adaptive material cards

for short and long fiber reinforced thermoplastics

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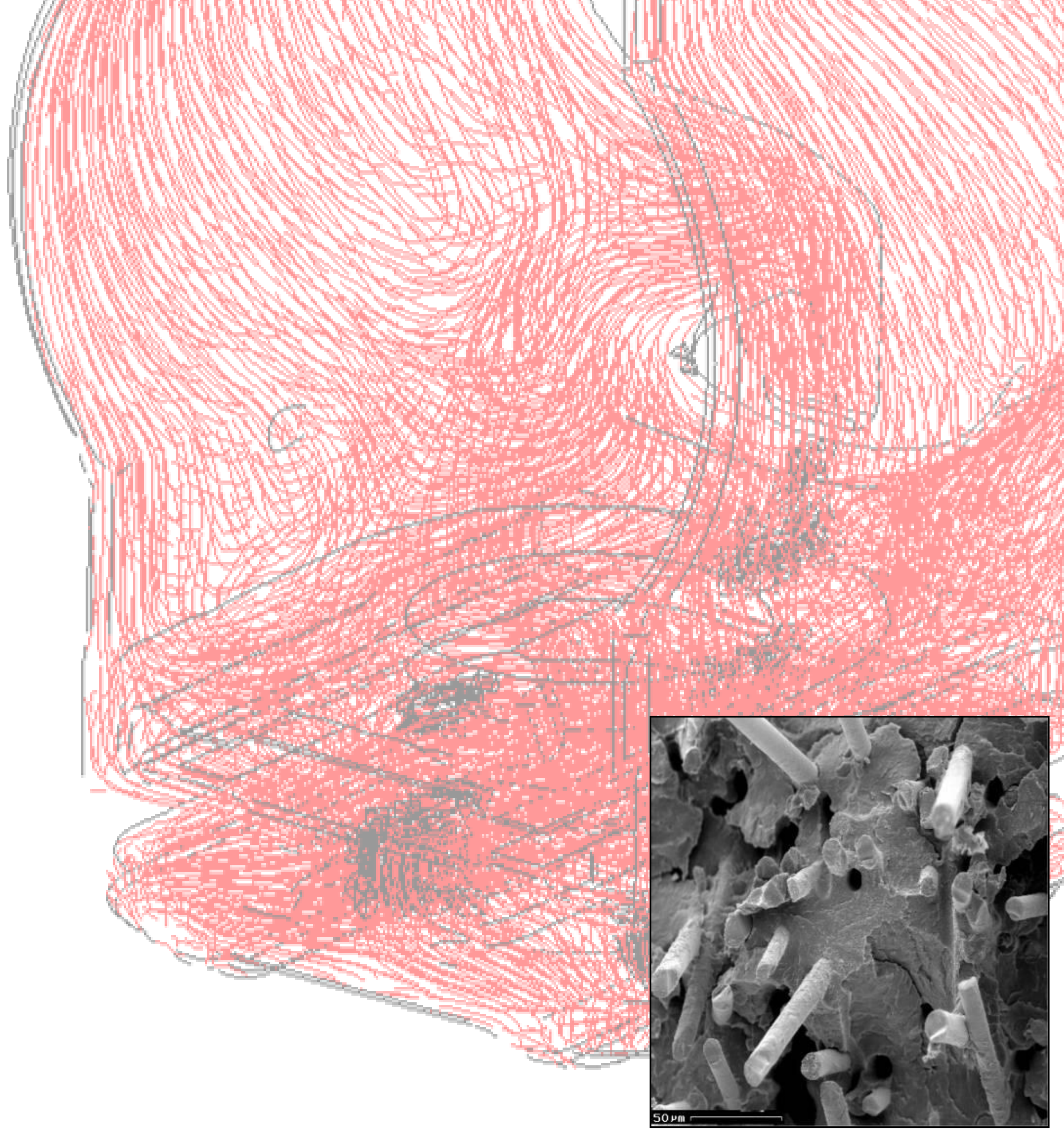
crashMAT Freiburg

9. Freiburg-Workshop zum Werkstoff- und Strukturverhalten bei Crashvorgängen
September 29 - 30, 2021
Freiburg, Germany

Content

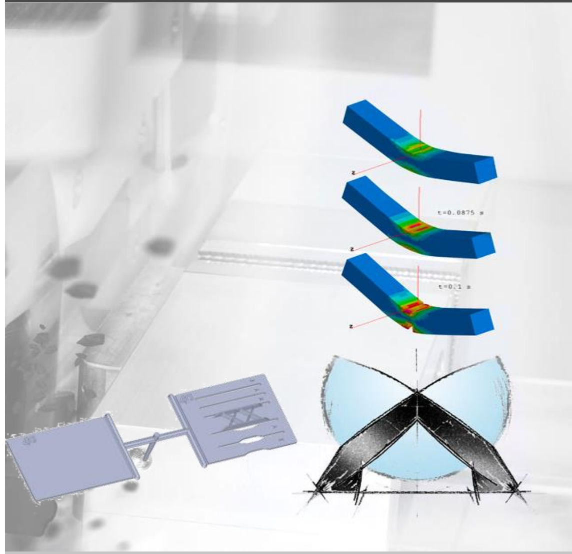


4a-engineering - Business Units

Testing hard- and software

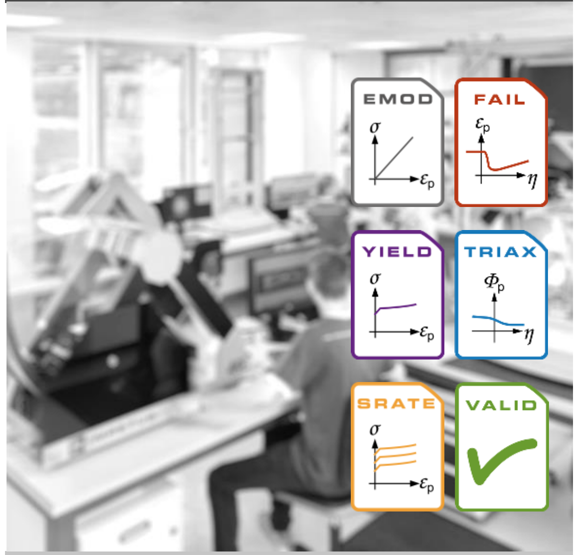
Seamless testing and simulation solution for automated material characterization

Material characterization



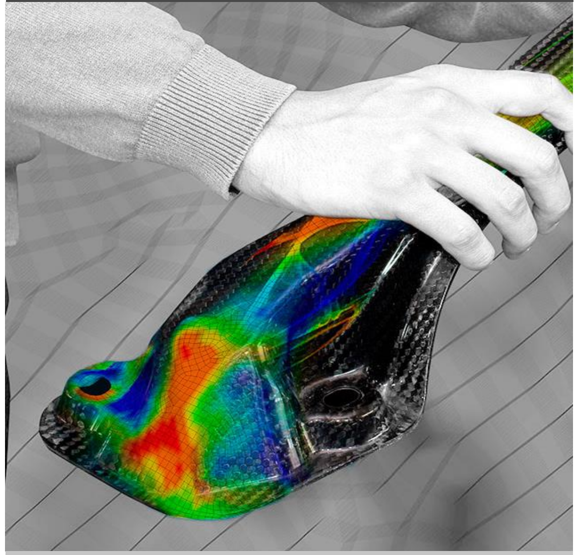
Static and dynamic material characterization from specimen to component validation – all under one roof

Validated material cards



Optimized packages for common material models for LS-Dyna, PamCrash and Abaqus.

