Powering Innovation That Drives Human Advancement

Finite Element based inverse Material Calibration

Christian Ilg & André Haufe

DYNA MORE / An Ansys Company

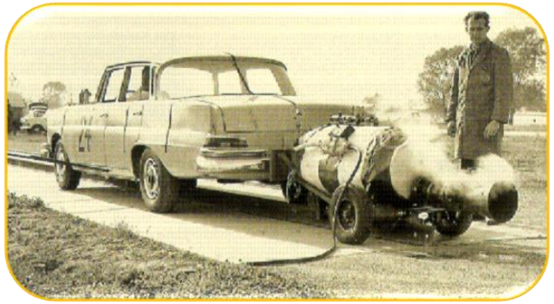
DYNAmore

Data | Software | Engineering | Materials

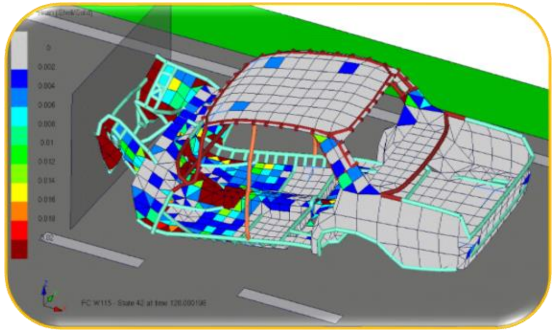
- Founded in 2001 with headquarters in Stuttgart, Germany
- In total more than 160 people
- Aeronautical, civil and mechanical engineers, mathematicians, computer scientists, etc.
- Employees from 13 different countries
- Distribution and **co-development** of LS-DYNA
- **Acquired by Ansys Inc. (USA) in January 2023**

Ansys

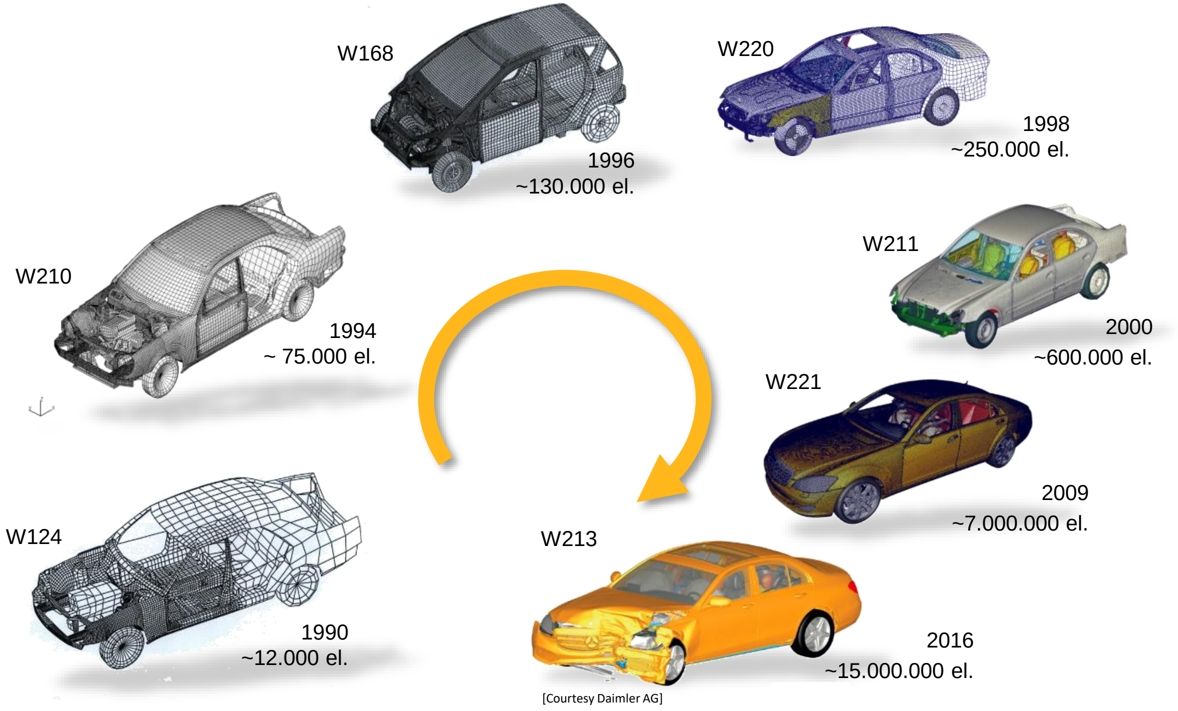
Crashworthiness: Where do we come from?



Rocket science for crash testing (around 1950)



FEM-Model of the 1970s simulated with LS-DYNA 9.70 in 2009
(Finite Elephant Method)



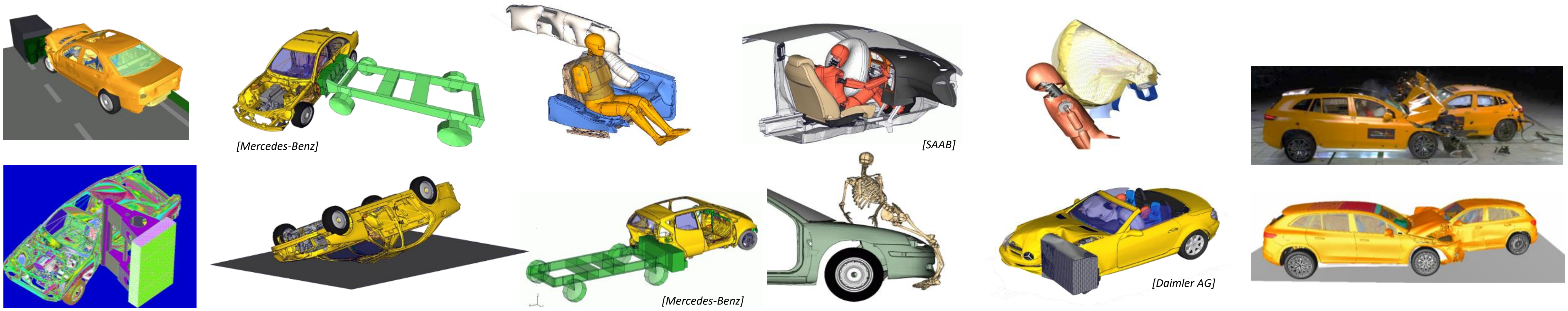
2024: X-ray during crash impact

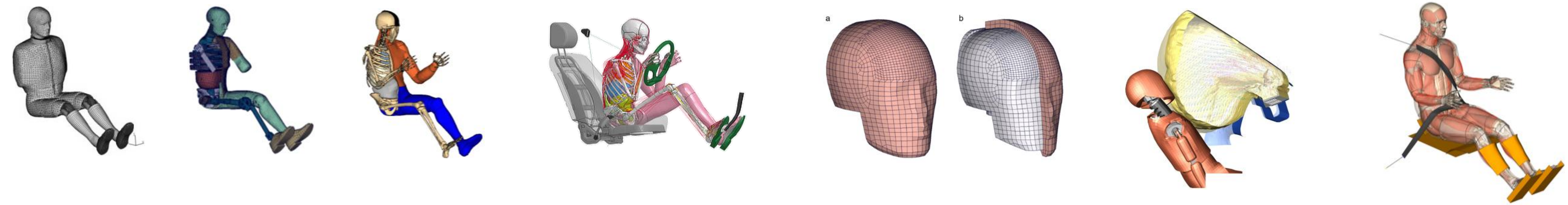
Typical model size 20+Mio. elements

„Complex computational structural models, partially inspired by continuum mechanics.“ [M. Bischoff, 23.6.2023]

Crashworthiness : Where do we come from?

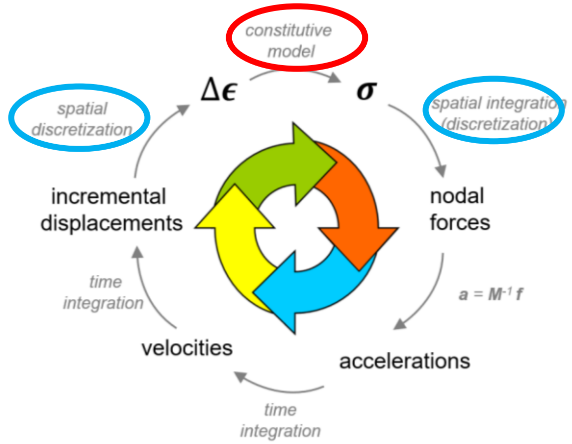
Typical crash/impact load cases and the evolution of anthropometric test devices (dummies)





What ensures predictiveness in crashworthiness?

The explicit cycle



Spatial discretization
(number of elements and model size)

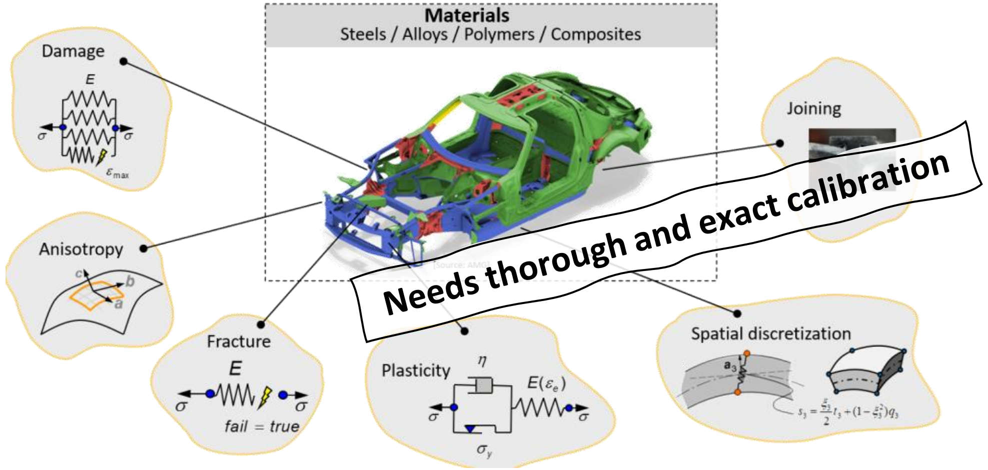
Constitutive modelling
(accuracy and calibration)

Spatial discretization

Tesla Model3 "old" BIW
(many parts + thousands of welds)

Tesla Model3 new BIW with megacasts
(2 parts, way less connections)

Constitutive modelling and calibration



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How can we ensure proper material data?

(The idea of a Material Competence Center…)

Material Competence Center

part of the

Materials, Methods and Homologation Group

part of the

Global Automotive Crashworthiness Team

part of

Ansys Customer Excellence

within

Ansys

The Material Competence Center

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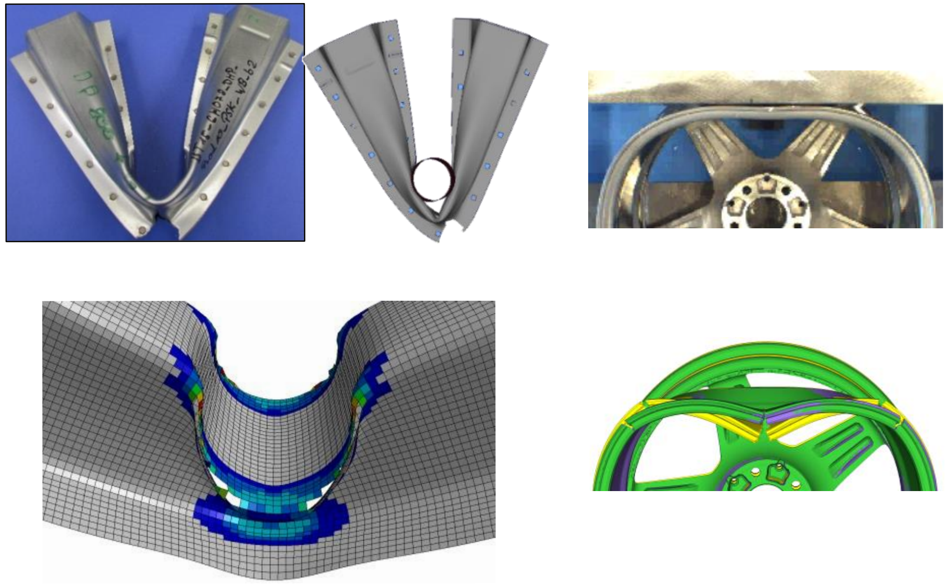
Stefan Wacker

