Material models for non-reinforced and reinforced thermoplastics in Abaqus®

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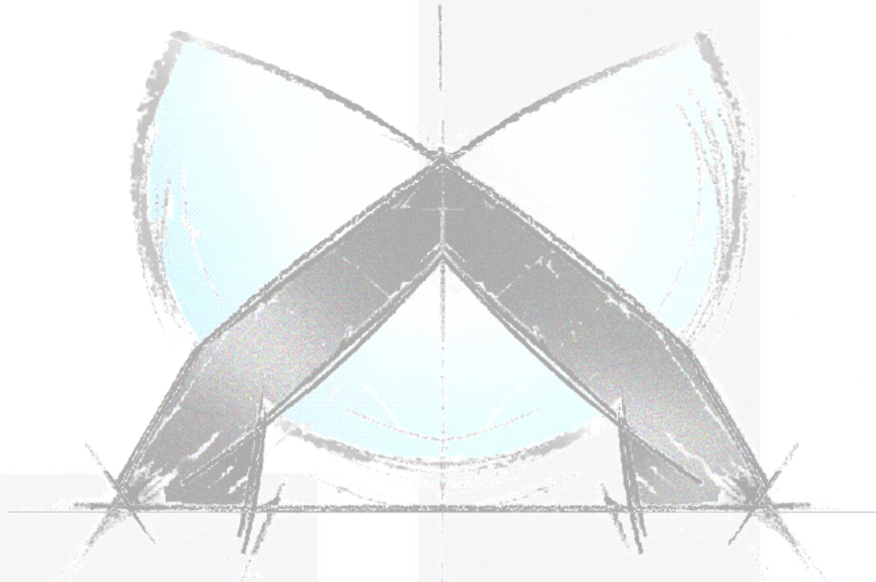

SIMULIA Austria Regional User Meeting
9.–10. November, Wien

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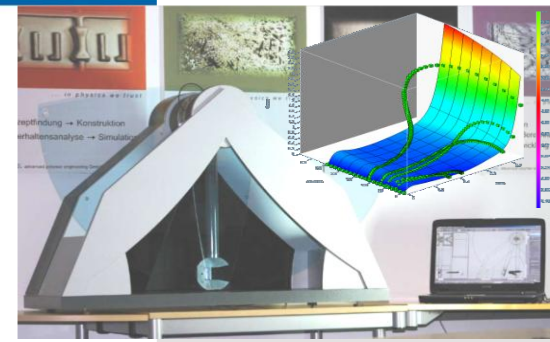
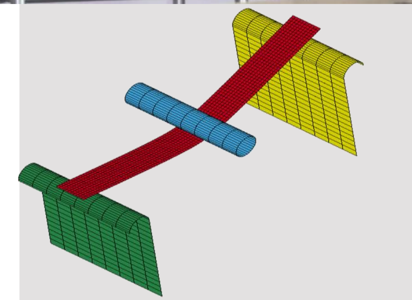
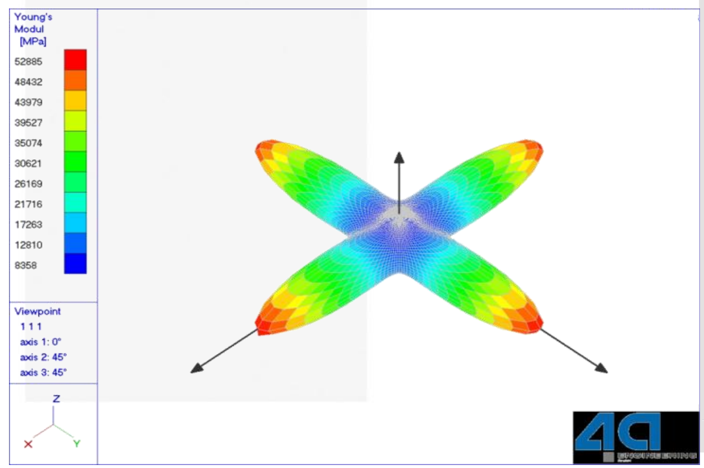
4a engineering GmbH

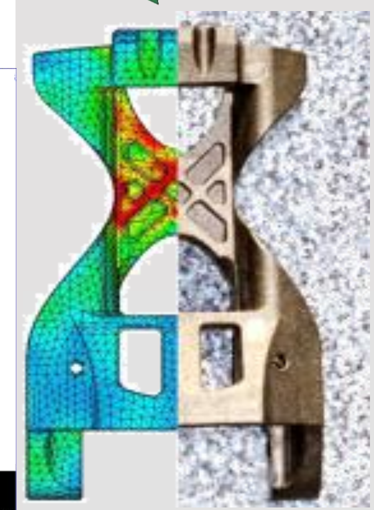




- R&D and engineering services
- Core competence
  - Polymer and materials science
  - Numerical simulation methods
  - Lightweight applications
  - Fiber reinforced plastics and composites
  - Method development for virtual engineering
- 15 to 20 key customers
- More than 500 projects
  - 45% automotive
  - 15% aerospace
  - 15% mechanical engineering
  - 10% medical engineering
  - 15% consumer goods

.. in physics we trust





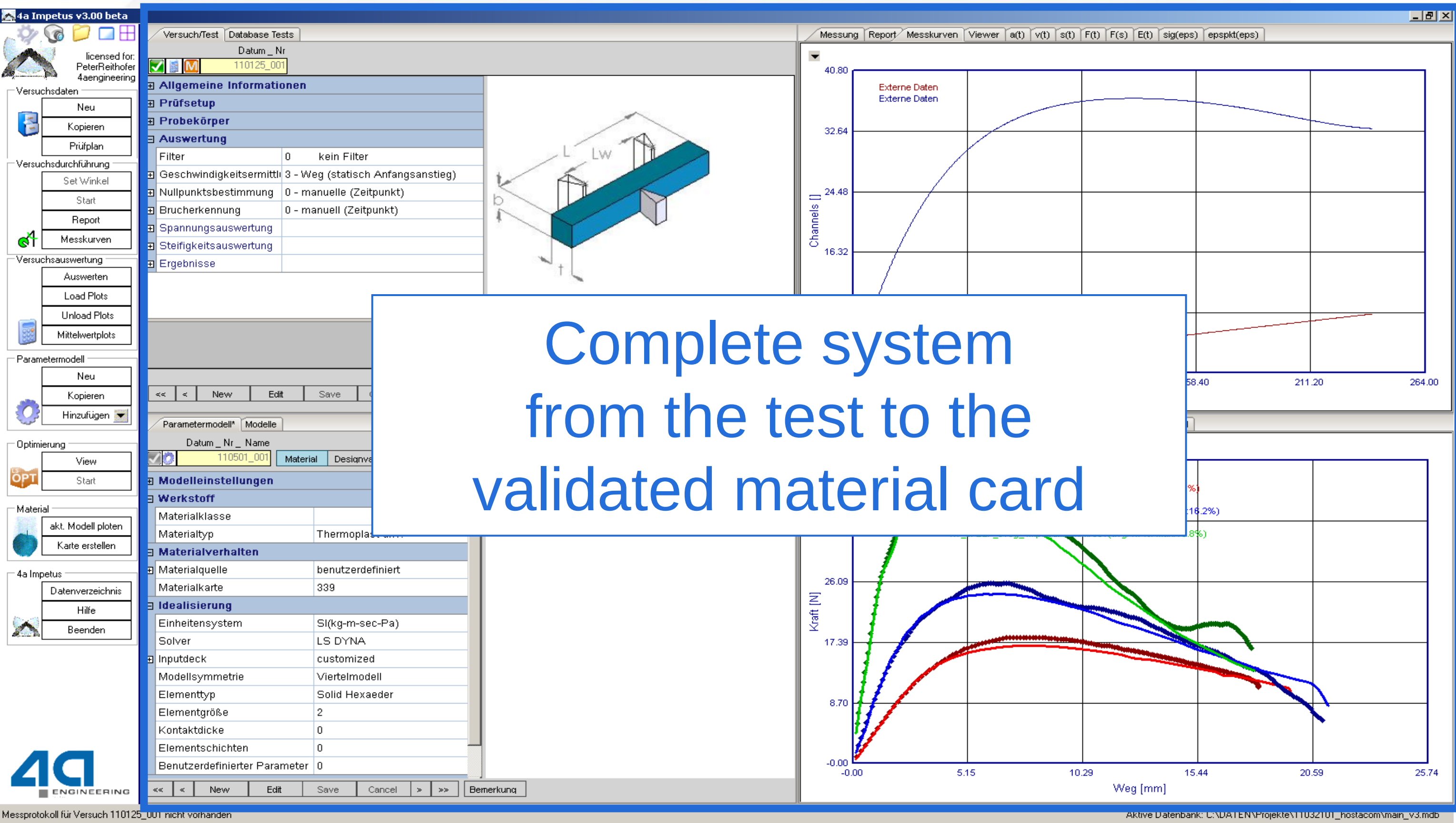
Content

- Demands of the industry
  - Material cards for a multitude of
    - Materials (reinforced and unreinforced thermoplastics, foams, composites, metals, wood, …) and
    - Solvers (Abaqus, LS Dyna, PamCrash, …)
  - Realistic loading, near to reality
  - Quick and cheap generation of the material card
  - Validation

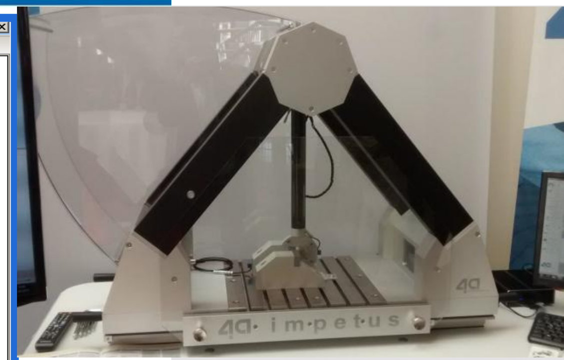
→ Development of 4a impetus

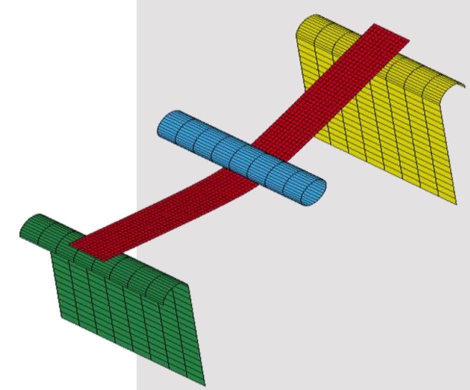
Complete system from the test to the validated material card

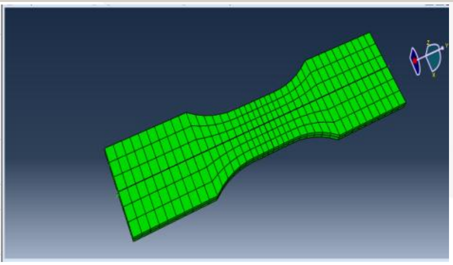
4a impetus

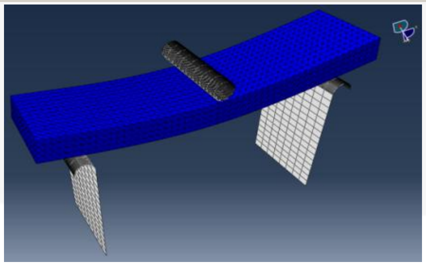


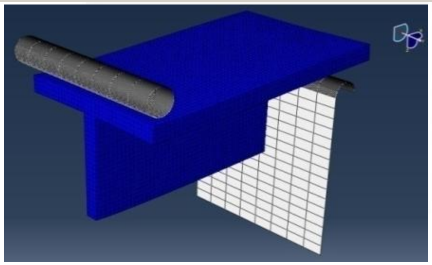
Complete system from the test to the validated material card

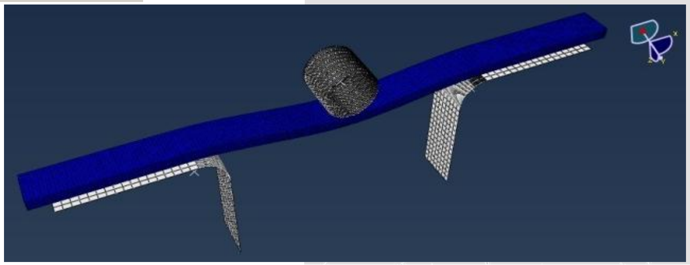












4a impetus
How does it work

Test database

- Geometry
- Loading
- Boundary condition
- Orientation
- Measurement results
  Force/Displacement
  Stress/Strain
  …

Model database

- Optimization/Validation
- Solver
  LS Dyna, Abaqus, …
- Material model
  von Mises
  general yield surface
  strain rate dependence
- Idealization
  Shell/Solid
  Meshsize

