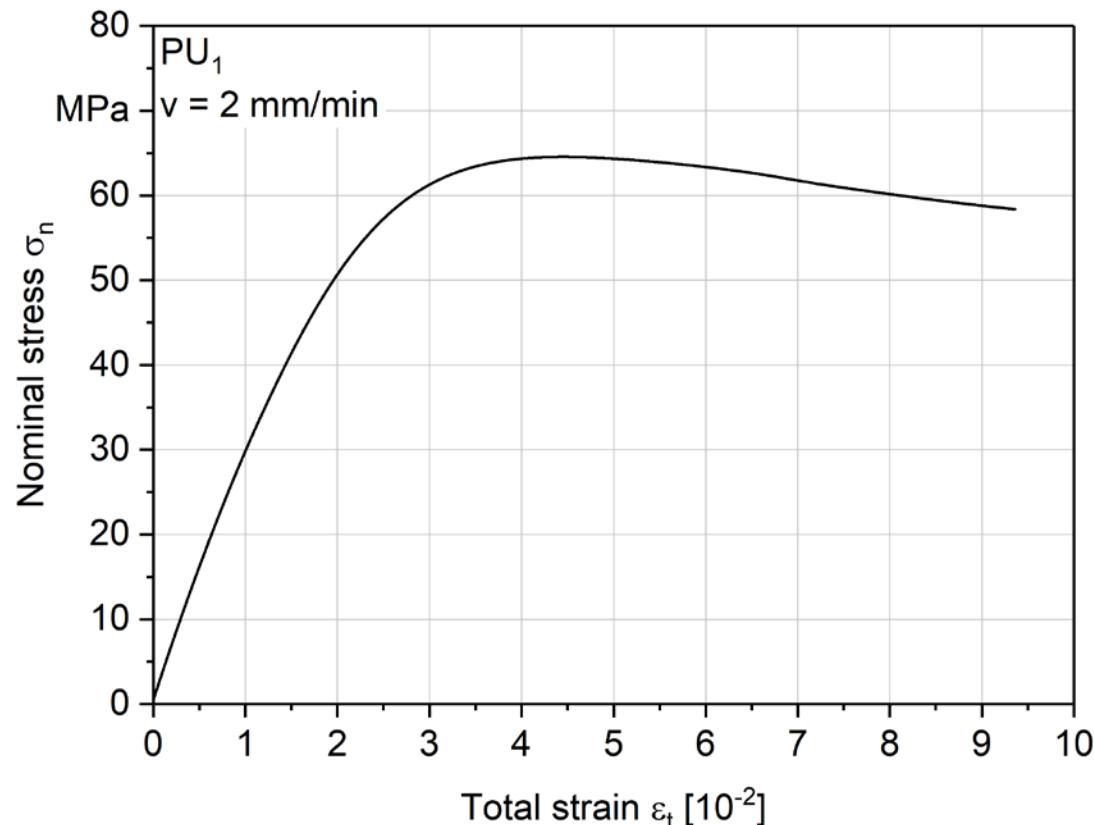
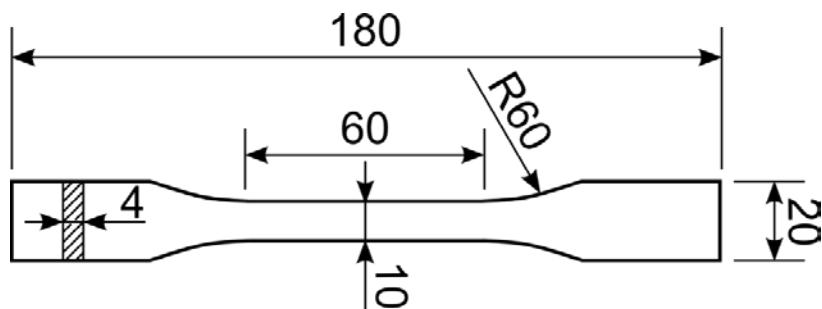


Experimental setup

Tensile test

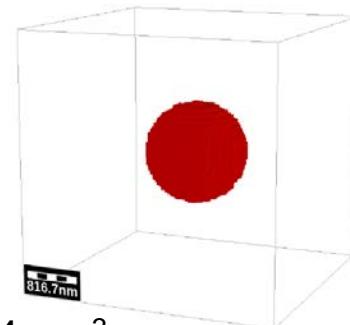


Designation	Value
v	2 mm/min ($\approx 6.7 \cdot 10^{-4} \text{ s}^{-1}$)



