*MAT_4A_MICROMEC – micro mechanic based material model

P. Reithofer[1], A. Erhart[2], A. Fertschej[1], S. Hartmann[2], B. Jilka[1]

[1]4a engineering GmbH, [2]Dynamore GmbH

1 Introduction

Nowadays a great number of short and long fiber reinforced thermoplastics play a decisive role in the automotive industry to ensure affordable lightweight design and availability in large quantities. The properties of these materials are especially highly influenced through the manufacturing process (typically injection molding for SFRT and LFRT). Due to the short filling times high speeds and pressures are necessary in those processes, This leads to a a development of a significant fiber orientation by the extensional and shear flows in the mould. Integrative simulation is considering this manufacturing-induced distribution in the structural simulation by mapping the fiber orientation from the process simulation to the structural analysis.

2 State of the art

Until now there are two approaches to consider the local process induced anisotropy. The first one is to use an additional external software library (like ULTRASIM®, DIGIMAT®, ...), which is typically linked as ***USERMATERIAL*** providing a high sophisticated micro mechanical material model that can handle the local anisotropy. The gain in accuracy however means an increase of needed CPU time and additional license costs combined with less flexibility in daily work (e.g. sharing input decks between project partners, library must be available, ...).
The second possibility is to consider the local anisotropy in LS-DYNA with standard available material models or composite layups. The first attempts to describe the anisotropic behavior can be found in these publications:

- [Reithofer2008] : **`*MAT_108`** only orthotropic elastic plastic
- [Nutini2010] : **`*MAT_103`** only orthotropic visco plasticity
- [Schöpfer2011] : **`*MAT_108`** + **`*MAT_054`** approach combining material models

Later approaches considered the fiber orientation by using composite layups or initialization methods (**`*INITIAL_STRESS_SHELL(SOLID)`** [Haufe2014]). Figure 1 shows the current simulation process chain to include the local mechanical anisotropy [Reithofer2015].

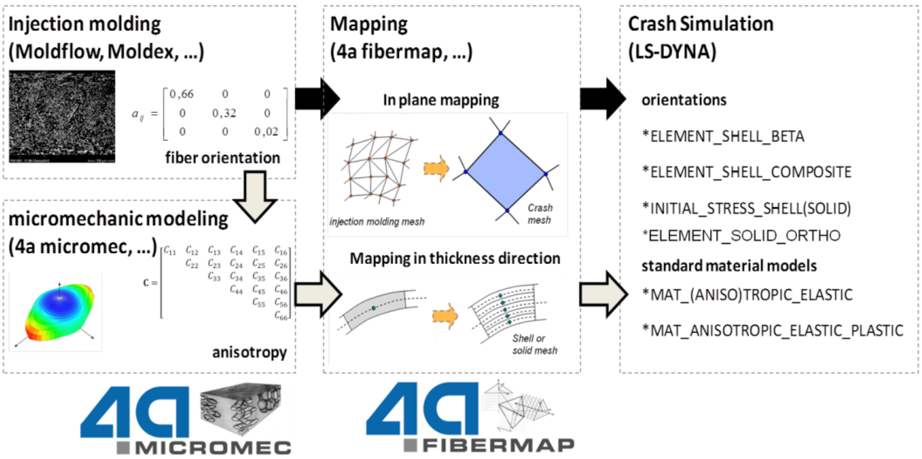

Fig.1: Available simulation process chain for injection molded parts [Reithofer2015].

The later approaches exhibits mainly two drawbacks:

- The used material models are based on a phenomenological description of the whole composite . This prevents the possibility to describe the mechanical behavior based on matrix and fiber dominant mechanical aspects, which can really be helpful in failure prediction and propagation.

- The pre- and post-processing of all these local material properties at each integration point may be cumbersome. A reasonable usage of these simulation methods stops at the mapping of local directional cosines.

3 New developments in LS-DYNA

To improve the current state of the art 4a provided DYNAmore a LS-DYNA usermaterial to be implemented as a standard LS-DYNA material model. Based on [Mlekusch1997] the core functionality to calculate the thermoelastic composite properties using the Mori Tanaka Meanfield Theory, can be found in the software product 4a micromec. Based on the material knowledge of fiber reinforced plastics in the past 15 years this model was extended to an elasto-viscoplastic matrix behavior.

The developments focused on the essential known mechanical material behavior, which leads to a fast and robust material model. The matrix failure is considered by a damage initiation and evolution model and fiber failure may be considered with a simple maximum stress criterion. The needed keyword input properties can be seen in fig. 2. Starting with R10 the presented material model shall be available as **`*MAT_215/ *MAT_4A_MICROMEC`**, implemented for shell, thick shell and solid elements.