Product development



From draft to craft – Engineering, simulation and prototyping

MCS Monte Carlo Simlation
DoE Design of Experiments
Optimization

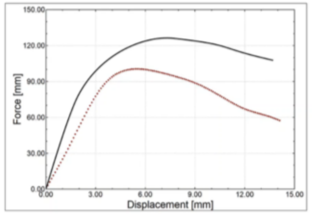
static & dynamic

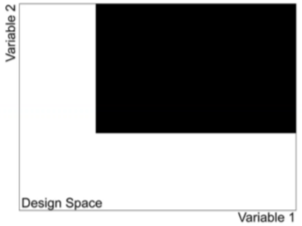
IMPETUS

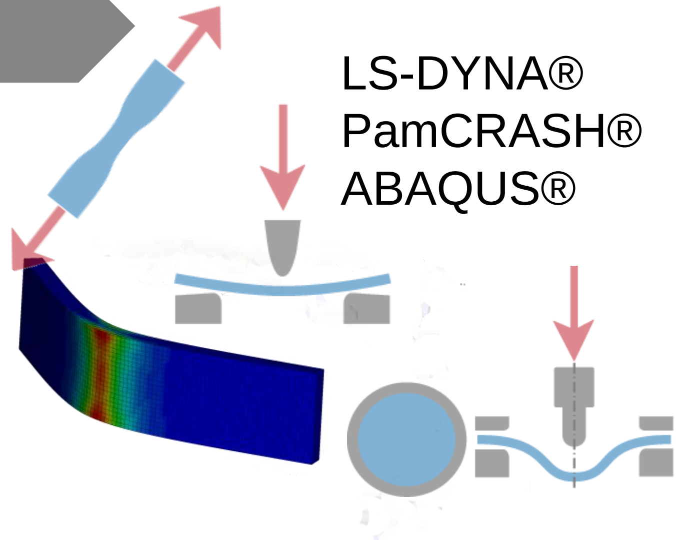
Photron

VALIMAT

database



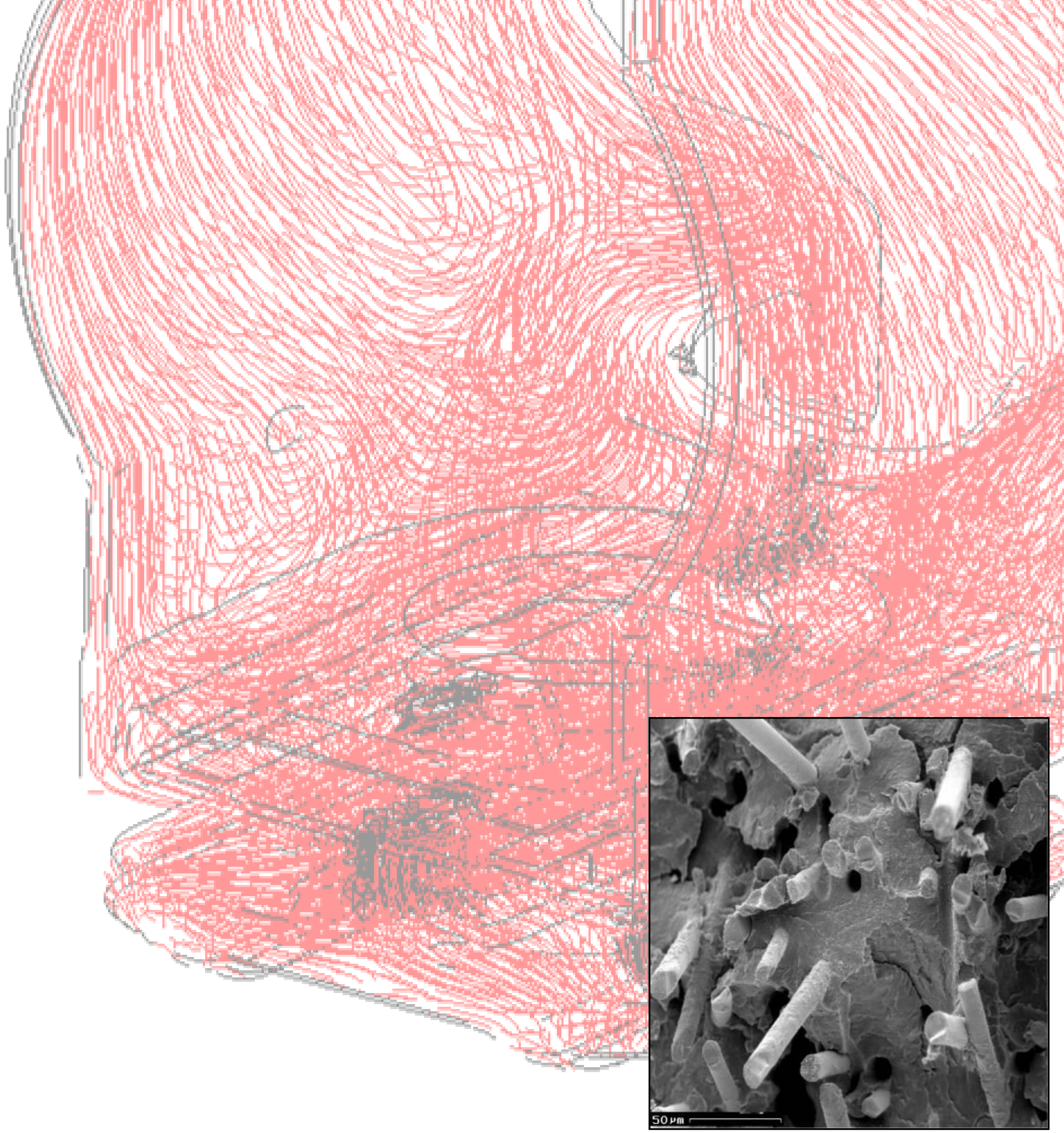




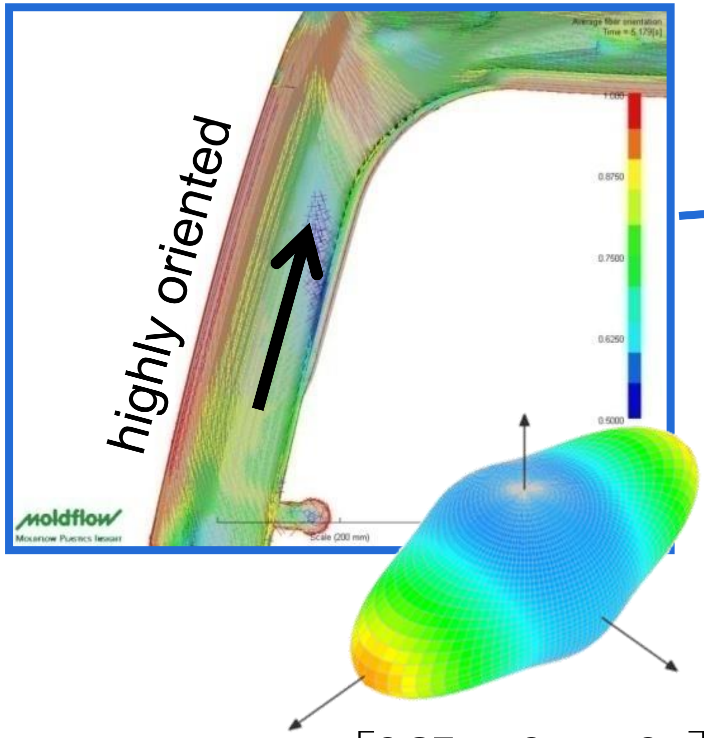
LS-DYNA®
PamCRASH®
ABAQUS®

Motivation – need adaptive material cards

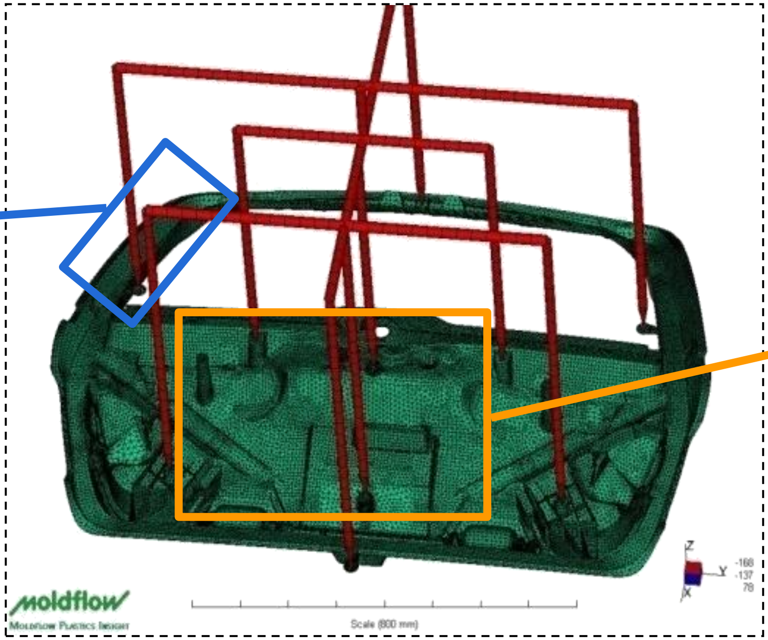
- Manufacturing scatter
  - Raw material – fiber content
  - Screw – fiber length
  - Flow – fiber orientation
- Increase understanding
  - Robust design
  - Robust process
- Early-stage development
  - How much fiber content is needed ?
- Last minute development – near SOP
  - Material change ?
- Influence Temperature / moisture

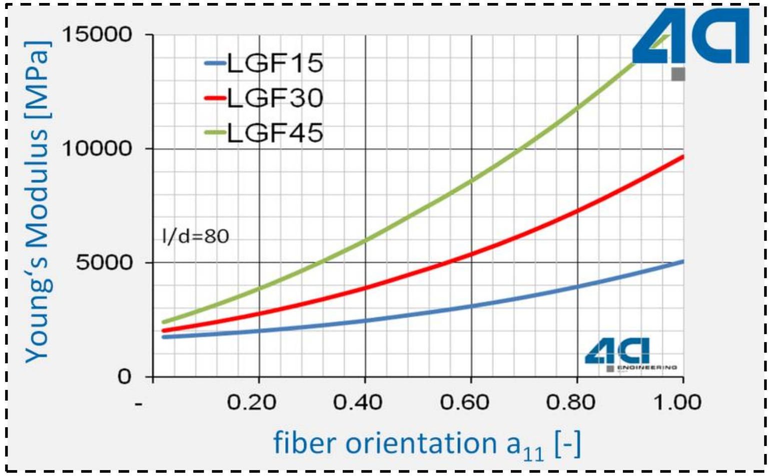


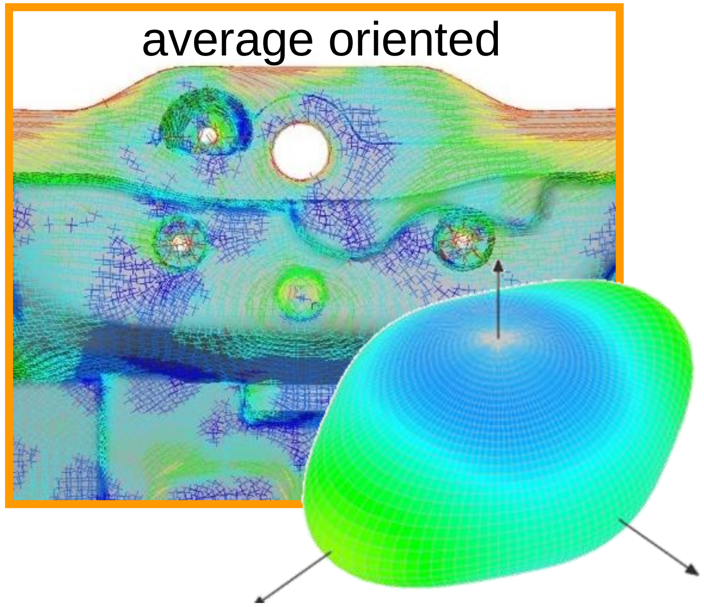
Fiber orientation – development in typical part



$$a_{ij} = \begin{bmatrix} 0{,}87 & 0 & 0 \\ 0 & 0{,}11 & 0 \\ 0 & 0 & 0{,}02 \end{bmatrix}$$





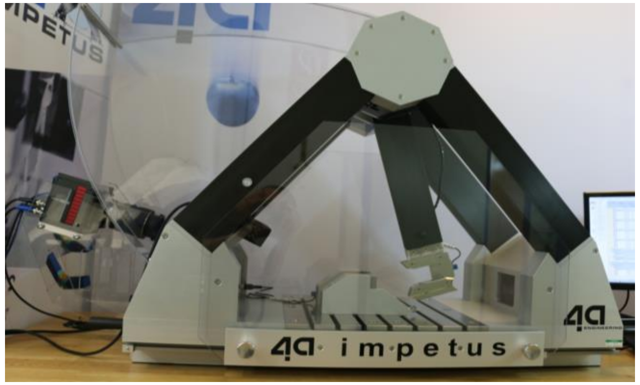


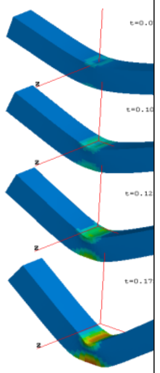
$$a_{ij} = \begin{bmatrix} 0{,}66 & 0 & 0 \\ 0 & 0{,}32 & 0 \\ 0 & 0 & 0{,}02 \end{bmatrix}$$

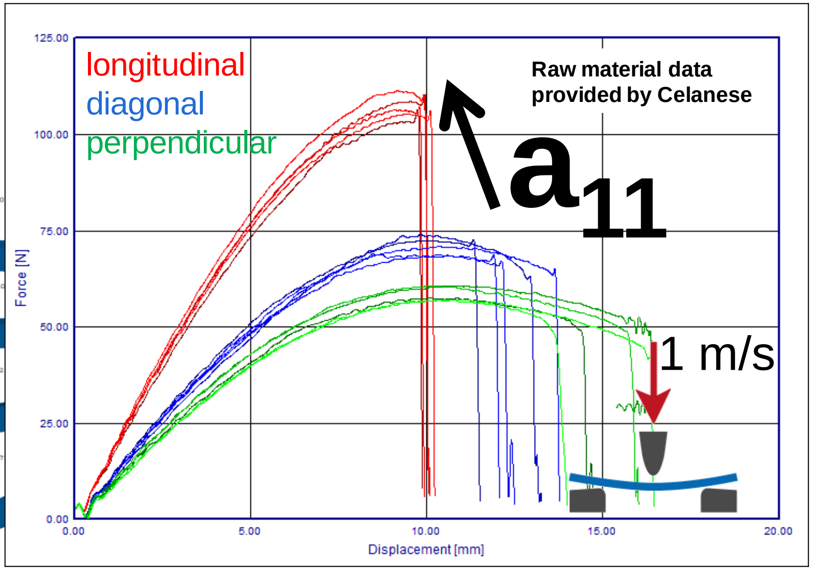
Source: P. Reithofer - *Integrative Simulation – Berücksichtigung der prozessbedingten Anisotropie,* 4a Technologietag 2011

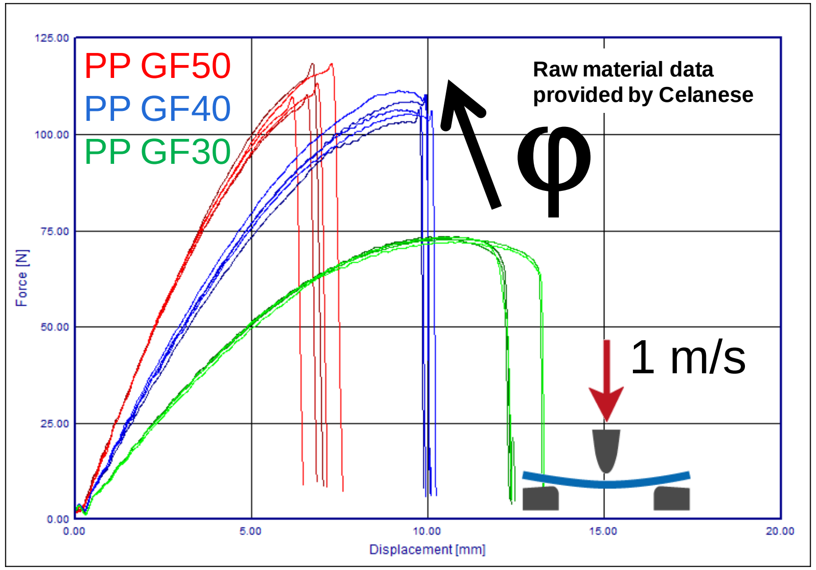
Typical material behavior – SFRT / LFRT

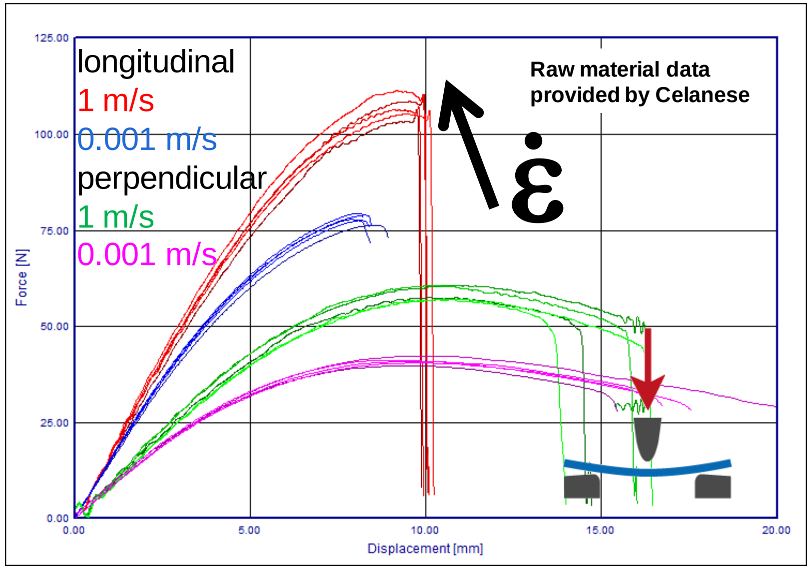
IMPETUS

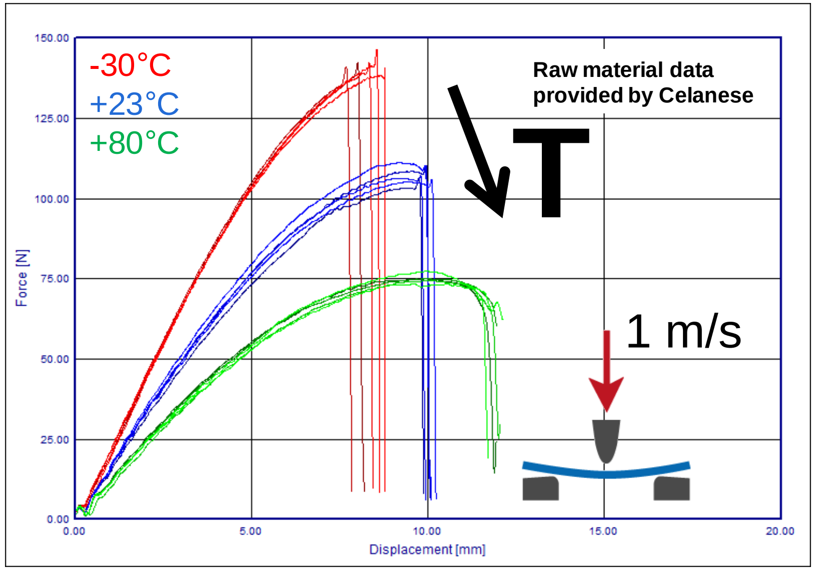












macro scale - constitutive law

Material description for different phenomena

- Elasticity

$$C^{-1} = \begin{bmatrix} \frac{1}{E_1} & -\frac{\nu_{12}}{E_2} & -\frac{\nu_{13}}{E_2} & 0 & 0 & 0 \\ -\frac{\nu_{21}}{E_1} & \frac{1}{E_2} & -\frac{\nu_{23}}{E_2} & 0 & 0 & 0 \\ -\frac{\nu_{31}}{E_1} & -\frac{\nu_{32}}{E_2} & \frac{1}{E_2} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{2(1+\nu_{23})}{E_2} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{G_{31}} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{G_{21}} \end{bmatrix}$$