- **Testing services**
  - Tensile, compression, puncture, bending testing
  - Static, dynamic, cyclic testing
  - Component testing
  - Sample processing and conditioning
  - 3D-DIC measurement of the strain field
- **Benefits**
  - Parameter identification from a single source
  - Minimize time and costs
  - The LS-DYNA developer team is always available

- **Material Characterization**
  - LS-DYNA material model calibration for: **Metals**, **polymers**, **glass**, **foams**, and more
  - Deformation behavior
    - Viscoelastic and visco-plastic
    - Isotropic and anisotropic
    - Tensile and compressive- asymmetry
  - Damage and failure modelling
    - GISSMO (General Incremental Stress State dependent damage Model)
    - DIEM (Damage Initiation and Evolution Model)

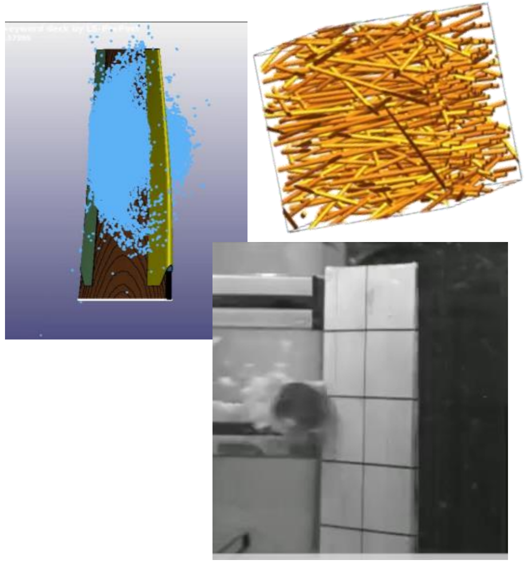
Material models developed by Ansys/DYNAmore MCC

Steel & Alloys



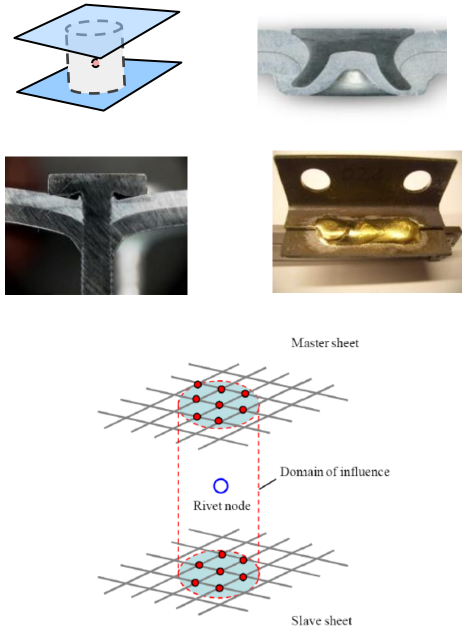
MAT24, MAT54, MAT36, MAT136, MAT187, GISSMO/eGISSMO, DIEM, …

Polymers & Composites



MAT157, MAT215, MAT249, …

Connection modelling



MAT100, SPR, cohesive, …

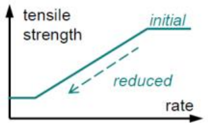
- Many of the material models in LS-DYNA have been developed by Ansys/DYNAmore researchers
- Parameter identification and calibration of respective models is our daily business
- The MCC offers a **one-stop-shop** for testing and calibration services to ensure accuracy of constitutive models

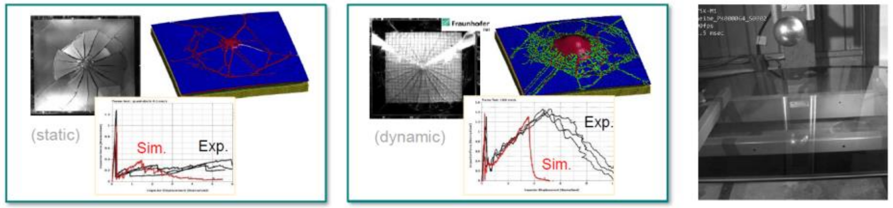
Methods – MCC

Glass model development

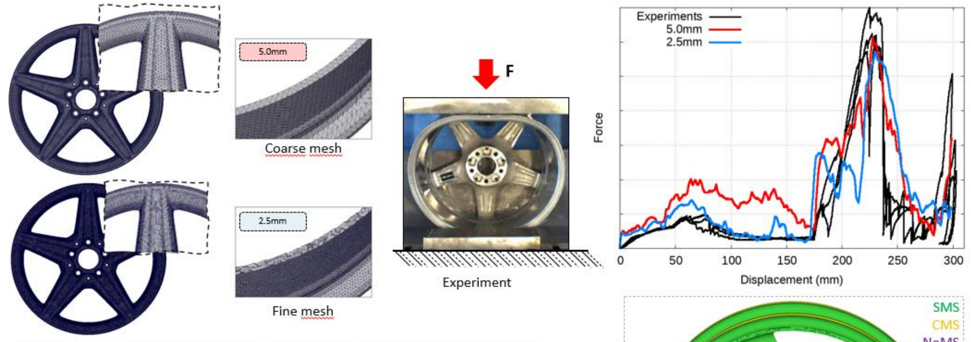
Glass:

- Improvements for *MAT_280 (glass model)
  - Nonlocal extensions unified in one model: Rate-dependent strength reduction in elements around cracks
  - Tests done at DYNAmore MCC to calibrate PVB interlayer & third party impact testing on windscreens.
  - Better agreement with tests (static & dynamic).



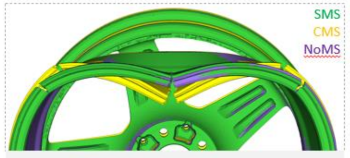


Material card generation for small overlap



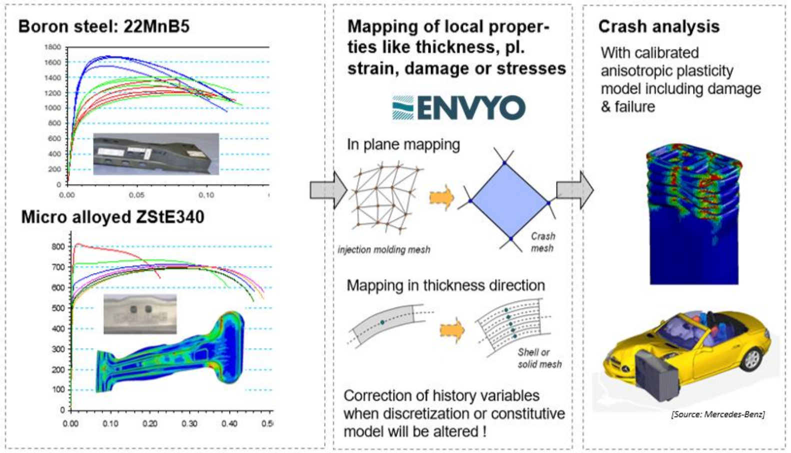
Element size	Number of elements	ELFORM	Computational time (64 CPU)
~5.0 mm	~225,000	13	0h18m
~2.5 mm	~1,600,000	13	9h00m

➡ **Fine mesh required for predictive solution but number of d.o.f. 8 times higher!**



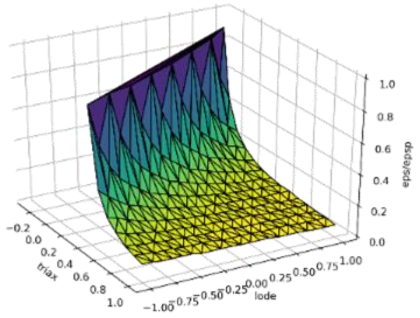
Contrary to CMS, Selective Mass Scaling has only little impact on the solution using the fixed time step of 0.5ms

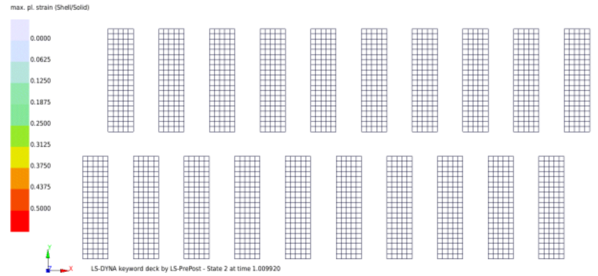
Calibration of manufacturing process chain



Constitutive modelling **and** correlated spatial discretization is key for predictive crash-worthiness simulation.

Investigations on instability, regularization, …





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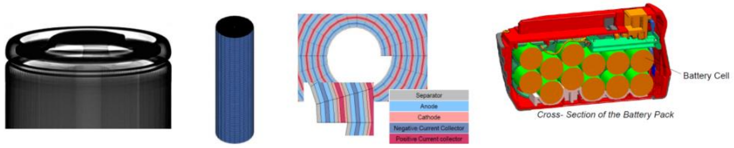
Methods – MCC

Battery model development

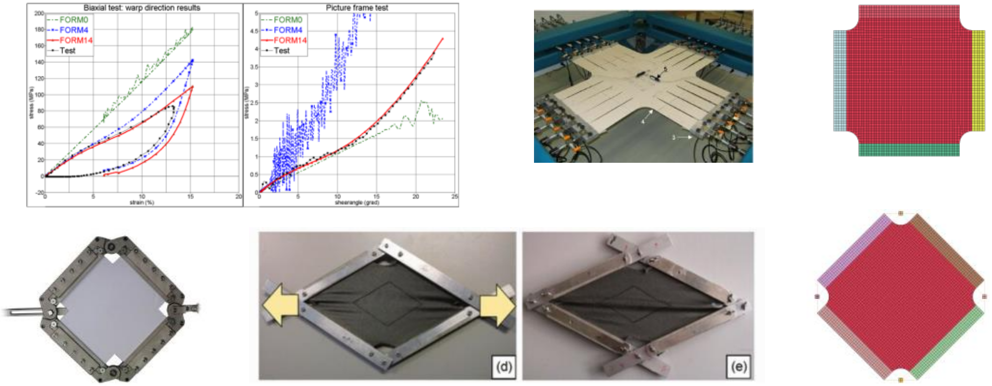
Research projects

COMET K1 VII 3.04a (2021 – 2024)

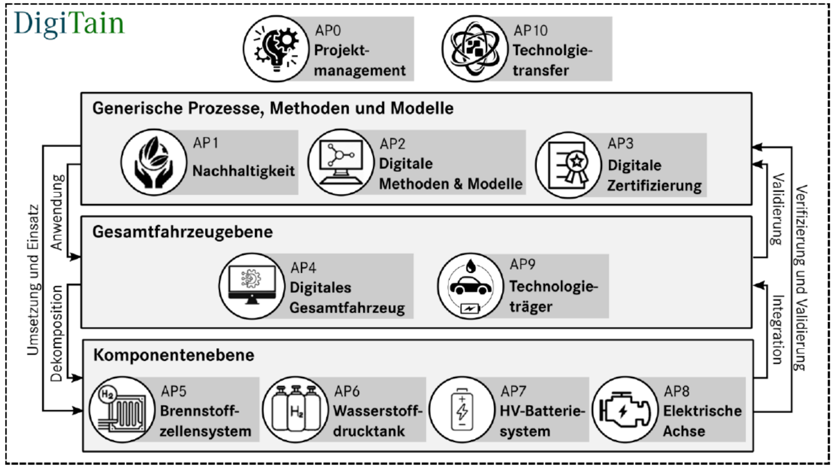
- Ensuring System Reliability via Battery Cell Simulation
  - Thermal and thermo-mechanical experiments on cell level
  - Predict deformation, damage and failure behavior under mechanical load
    - Development of a detailed simulation model of battery cells
    - Derive homogenized macroscopic battery cell models based on the detailed simulation approaches
  - Define criteria to assess critical and non-critical damage patterns
  - Demonstration on 21700 battery cell in consumer products



Airbag fabric calibration

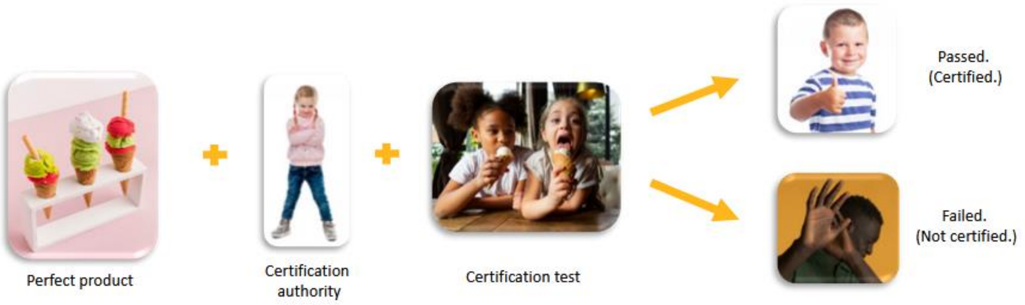


CbA/Homologation in R&D



New modelling techniques for **fuell cells, batteries, H2-vessels.**
New methods for homologation by analysis.
Accounting of CO2 footprint.