Description of the different geometries

- Structure 1: A unique 1.5 µm diameter pore



Domain: $3.94 \cdot 3.94 \cdot 3.94 \mu\text{m}^3$

Hardening function

$$\sigma_h = \sigma_Y + a_1(1 - e^{-a_2 \epsilon_p})$$

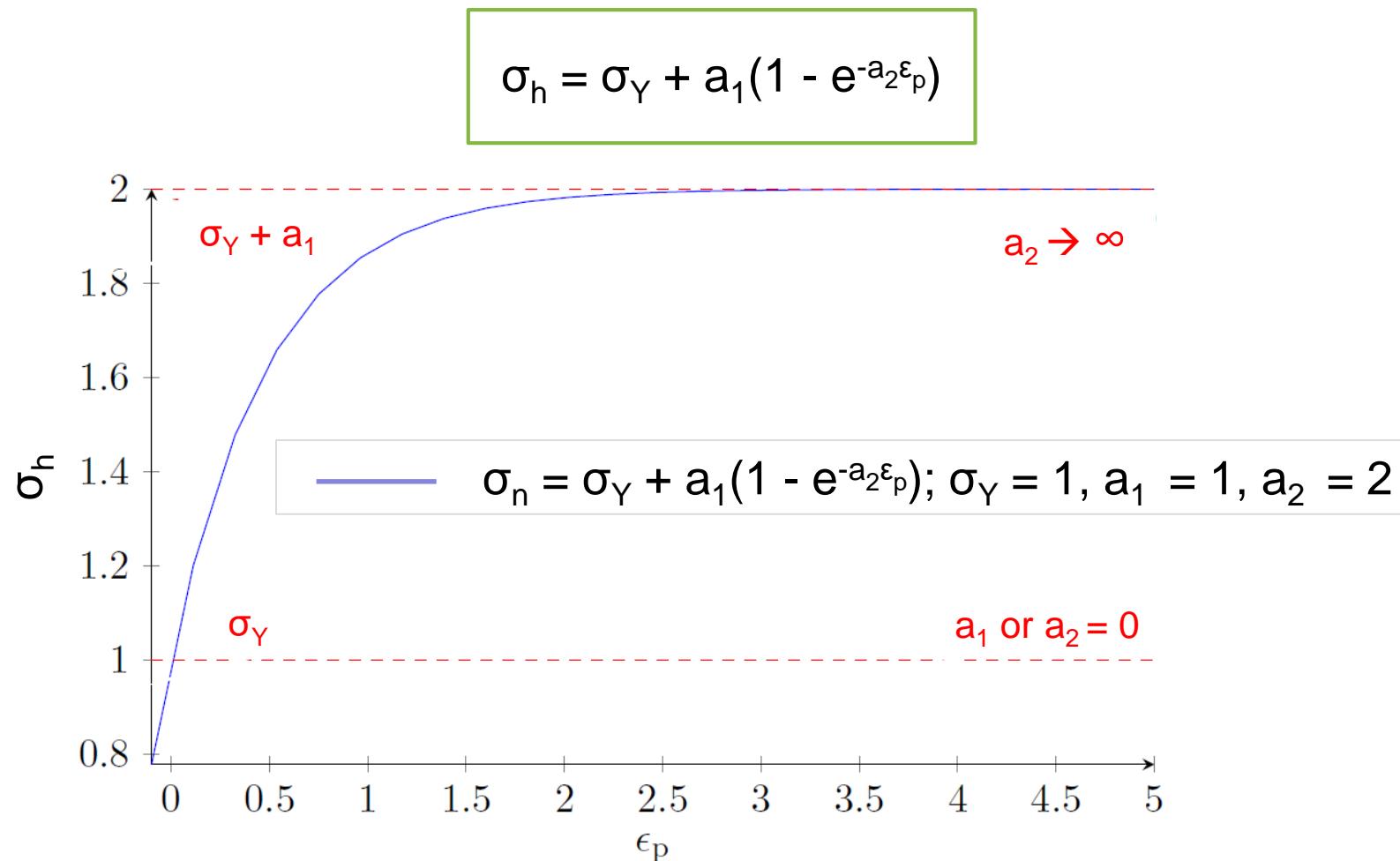
- σ_h corresponds to the hardening (GPa)
 - σ_Y = yield stress (GPa)
 - ϵ_p = plastic strain
- 
- a_1 (in GPa) and a_2 (no unit) have to be determined

Influence of a_1 and a_2

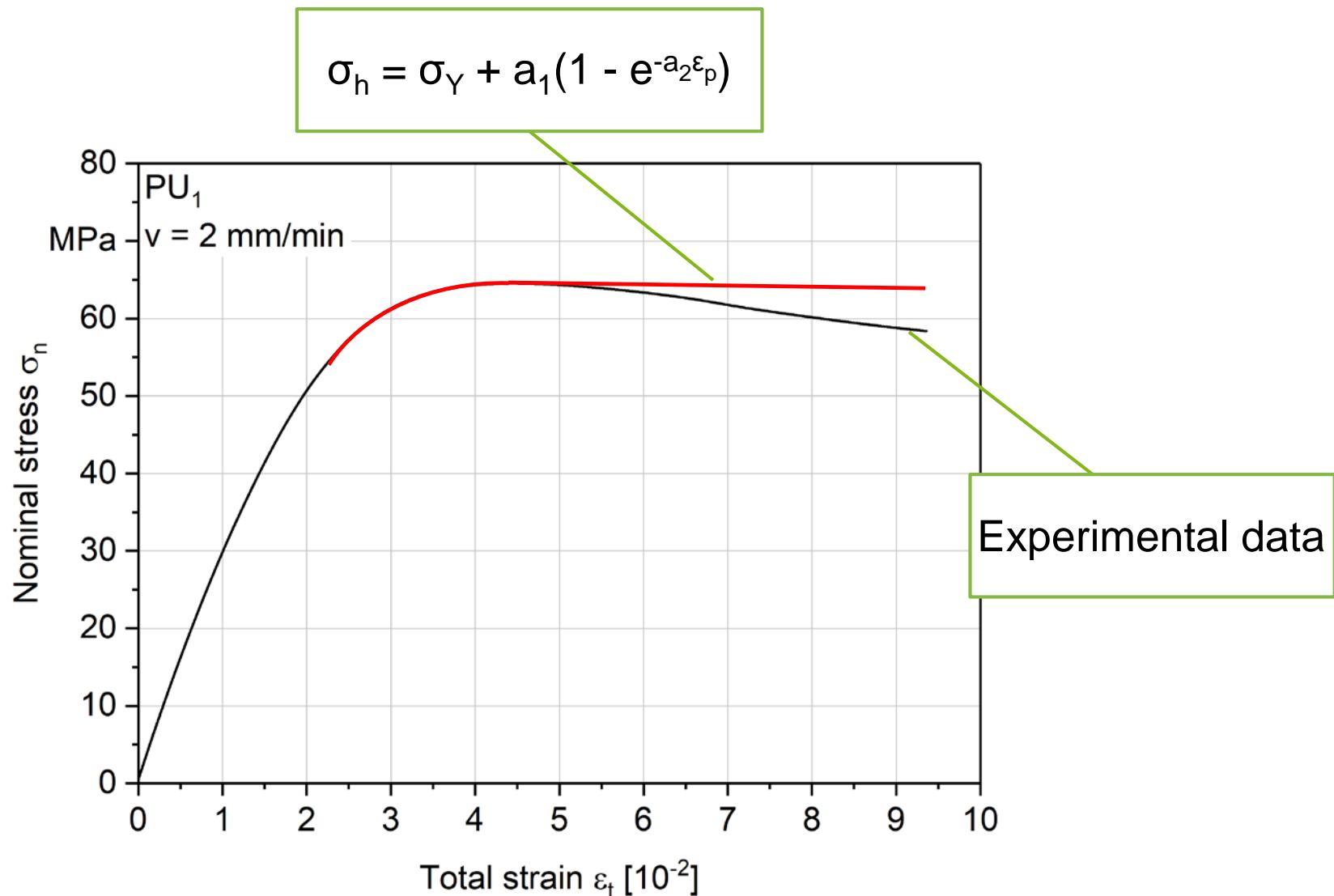
- a_1 defines the width of the hardening domain for plastic deformation
- a_2 defines the speed with which the plastification will reach the maximum value of hardening

Hardening function

Hardening function



Tensile deformation behavior



Parameters determination

Young's modulus (E), Yield stress (σ_Y), a_1 and a_2 .

Why Nelder-Mead method?