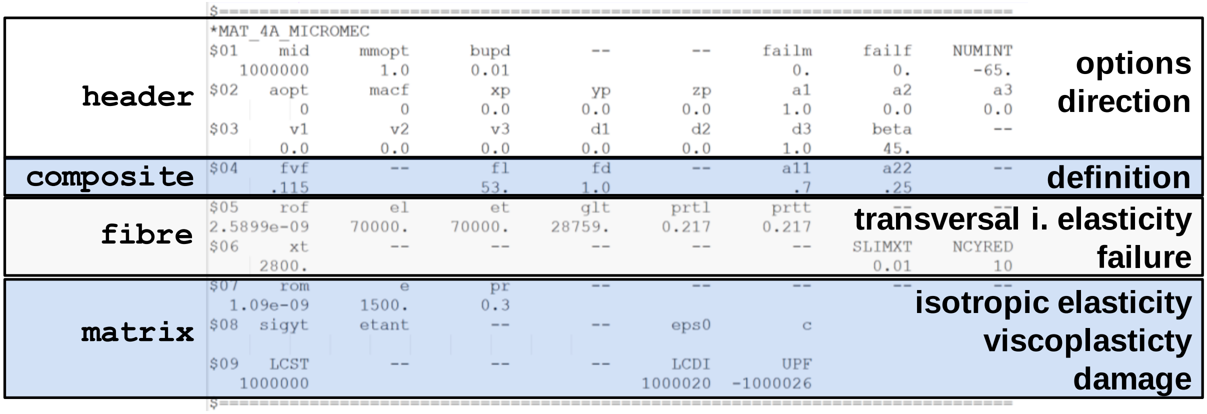

Fig.2: Typical keyword input for ***`*MAT_215/*MAT_4A_MICROMEC`.***

4 Verification / Validation / CPU consumption

In the presentation some simulation verification (e.g. matrix only, fiber only, DOE on fiber content/-orientation/aspect ratio, ...) and validation results on coupon level of PP fiber reinforced material will be shown. The model calibration [Reithofer2016] and usage in the simulation process chain will be roughly described. Also results on CPU time consumption and current experiences on large models will be discussed. Finally an outlook to further possible developments and improvements will be given.

5 Literature

[Reithofer2008] Reithofer, P. et. al: *Kurzfaserverstärkte Kunststoffbauteile Einfluss der prozessbedingten Faserorientierung auf die Strukturmechanik*, 7. LS-DYNA Anwenderforum, Bamberg 2008

[Nutini2010] Nutini, M. et. al: *Simulating anisotropy with LS-Dyna in glass-reinforced, polypropylene-based components*, 9. LS-DYNA Forum, Bamberg 2010

[Schöpfer2011] Schöpfer, J.: *Spritzgussbauteile aus kurzfaserverstärkten Kunststoffen: Methoden der Charakterisierung und Modellierung zur nichtlinearen Simulation von statischen und crashrelevanten Lastfällen*, Dissertation, Institut für Verbundwerkstoffe GmbH 2011

[Haufe2014] Haufe, A. et. al: *Zum aktuellen Stand der Simulation von Kunststoffen mit LS-DYNA*, 11. 4a Technologietag, Schladming 2014

[Mlekusch1997] Mlekusch, B. A.: Kurzfaserverstärkte Thermoplaste, Dissertation, Montanuniversität Leoben (1997)

[Reithofer2015] Reithofer, P. et. al: *Short and long fiber reinforced thermoplastics material models in LS-DYNA*, 10th European LS-DYNA Conference, Würzburg 2015

[Reithofer2016] Reithofer, P. et. al: *Material characterization of composites using micro mechanic models as key enabler*, NAFEMS DACH, Bamberg 2016

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Deutsches LS-DYNA Forum
10. – 12. October 2016, Bamberg