CbA/Homologation in early application…



Methods – MCC

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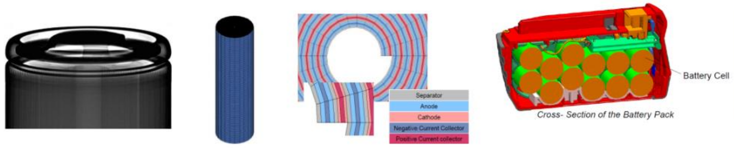


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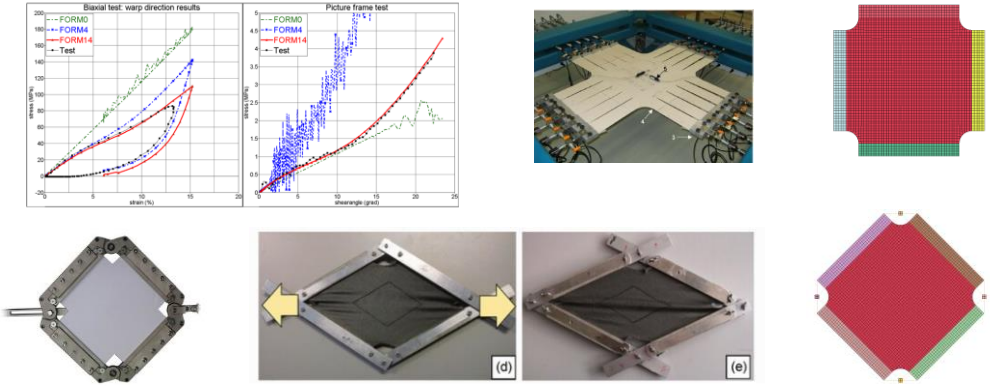

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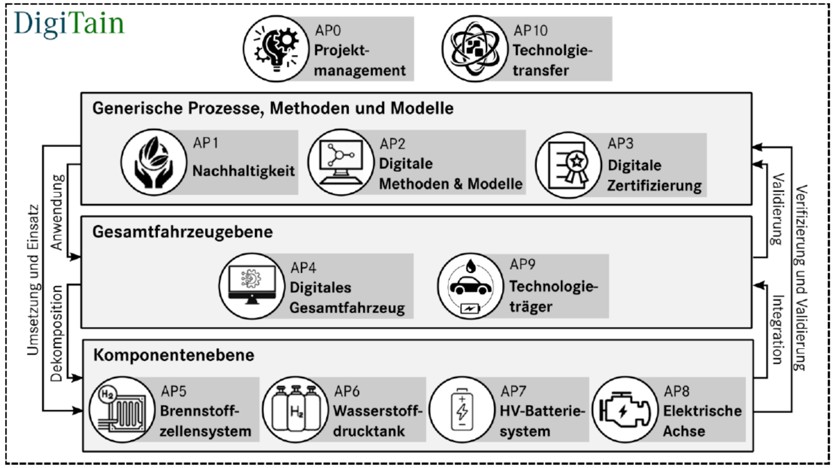

New modelling techniques for **fuell cells, batteries, H2-vessels.**
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CbA/Homologation at LS-DYNA Conference

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Certification by Analysis:
A discussion of solver requirements

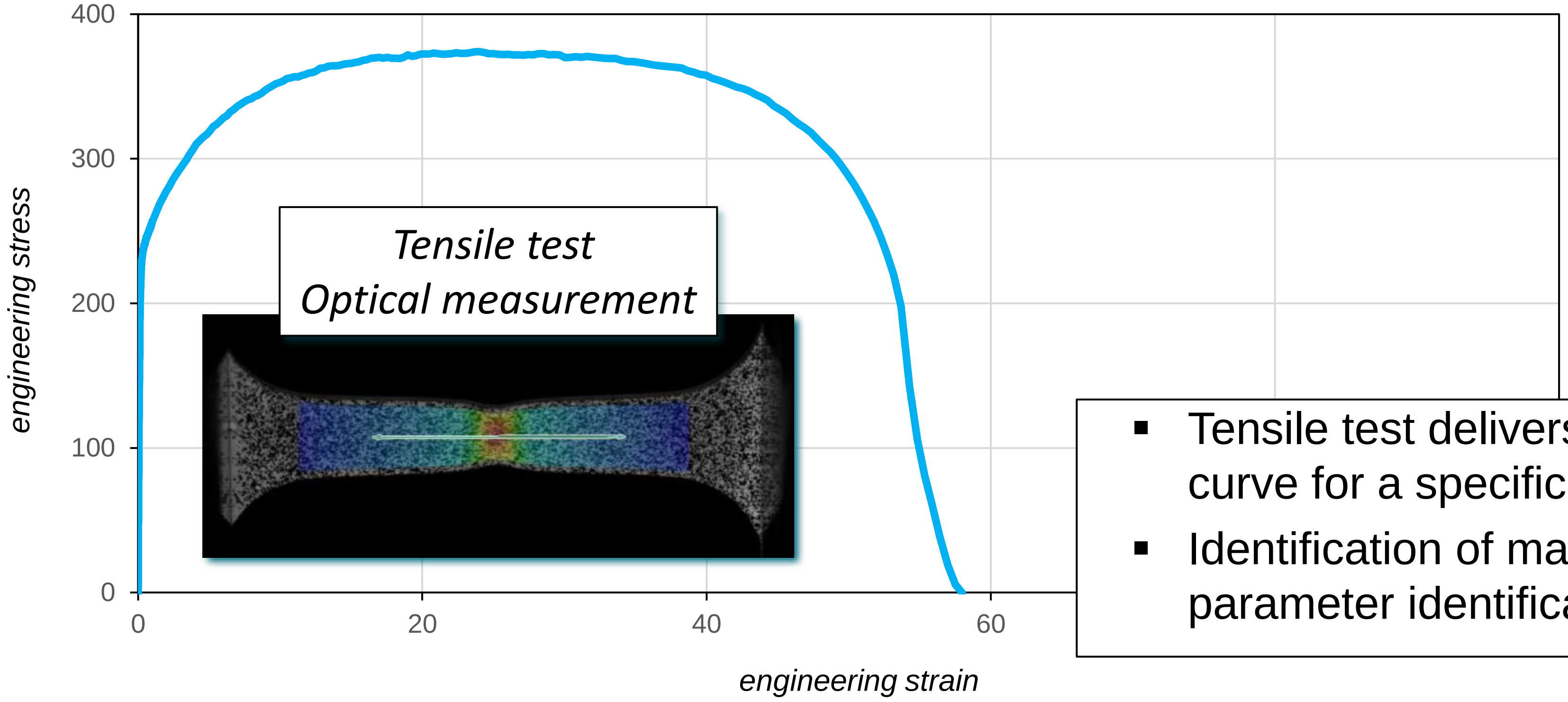
Alexander Gromer & André Haufe

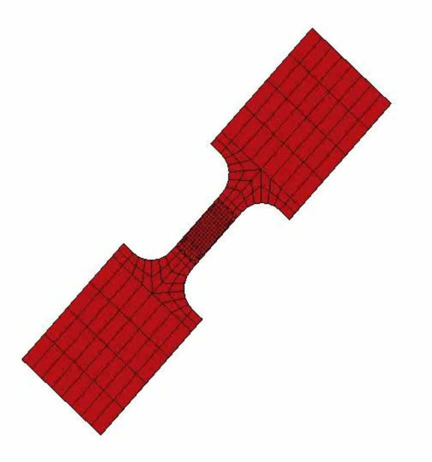
Powering Innovation That Drives Human Advancement Ansys

Classical Material Characterization

Introduction

- Classical scheme of characterizing the yield behavior of a material
  - Engineering stress-strain curve with a predefined reference length (here: l_0 = 9 mm)

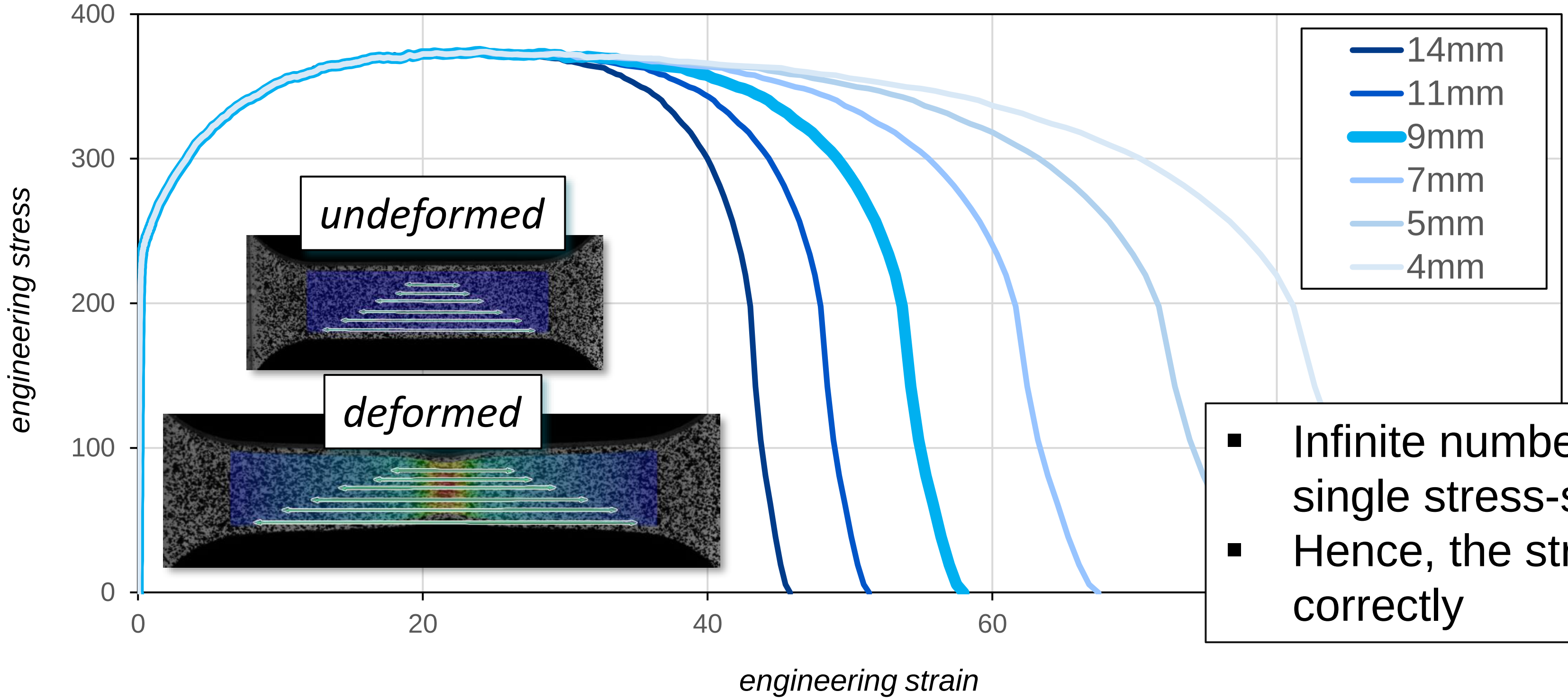


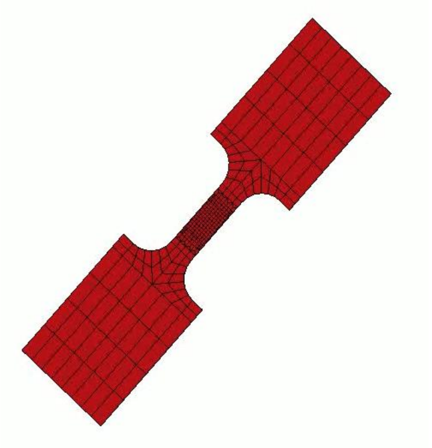


- Tensile test delivers engineering stress vs. strain curve for a specific reference length.
- Identification of material parameters via inverse parameter identification

Introduction

- Engineering stress-strain curves with a different reference/gauge lengths
  - Flow curve generated with the classical approach able to capture all the stress-strain curves?