- Minimization of multivariate scalar functions
- Gradient-free algorithm
- Heuristic method → reduces calculation cost
- Only needs a first set of parameters and the function to minimize variables

Error function

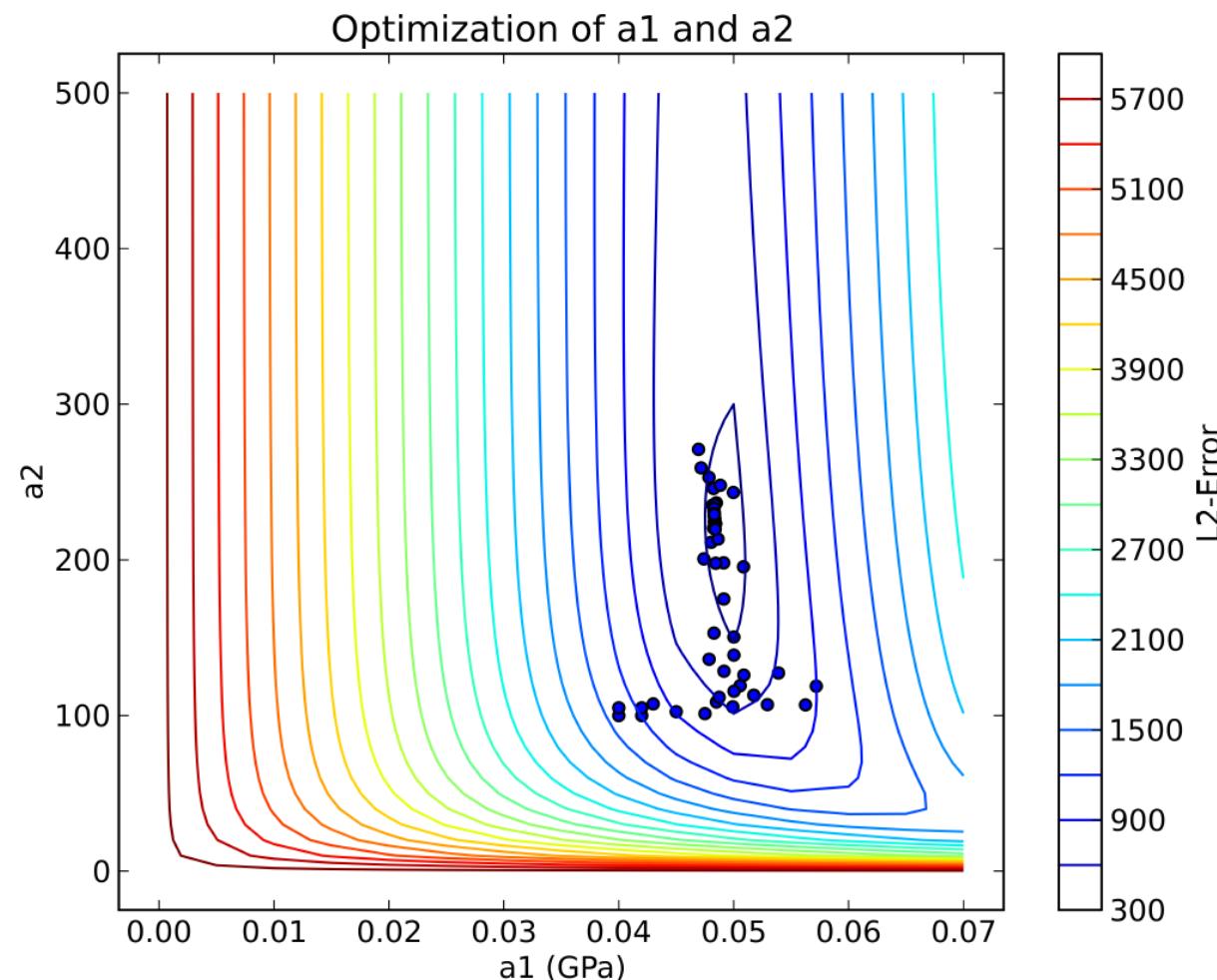
$$\text{Error}(E, \sigma_Y, a_1, a_2) = \|\sigma_{\text{measured}} - \sigma_{\text{simulated}}(E, \sigma_Y, a_1, a_2)\|_2$$

where $\|\cdot\|_2$ corresponds to the L^2 -norm.



Minimizing the Error

Parameter determination



- Convergence of Nelder-Mead method with $(a_1, a_2) = (0.04, 100)$ as a first set of parameters

Error function

$$\text{Error}(E, \sigma_Y, a_1, a_2) = \|\sigma_{\text{measured}} - \sigma_{\text{simulated}}(E, \sigma_Y, a_1, a_2)\|_2 \quad (1)$$

where $\|\cdot\|_2$ corresponds to the L^2 -norm.

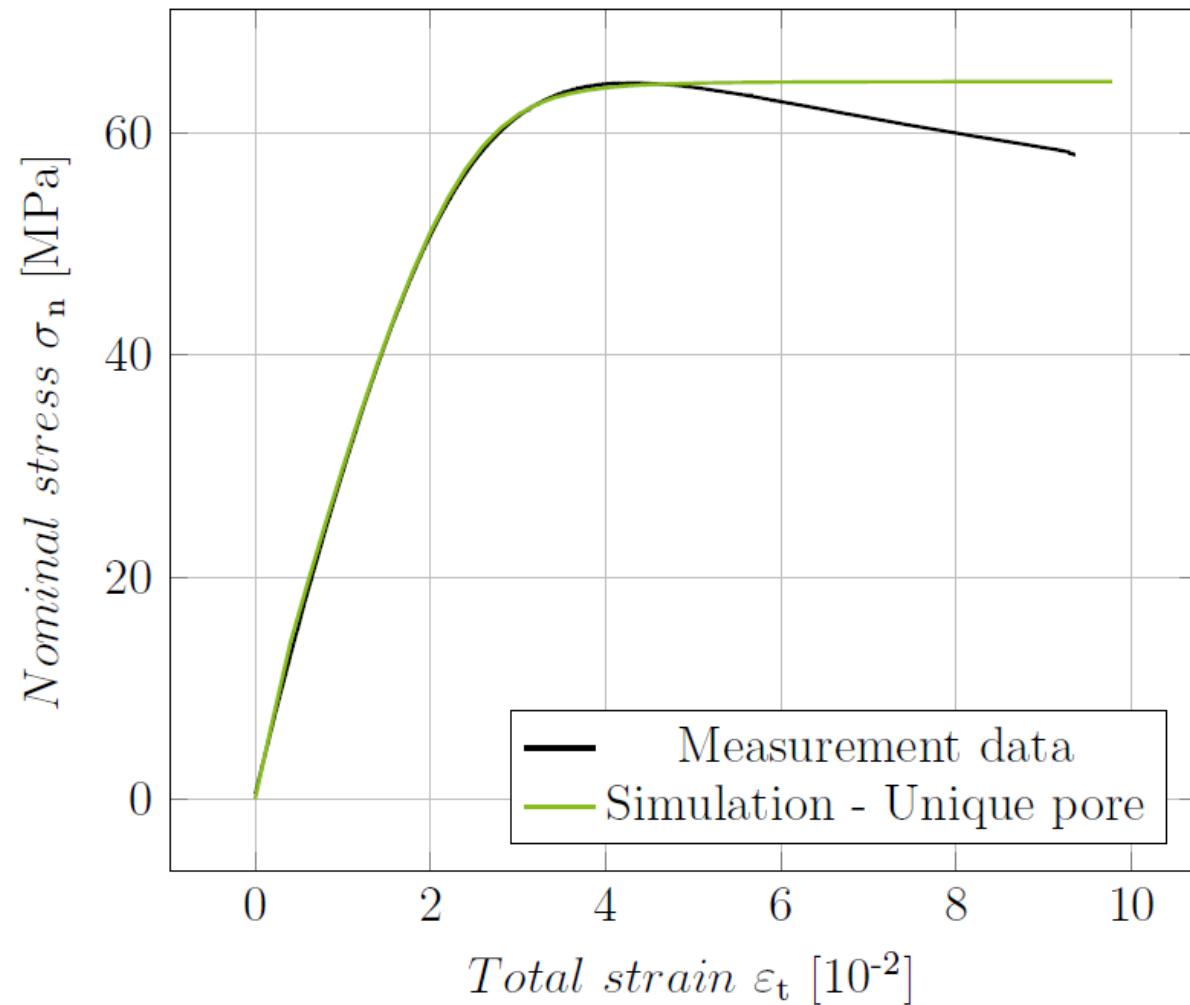
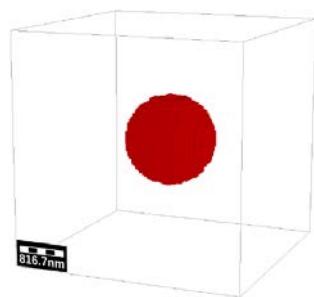
Parameters	Defined by engineer	Start values for unknown parameters	2-parameters optimization
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E (GPa)	3.671	-	3.671
σ_Y (GPa)	0.0172	-	0.0172
a_1 (GPa)	-	0.04	0.05121
a_2	-	100	243.727