Directly linked to model build up

Evaluation
Filtering
Averaging

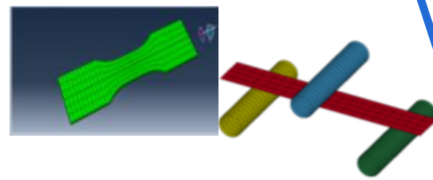
Automatic
LS-OPT input-deck

Directly linked to solver run scripts

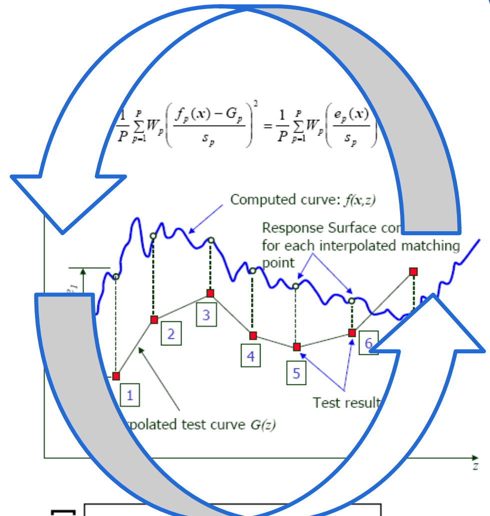
Material optimized parameterized models

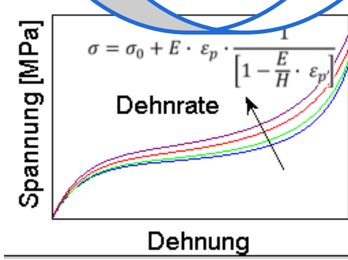
Automatic mesh generation

FE-Model of the test



Reverse Engineering





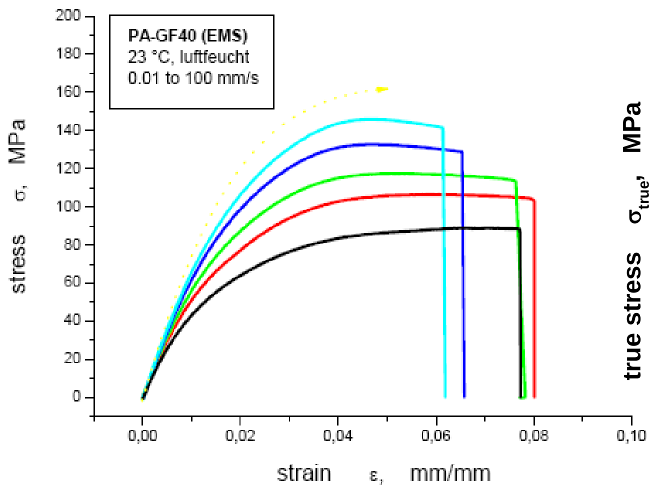
parameterized material card

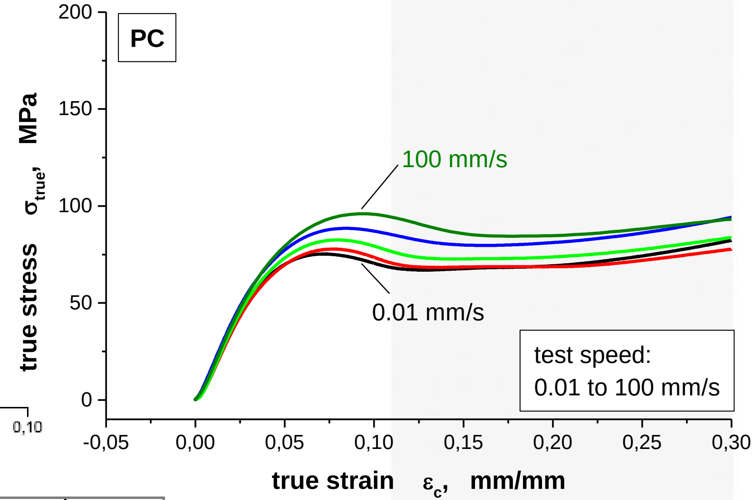
validated material card

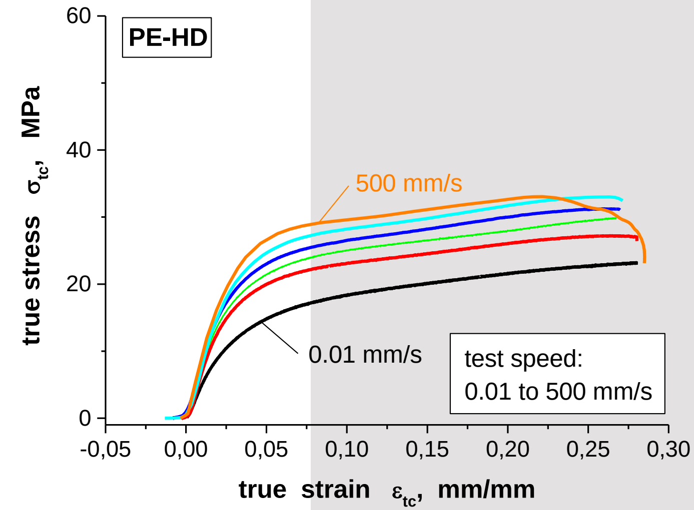
Material behavior of plastics
Dynamic behavior

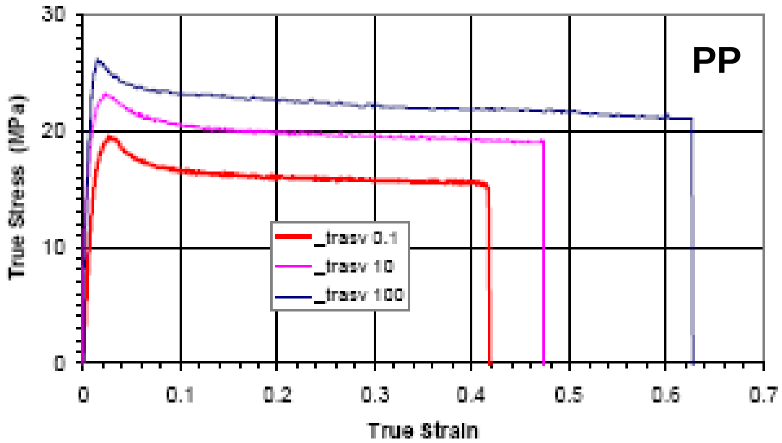
Dependent on the material the dynamic behavior is more or less distinct.

Examples for various materials: [1], [2], [3]









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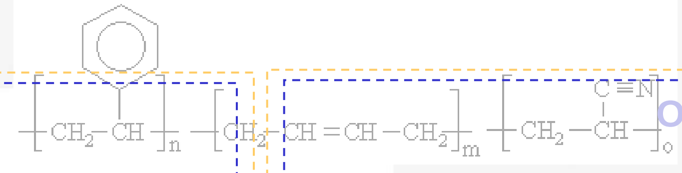
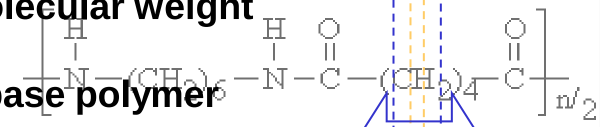




Material

Compounding of polymers

Chemical structure

Distribution of molecular weight

Morphology of base polymer

Filler material (Talcum)

Reinforcements

Additives

Properties
Ratio
Orientation behaviour

Manifacturing conditions

Flow path

Cooling rate

Application

Operational conditions

Operational temperature

Nature, direction and level of load

Triaxiality of load case

Loading rate

Ambient humidity

Geometry

Component geometry and structure

Material behavior of plastics
Influences

- Mechanical behavior could depend on
  - temperature
  - strain rate (loading velocity)
  - moisture content
  - anisotropy (fiber reinforced)
  - loading (tension, compression, shear, bending)

  } **ranking through application**

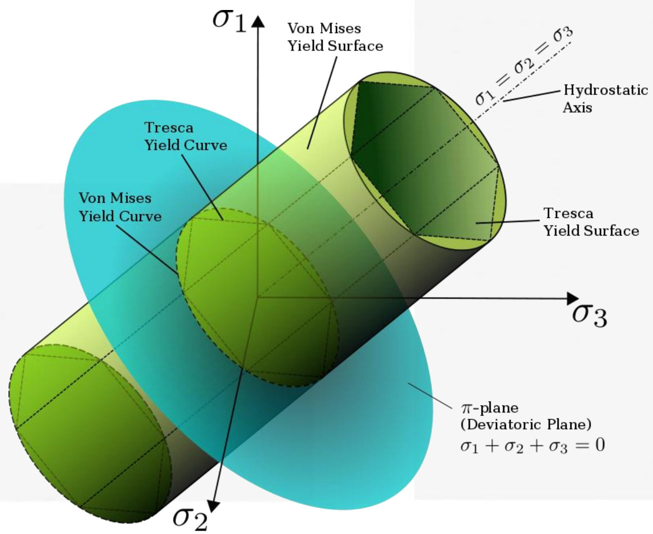
- Engineer's choice between
  - simple robust material model
  - complex expensive (costs + cpu) material model

→ **Application driven**

→ **Simulation task driven**

} **different requirements**

- *PLASTIC: simple material model
  - **von Mises** yield surface (cylinder), **plastic isochoric (constant volume)**
  - standard:
    density, Young‘s Modulus, Poisson‘s ratio and yield curves necessary → quick determination of the material data by bending or tensile tests
  - optional:
    consideration of temperature dependency, strain rate dependency



https://en.wikipedia.org/wiki/Plasticity_%28physics%29#/media/File:Yield_surfaces.svg

- *PLASTIC: typical input

```
*MATERIAL, SRATE FACTOR=0.9, STRAIN RATE REGULARIZATION=LOGARITHMIC, NAME=PlasticMaterial
*DENSITY
1.36E-09,
*ELASTIC
1267.2, 0.3
*PLASTIC, RATE=0, HARDENING= ISOTROPIC
8.0,0
9.4,0.00143
10.7,0.0034
11.6,0.00563
12.3,0.00813
...
*PLASTIC, RATE=0.01
9.2,0
10.9,0.00143
12.3,0.0034
13.4,0.00563
14.1,0.00813
...
```

strain rate filtering

regularisation of the strain rate
option: LINEAR

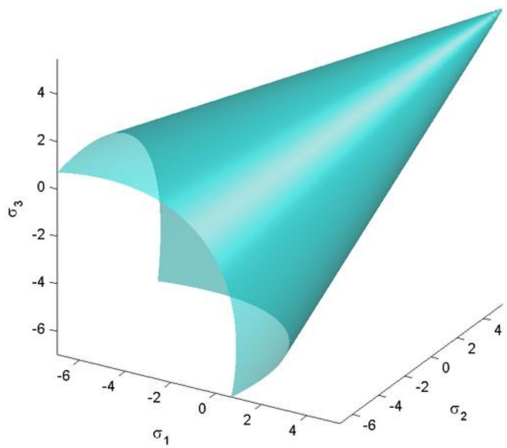
1. strain rate

further hardening options:
KINEMATIC, COMBINED, JOHNSON COOK, USER

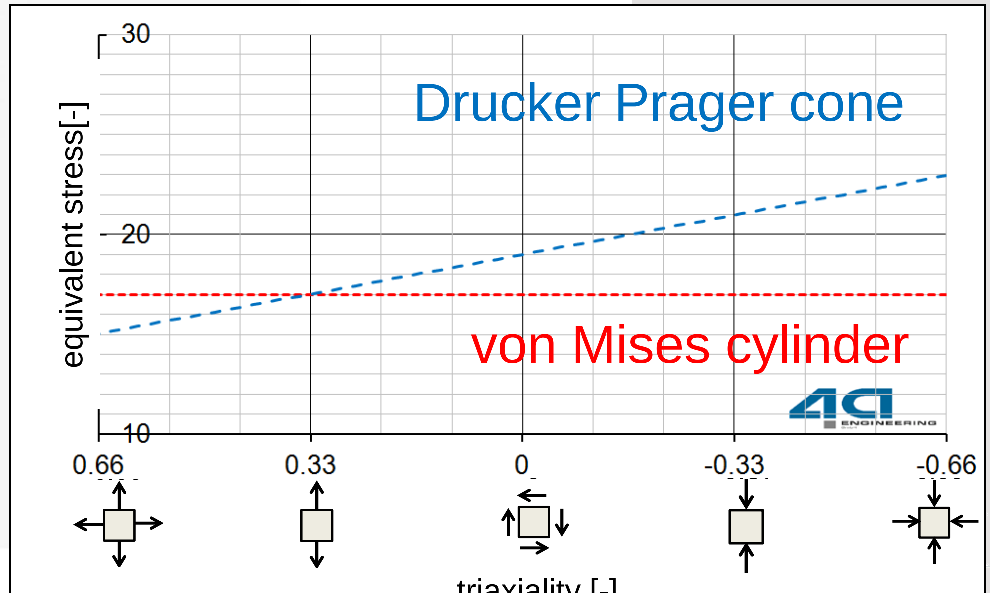
stress, plastic strain
optional: temperature

2. strain rate

- *DRUCKER PRAGER: more complex material model
  - yield surface is a cone, **tension/compression-asymmetry** is considered
  - to determine the material data bending tests and tensile/compression/clamped bending tests are necessary
  - optional: consideration of temperature dependency, strain rate dependency



https://en.wikipedia.org/wiki/Drucker%E2%80%93Prager_yield_criterion



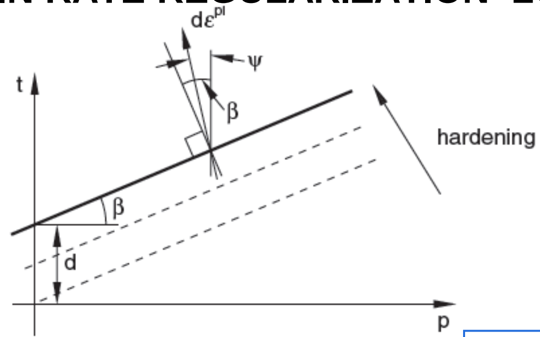
$$triaxiality = -\frac{hydrostatic\ pressure}{equivalent\ stress}$$