- Plasticity

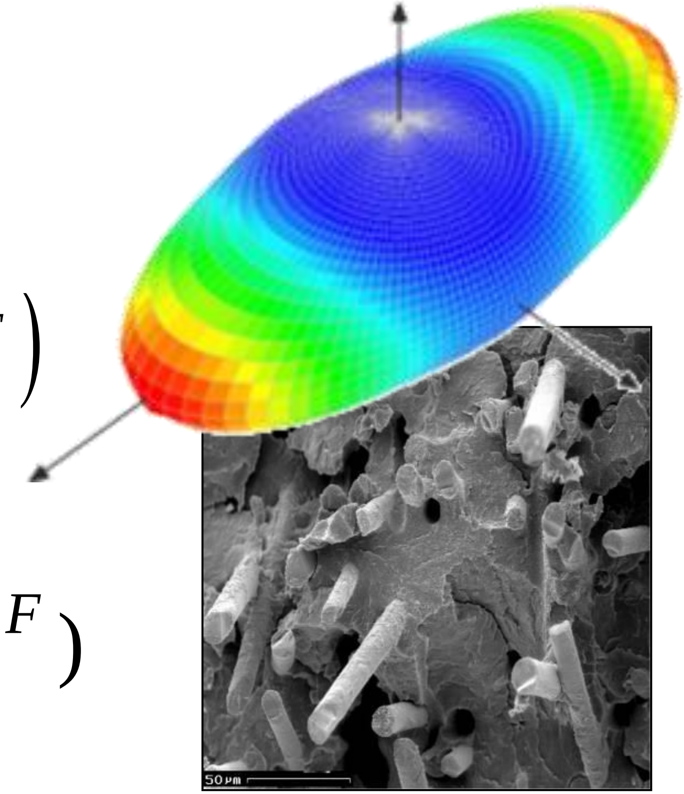
$$f(\sigma) = \sqrt{\begin{matrix} F(\sigma_{22}^b - \sigma_{33}^b)^2 + G(\sigma_{33}^b - \sigma_{11}^b)^2 + H(\sigma_{11}^b - \sigma_{22}^b)^2 \\ + 2(L\sigma_{23}^2 + M\sigma_{13}2 + N\sigma_{12}^2) \end{matrix}} - \sigma_0$$

$$\text{with } \sigma_{ii}^b := \sigma_{ii} - b_{ii}$$

- Hardening Law
- Viscosity
- Damage + Failure

$$C_{ij}\left(a_{ij}, \varphi, C^M, C^F\right)$$

$$f\left(a_{ij}, \varphi, \sigma^M, \sigma^F\right)$$

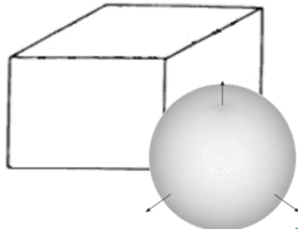


$$\sigma^M(\varepsilon, \dot{\varepsilon}, T, m) \quad \sigma^F(l/d)$$

$\dot{\varepsilon}$ … *strain rate*
T … *Temperature*
m… *moisture*

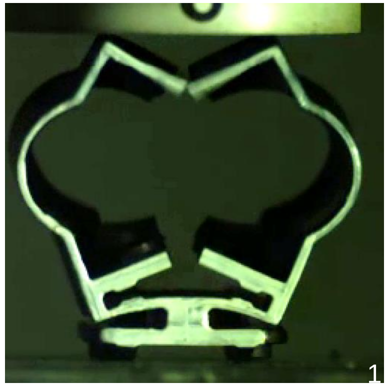
φ… *fiber content*
l/d… *fiber length*
a_{ij} … *fiber orientation*

Some material models in LS-DYNA

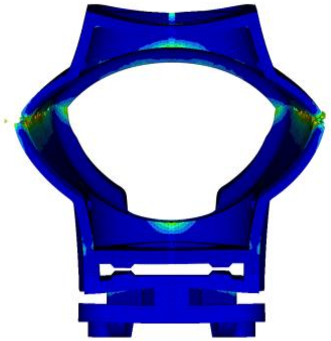


CARD	SCALE	Elasticity	Plasticity	Visco-plasticty	Damage & Failure
24	Macro Composite	ISOTROPIC	MISES	✓	equivalent plastic strain*

test

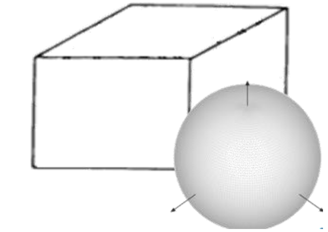


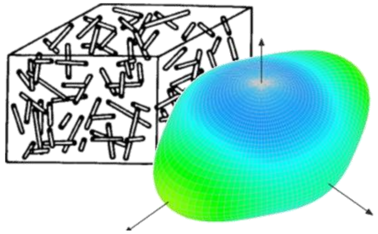
*MAT_24



Source: R. Steinberger, et.al. Hirtenberger Automotive Group – *Considering the Local Anisotropy of Short Fiber Reinforced Plastics, European Dynaforum 2017*

Some material models in LS-DYNA





CARD	SCALE	Elasticity	Plasticity	Visco-plasticty	Damage & Failure
24	Macro Composite	ISOTROPIC	MISES	✓	equivalent plastic strain*
22	Macro Composite	ORTHOTROPIC	✗	✗	Stress based criteria direction
157	Macro Composite	ANISOTROPIC	HILL	✓	equivalent plastic strain*

VALIMAT MICROMECHANICS as key enabler to find material parameter

* - simple criteria up to dependency of strain rate and loading

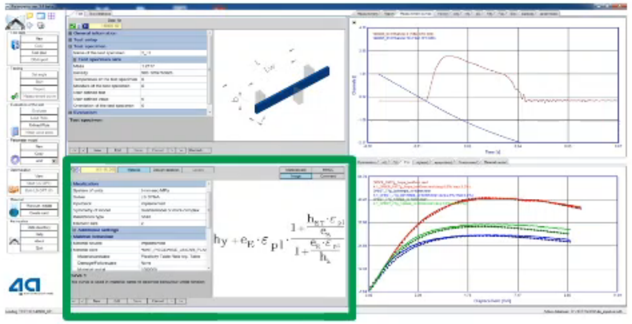
Micro mechanic models as key enabler

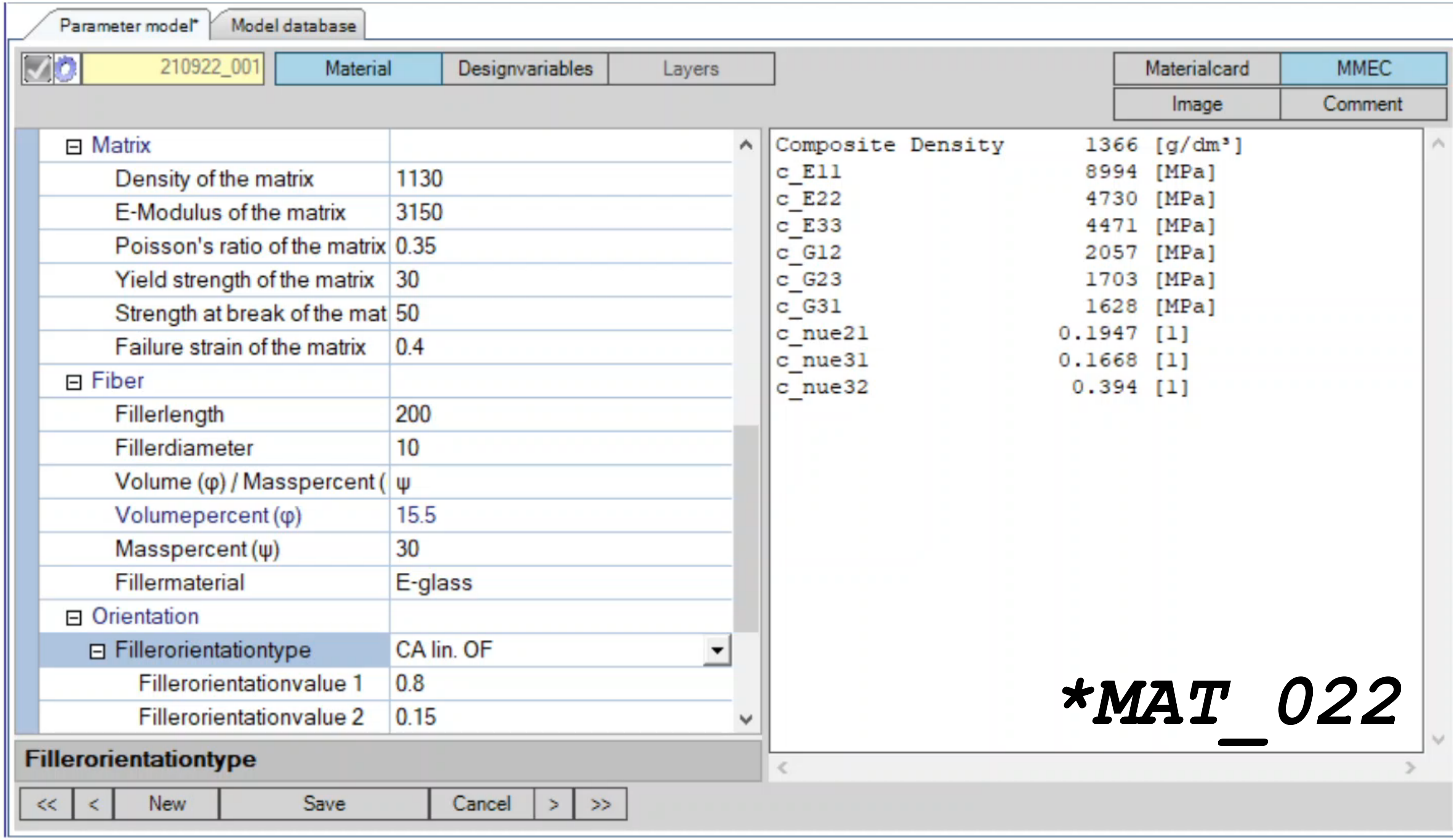
VALIMAT

160223_006 | Material | Designvariablen | Layers

⊟ Strain rate dependency	Table	
⊞ Strain rate dependency	Johnson Cook	
⊟ Micromec	User defined	
⊟ Matrix		
Density of the matrix	900	matrix
E-Modulus	1500	matrix
Poisson's ratio	0.3	matrix
Yield strength	15	matrix
Strength at Break	17	matrix
Failure strain	0.05	matrix
⊟ Fiber		
Fillerlength	1000	filler
Fillerdiameter	20	filler
Phi or Psi	φ	filler
Phi	12.9	filler
Psi	30.1	filler
Fillermaterial	E-Glas	filler
⊟ Orientation		
⊟ Fillerorientationtype	CA lin. OF	orientation
Fillerorientationvalue 1	0.6	orientation
Fillerorientationvalue 2	0.33	orientation

Composite Density	1126	[g/dm³]
c_C11	6172	[MPa]
c_C12	1808	[MPa]
c_C13	1231	[MPa]
c_C14	0	[MPa]
c_C15	0	[MPa]
c_C16	0	[MPa]
c_C22	4135	[MPa]
c_C23	1181	[MPa]
c_C24	0	[MPa]
c_C25	0	[MPa]
c_C26	0	[MPa]
c_C33	2616	[MPa]
c_C34	0	[MPa]
c_C35	0	[MPa]
c_C36	0	[MPa]
c_C44	1554	[MPa]
c_C45	0	[MPa]
c_C46	0	[MPa]
c_C55	888.6	[MPa]
c_C56	0	[MPa]
c_C66	957.5	[MPa]
y_r00	1	[1]
y_r45	0.5105	[1]
y_r90	0.2665	[1]
	3.076	[1]