- Infinite number of possible strain fields for a single stress-strain flow curve
- Hence, the strain field may not be captured correctly

Data which can be used from the experiment

- Parametrization of the flow curve

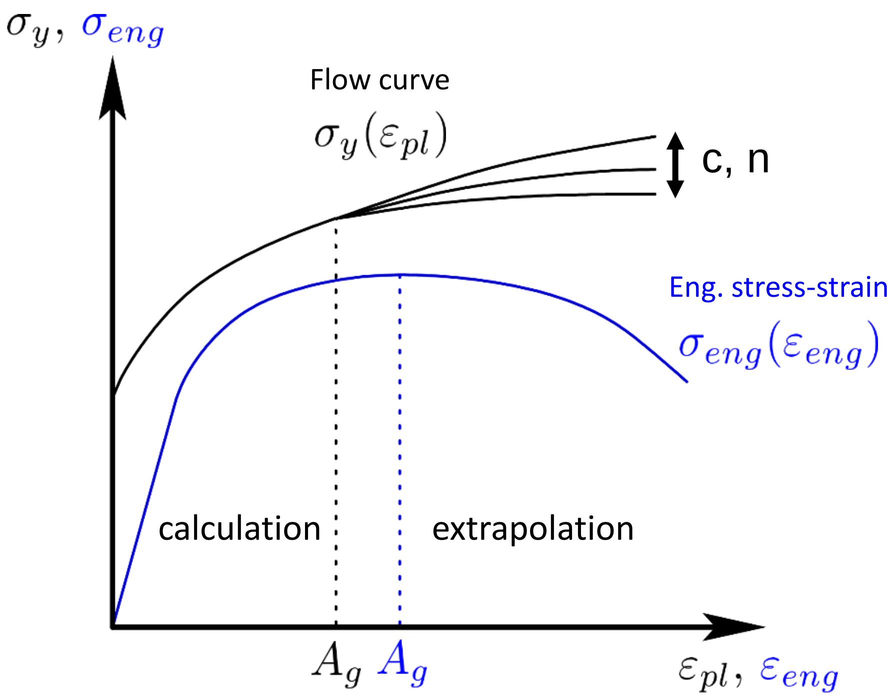
Assuming isochoric behavior and calculation of the flow curve up to A_g

$$\sigma_y = \sigma_{eng}(1+\varepsilon_{eng})$$
$$\varepsilon_{pl} = \ln(1+\varepsilon_{eng}) - \frac{\sigma_{eng}}{E}$$

Extrapolation from A_g with Hockett-Sherby (or else)

$$\sigma_y(\varepsilon_{pl}) = A - B\, e^{(-c\, \varepsilon_{pl}^n)}$$

C^1-continuity at A_g:
>> Reduces two variables from the equation



Remaining variables c and n are chosen as optimization variables

Full Field Calibration

Introduction

FFC – Concept

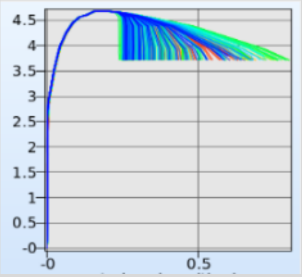
Experiment

Measurement:
- Force
- Strain field

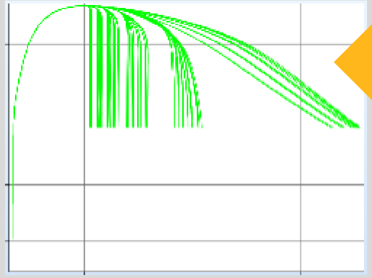
Optimization

Input from experiment

Input from simulation

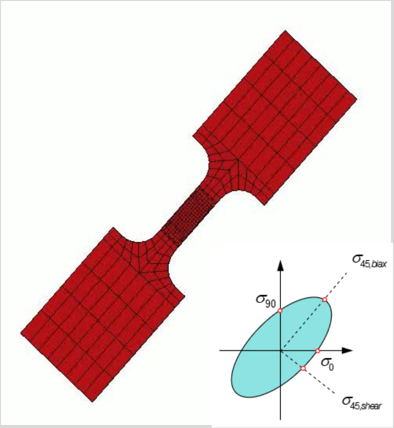


Force vs. strain



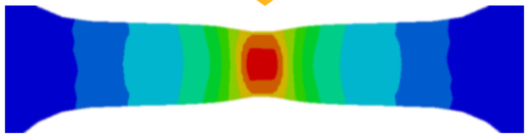
Force vs. strain

Simulation



Measured strain field (facet size?)

Objective:
identical strain fields in time

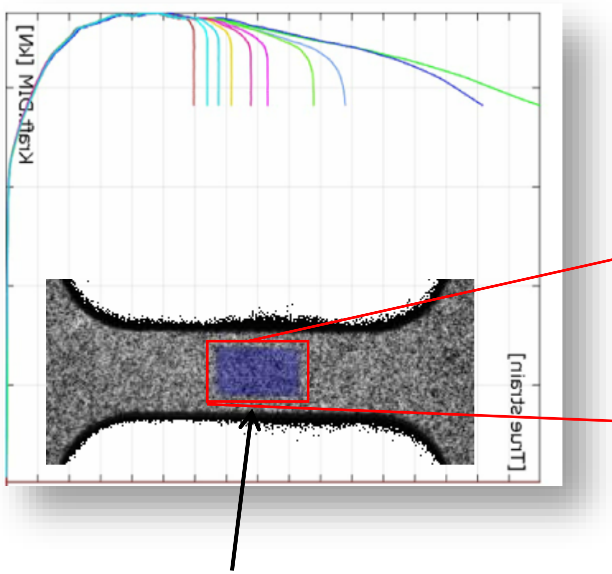


Simulated strain field (element size?)

Introduction

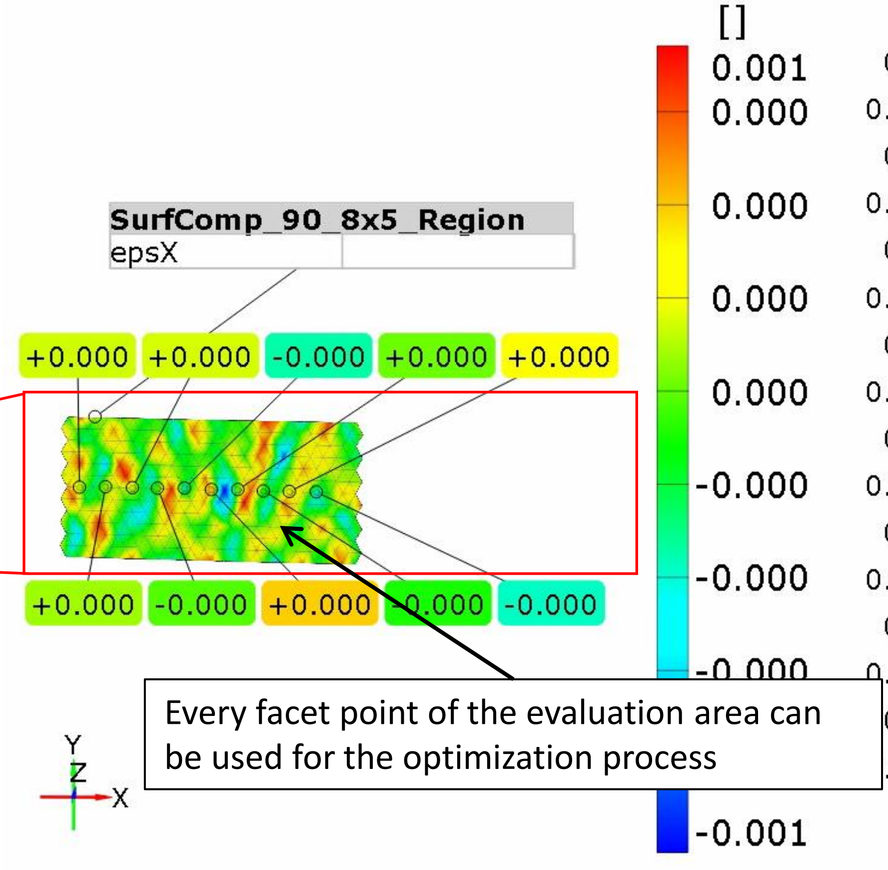
- Example of data which can be used for the optimization (mini flat tensile test geometry)

Tensile test and optical measurement

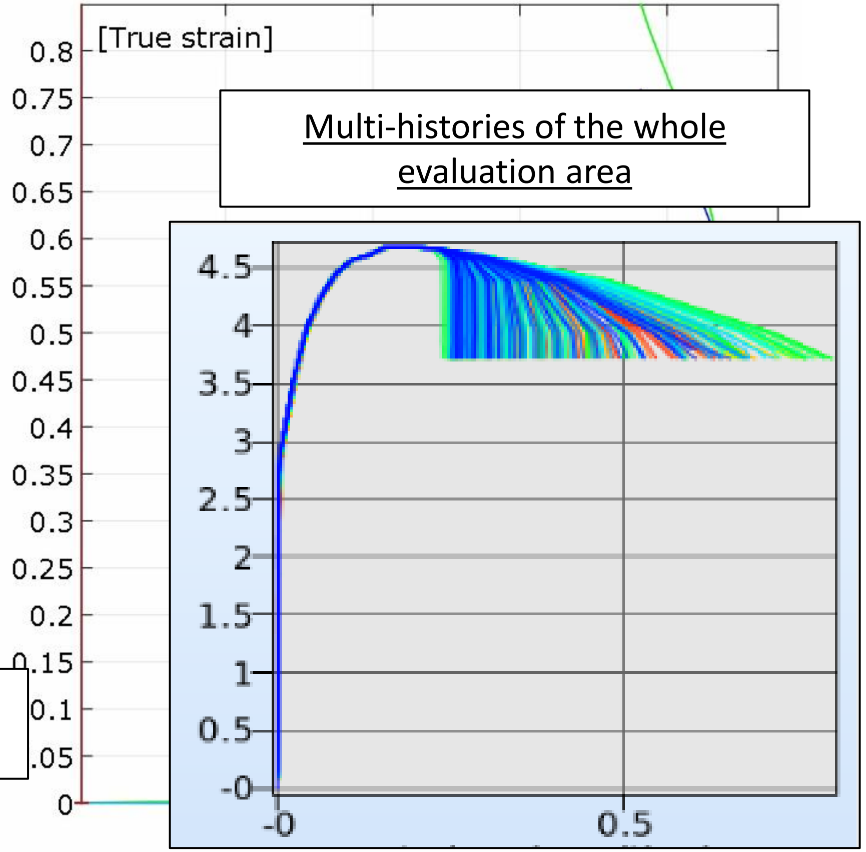


Evaluation area

Selection of 10 points on the evaluation area



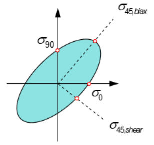
True strain vs. force of the 10 points (ARAMIS export via xml)