Material behavior of plastics

simple yield surface

- *DRUCKER PRAGER: typical input

***MATERIAL, SRATE FACTOR=0.9, STRAIN RATE REGULARIZATION=LOGARITHMIC, NAME=PlasticMaterial**




```
**
**
*DENSITY
1.36E-09,
*ELASTIC
1267.2, 0.3
*DRUCKER PRAGER, SHEAR CRITERION=LINEAR
beta,  K (0.778<=K<=1), psi (dilatation angle), optional: temperature
*RATE DEPENDENT, TYPE=JOHNSON COOK
0.3, 0.001
*DRUCKER PRAGER HARDENING, TYPE=COMPRESSION
22.815,  0
23.531,  0.001
24.234,  0.002
…
```

← flow criterion (*DRUCKER PRAGER, SHEAR CRITERION=LINEAR)

← strain rate dependency
optional: POWER LAW (Cowper Symonds) (*RATE DEPENDENT, TYPE=JOHNSON COOK)

← hardening
optional: TENSION or SHEAR (*DRUCKER PRAGER HARDENING, TYPE=COMPRESSION)

K is the ratio of the yield stress in triaxial tension to compression
psi>0: plastic volume increase

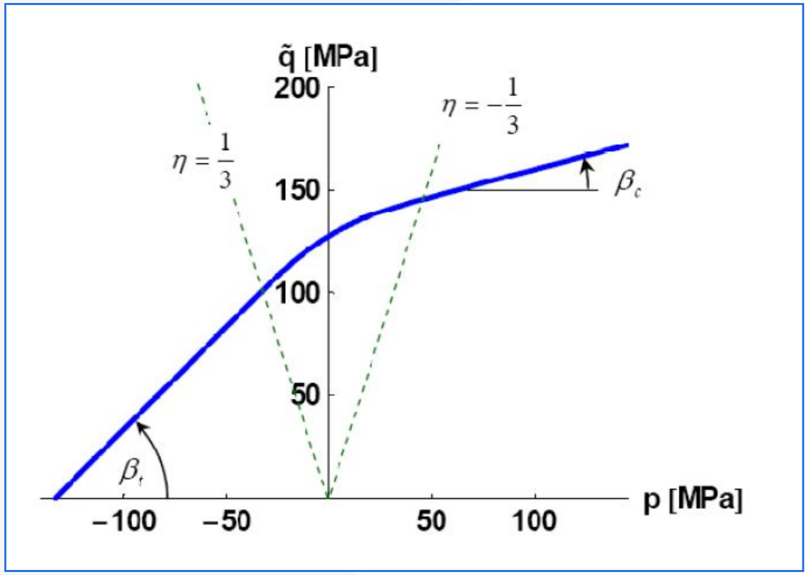
Material behavior of plastics
general yield surface: ABQ_MOLDED_PLASTIC

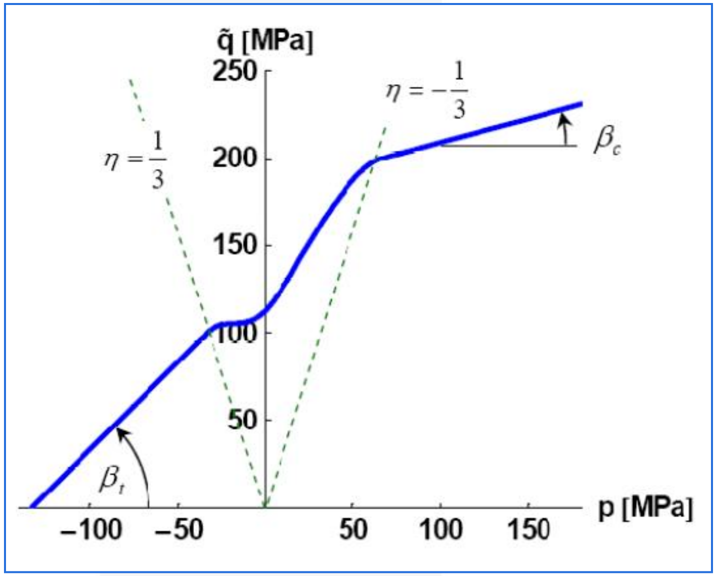
- Especially for plastics: ABQ_MOLDED_PLASTIC, a non-standard material model (implemented as VUMAT) [4]
- The yield curves can be specified for tension, compression and shear, also a strain rate dependency (Johnson-Cook or Cowper-Symonds) for those curves
- The yield surface consists of „2 cones“ (for tension and compression) and a transition surface in the shear region (convex or non-convex)
- Damage Initiation and Evolution for ductile and shear criterion implemented.
  Damage/failure can be defined in dependence on the load (triaxiality and strain rate).

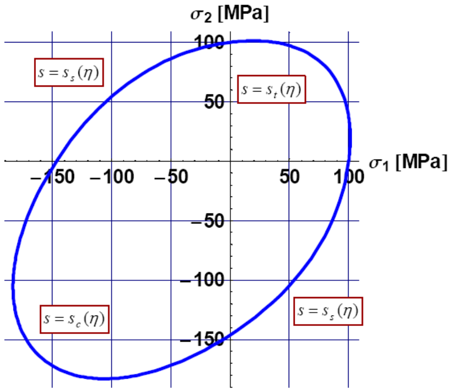
Material behavior of plastics

general yield surface: ABQ_MOLDED_PLASTIC

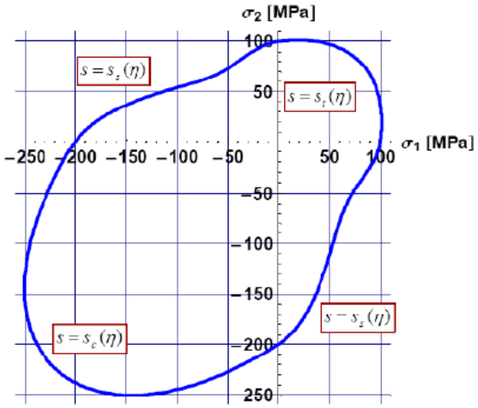
- The convexity is determined using 3 criteria, usually plastics show a non-convex transition surface.







transition surface:
convex (left, e.g. PA) and non-convex (right, e.g. PE)



Material behavior of plastics

general yield surface: ABQ_MOLDED_PLASTIC

- The plastic deformation of plastics is not isochoric (constant volume). Using the so called dilatation angle (beta) the plastic Poisson‘s ratio can be determined. If beta=0 → isochoric flow behavior.

$$
\begin{aligned}
d\lambda\beta &= (1-2\nu_{pl})d\lambda\left(1+\frac{\beta}{3}\right)\\
\beta &= (1-2\nu_{pl})\left(1+\frac{\beta}{3}\right)\\
\beta &= 1-2\nu_{pl}+\frac{\beta}{3}-\frac{2}{3}\nu_{pl}\beta\\
2\beta+2\nu_{pl}\beta &= 3-6\nu_{pl}\\
\Rightarrow \beta &= \frac{3}{2}\frac{1-2\nu_{pl}}{1+\nu_{pl}} \quad \Leftrightarrow \quad \nu_{pl}=\frac{3-2\beta}{6+2\beta}
\end{aligned}
$$

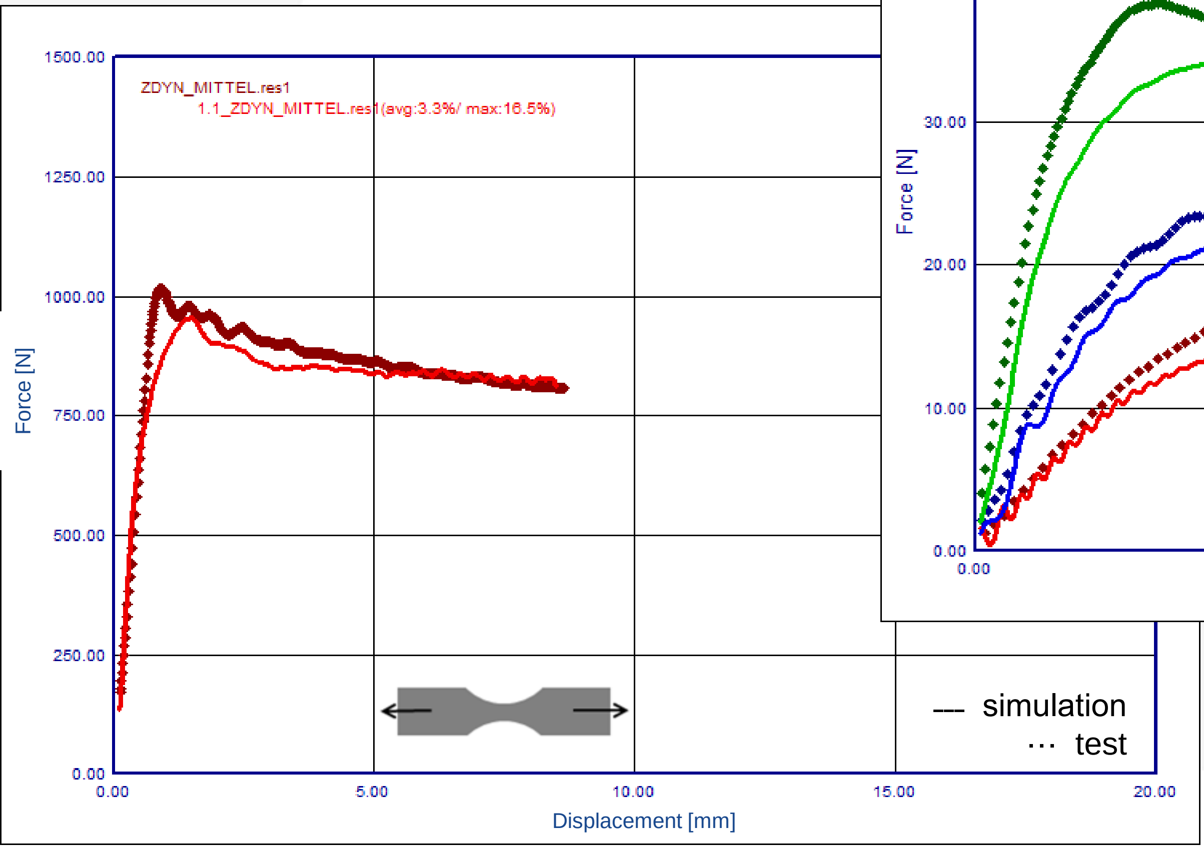
ν_{pl}	β
0	85.9
0.05	73.7
0.1	62.5
0.15	52.3
0.2	43.0
0.25	34.4
0.3	26.4
0.35	19.1
0.4	12.3
0.45	5.9
0.5	0.0

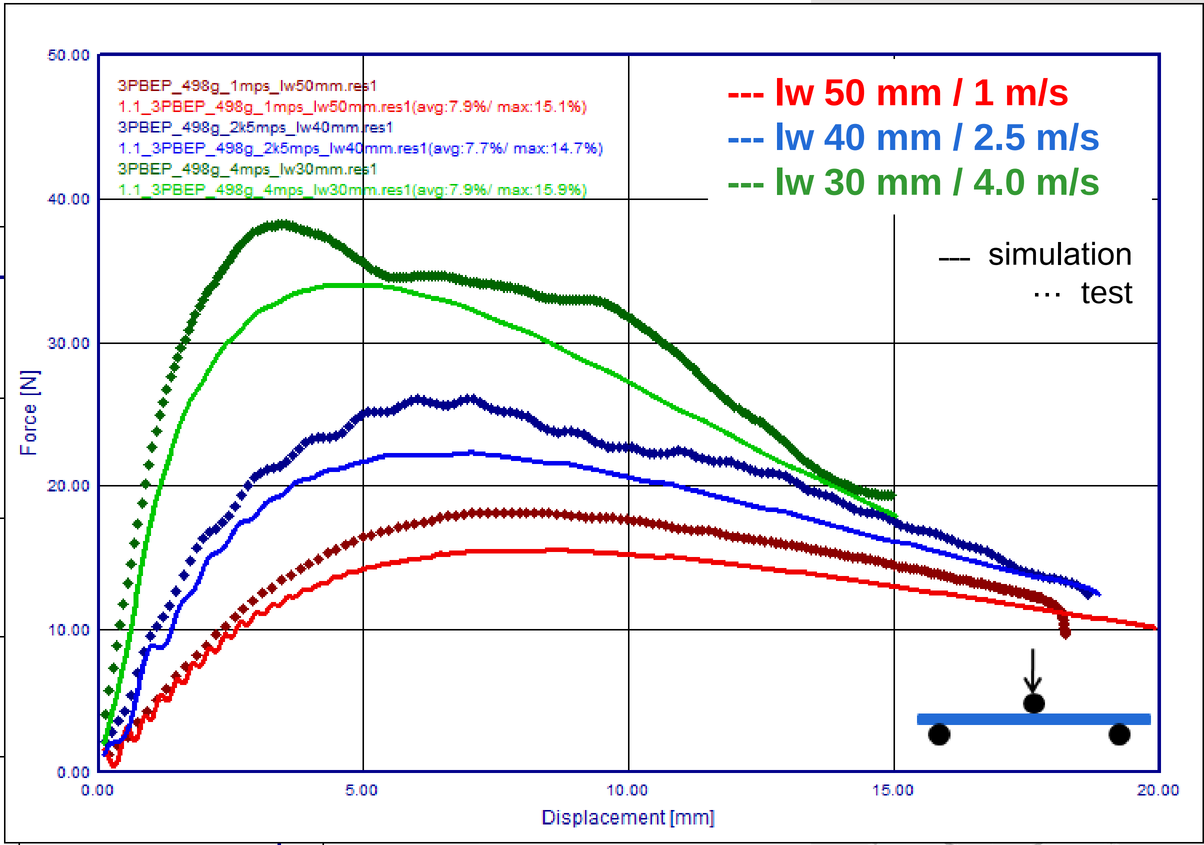
Source: [5]