Error	/	1846.132	0.1555
Evaluations	/	/	302

Results for the 2 tests using Nelder-Mead method with unique pore geometry.

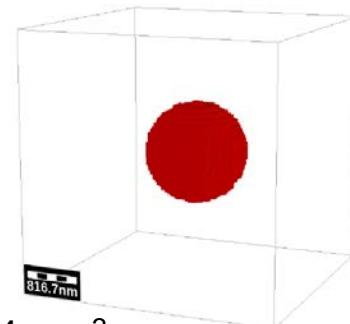
Results



Variation of the pore size distribution

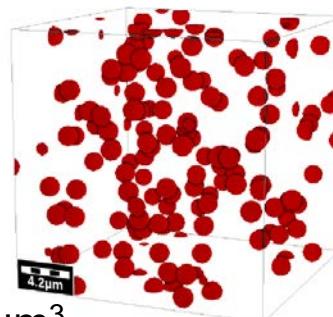
Description of the different geometries

- Structure 1: A unique 1.5 µm diameter pore



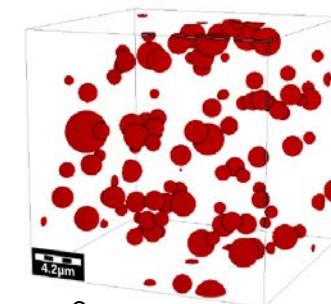
Domain: $3.94 \cdot 3.94 \cdot 3.94 \mu\text{m}^3$

- Structure 2: Unique pore diameter of 1.5 µm



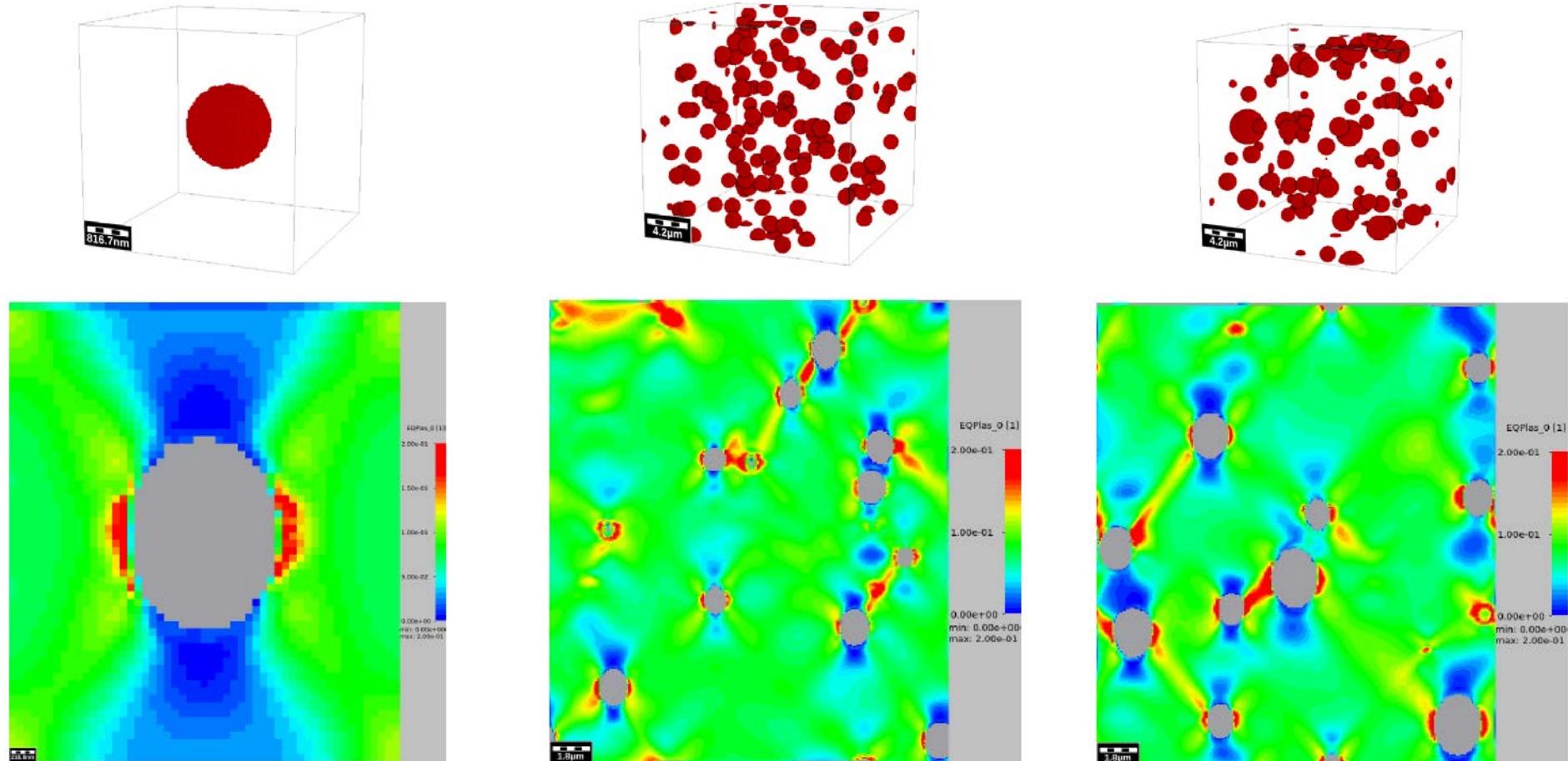
Domain: $20 \cdot 20 \cdot 20 \mu\text{m}^3$