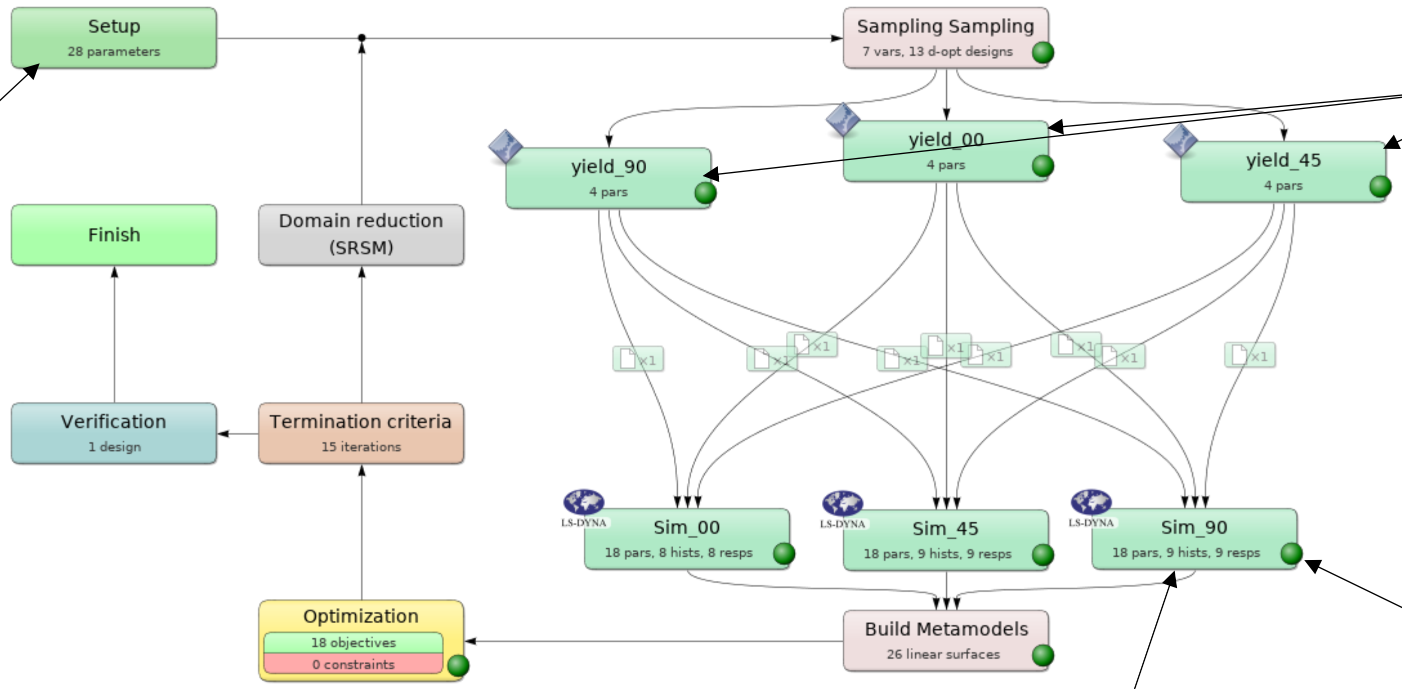
Optimization setup

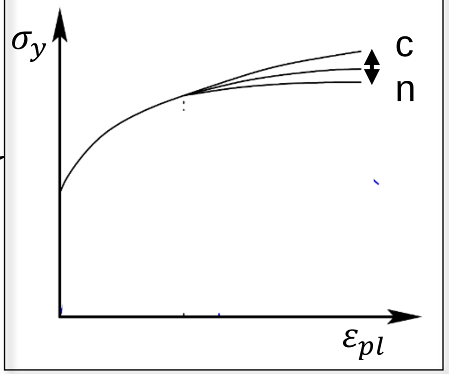
- Optimization setup for parameter calibration in LS-OPT

Enhanced Barlat
Variables ***c*** and ***n*** for 0°, 45° and 90° w.r.t. the rolling direction
- c_{00}, n_{00}
- c_{45}, n_{45}
- c_{90}, n_{90}

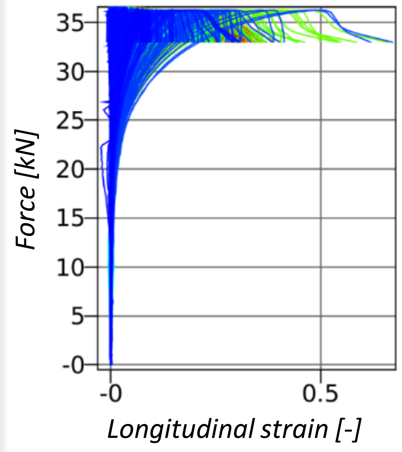


Exponent of the yield surface *m*

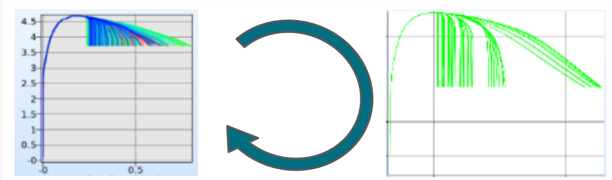


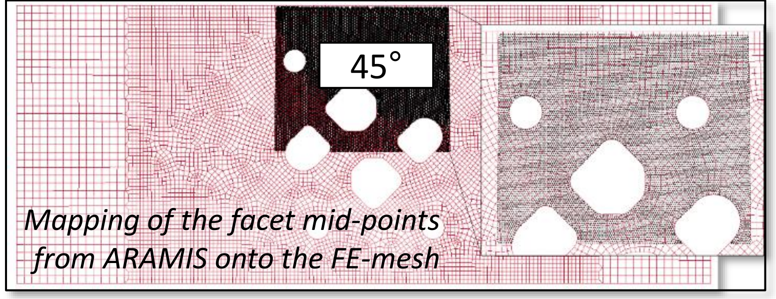


Multi-histories from ARAMIS via xml import



Curve matching between experimental and numerical data





Mapping of the facet mid-points from ARAMIS onto the FE-mesh

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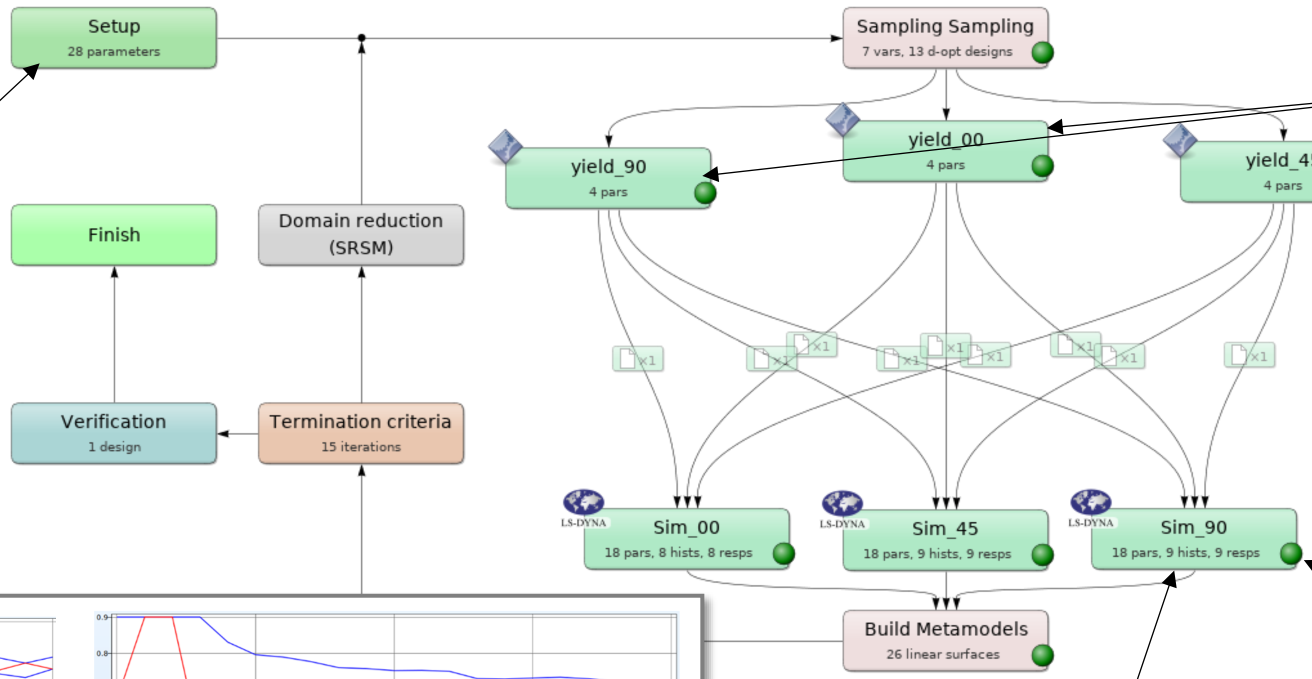
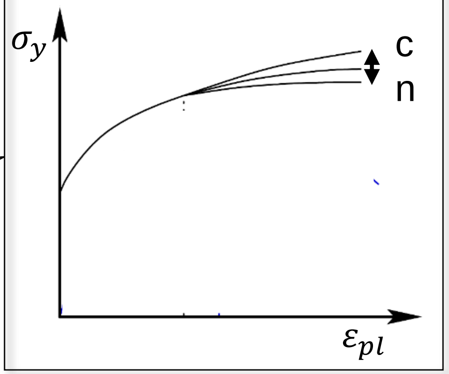
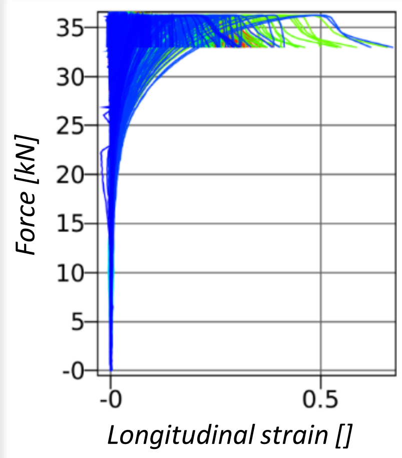
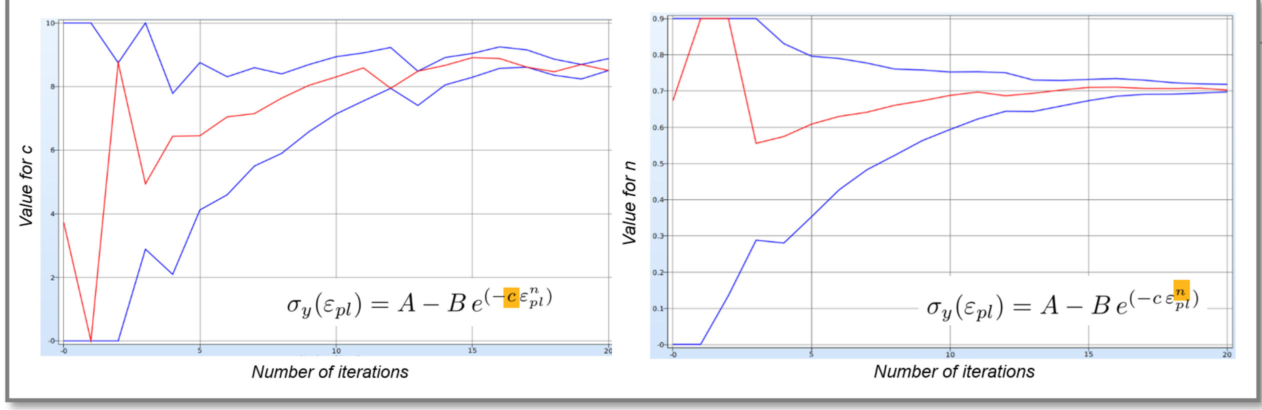


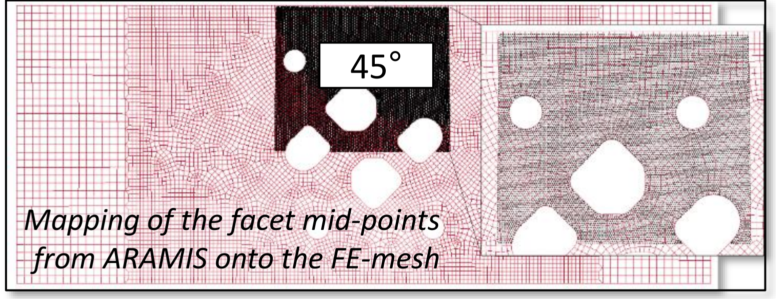
Up to 3 flow curves



Multi-histories from ARAMIS via xml import







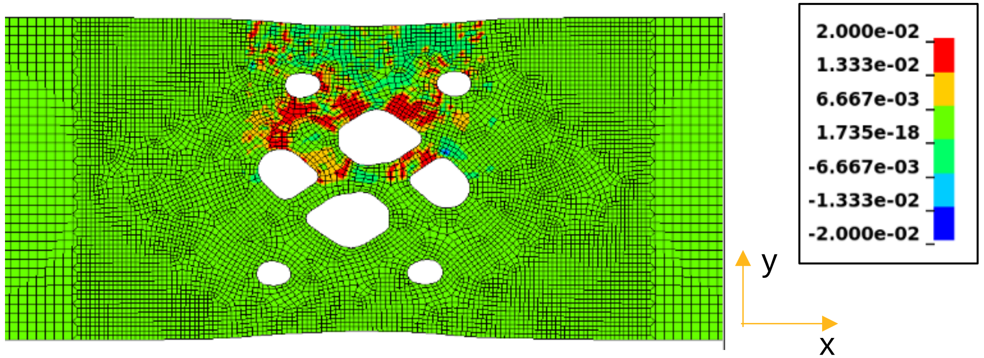
Mapping of the facet mid-points from ARAMIS onto the FE-mesh