VALIMAT

I N P H Y S I C S W E T R U S T

Micro mechanic models as key enabler

VALIMAT

30 design variables for *MAT_157

160223_006 | Material | Designvariablen | Layers

Name	Start	const...	Description
GroupName: 10_elasticity			
c_C11	MMEC	✓	constitutive matrix 11
c_C12	MMEC	✓	constitutive matrix 12
c_C13	MMEC	✓	constitutive matrix 13
c_C14	MMEC	✓	constitutive matrix 14
c_C15	MMEC	✓	constitutive matrix 15
c_C16	MMEC	✓	constitutive matrix 16
c_C22	MMEC	✓	constitutive matrix 23
c_C23	MMEC	✓	constitutive matrix 23
c_C24	MMEC	✓	constitutive matrix 24
c_C25	MMEC	✓	constitutive matrix 25
c_C26	MMEC	✓	constitutive matrix 26
c_C33	MMEC	✓	constitutive matrix 33
c_C34	MMEC	✓	constitutive matrix 34
c_C35	MMEC	✓	constitutive matrix 35
c_C36	MMEC	✓	constitutive matrix 36
c_C44	MMEC	✓	constitutive matrix 44
c_C45	MMEC	✓	constitutive matrix 45
c_C46	MMEC	✓	constitutive matrix 46
c_C55	MMEC	✓	constitutive matrix 55
c_C56	MMEC	✓	constitutive matrix 56
c_C66	MMEC	✓	constitutive matrix 66

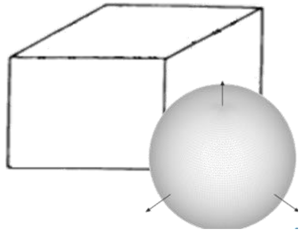
160223_006 | Material | Designvariablen | Layers

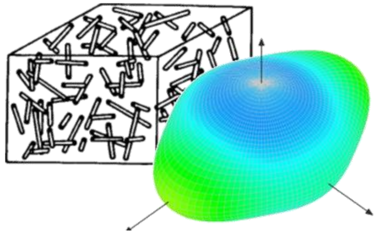
Name	Start	const...	Description
GroupName: 10_elasticity			
GroupName: 20_yield			
y_0	90	■	yield stress
y_scale...	MMEC	✓	yield scale 11 direction
y_r00	MMEC	✓	yield hill anisotropy ratio 0°
y_r45	MMEC	✓	yield hill anisotropy ratio 45°
y_r90	MMEC	✓	yield hill anisotropy ratio 90°
GroupName: 21_hardening			
h_ET	50	■	
h_y	90	✓	
GroupName: 31_strainrate			
v_epspkt	0.01	✓	initial strain rate threshold
v_p	15	■	strain rate scale (1/vp)
GroupName: 51_failure			
xf_NUM...	0.75	✓	Number of failed integration points prior to

MMEC – design variable calculated by micro mechanic model

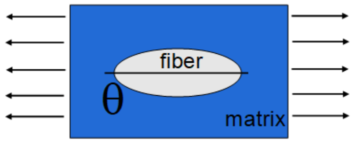
Less free design variables left for material parameter identification

Some material models in LS-DYNA





$$\bar{\sigma}^{C} = \varphi\bar{\sigma}^{F} + (1-\varphi)\bar{\sigma}^{M}$$

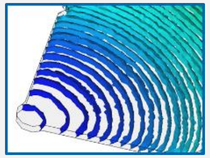


CARD	SCALE	Elasticity	Plasticity	Visco-plasticty	Damage & Failure
24	Macro Composite	ISOTROPIC	MISES	✓	equivalent plastic strain*
22	Macro Composite	ORTHOTROPIC	✗	✗	Stress based criteria direction
157	Macro Composite	ANISOTROPIC	HILL	✓	equivalent plastic strain*
215	Micro Matrix	ISOTROPIC	MISES	✓	equivalent plastic strain*
	Micro Fiber	ORTHOTROPIC	✗	✗	Stress based criteria fiber

* - simple criteria up to dependency of strain rate and loading

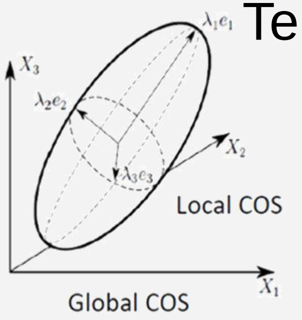
Mapping process information

Process simulation



$$a_{ij} = \begin{bmatrix} a_{xx} & a_{xy} & a_{xz} \\ & a_{yy} & a_{yz} \\ & & a_{zz} \end{bmatrix}$$

Tensor 2nd order



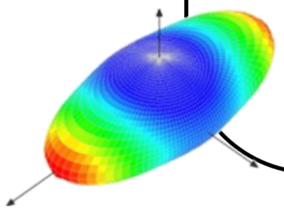
CADMOULD 3D-F SIMULATION

Moldex3D MOLDING INNOVATION

MOLDFLOW

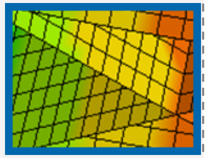
FIBERMAP

$$C^{-1} = \begin{bmatrix} \frac{1}{E_1} & -\frac{\nu 21}{E_2} & -\frac{\nu 31}{E_3} & 0 & 0 & 0 \\ -\frac{\nu 12}{E_1} & \frac{1}{E_2} & -\frac{\nu 32}{E_3} & 0 & 0 & 0 \\ -\frac{\nu 13}{E_1} & -\frac{\nu 23}{E_2} & \frac{1}{E_3} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{G_{23}} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{G_{31}} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{G_{21}} \end{bmatrix}$$



MICROMEC

Structural simulation



Homogenization (Micro Scale)

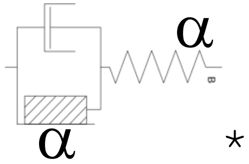
Mean Field Theory

$$\overline{\sigma}^{C} = \varphi \overline{\sigma}^{F} + (1-\varphi)\overline{\sigma}^{M}$$

*MAT_215

Composite (Macro Scale)

Hill Plasticity

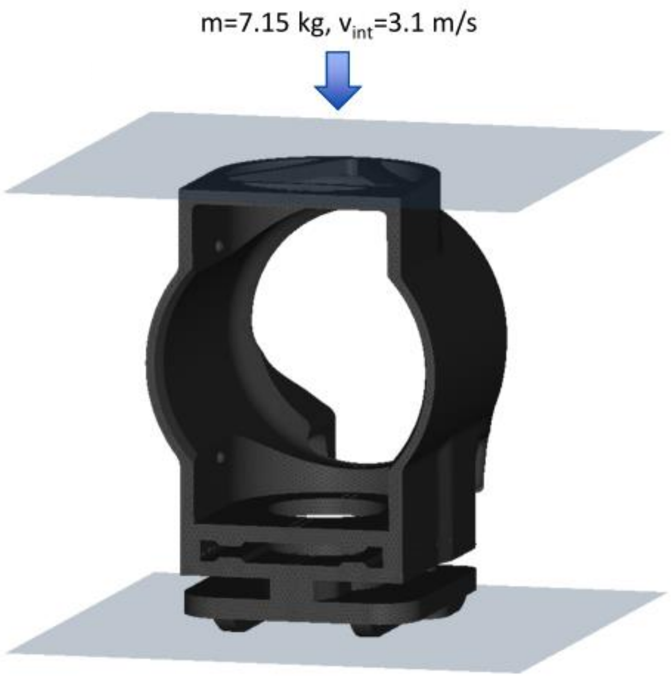


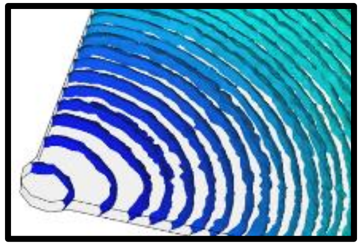
*MAT_157

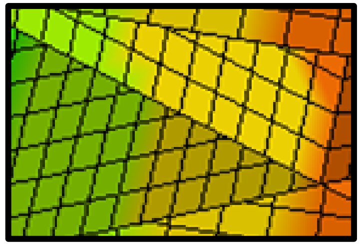
LSTC Livermore Software Technology Corp.

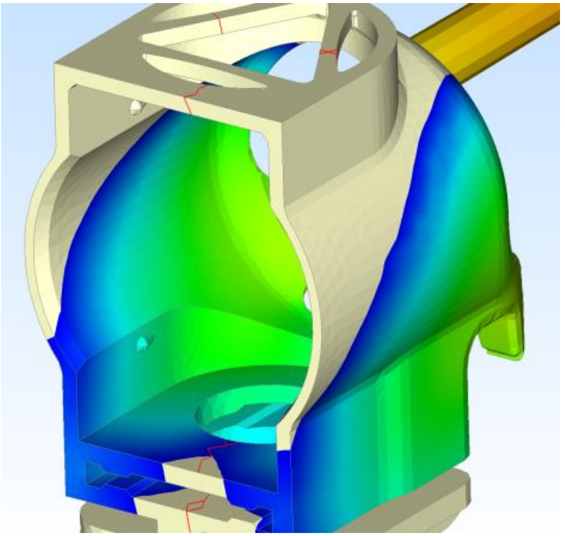
LS-DYNA®

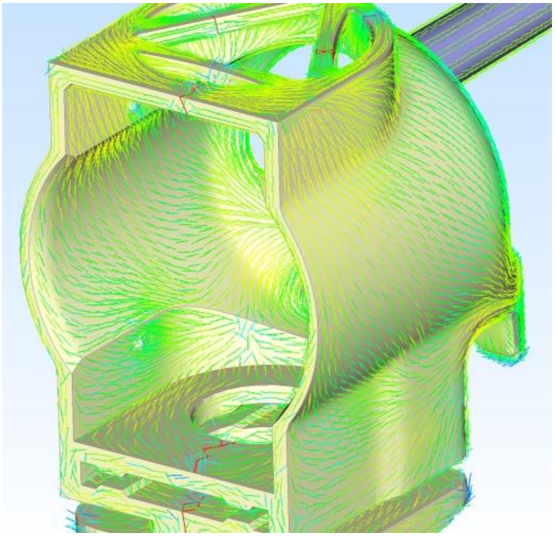
Case study - sleeve

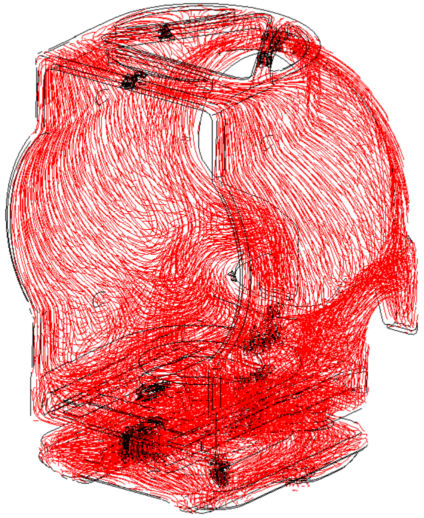








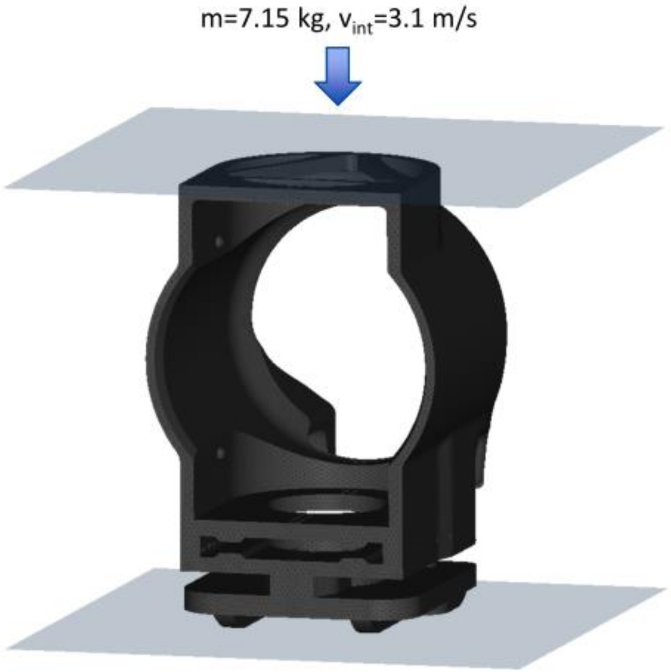




Typical element size : 0.25 mm
Element type : Tetrahedron Type 10
Number of elements : 469470

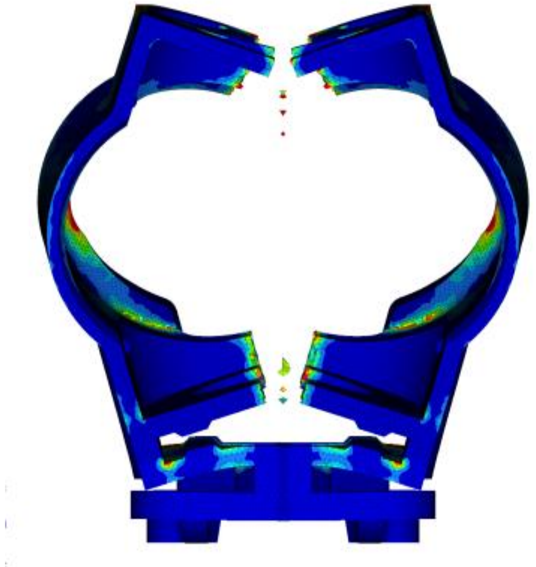
Source: R. Steinberger, et.al. Hirtenberger Automotive Group – *Considering the Local Anisotropy of Short Fiber Reinforced Plastics, European Dynaforum 2017*