Material behavior of plastics

von Mises material behavior

- Abaqus: *PLASTIC (von Mises), no tension/compression-asymmetry
  - → Good match for tensile test
  - → No match for bending





Material behavior of plastics
von Mises material behavior

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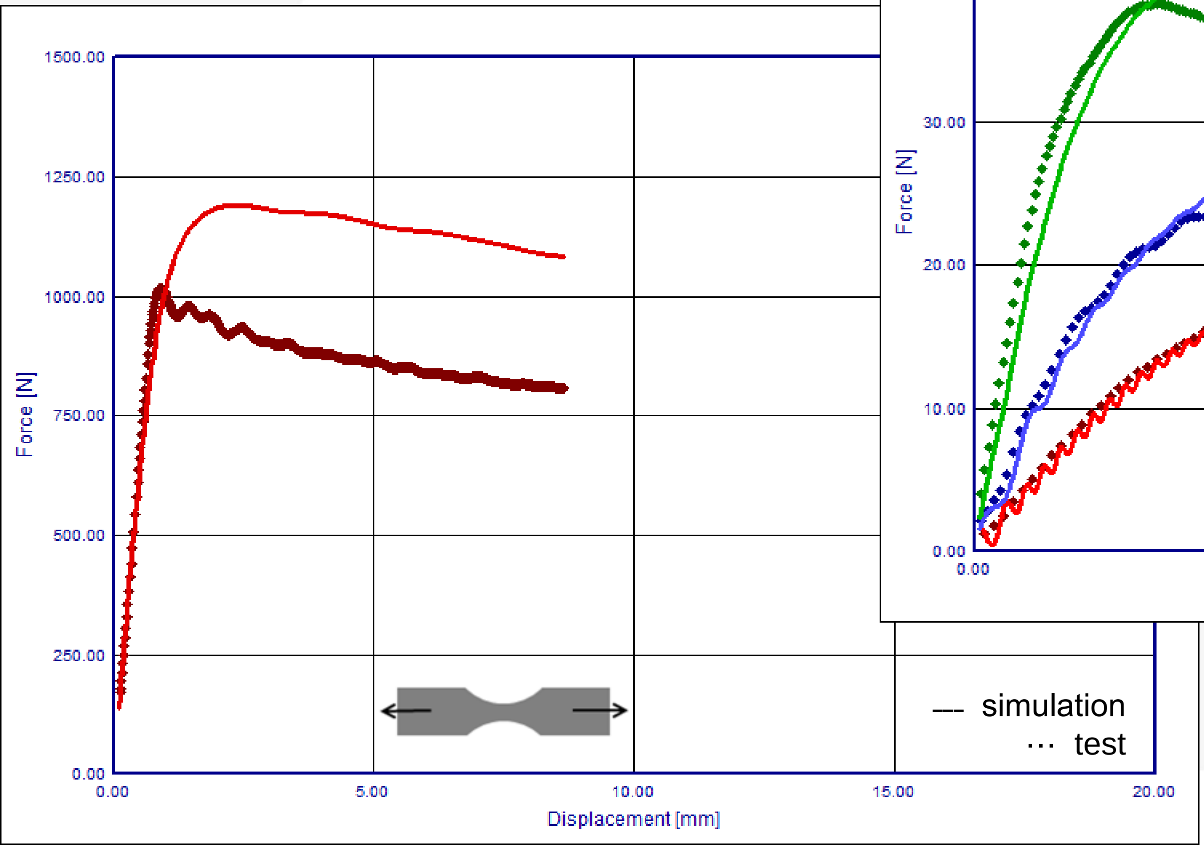
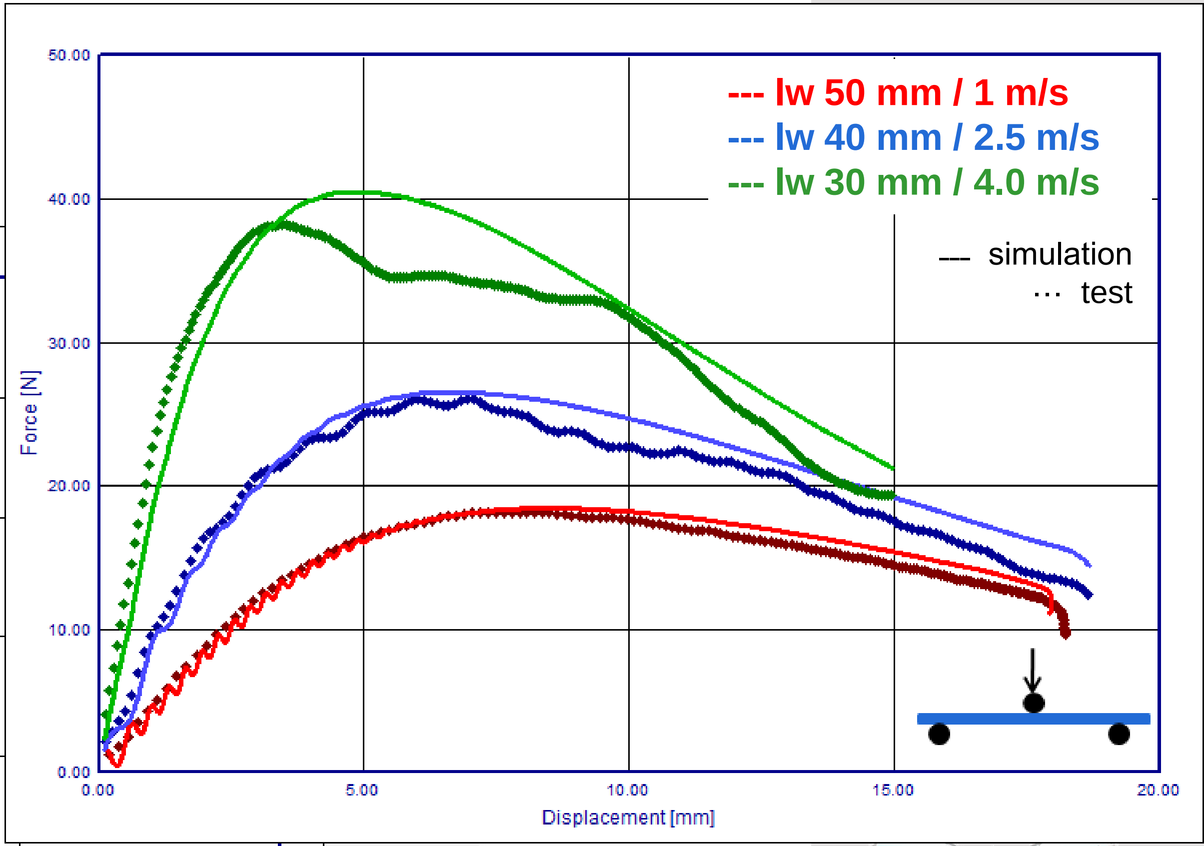


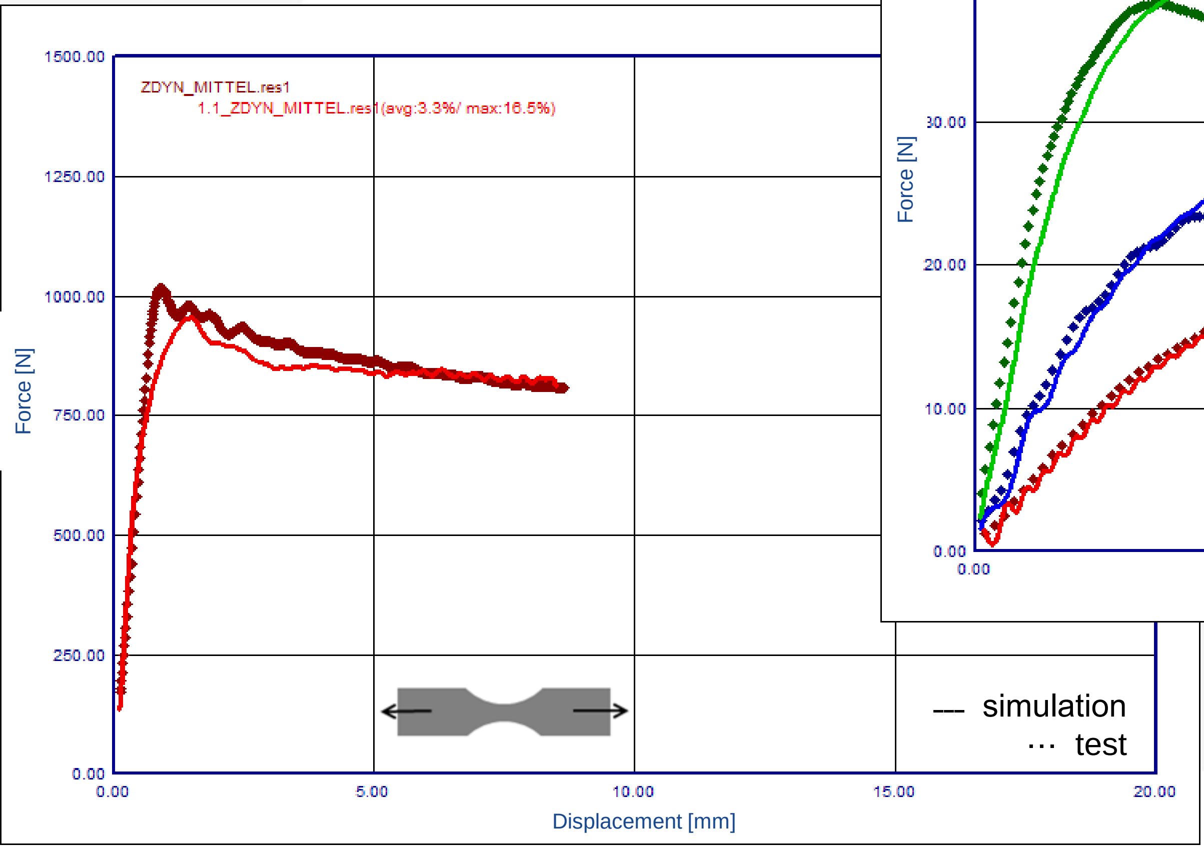


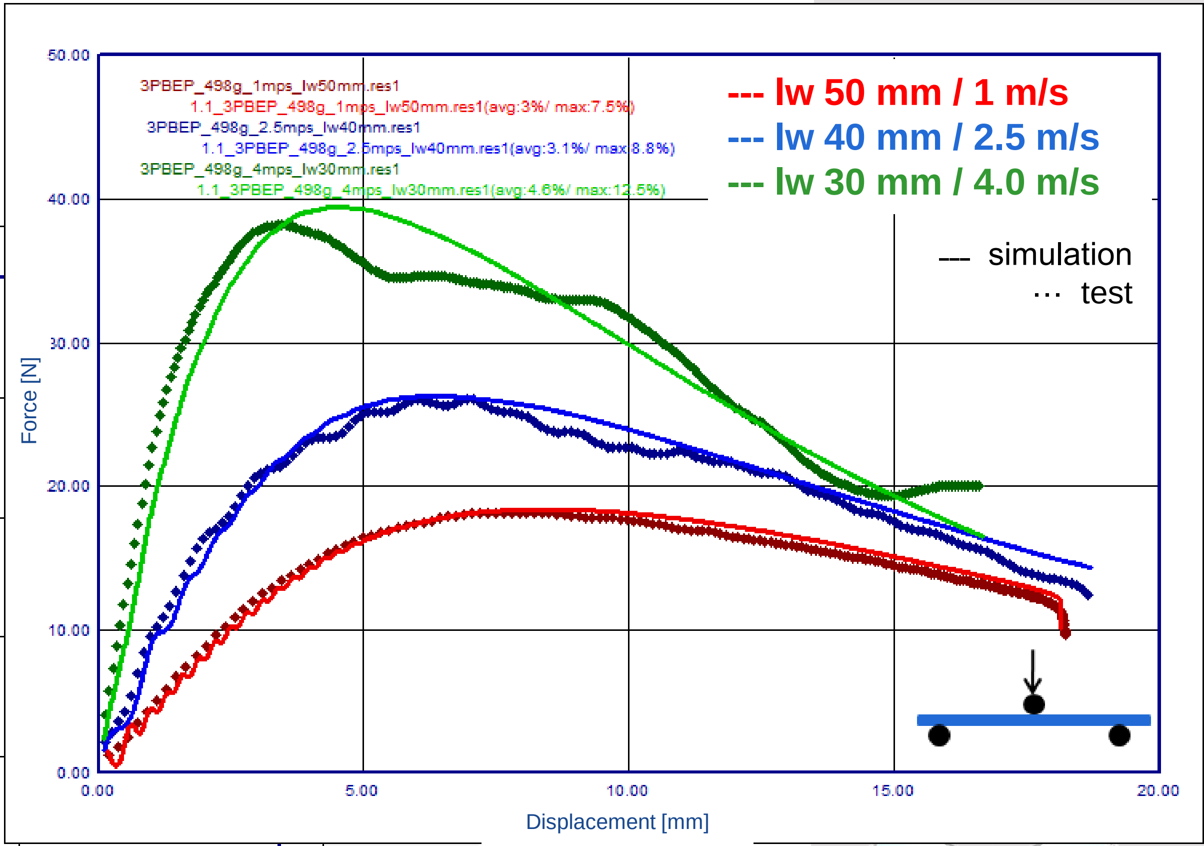
Material behavior of plastics
general yield surface