Results: Experiment vs. Simulation

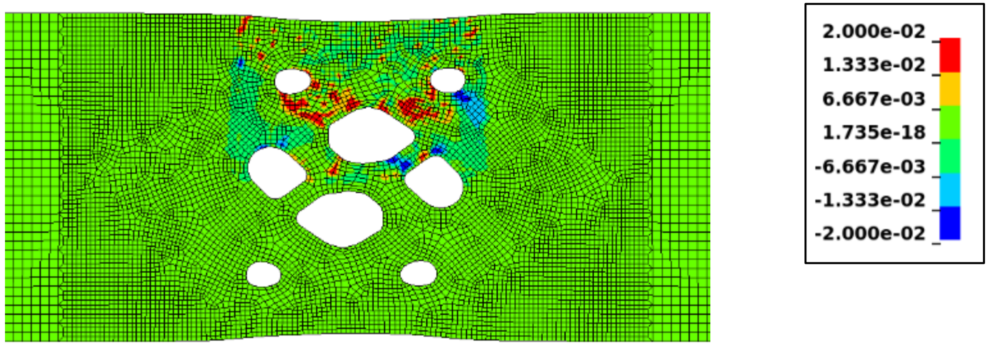
- Comparison of difference of the strain fields for 0° – strains in x- and y-direction

x-strains

Baseline run

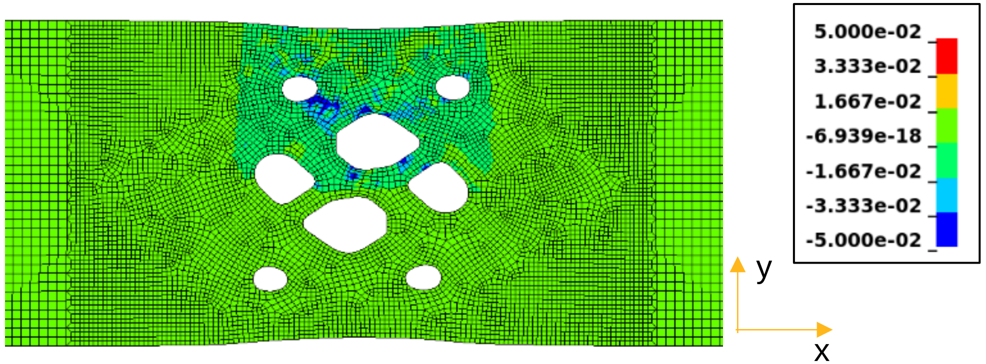


After 20 optimization iterations



y-strains

Baseline run



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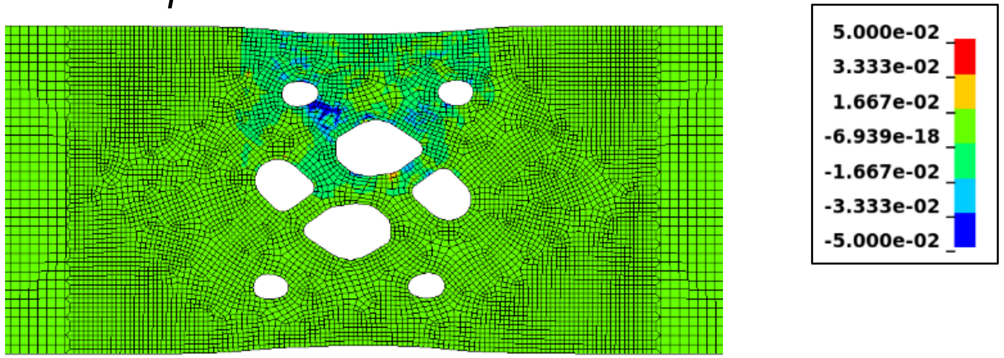
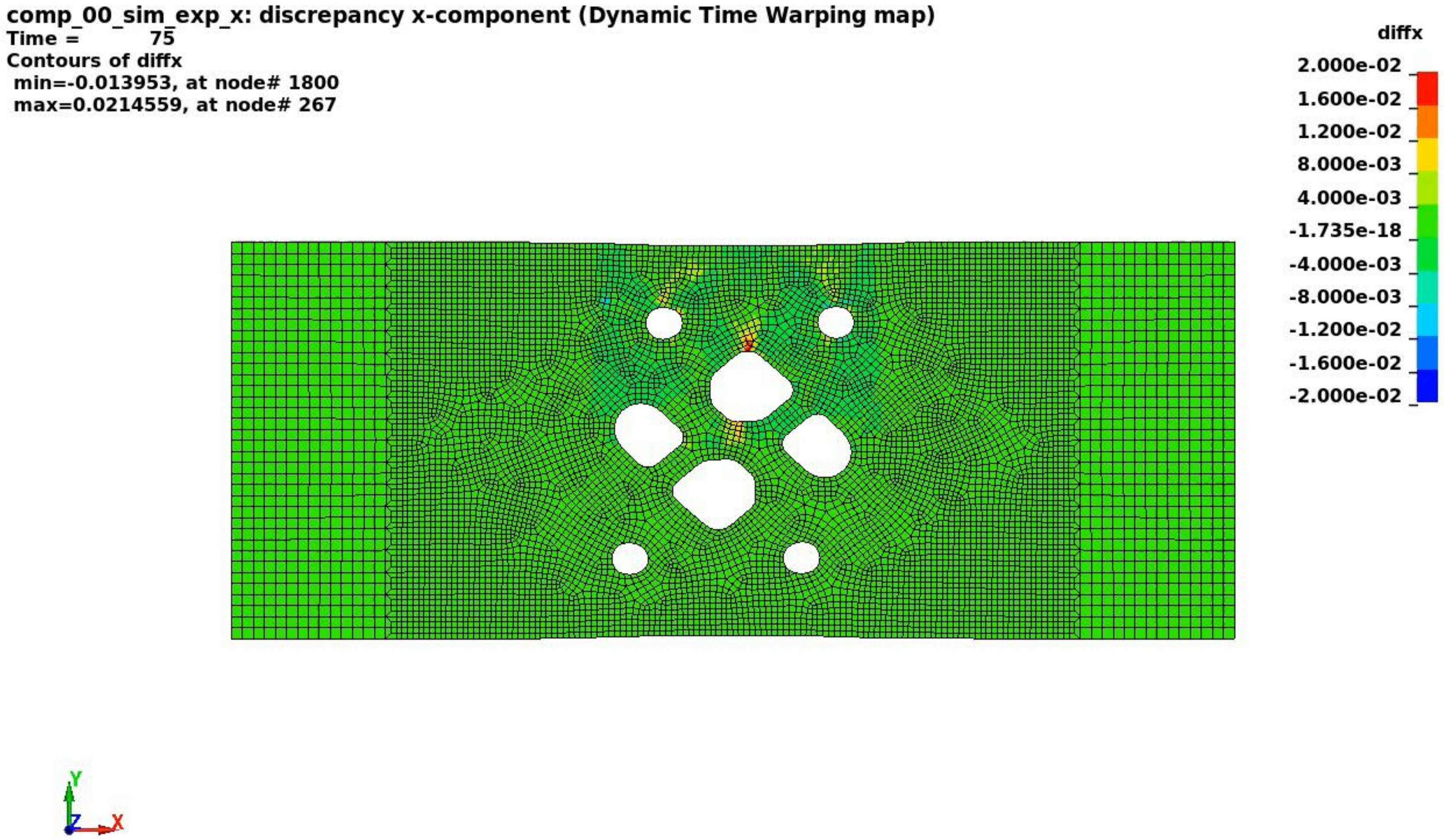


Results: Experiment vs. Simulation

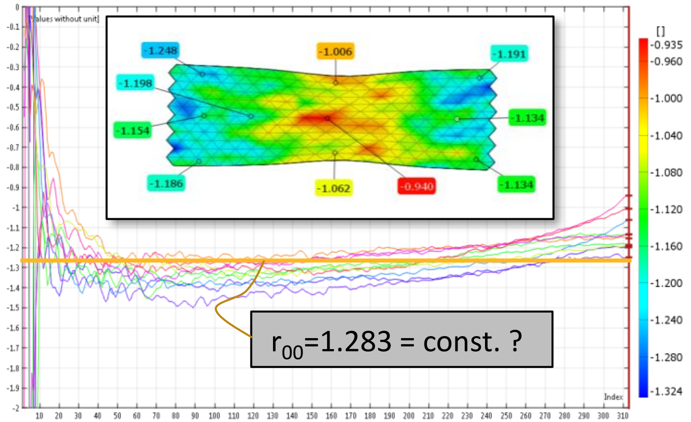
- Difference of the experimental strain fields for 0° w.r.t simulated strains in x-direction

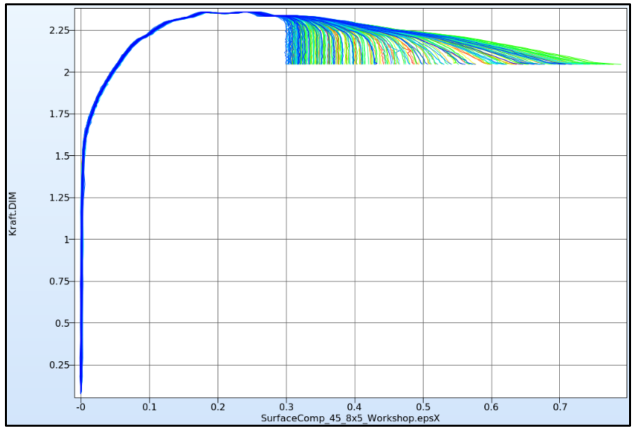


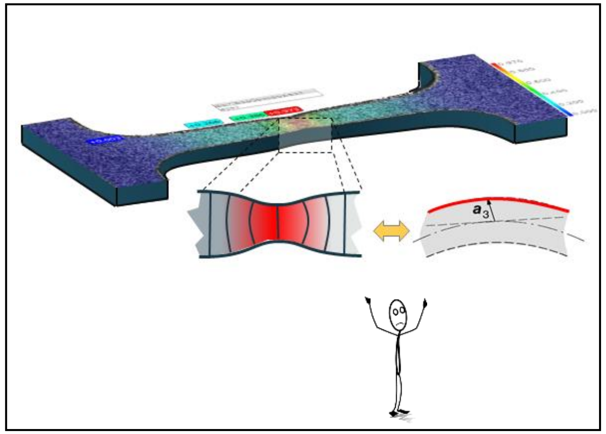
Limitations

Possible reasons for deviations

- Constitutive model not rich enough to represent reality:
  - Varying R-value
  - Yield locus still too simple
  - 3D effects in thickness direction
  - No damage
  - Yield curve extrapolation too simple
- Strain rate dependency
- Evolution of temperature
- Noise from DIC
- DIC surface measurement (but shell assumptions)







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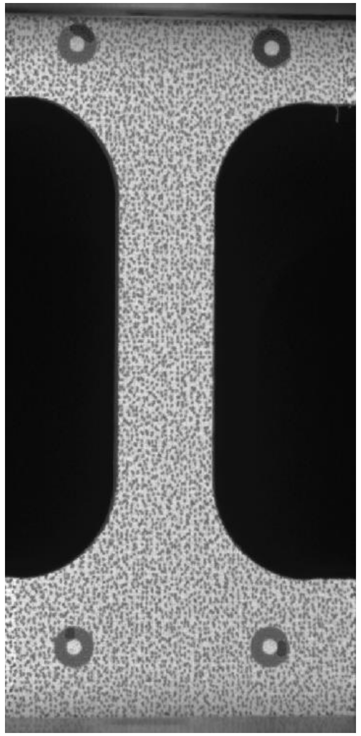
Experimental Full Field Method

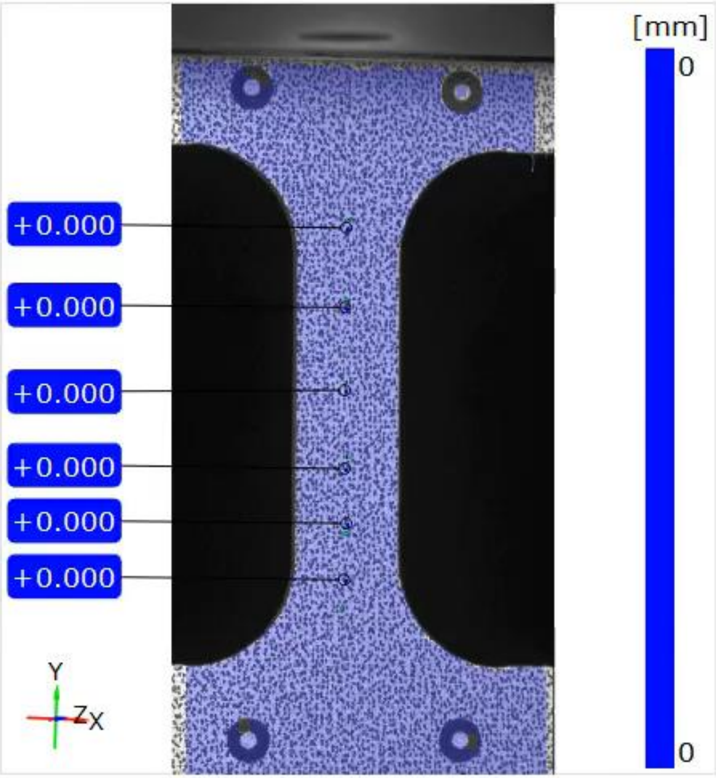
Idea

- Other data that might be used for the optimization scheme (mini flat tensile test)