Case study - sleeve

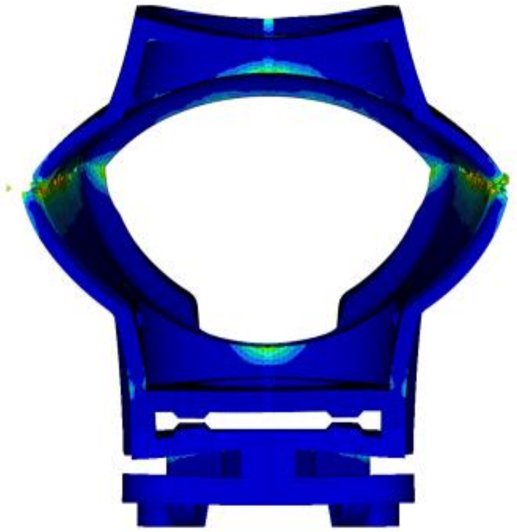


test

*MAT_157/215
local anisotropy



*MAT_24
isotropic



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hirtenberger Automotive Safety

*MAT_4A_MICROMEC KEYWORD (more see Summer-School-Day7.pdf)

CARD 1: General Options / Parameter

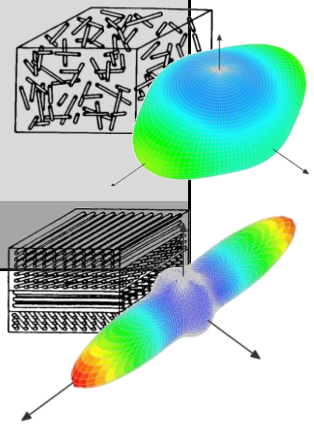
CARD 2-3: Element orientation*

analog to LSDYNA standard anisotropic material cards

CARD 4: Composite Buildup*

FIBER

Card 4	1	2	3	4	5	6	7	8
	FVF		FL	FD		A11	A22	
PP GF30	**-0.3**		**200.0**	**10.0**		**0.7**	**0.25**	
PP LGF50	**-0.5**		**1000.0**	**20.0**		**0.65**	**0.30**	
PA6 GF45	**-0.45**		**250.0**	**10.0**		**0.8**	**0.15**	
Carbon UD	**0.6**		**10000.0**	**10.0**		**1.0**	**0.0**	



FVF > 0: fiber volume fraction → Composite
FVF < 0: fiber mass fraction → SFRT/LFRT

*may be overwritten by
`*INITIAL_STRESS_SHELL/SOLID`

exemplary values without any warranty

P. Reithofer, H. Pothukuchi, pres_21093001_pr_hpot_eng_crashMAT

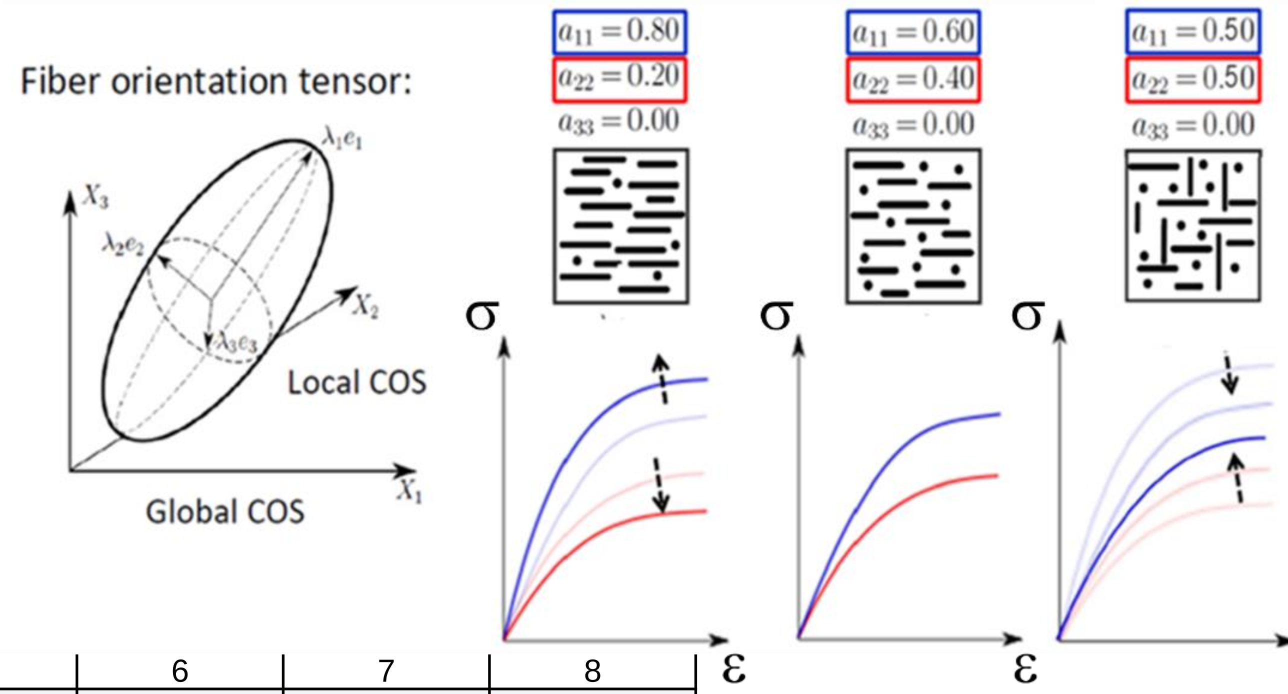
IN PHYSICS WE TRUST

*MAT_4A_MICROMEC KEYWORD (more

CARD 1: General Options / Param

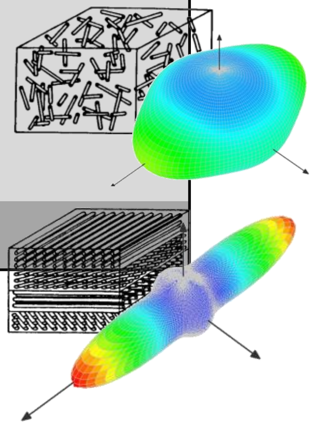
CARD 2-3: Element orientation*

analog to LSDYNA standard anisotropic material cards



CARD 4: Composite Buildup*

Card 4	1	2	3	4	5	6	7	8
	FVF		FL	FD		A11	A22	
PP GF30	**-0.3**		**200.0**	**10.0**		**0.7**	**0.25**	
PP LGF50	**-0.5**		**1000.0**	**20.0**		**0.65**	**0.30**	
PA6 GF45	**-0.45**		**250.0**	**10.0**		**0.8**	**0.15**	
Carbon UD	**0.6**		**10000.0**	**10.0**		**1.0**	**0.0**	

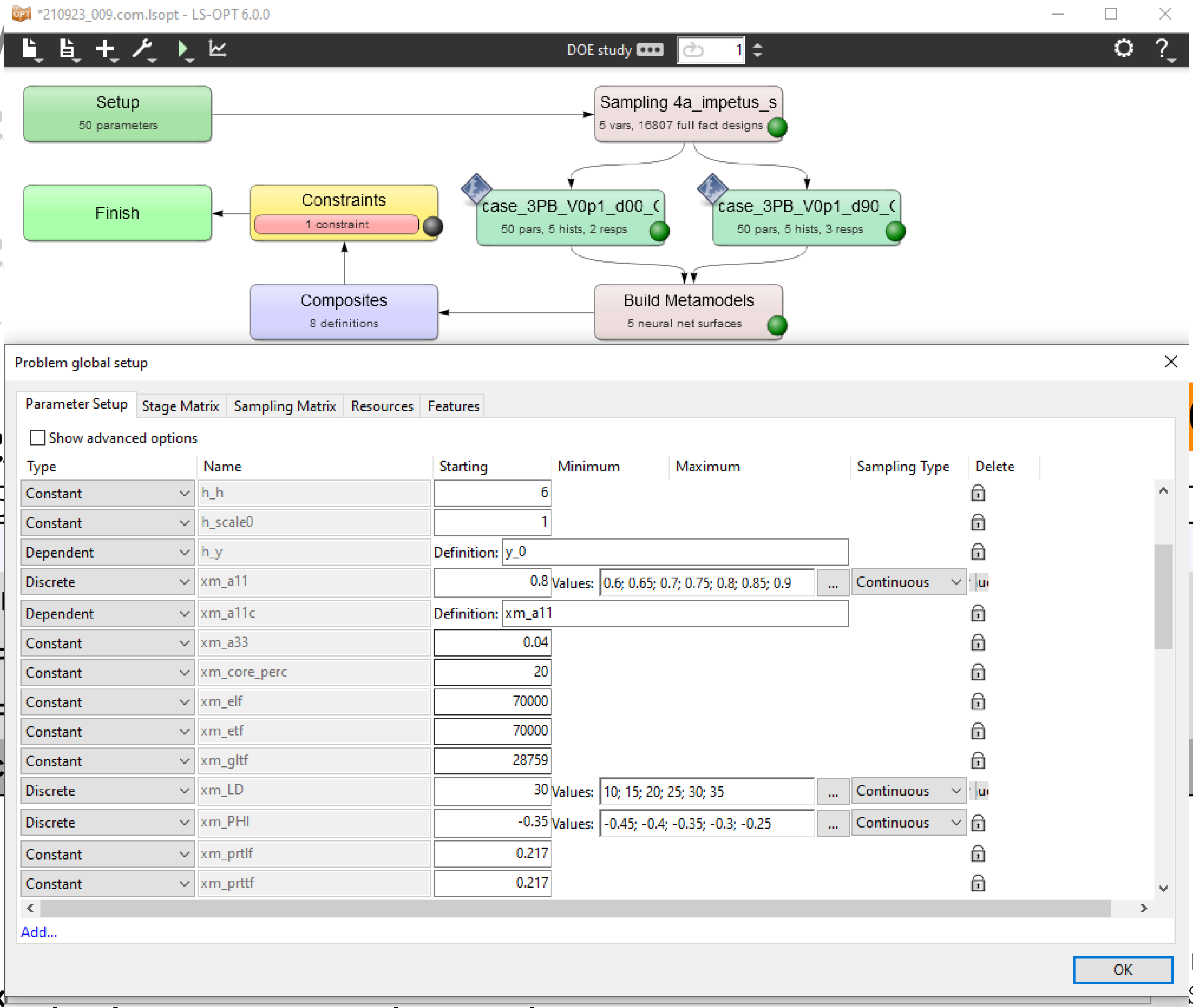


FVF > 0: fiber volume fraction → Composite
FVF < 0: fiber mass fraction → SFRT/LFRT