➢Abaqus: *ABQ_MOLDED_PLASTIC (general yield surface), consideration of tension/compression-asymmetry

→ Good match for bending

→ Good match for tensile test





Material behavior of plastics

Interfaces in 4a impetus V3.3

- Actually implemented for Abaqus
  - *PLASTIC — von Mises
  - *DRUCKER PRAGER — Drucker Prager
  - *MATERIAL, name=ABQ_MOLDED_PLASTIC ** — gen. yield surface

  ** Currently available just as user defined material card

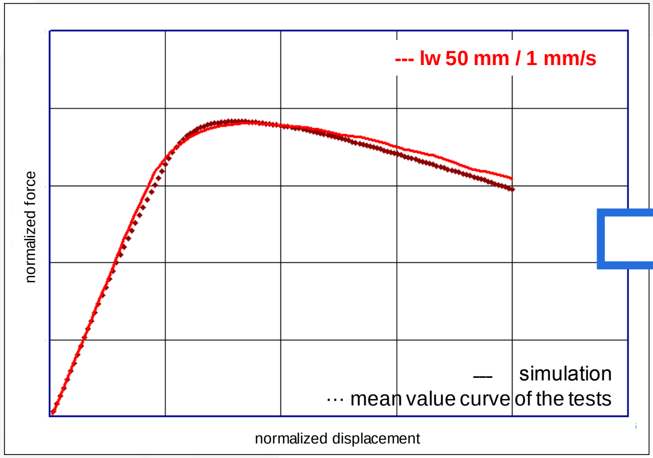
Material behaviour	
Material source	Implemented
Density	-1310.77238769531
Poisson's ratio	0.3
Failure strain	0
Elasticity	Linear elastic
Plasticity	vonMises
Curve 1	4a Model A
Strain rate dependency	Table
Strain range upto	0.2
Sampling points	50
Bias factor	10
Material card	6011_ELASTICPLASTIC

Material behaviour	
Material source	Implemented
Density	-1310.77238769531
Poisson's ratio	0.3
Failure strain	0
Elasticity	Linear elastic
Plasticity	Drucker-Prager
Curve 1	4a Model A
Curve 2	Kurve 1 skaliert
Strain rate dependency	Table
Strain range upto	0.2
Sampling points	50
Bias factor	10
Material card	6021_Drucker Prager

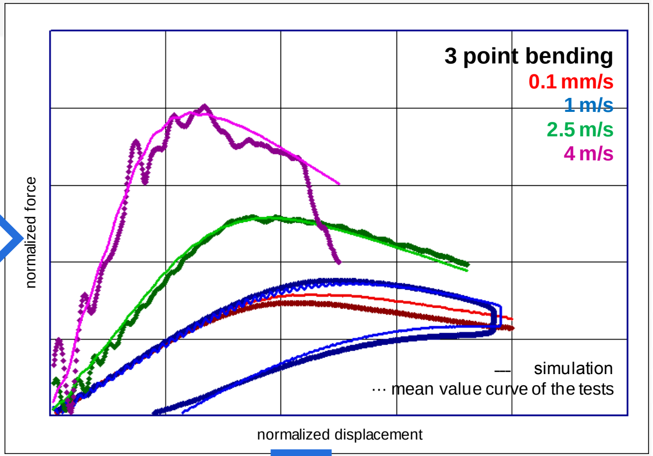
Material behaviour	
Material source	Implemented
Density	-1310.77238769531
Poisson's ratio	0.3
Failure strain	0
Elasticity	Linear elastic
Plasticity	general yield surface (3 curves)
Curve 1	4a Model A
Curve 2	Kurve 1 skaliert
Curve 3	Kurve 1 skaliert
Strain rate dependency	Table
Strain range upto	0.2
Sampling points	50
Bias factor	10
Material card	

- All ABAQUS material cards are available by user defined material cards

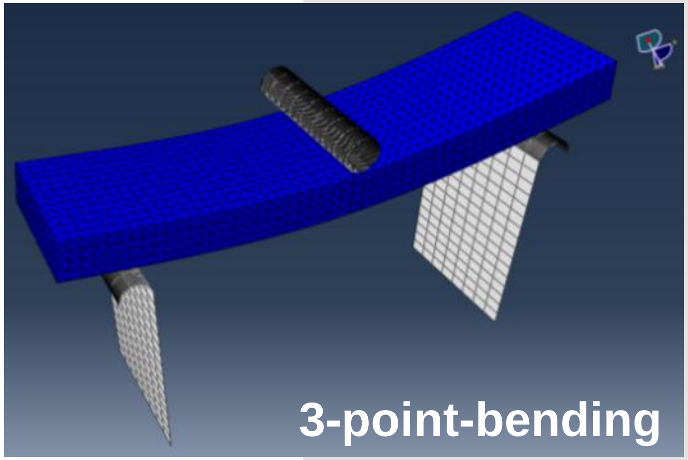
Reverse Engineering 4a impetus (*ABQ_MOLDED_PLASTIC)

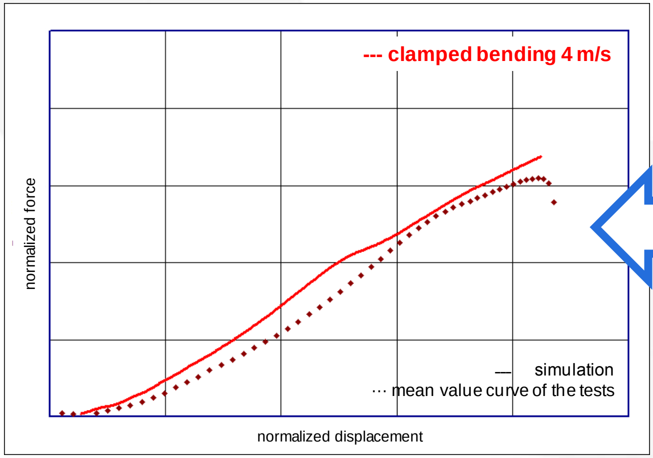


static behavior - yield

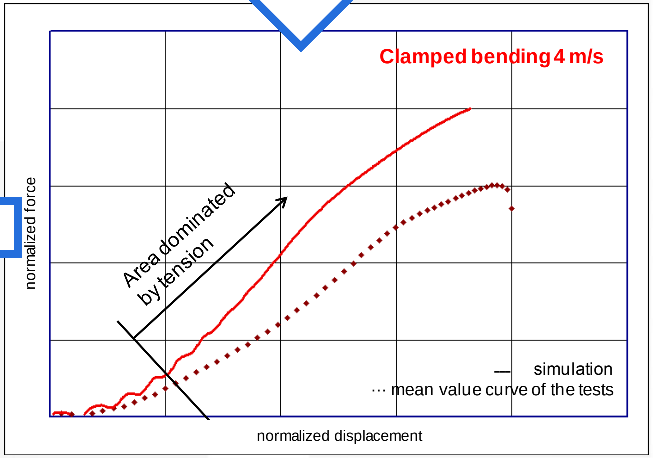


dynamic behavior – strain rate

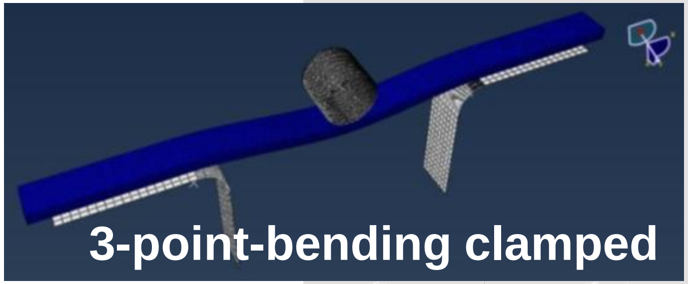




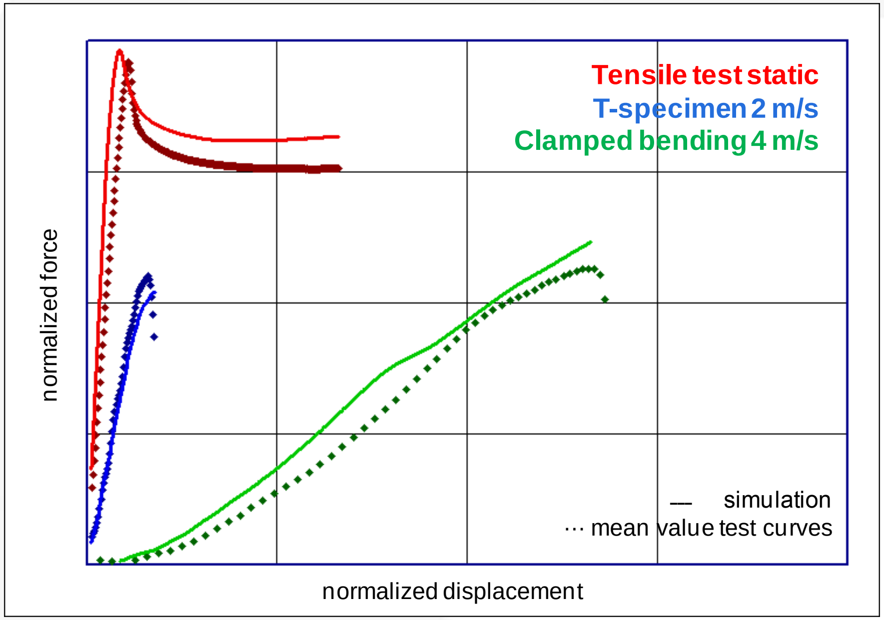
fit compression/tension behavior

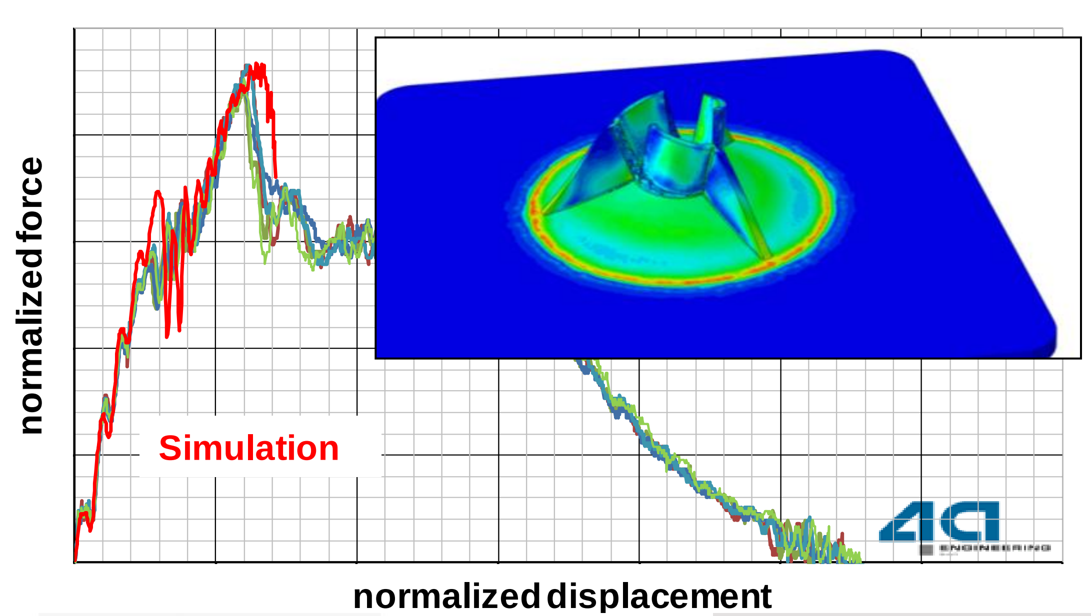


check compression/tension behavior



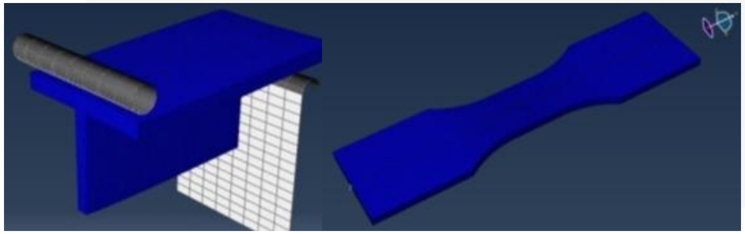
Validation 4a impetus (*ABQ_MOLDED_PLASTIC)