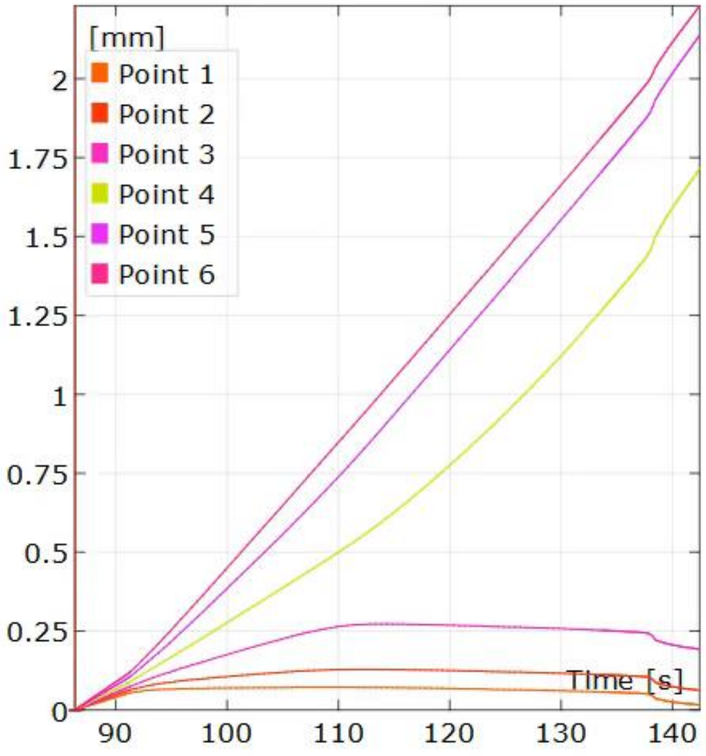
Tensile test with speckle pattern



Selection of 6 points on the evaluation area



Displacement in longitudinal direction which can be exported via xml



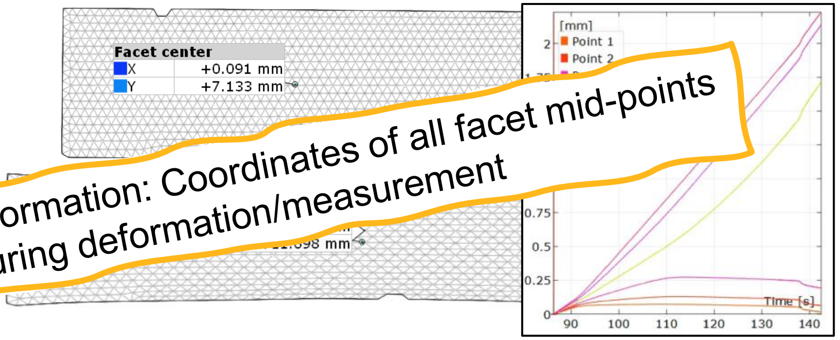
Idea

- Optimization scheme

Experiment

Undeformed

Deformed



Information: Coordinates of all facet mid-points during deformation/measurement

Simulation

Boundary conditions:

- *BOUNDARY_PRESCRIBED_MOTION_NODE
  Boundary condition for all single nodes can be defined
- *DEFINE_CURVE – Time vs displacement curves can be assigned to the boundary conditions

ENVYO

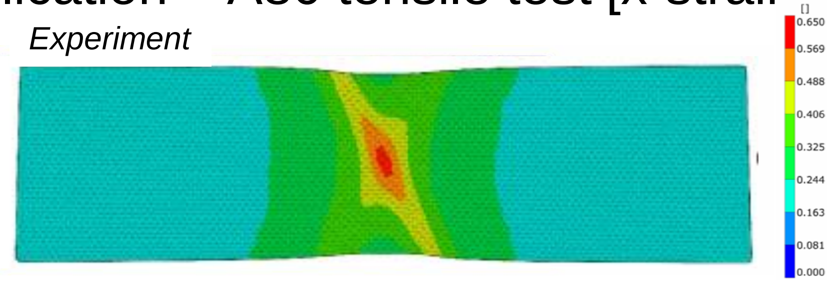
Use the information from x and y displacement of every time step/stage

Generate LS-DYNA input deck

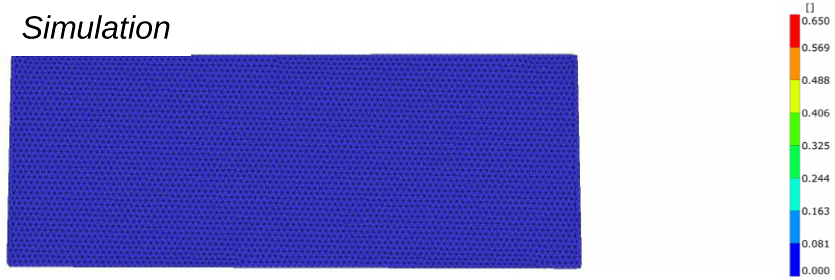
- Mesh and boundary conditions

Application – A80 tensile test [x-strain]

Experiment

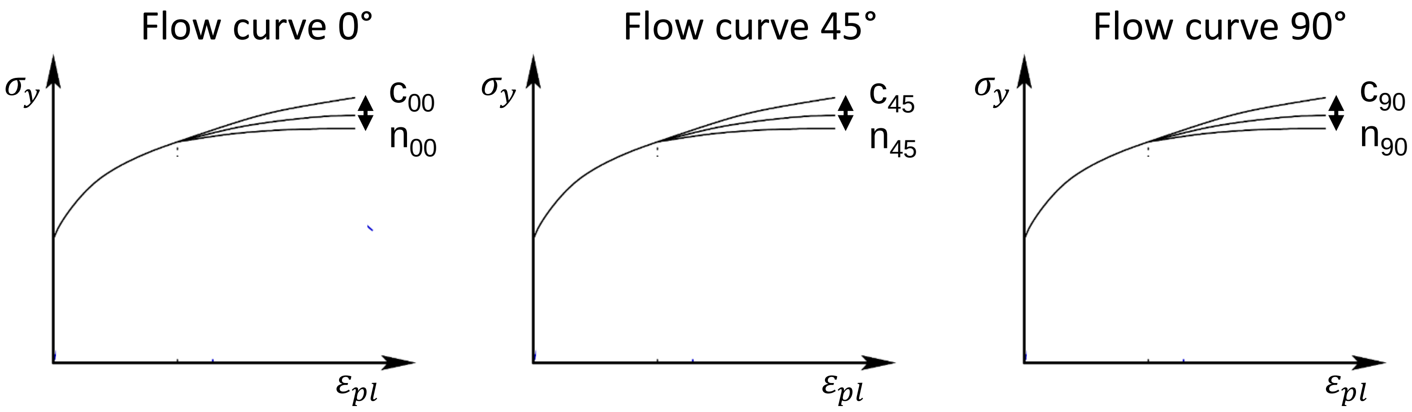


Simulation



Optimization parameters and targets for extended Barlat (MAT_36, HR=7)

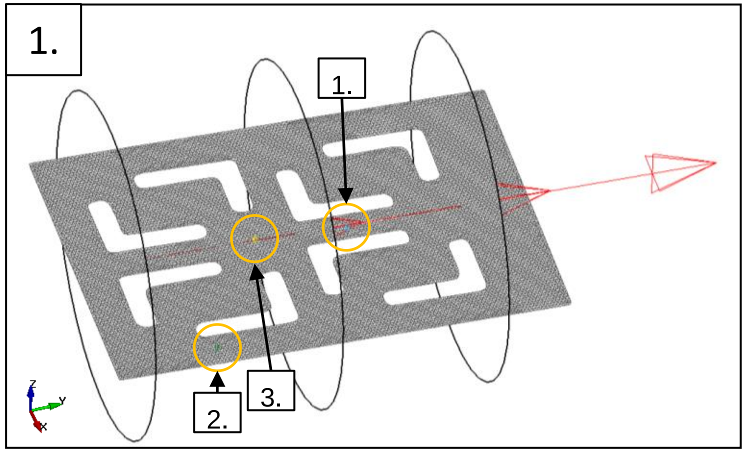
- Optimization parameters:
  - Variables ***c*** and ***n*** for 0°, 45° and 90° w.r.t. the rolling direction
    - c_{00}, n_{00}
    - c_{45}, n_{45}
    - c_{90}, n_{90}
  - Exponent of the yield surface ***m***

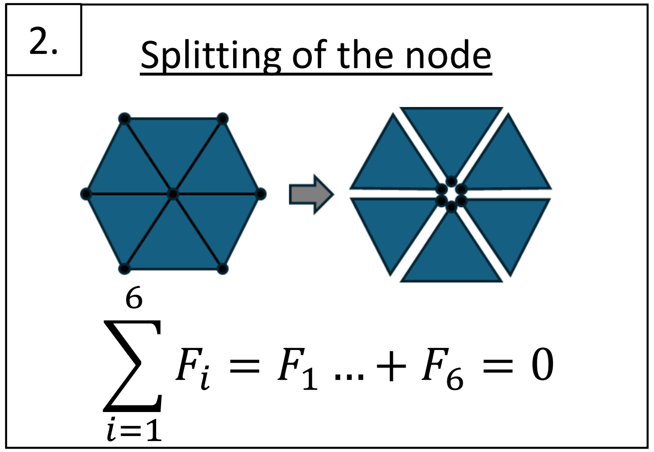


- Optimization targets:
  - Global force in different cross sections

  and/or

  - Splitting node to access and control local force equilibrium



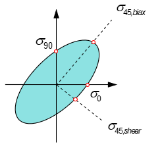


Optimization setup [1]

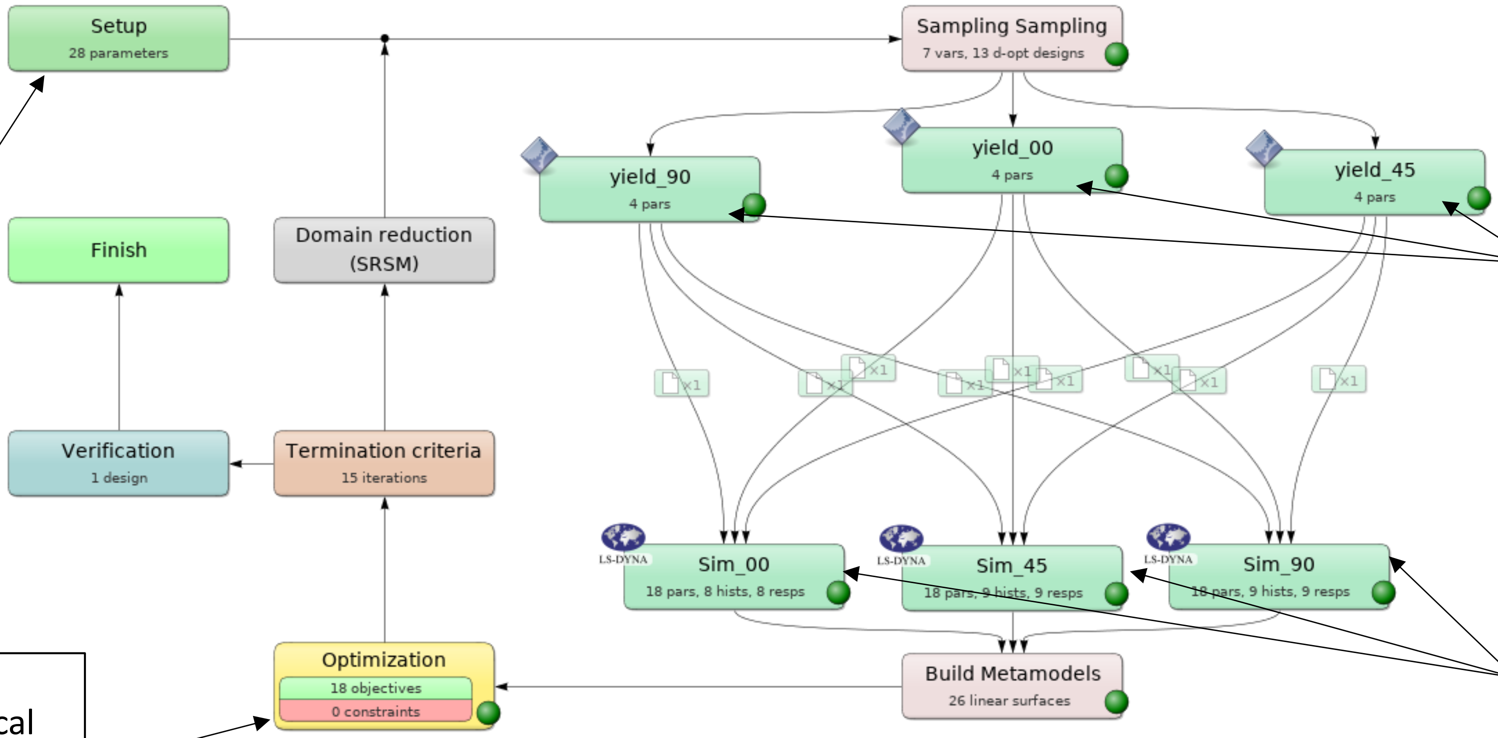
- Optimization setup for parameter calibration in LS-OPT (global and local criteria)