*may be overwritten by
`*INITIAL_STRESS_SHELL/SOLID`

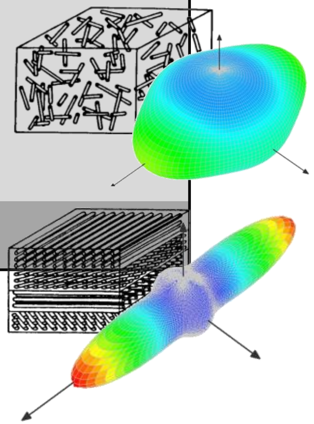
exemplary values without any warranty

*M

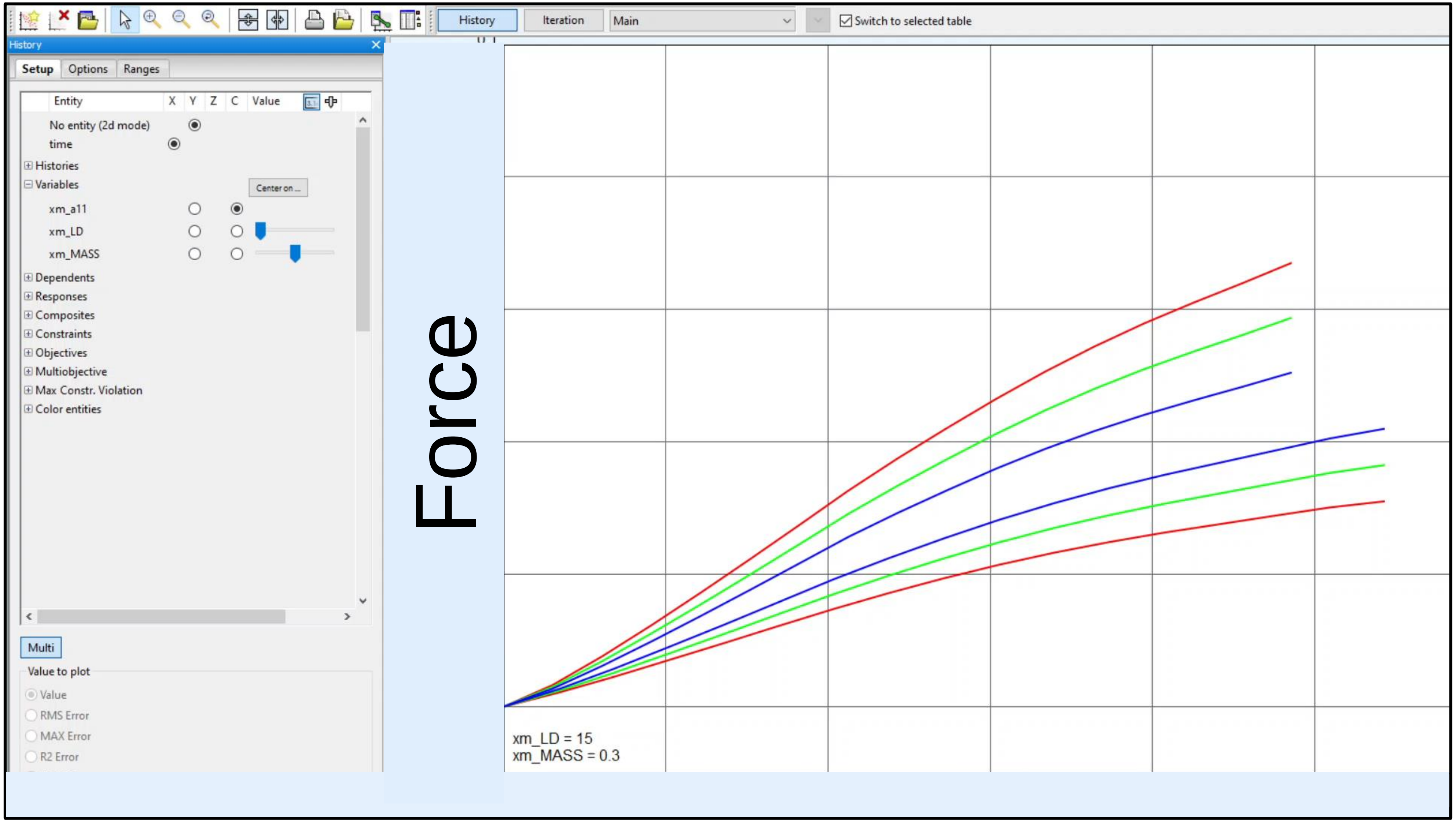


OE STUDY

7	8
A22	
0.25	
0.30	
0.15	
0.0	



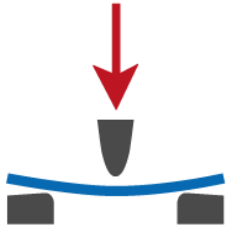
rwritten by
_STRESS_SHELL/SOLID



0° direction

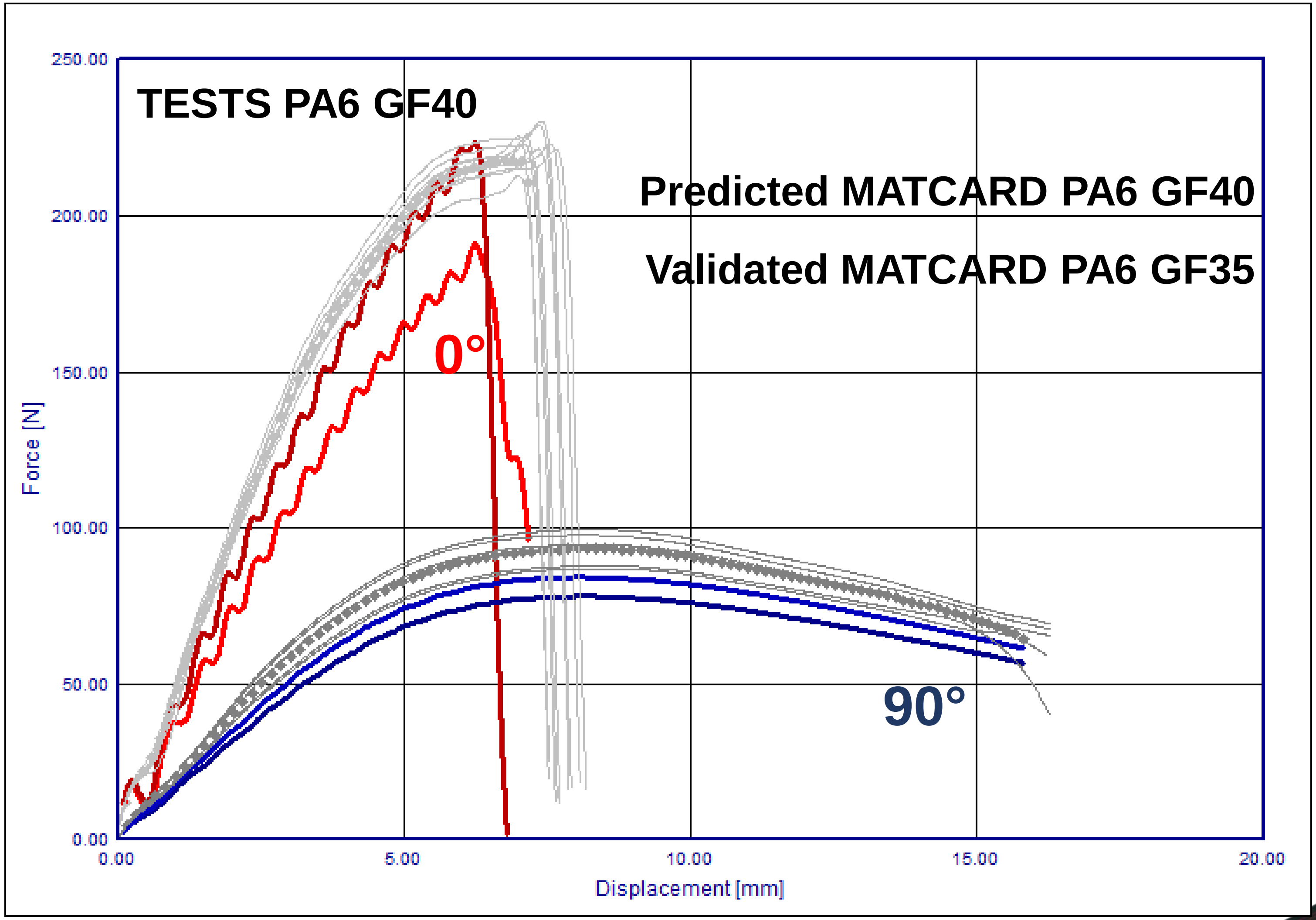
a11 0.80 / 0.70 / 0.60
a22 0.16 / 0.26 / 0.36

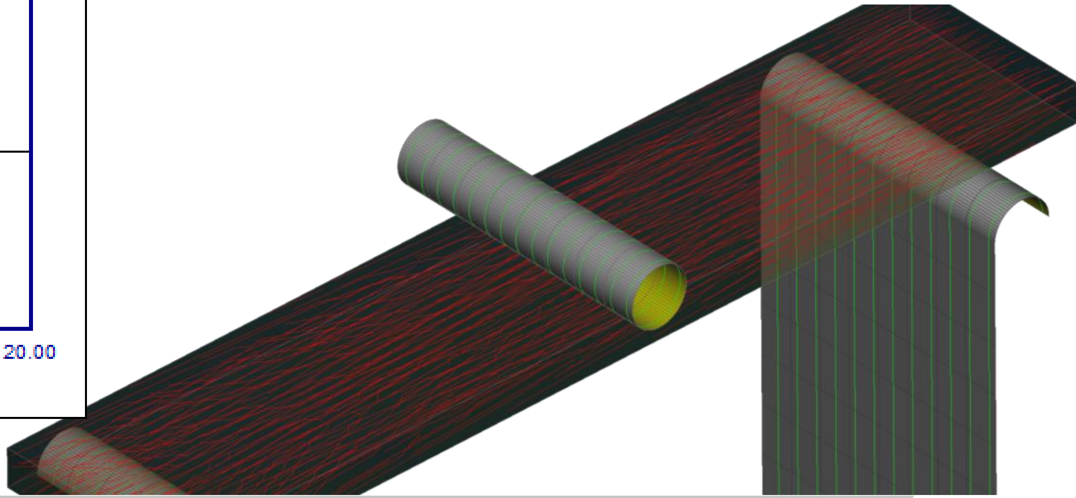
90° direction



static bending

dynamic 3pt bending – change in fiber content



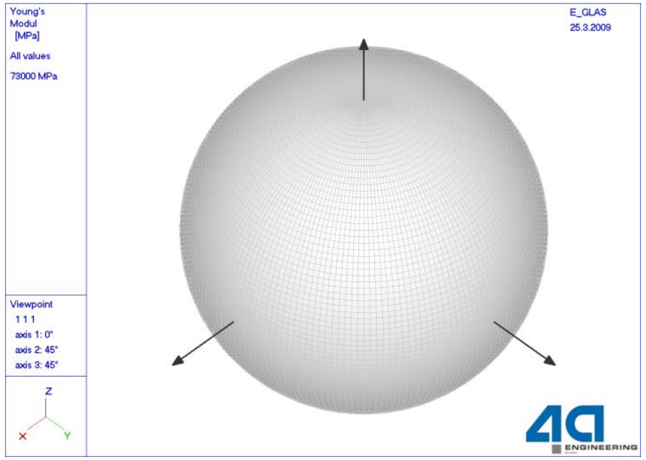


*MAT_4A_MICROMEC KEYWORD

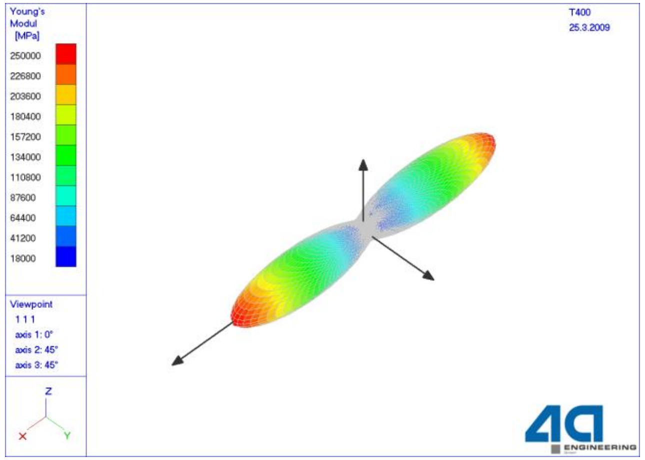
CARD 5: fiber material

Card 5	1	2	3	4	5	6	7	8
FIBER	ROF	EL	ET	GLT	PRTL	PRTT		
UNITS	kg/mm³	GPa	GPa	GPa	-	-		
glass	**2.59E-6**	**70.0**	**70.0**	**28.8**	**0.217**	**0.217**		
T400	**1.76E-6**	**218.8**	**28.0**	**50.0**	**0.02943**	**0.390**		

glass fiber (isotropic)



T400 (transversal isotropic)



exemplary values without any warranty

*MAT_4A_MICROMEC KEYWORD

CARD 7-8: matrix material

from material characterization (e.g. VALIMAT® Workflow)

MATRIX

$$\sigma^M(\varepsilon, \dot{\varepsilon}, T, m)$$

Card 7	1	2	3	4	5	6	7	8
Matrix	ROM	E	PR					
Units	kg/mm³	GPa	-					
PP	**0.9E-6**	**1.5**	**0.4**					
PA6 dry	**1.2E-6**	**3.2**	**0.35**					
PA6 cond.	**1.2E-6**	**2.0**	**0.35**					

elasticity

Card 8	1	2	3	4	5	6	7	8
Matrix	SIGYT	ETAN			EPS0	C		
Units	GPa	GPa	-		1/ms	-		
PP	**0.015**	**0.5**			**1.E-6**	**10**		
PA6 dry	**0.06**	**1.0**			**1.E-6**	**15**		
PA6 cond.	**0.04**	**0.8**			**1.E-6**	**10**		