- Structure 3: Multiple pore diameter with log-normal distribution



Domain: $20 \cdot 20 \cdot 20 \mu\text{m}^3$

Deformation for 10% total strain

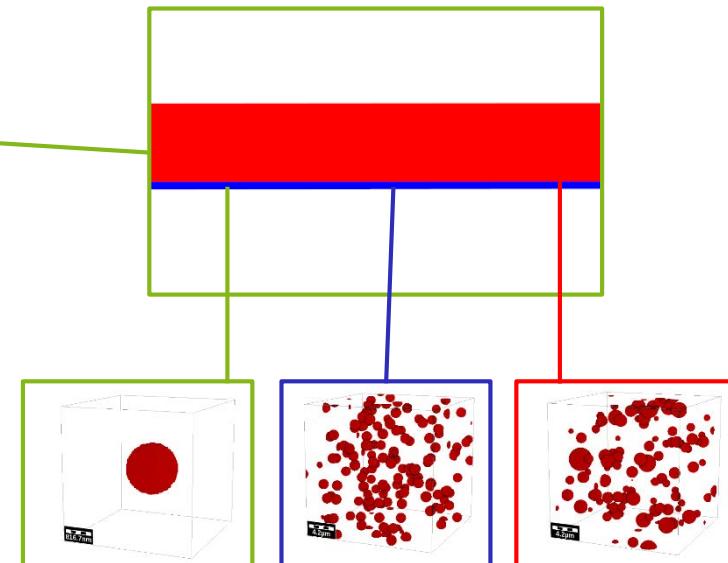
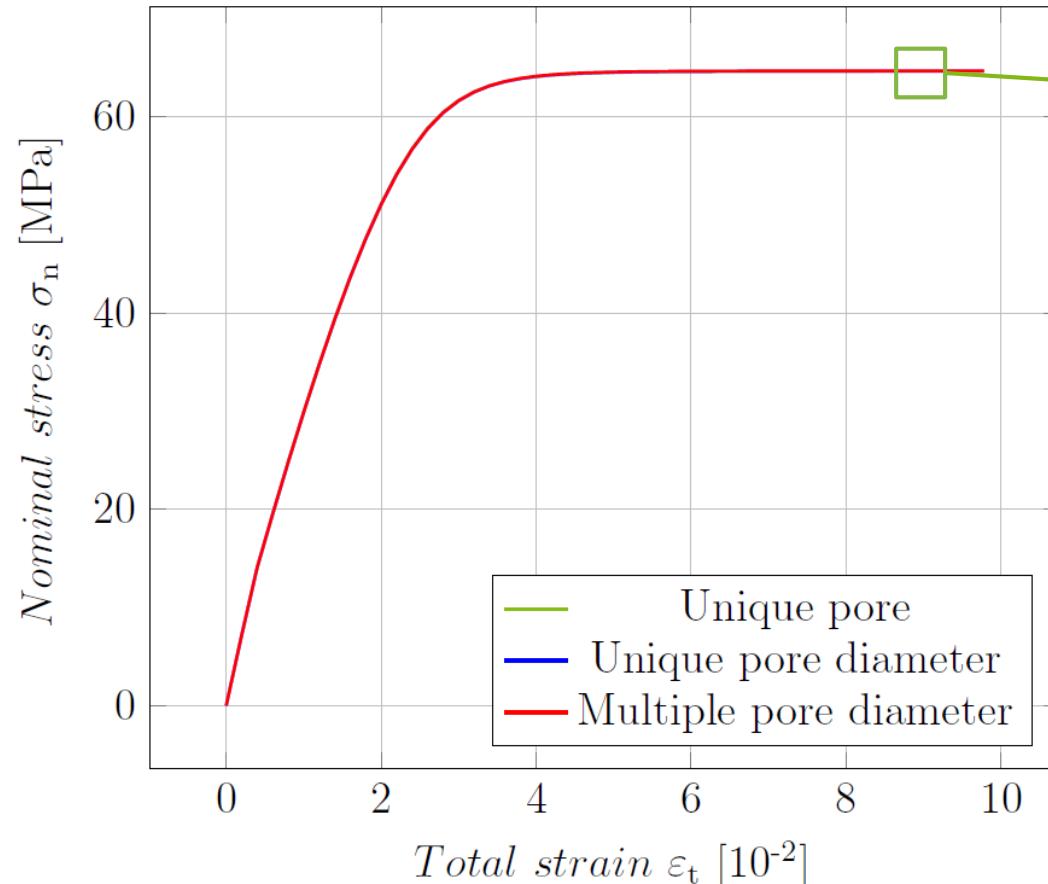


The pictures represent a cross-sectional view along x-axis while the force is applied along z-axis.

Results

RVE study

RVE study using successive optimization values – Error calculated between simulation and non-adjusted measurement.