Static tension test
dynamic T-specimen

Dynamic puncture test with the part
The test curves are matched very well

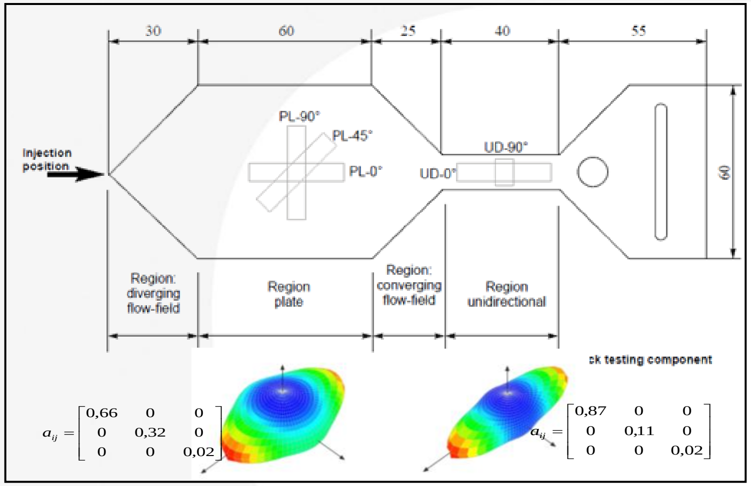


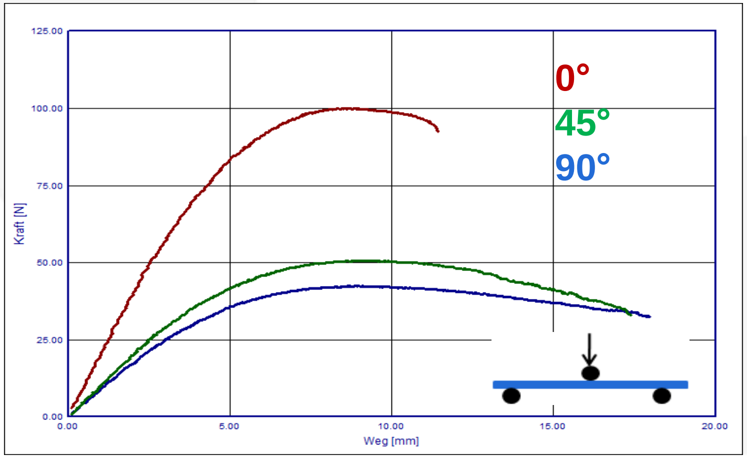
Material models for composites

IN PHYSICS WE TRUST

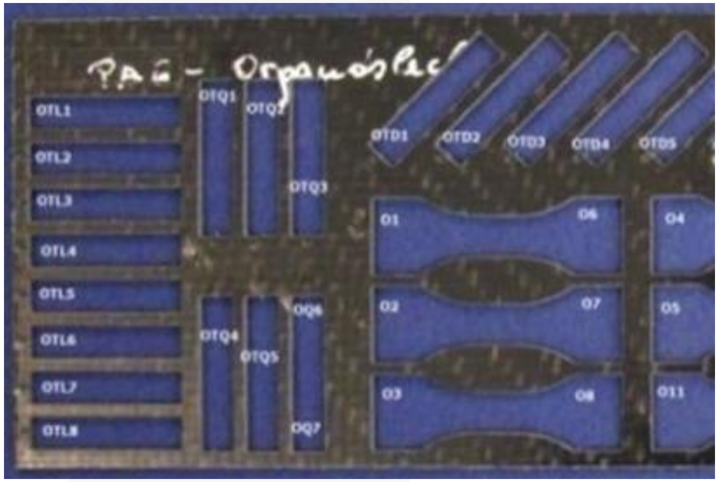
Composites
Influence of the orientation

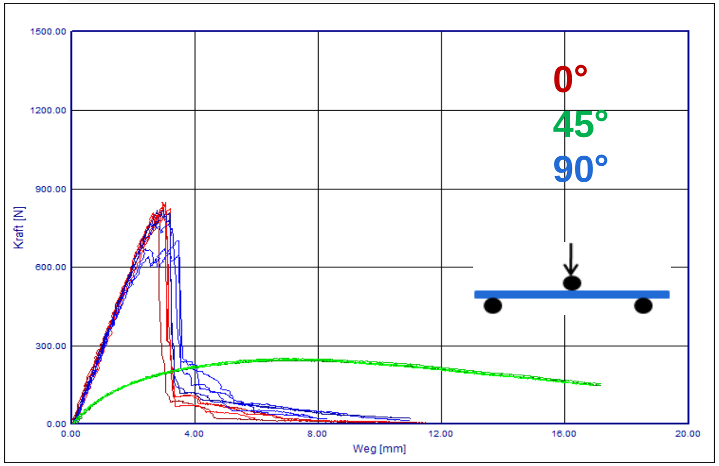
Short fiber reinforced thermoplastics [6]





Composites – “Organic sheet” [7]



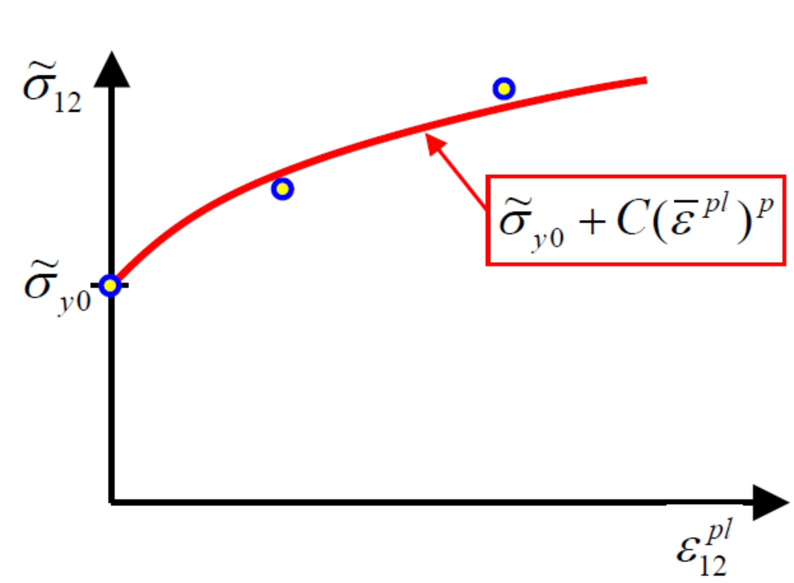


Composites

Material models for composites

- Abaqus provides a VUMAT *ABQ_PLY_FABRIC analogous to the thermoplastics [8]
- The most important material parameters are
  - Young's Moduli in 0° and 90° direction for tension and compression
  - Shear modulus (45° direction)
  - Poisson's ratios ν_{12} for tension and compression
  - Strengths in 0° and 90° direction for tension and compression
  - Shear strength
- To determine these values bending tests resp. tensile tests in 0°, 45° and 90° orientation are necessary.
- With the aid of micromechanics (e.g. 4a micromec) the elastic properties can be directly calculated/estimated.

- In the material model *ABQ_PLY_FABRIC appropriate damage parameters can/have to be specified (e.g. failure energy). → **Calibration of the idealisation**
- Important for fabrics: adaption of the material data should be done on 45° orientation → **representative test specimen width!**



Composites

Material models for composites

- * ABQ_PLY_FABRIC: typical input

```
*MATERIAL, NAME= ABQ_PLY_FABRIC
*DENSITY
```
ρ

```
*USER MATERIAL, CONSTANTS=40
** Line 1:
```
E_{1+}, E_{2+}, ν_{12+}, G_{12}, E_{1-}, E_{2-}, ν_{12-} ← Young‘s Modulus in 0° (tension), Young‘s Modulus in 90° (tension), Poisson‘s ratio ν_{12} (tension), Shear Modulus, Young‘s Modulus in 0° (compression), Young‘s Modulus in 90° (compression), Poisson‘s ratio ν_{12} (compression),

```
** Line 2:
```
X_{1+}, X_{1-}, X_{2+}, X_{2-}, S ← strength in 0° (tension), strength in 0° (compression), strength in 90° (tension), strength in 90° (compression), shear strength

```
** Line 3:
```
G_f^{1+}, G_f^{1-}, G_f^{2+}, G_f^{2-}, α_{12}, d_{12}^{max} ← damage parameter

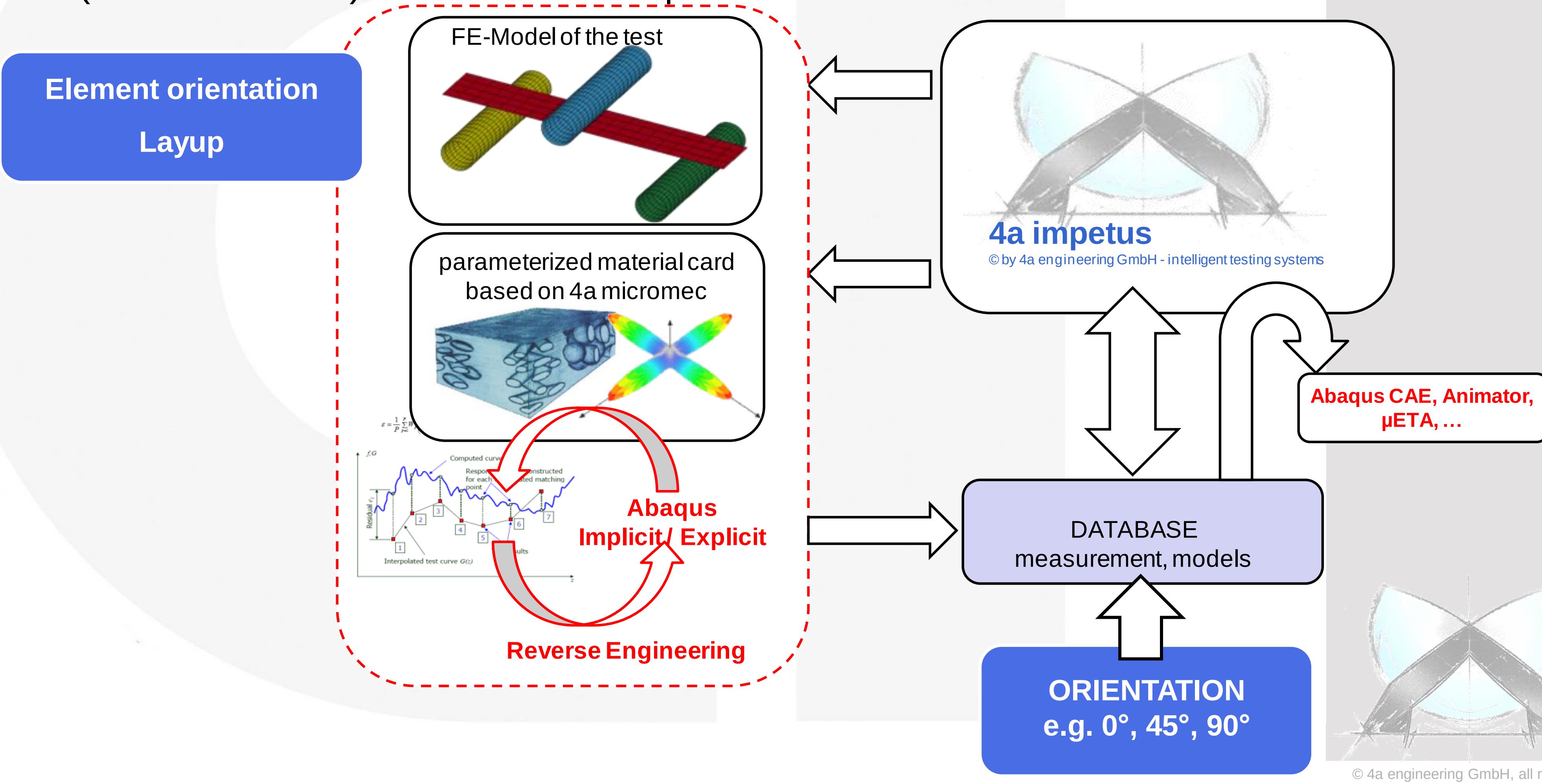
```
** Line 4:
```
$\tilde{\sigma}_{y0}$, C, p ← shear hardening data

```
** Line 5:
```
lDelFlag, d_{max}, $\bar{\varepsilon}_{max}^{pl}$, $\hat{\varepsilon}_{max}$, $\hat{\varepsilon}_{min}$ ← data for element erosion

```
*DEPVAR, DELETE=16
16
```

Composites
Coupling to micromechanics

- The influence of the manufacturing process on the material behavior (fiber orientation) is included in the process chain.



Input

Output

Material Data of Components (E,α,λ)