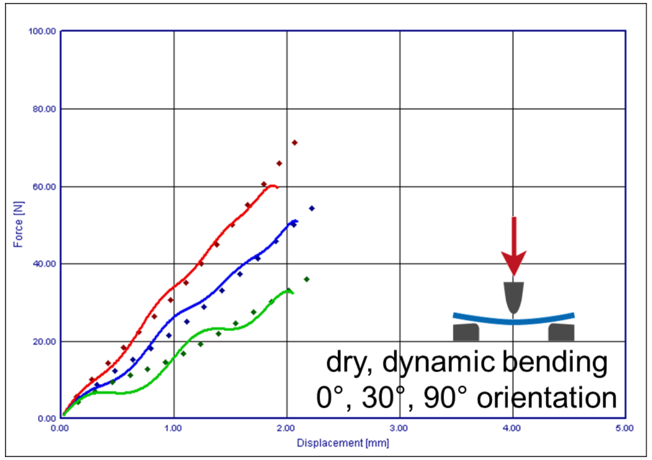
visco plasticity

Bilinear + Johnson Cook

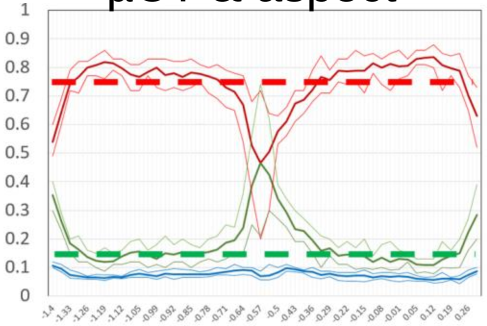
exemplary values without any warranty

*MAT_4A_MICROMEC – *case study PA6 GF30 I*

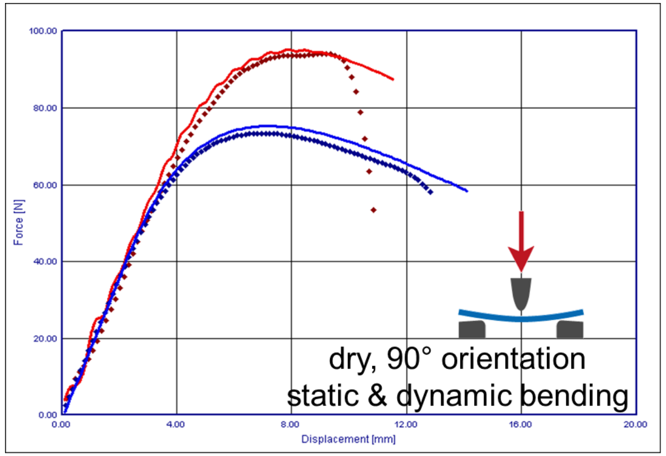
1st step: set up the composite



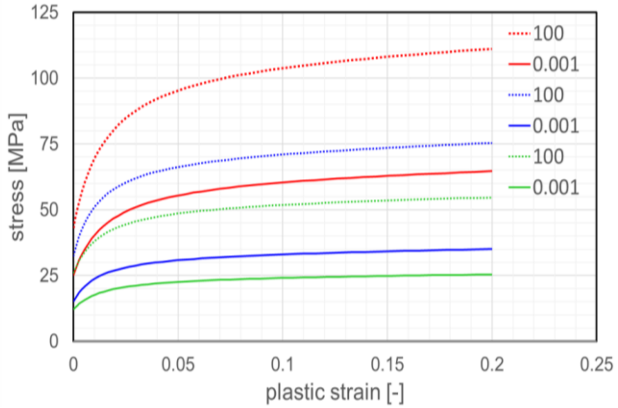
µCT & aspect



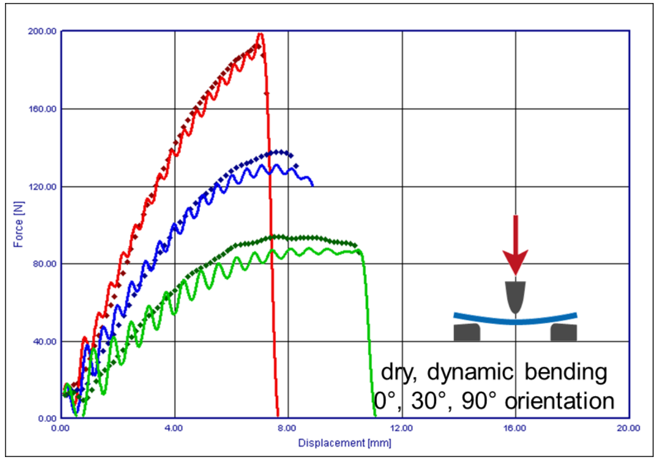
2nd step: matrix hardening



Young's Mod.	dry	cond.	wet
[MPa]	2500	1600	1450



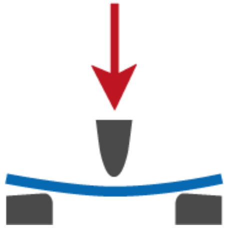
3rd step: validation



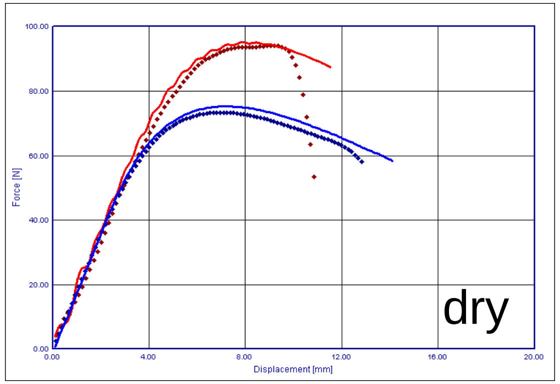
4th step: failure strains

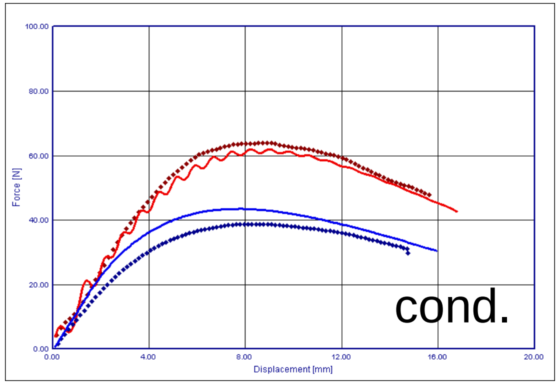
Source: P Reithofer, et.al., failure criteria SFRT and LFRT

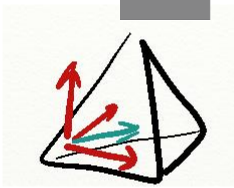
*MAT_4A_MICROMEC PA6 GF30 different moisture contents



90° orientation
static & dynamic bending

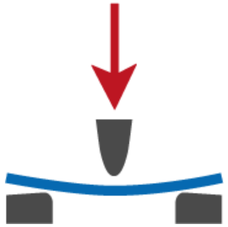




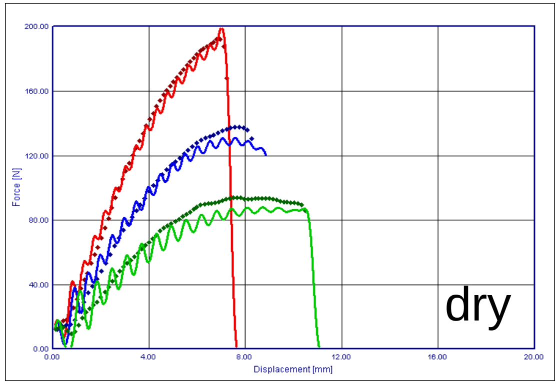


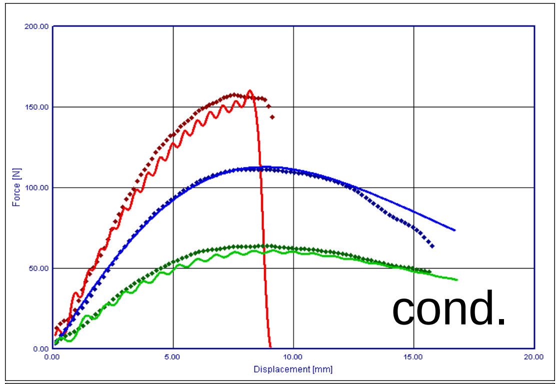
ELTYP4
0.5 mm

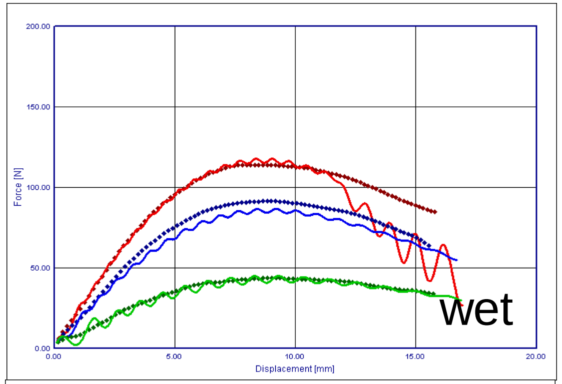
···· averaged test curves
— result of simulation