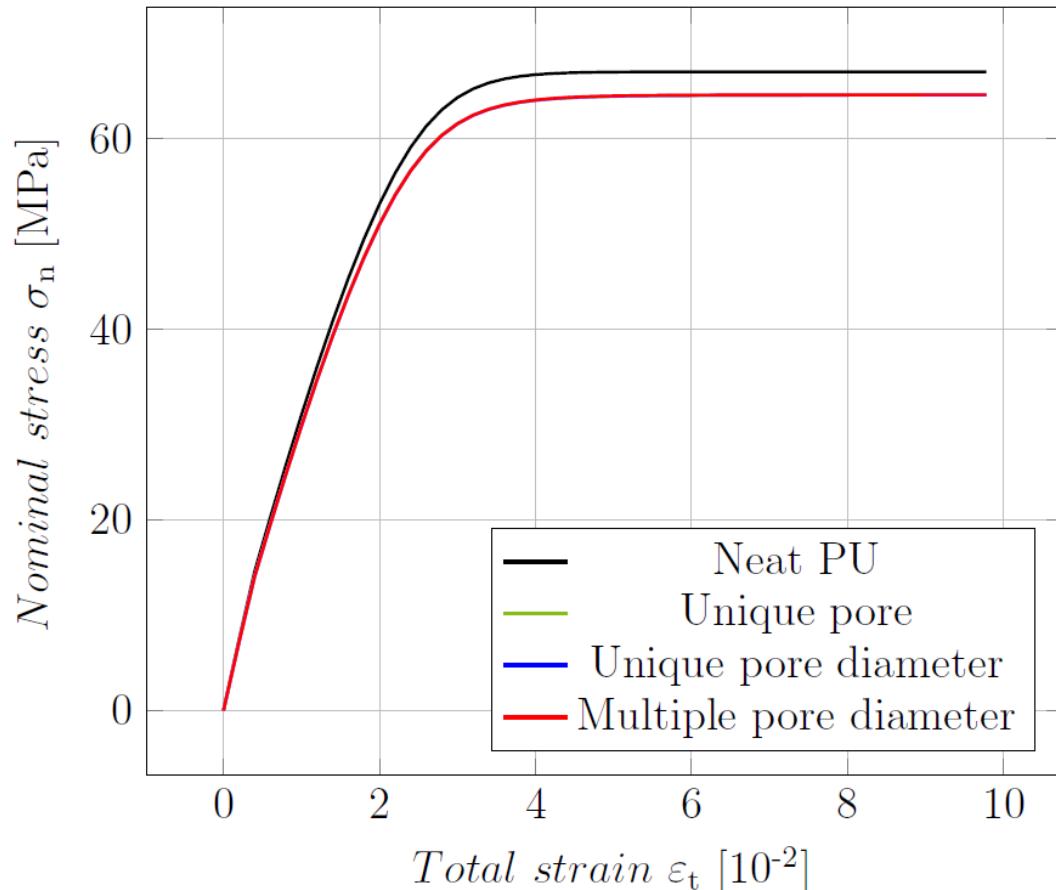


Geometry	Error
Unique pore	0.1555
Unique pore diameter	0.1615
Multiple pore diameter	0.1593

Results

RVE study

RVE study using successive optimization values – Error calculated between simulation and non-adjusted measurement.



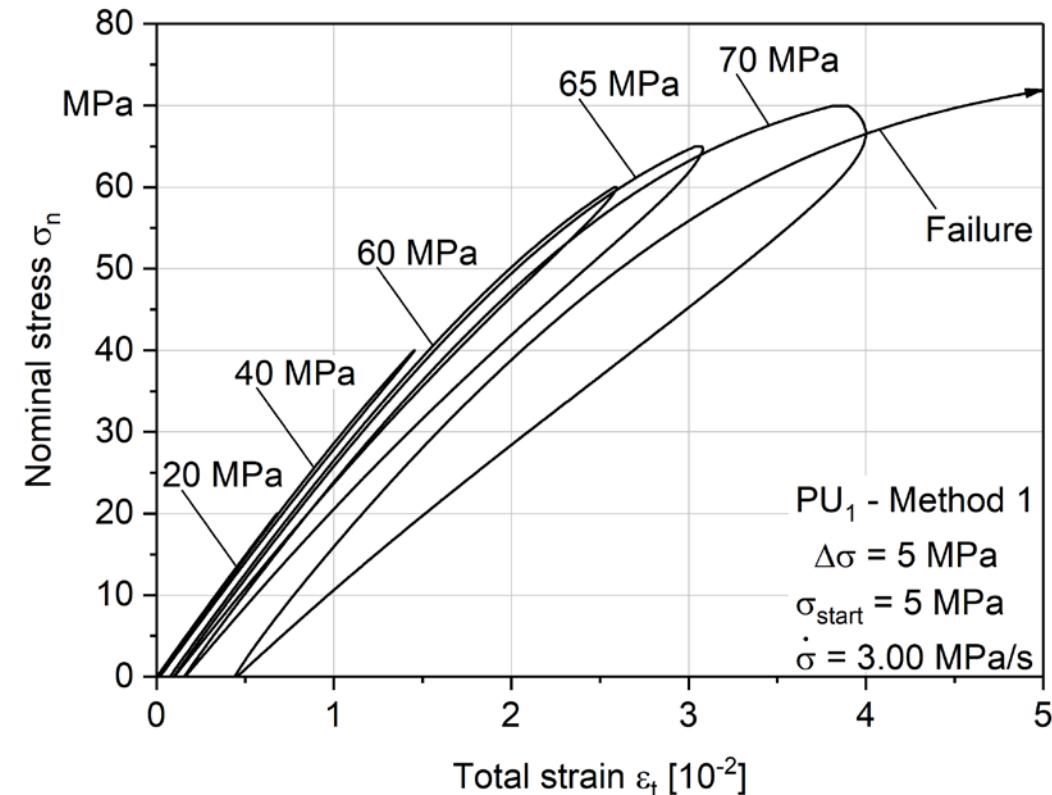
- The properties of the PU can be improved by 12 % stiffness and 6 % tensile strength.