Matrix
Reinforcements
Fillers

Data-Base

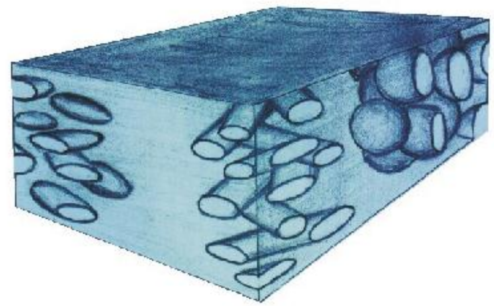
Fibre and Particle Orientation

Data-Base

Fibre and Particle Shape

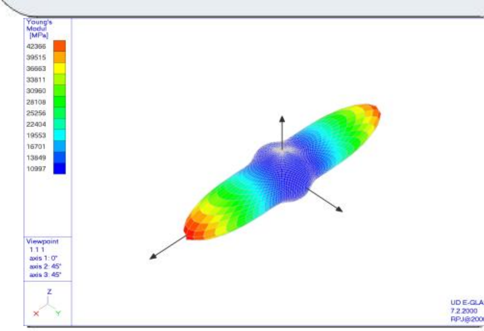
Data-Base

4a micromec

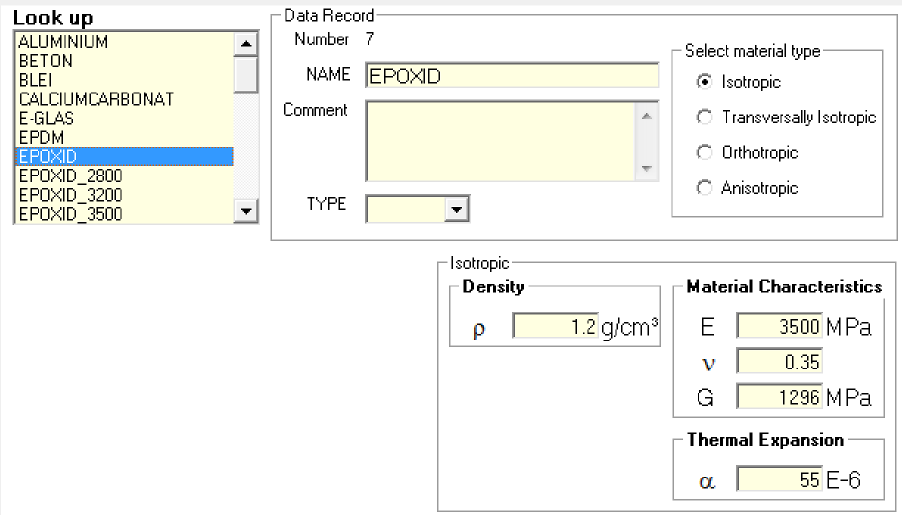


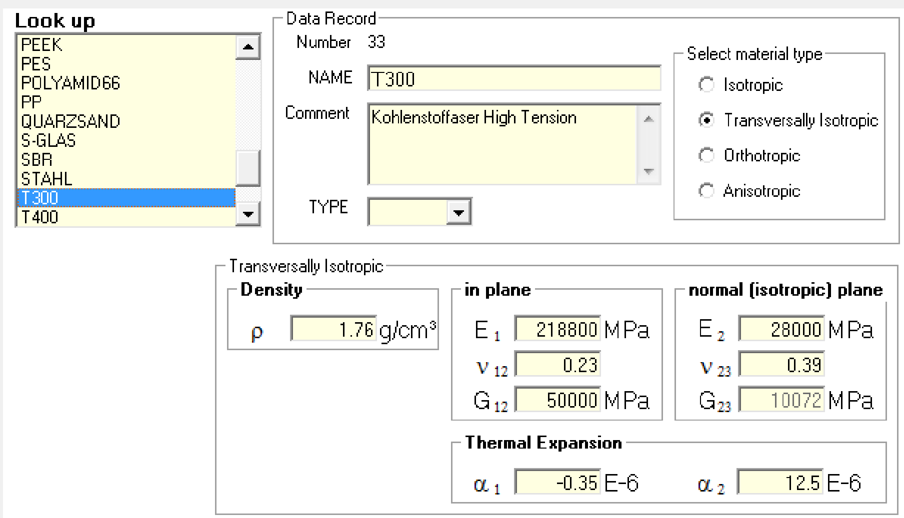
Virtual Material Design

3D Composite Data

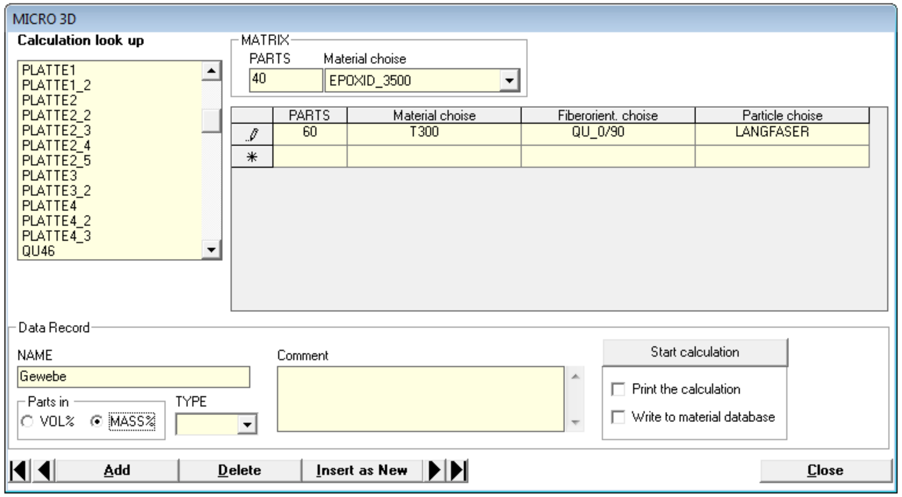


- Standard material parameters from 4a micromec

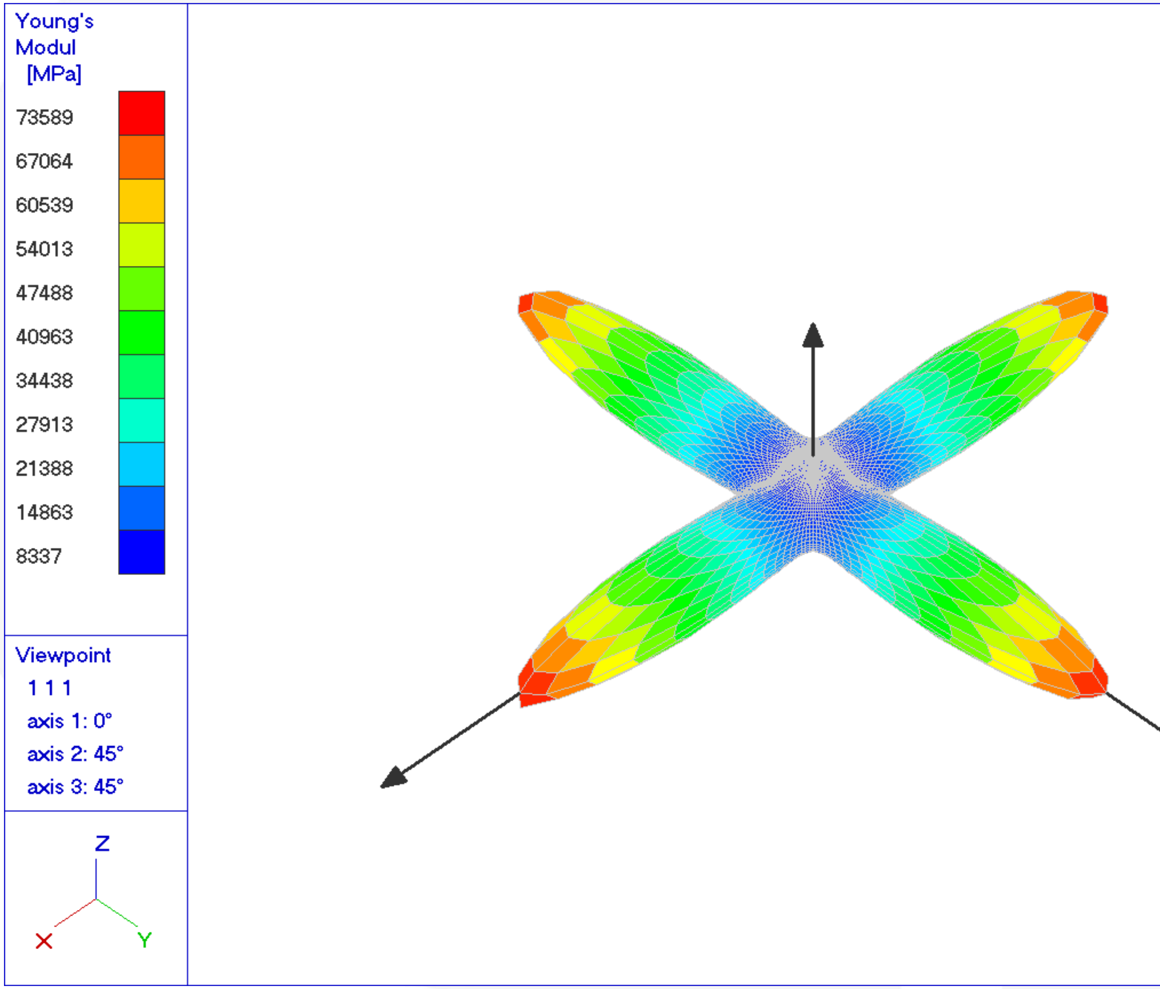


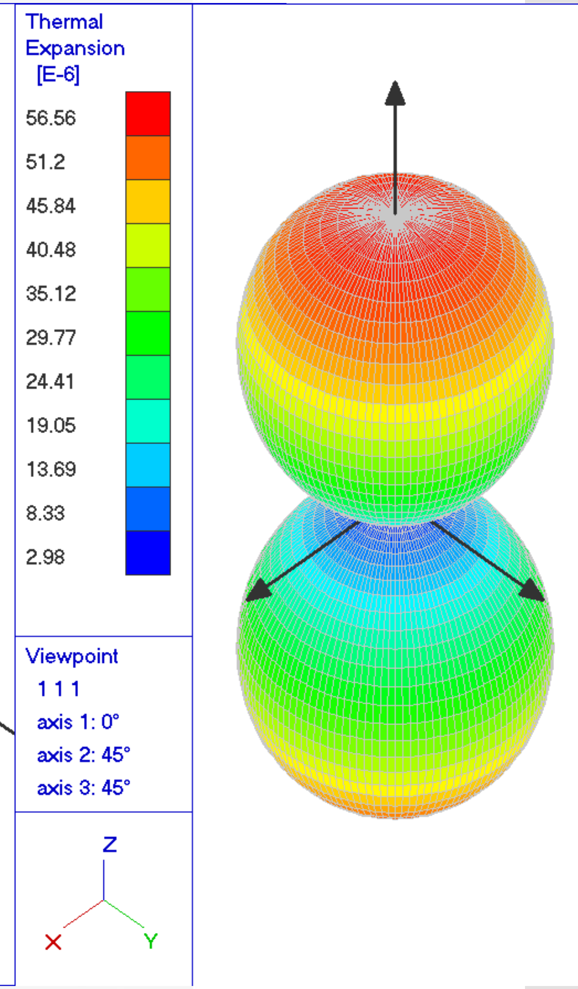


- Setup for the calculation

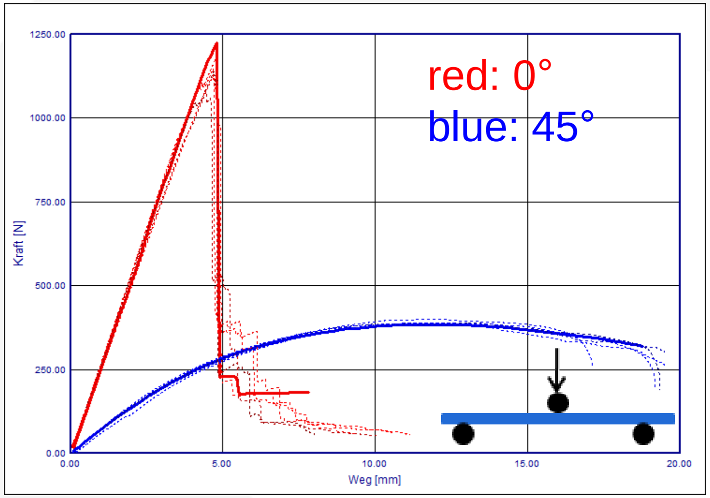


Result

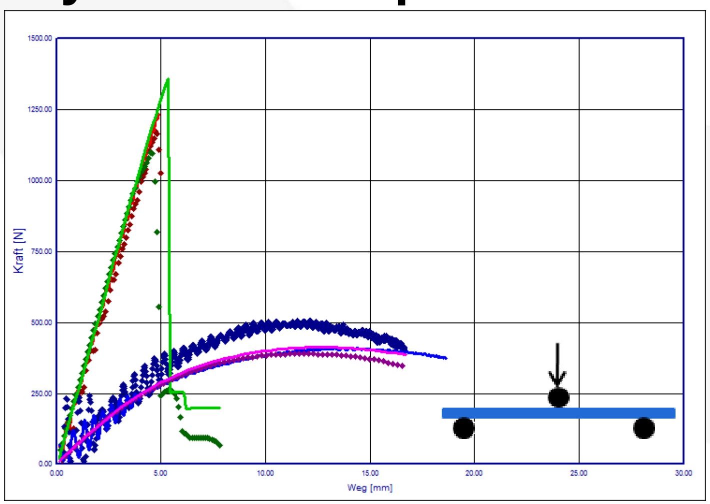

Young's
Modul
[MPa]
73589
67064
60539
54013
47488
40963
34438
27913
21388
14863
8337
Viewpoint
1 1 1
axis 1: 0°
axis 2: 45°
axis 3: 45°
Z
X
Y


Thermal
Expansion
[E-6]
56.56
51.2
45.84
40.48
35.12
29.77
24.41
19.05
13.69
8.33
2.98
Viewpoint
1 1 1
axis 1: 0°
axis 2: 45°
axis 3: 45°
Z
X
Y