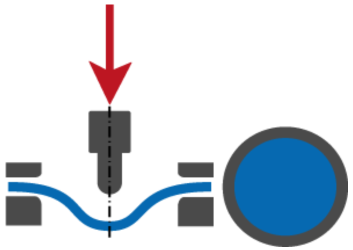


dynamic bending
0°, 30°, 90° orientation

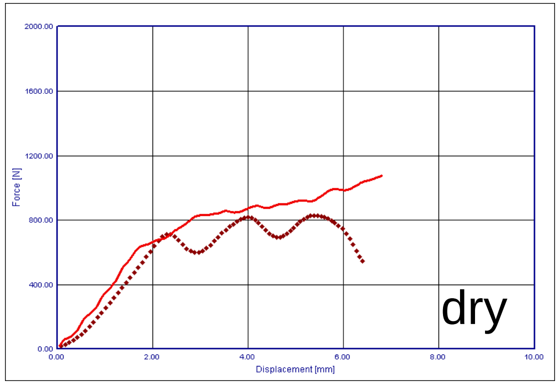


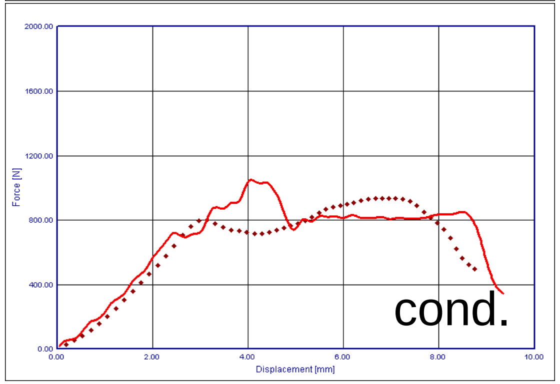


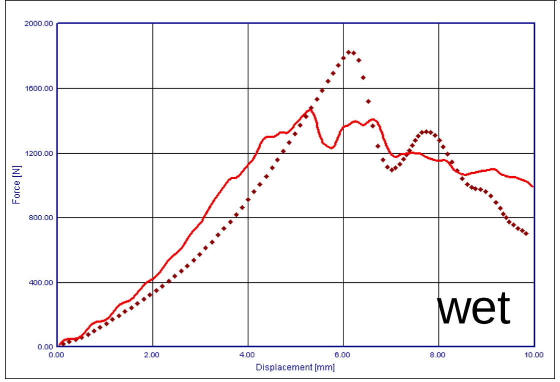




dynamic puncture test



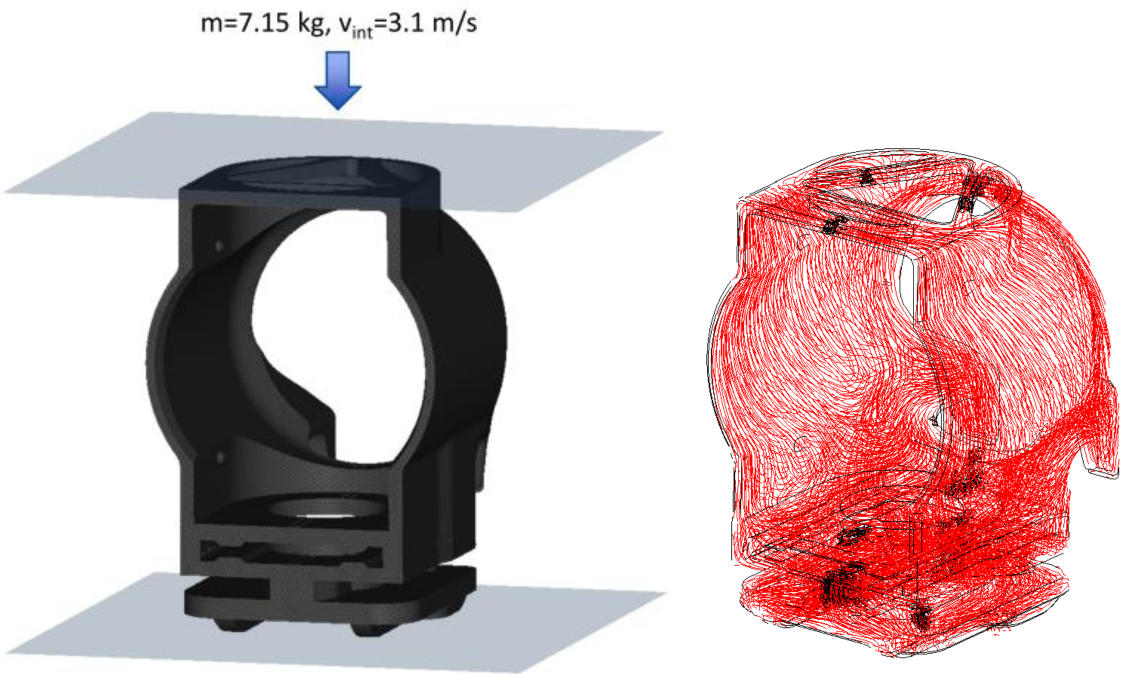


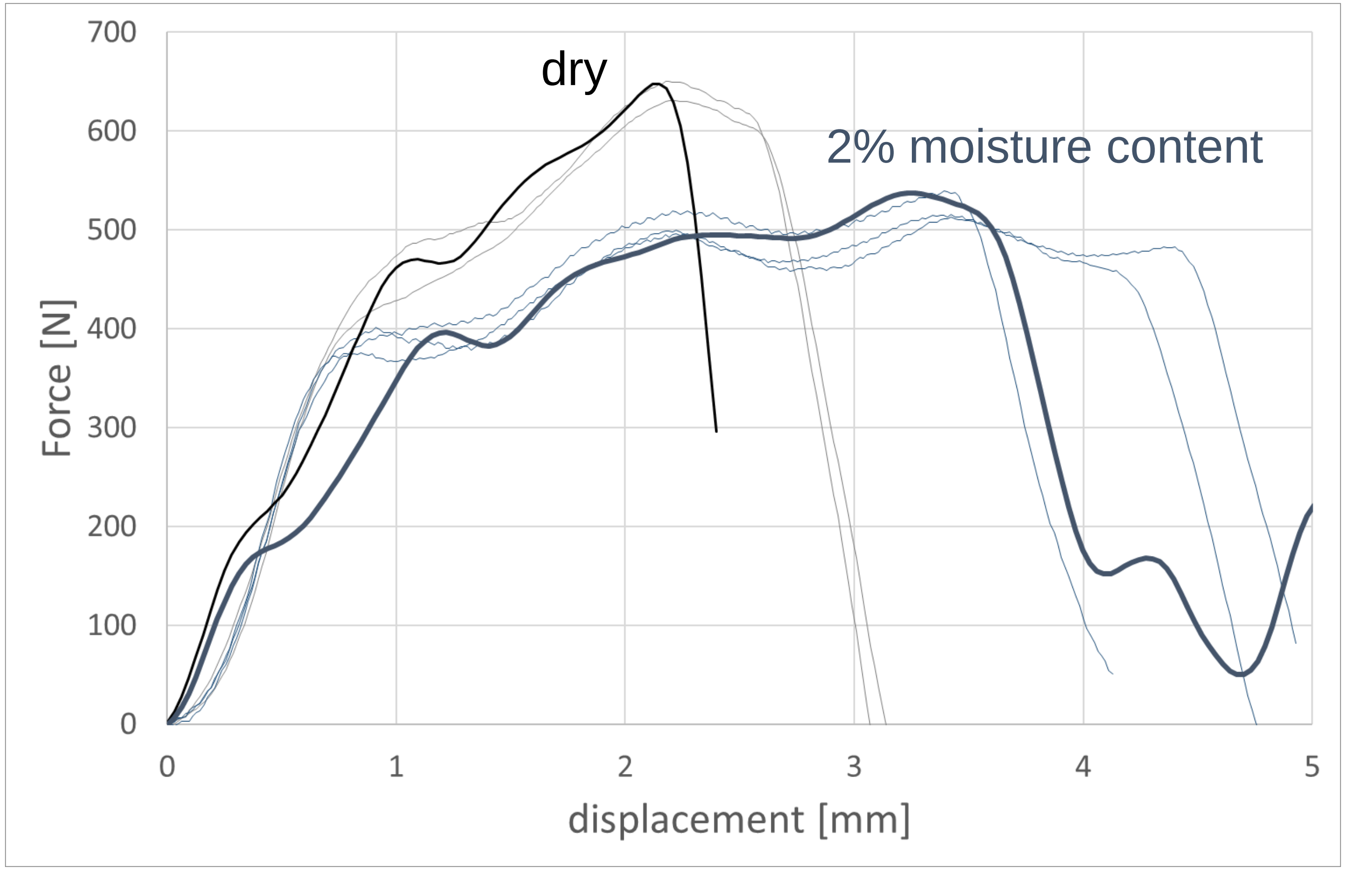


Source: P Reithofer, failure criteria SFRT and LFRT

Case study - sleeve

Further investigations

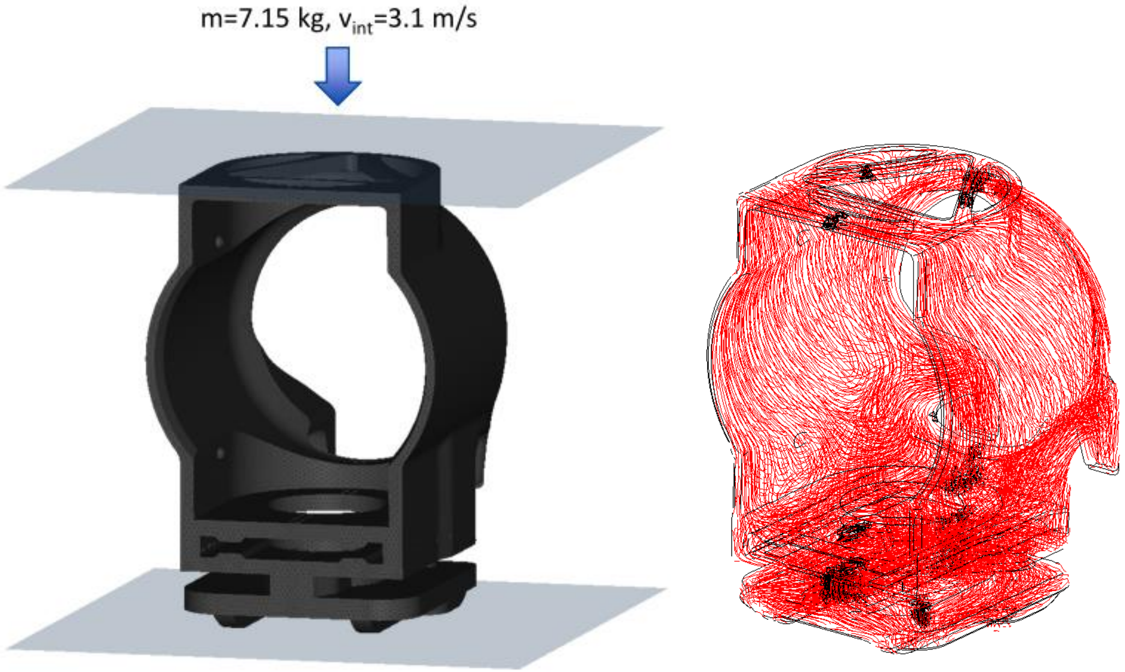


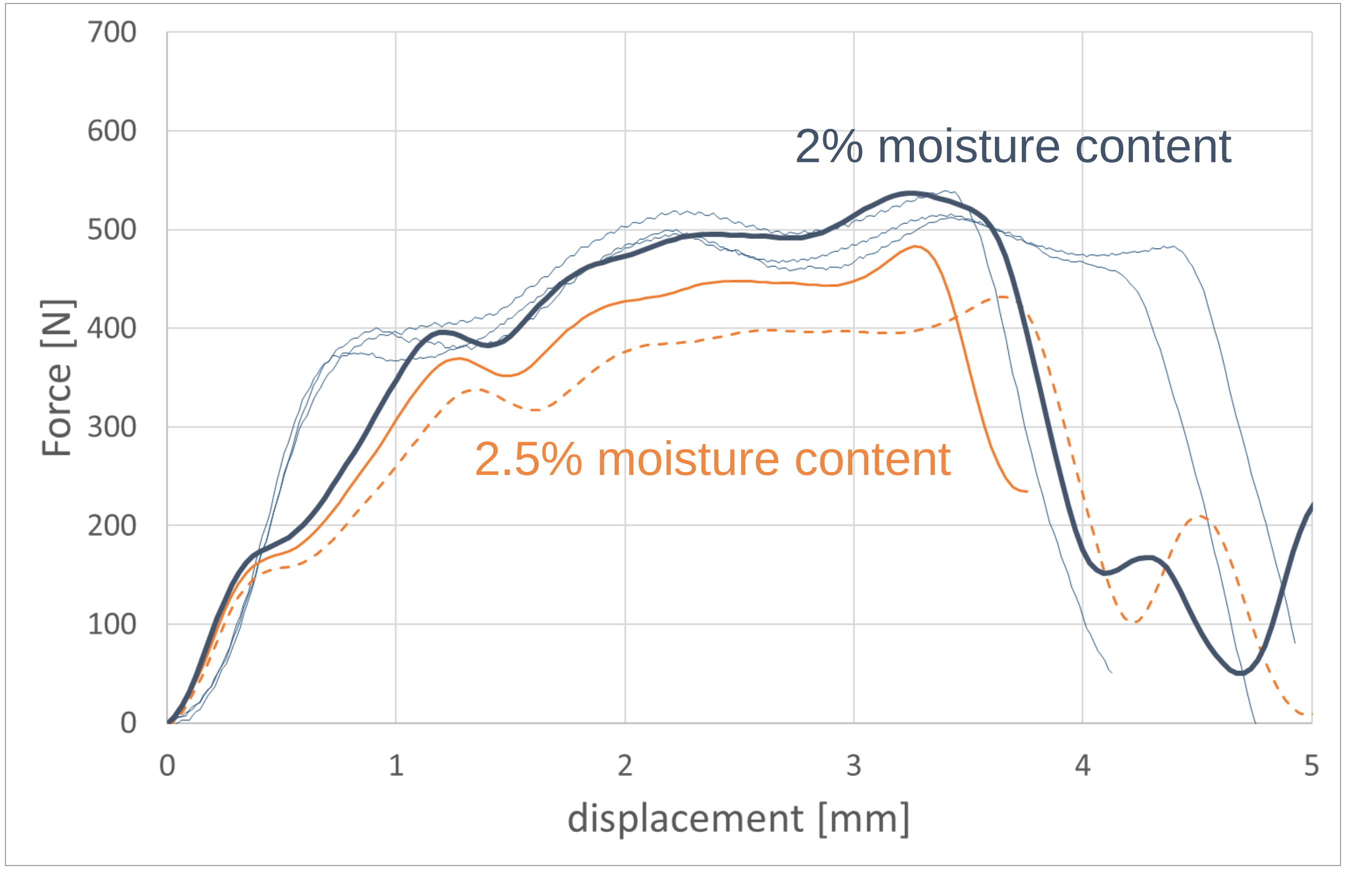


Typical element size : 0.25 mm
Element type : Tetrahedron Type 10
Number of elements : 469470

—— material cards based on mapped FOT
—— test curves

Case study - sleeve
Further investigations



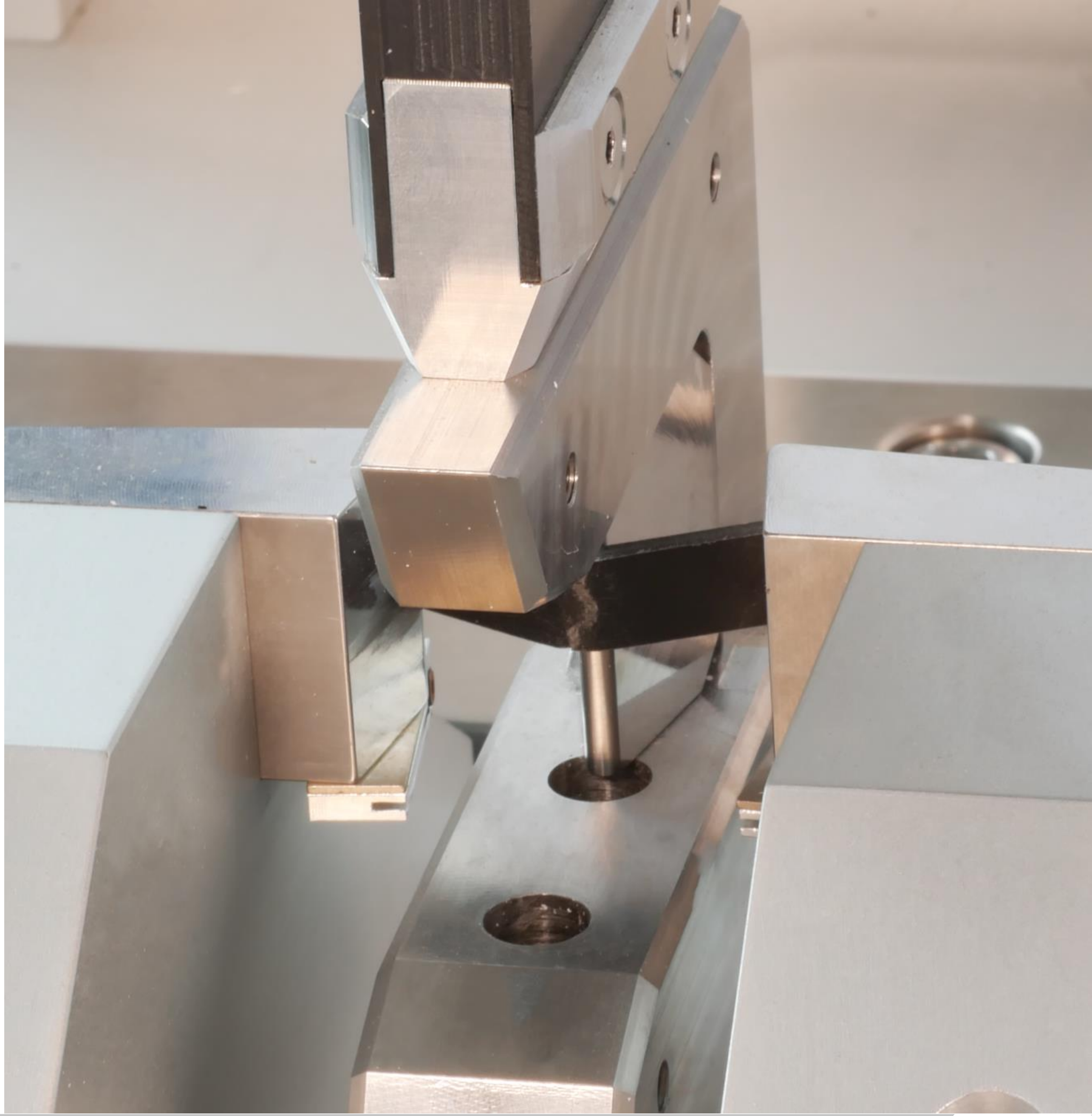


Typical element size : 0.25 mm
Element type : Tetrahedron Type 10
Number of elements : 469470

- - - material cards based on measured FOT by µCT
—— material cards based on mapped FOT
—— test curves

Summary

- Exemplary depiction of main influences
  - MATRIX – Temp. & strain rate
  - FIBER – content & orientation
- Adaptive material card
  → key enabler micro mechanics
- Material models
  - Macro scale
    → computational efficient
  - Micro scale
    → user flexibility and predictive



Thanks for your attention

[YouTube CHANNEL]