Experimental setup

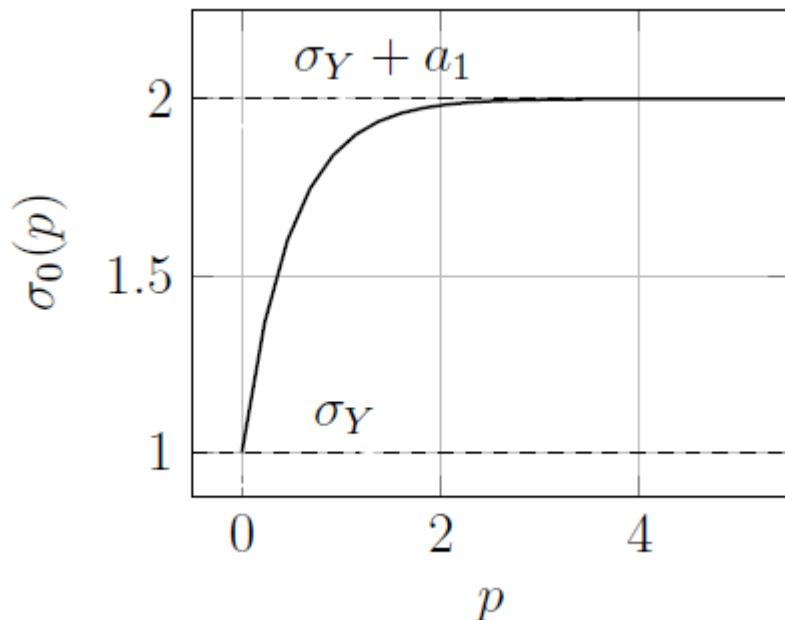
Cyclic tensile test



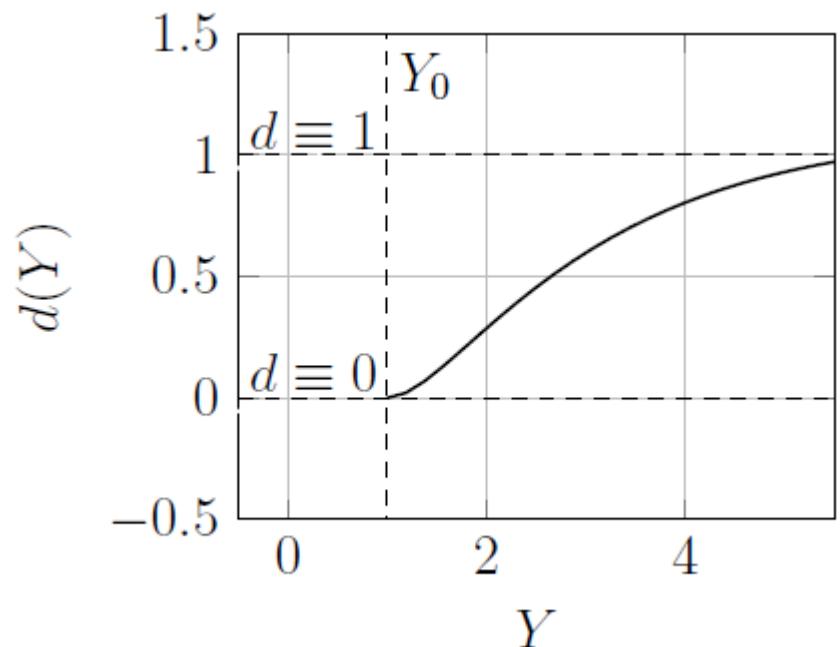
Designation	Value	
	Method 1	Method 2
σ_{start}	5 MPa	30 MPa
$\Delta\sigma$	5 MPa	2.5 MPa
v_1	$3 \text{ MPa/s} (\approx 0.1 \text{ s}^{-1})$	
v_2	$0.02 \text{ MPa/s} (\approx 6.7 \cdot 10^{-4} \text{ s}^{-1})$	



Plastification



Damage evolution



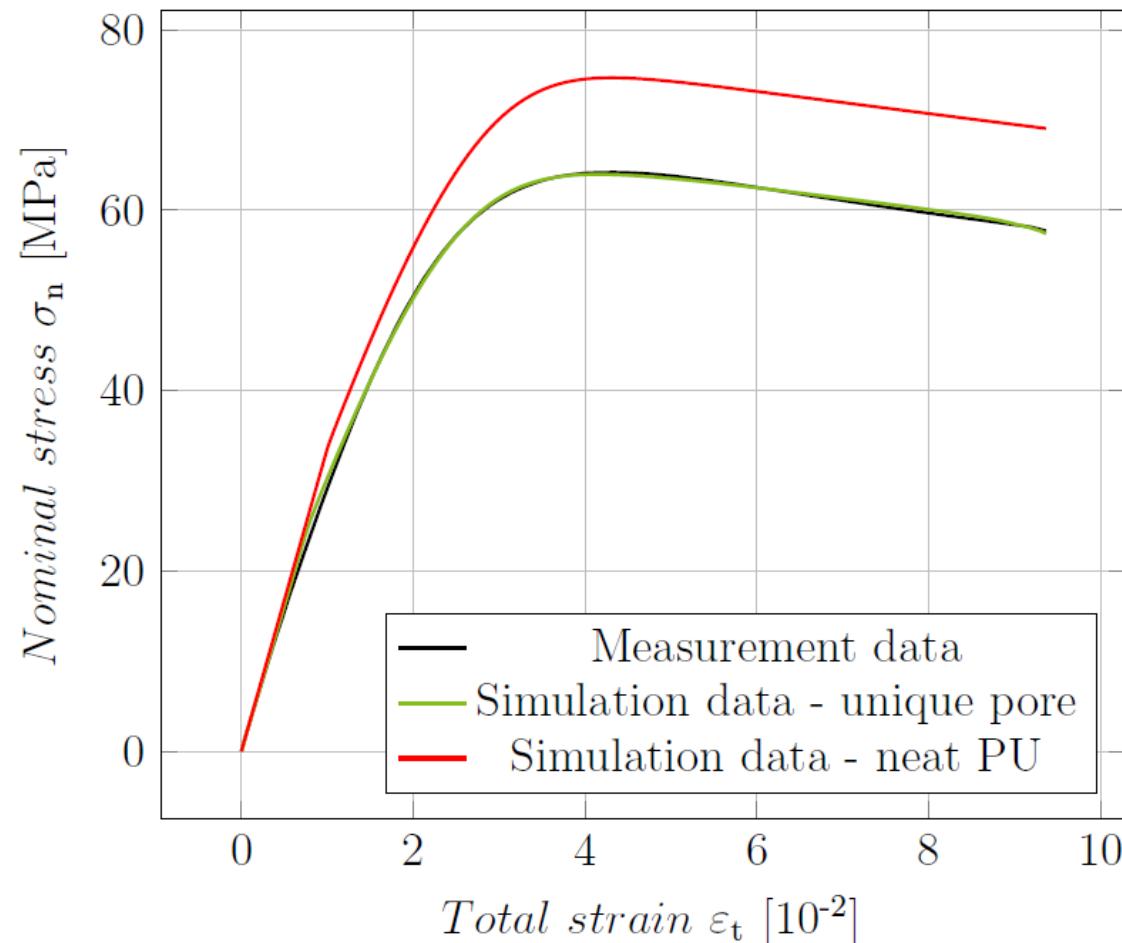
$$\dot{\sigma} = (1 - d)\mathbb{C} : (\dot{\varepsilon} - \dot{\varepsilon}^p), \quad \dot{\varepsilon}^p = \dot{p} \frac{3}{2} \frac{\sigma_D}{(1 - d)\sigma_{eq}}$$

$$d(Y) = \begin{cases} \frac{Y - Y_0}{Y} + b_1 \left(\frac{Y_0}{Y} - e^{-b_2(Y - Y_0)} \right), & Y > Y_0 > 0 \\ 0, & Y \leq Y_0 \end{cases}$$

Parameters determination

Parameter	Unit	Initial parameters	After optimization
E	GPa	3.730496	3.730496
ν	1	0.4	0.4
σ_Y	GPa	0.013540146238	1.4527377212e-05
a_1	GPa	0.0535249831931	0.110060913115
a_2	(GPa) $^{-1}$	233.316844006	6760.53737336
Y_0	GPa	9.3e-05	0.000119444952376
b_1	GPa	0.631262	0.623706623718
b_2	(GPa) $^{-1}$	2.63398	8.09153398372
Error	MPa	17.4716204872	2.22367545047
Iterations	1		335