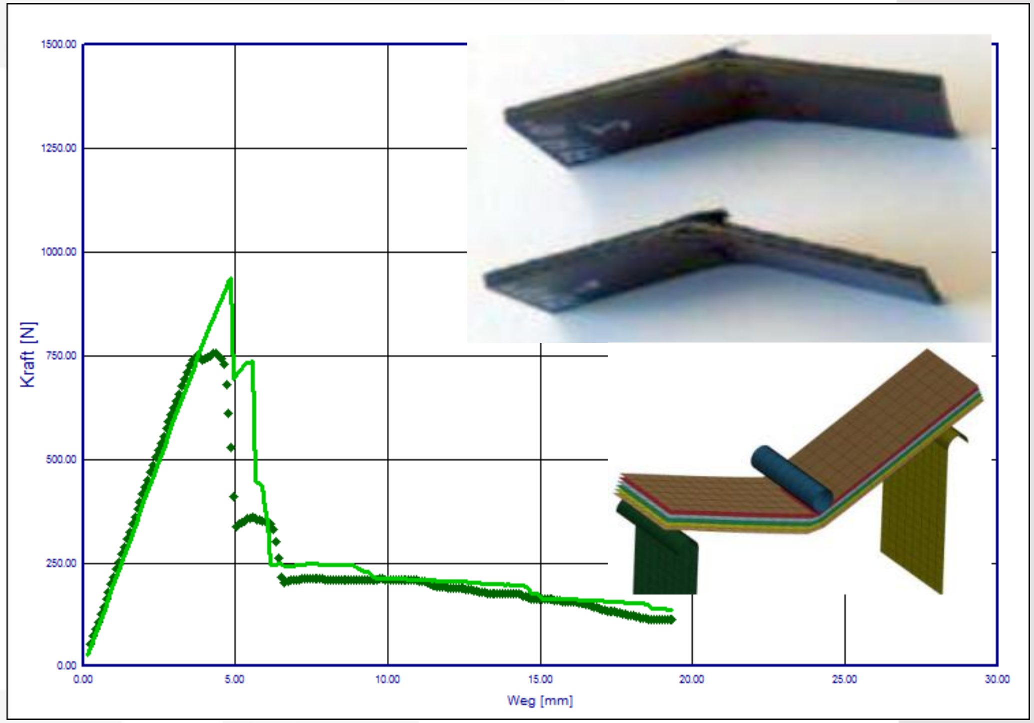
Orientation



Dynamic 4a impetus



Multilayer Setup

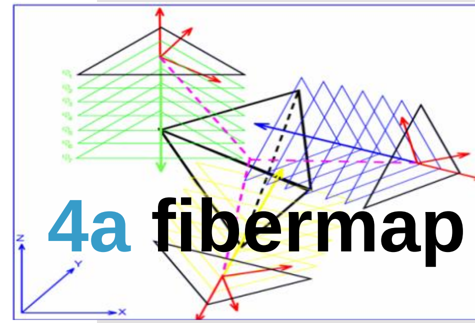


…. test
— simulation

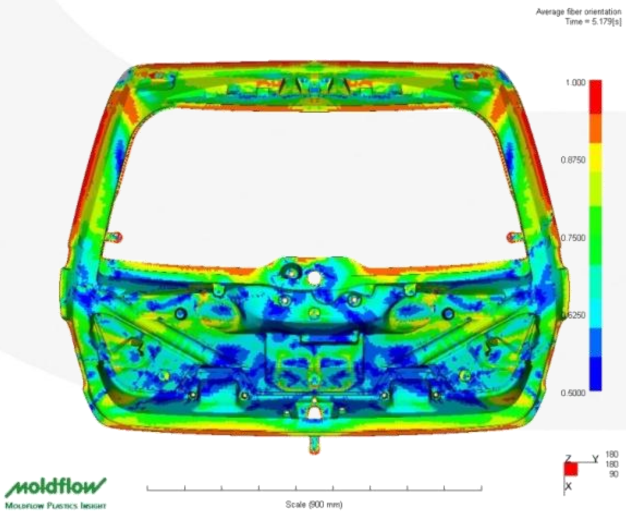
Results with kindly permission of
MAGNA STEYR Fahrzeugtechnik AG & Co KG [7]

Reinforced materials
*DISTRIBUTION

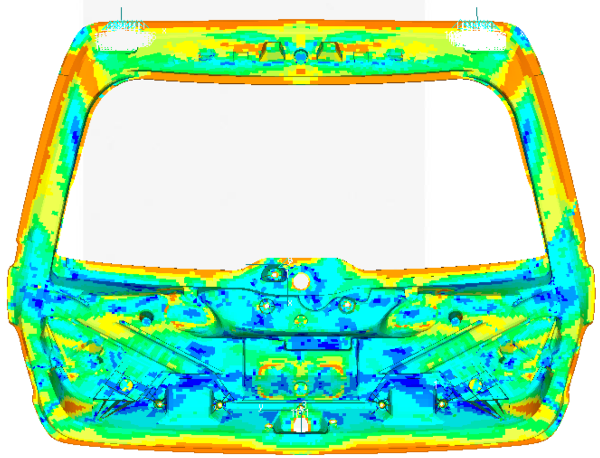
- *DISTRIBUTION: specifying the fiber orientation of the elements
- anisotropic material model (e.g. *ELASTIC, TYPE=ENGINEERING CONSTANTS) → accurately description of the resulting fiber orientation in a part resp. model
- rheological simulation for determination of fiber orientation
- transfer from the rheological simulation to the structural simulation (e.g. using 4a fibermap).



Injection molding simulation



FEM simulation



Reinforced materials
*DISTRIBUTION

- Typical input:

```
*MATERIAL, name=PPLGF30
*Density
1.1E-06,
*ELASTIC, TYPE=ENGINEERING CONSTANTS
**     E1,    E2,     E3,      V12,      V13,      V23,   G12,    13
     5.8,   2.7,    1.9,    0.423,    0.310,    0.432,   1.3,    .6
** G23
    .6
*ORIENTATION, NAME=MatOrient
Distr1
3, 0
*DISTRIBUTION TABLE, Name=Table1
COORD3D, COORD3D
*DISTRIBUTION,Name=Distr1, LOCATION=element, TABLE=Table1
 , 1,0,0,0,1,0
EL_ID, X-coord. of a, Y-coord. of a, Z-coord. of a, X-coord. of b,Y-coord. of b, Z-coord. of b
```

Material model

Definition of a local coordinate system for each element

Summary

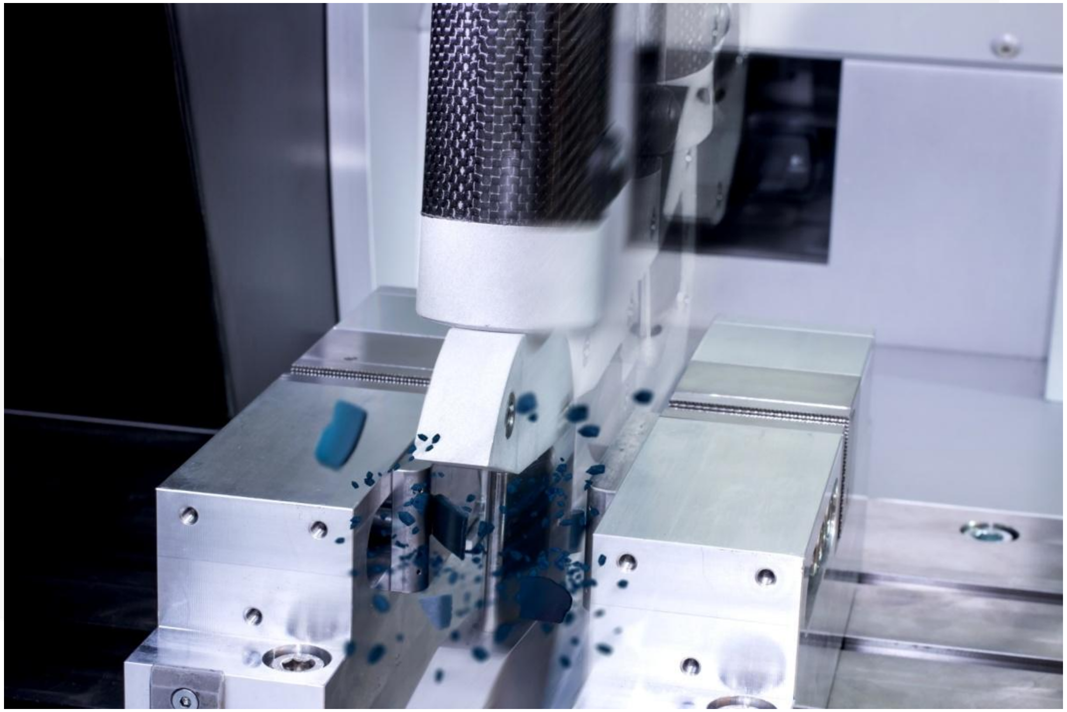
- **Abaqus** offers a multitude of material models to describe the dynamic material behavior of **plastics and composites** very well.
- With **increasing complexity** the accurateness of the characterization as well as the effort to adapt the material models rises. Therefore it is essential to **stay focused** on the **significant influences**.
- Tools like **4a impetus** or **4a micromec** ensure **quality and reproducibility** in the **process of generating material cards**, especially as the material card is linked to the chosen idealization (solver, element type, element size, …).
- As plastics will be used much more for mechanical loaded parts, **modeling of failure** will be the **next challenge in future**.

Event Note

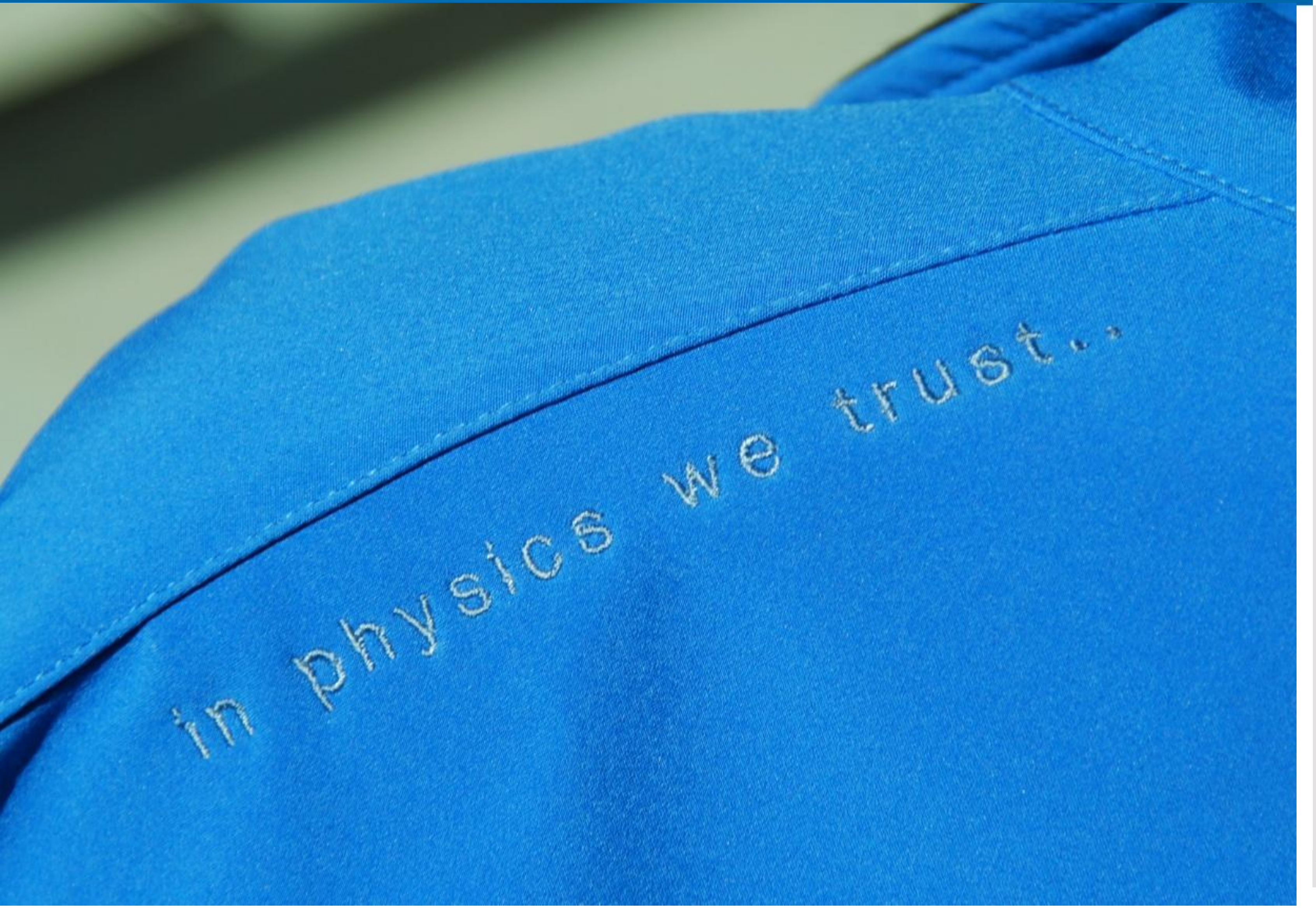
The 13th 4a TECHNOLOGIETAG takes place from **25.- 26. February 2015** in Schladming.

This year's topic is **„Plastics on the trial – Testing and Simulation"**.

More information you can find on the homepage *http://technologietag.4a.co.at/*



Thank you for your attention!



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R. W. Lang, Vorlesungsbehelf IWKP, 2002

[2] **Characterization of Dynamic Behavior of Engineering Polymers**

Z. Major, M. Reiter, 4a –VDI Technologietag 2008

[3] **Material data for CAE simulation. The approach of Basell Polyolefins**

M*. Nutini, 4a –VDI Technologietag 2008*

[4] **VUMAT for Molded Plastics**, Simulia - Dassault Systèmes,

http://simulia.custhelp.com

[5] **Viskoplastische Stoffgesetze für Thermoplaste in LS-DYNA:**

Theorie und Aspekte der Programmierung

Matthias Vogler, VDM Verlag Dr. Müller

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[6] **4a micromec für die integrative Simulation faserverstärkter Kunststoffe**

A. Fertschej, B. Jilka, P. Reithofer (4a engineering GmbH)

11. LS-DYNA Forum 2012, Ulm

http://www.dynamore.de/de/download/papers/ls-dyna-forum-2012/documents/materials-3-2

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B. Hofer, B. Fellner (MAGNA STEYR Fahrzeugtechnik AG & Co KG)

10. 4a Technologietag 2013, Schladming

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[8] **VUMAT for Fabric Reinforced Composites** , Simulia - Dassault Systèmes;

http://simulia.custhelp.com

[9] **Integrative Simulation - Berücksichtigung der prozessbedingten Anisotropie**

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