Enhanced Barlat:
Variables c and n for 0°, 45° and 90° w.r.t. the rolling direction

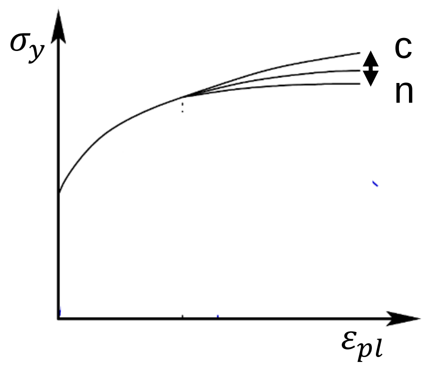
$-c_{00}, n_{00}$
$-c_{45}, n_{45}$
$-c_{90}, n_{90}$

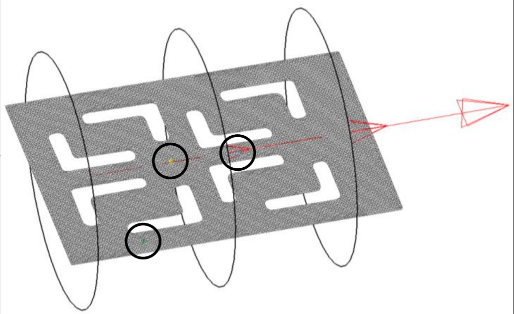


Exponent of the yield surface *m*



3 flow curves





- Curve matching between experimental and numerical global force
- $\sum_{i=1}^{6} F_i = F_1 \dots + F_6 = 0$

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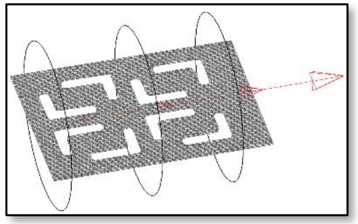
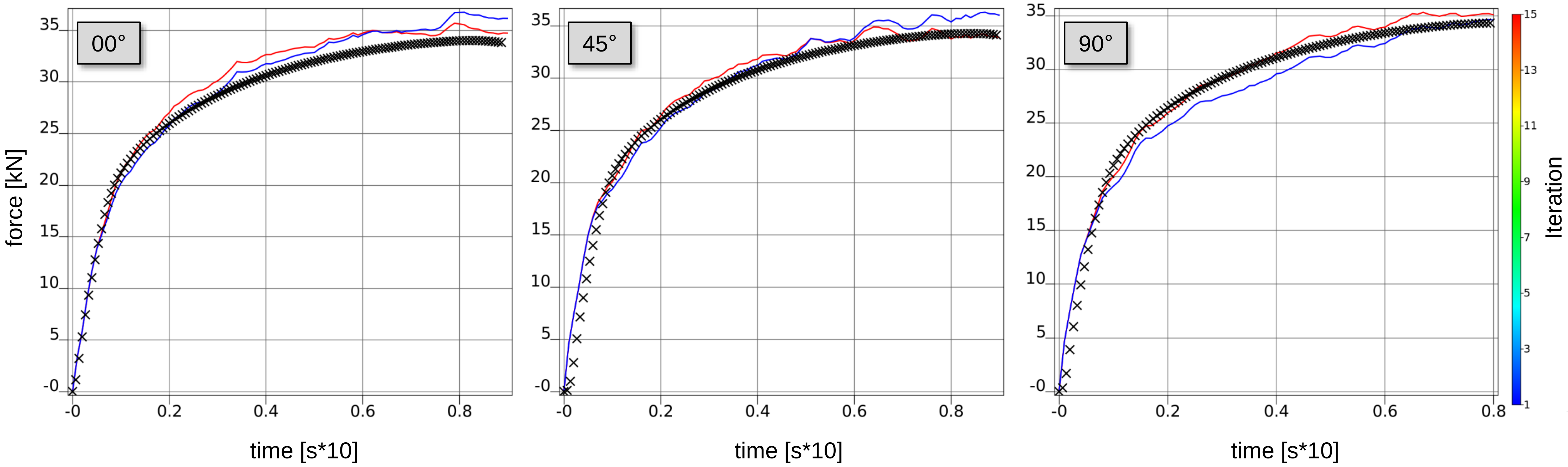
Early results

- Optimization based on the global force
  - Exemplified by one cut section of each simulation (0°, 45° and 90°)
  - Baseline run (blue) vs final run (red) vs experimental data (black)

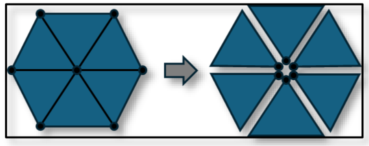




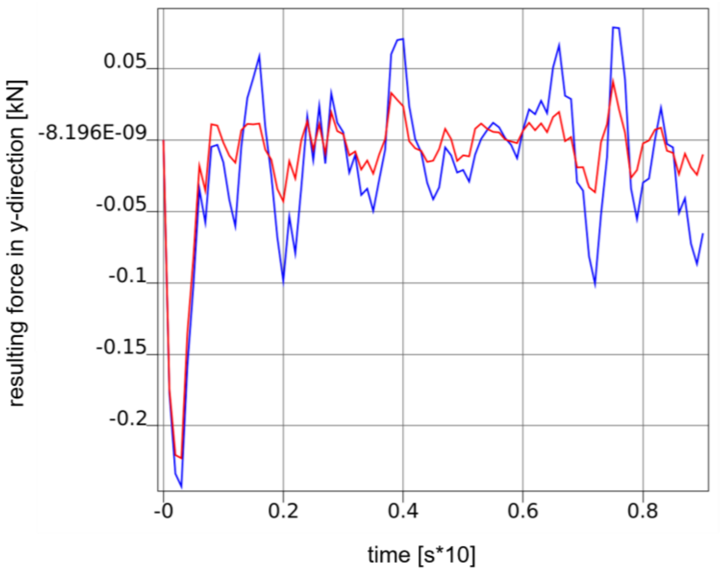
  - Slight improvement of the resulting global forces
  - But the results are still noisy

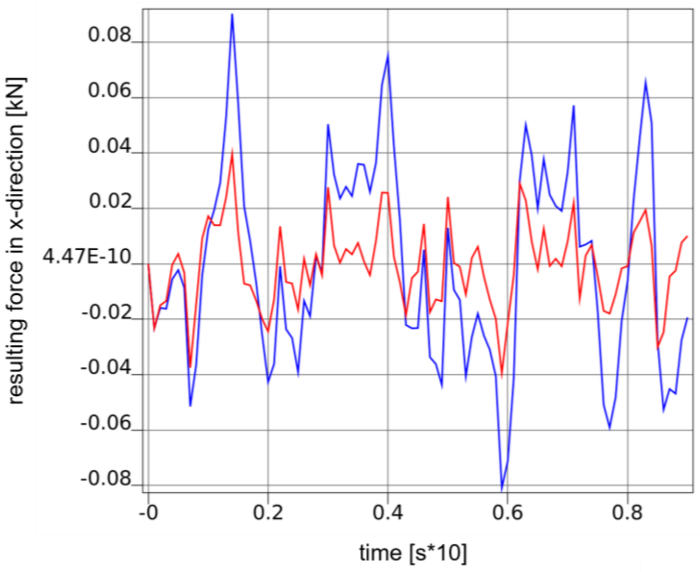
Early results

- Optimization based on the <u>equilibrium of the nodal forces</u>



  - Exemplified by one point of one simulation (0°)
  - Baseline run (blue) vs final run (red)

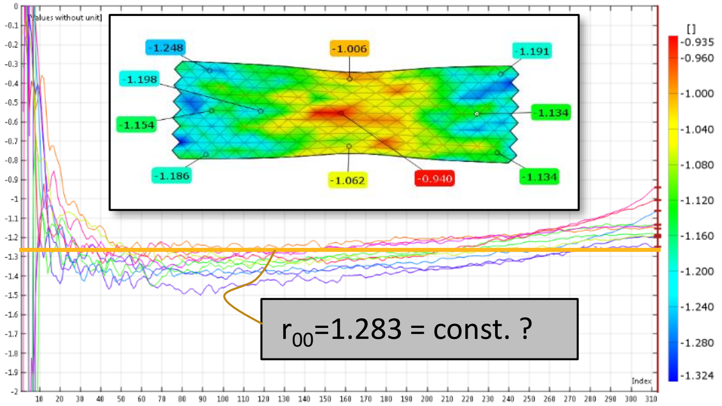


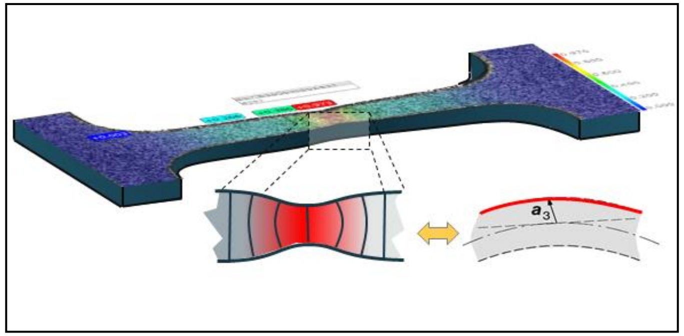


  - Slight improvement of the resulting global forces
  - But the results are still noisy

Conclusion

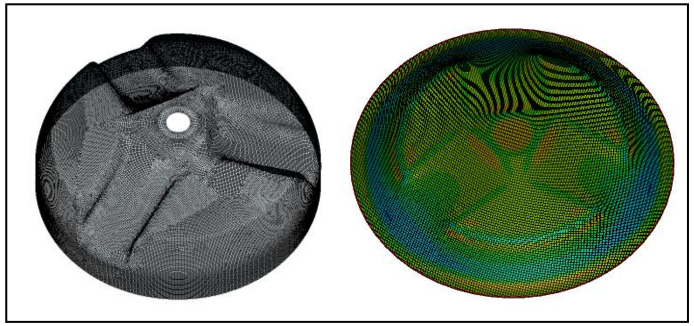
- Results of the optimization methods are promising
- New specimen geometries with a wider range of triaxialities open up new possibilities
- <u>Limitations</u> in the current setup:
  - Noise of the test data
  - Displacements in thickness direction were neglected (i.e. projection of the optical measurement in shell mid-plane needed and/or higher order shell formulation)
  - Improve spatial discretization
  - We need to tackle strain rate effects and heat release in localization areas

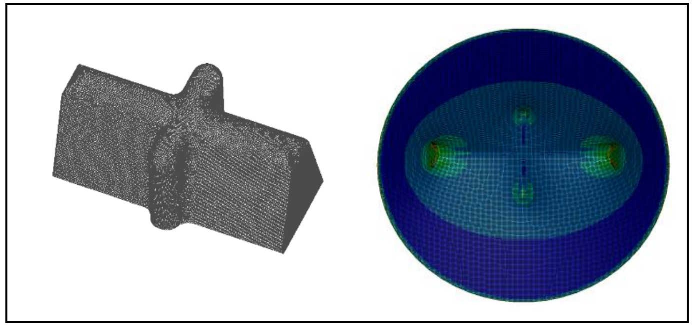




Outlook

- Use more options/enhance the material model:
  - Shear and biaxial flow curves
  - Definition of r-values vs. plastic strain
  - Go into 3D for higher order shells
- Filtering of the test data
  - Mapping on a regular mesh
  - Elimination of the ground noise
  - Merging of data from several tests (increase sample size)
- Comparison with a conventionally calibrated material card using a component test
- Combine the method with DVC (for respective materials)





Think also outside of metallic materials…

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