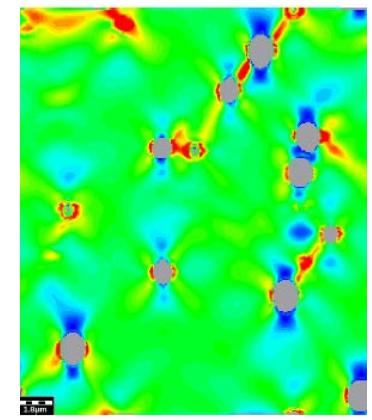
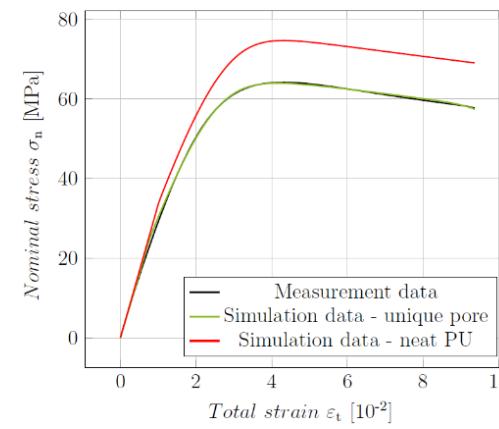
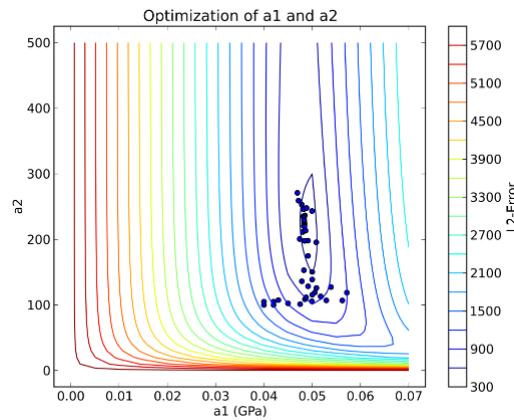
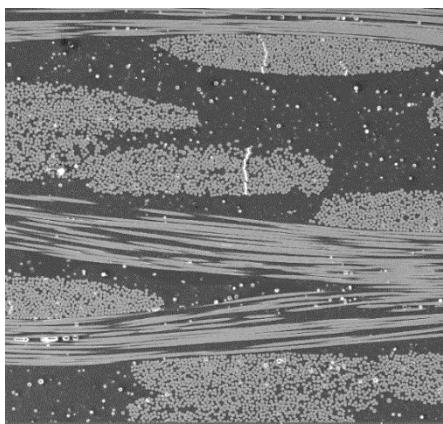
Comparison of measurement data and simulation



Conclusions

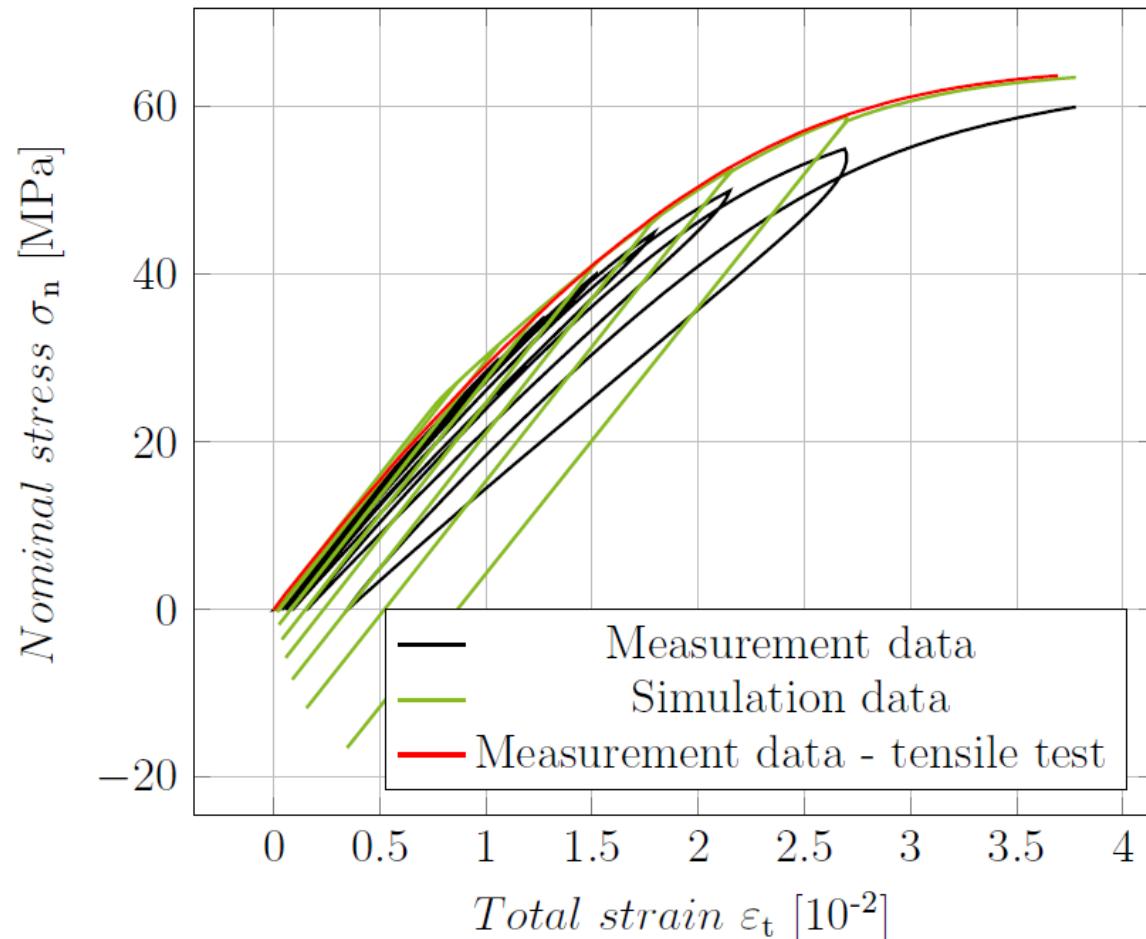
Conclusions

- Outgassing leads to pore content in PU
- Nelder-Mead method was successfully applied to optimize the calibration for tensile loading
- The deformation behavior of PU under tensile loading can be described by an elasto-plastic damage model
- The pore geometrie and distribution had no influence on the deformation behavior



Cyclic tensile test

- Sensitivity study
- Calibration of elasto-plastic damage model to cyclic tensile loading and influence of temperature





QUESTIONS...?

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