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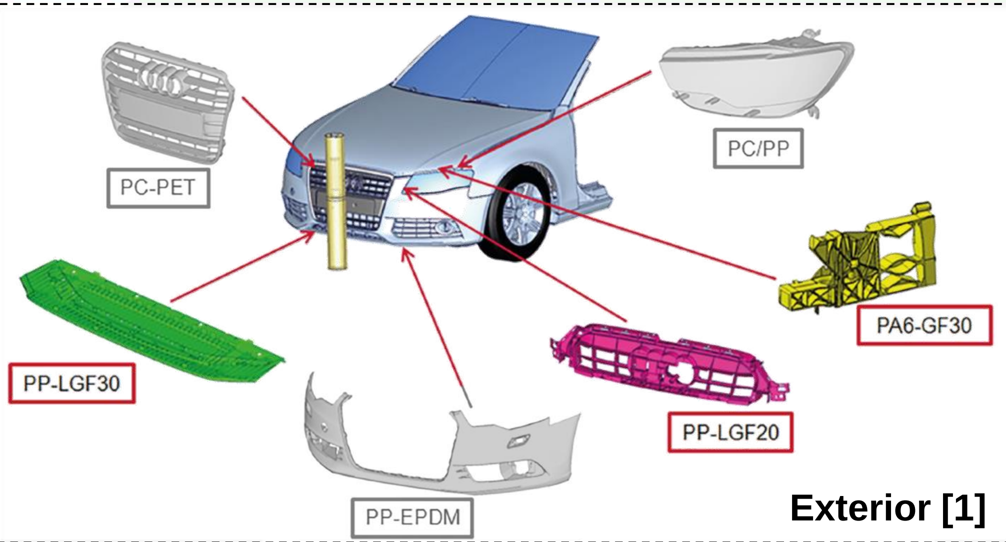
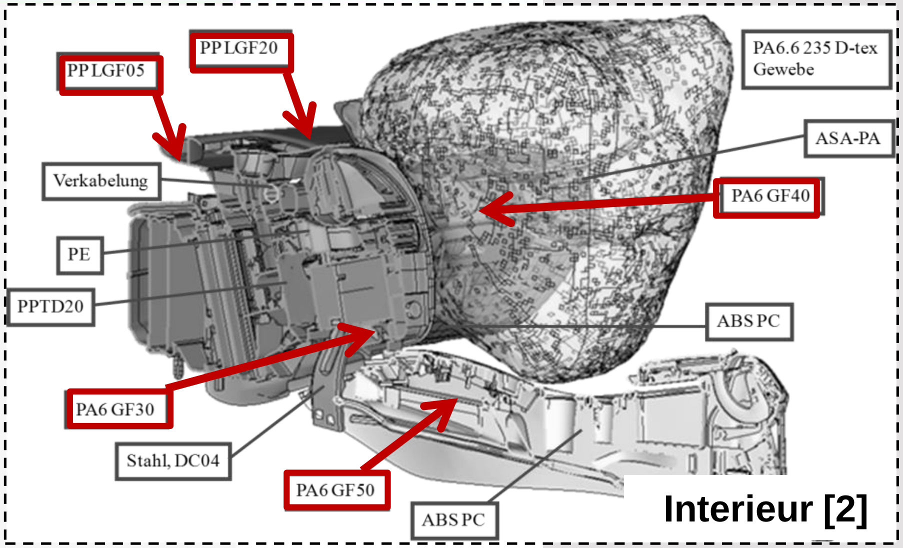
Content

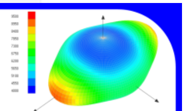
- Introduction
- Simulation process chain
- Constitutive material models in LS-DYNA
- **`*MAT_215 – *MAT_4A_MICROMEC`**
  - mean field homogenization
  - Keyword format
  - verification
  - validation
  - CPU time
- Case studies
- Conclusion

Introduction
plastics in typical automotive applications



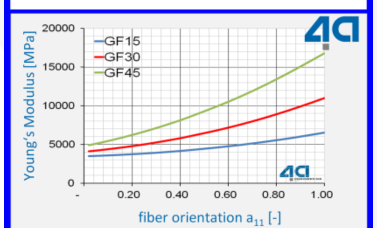


H1



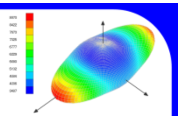
PA6GF30

polyamide short glass fiber reinforced



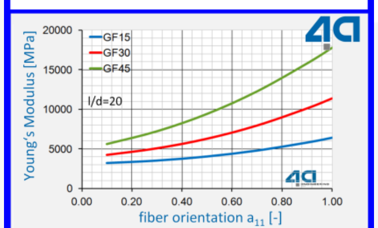
P: 3.4 €/kg
ρ: 1.4 g/cm³
E_1: 9700 MPa
α_1: $64\cdot10^{-6}$ 1/K
σ_y: 140 MPa
ε_B: 4%
T_G: 50 °C
a_c: 100(15) kJ/m²

H2



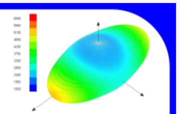
PBTGF30

polybutylene terephthalate short glass fiber reinforced



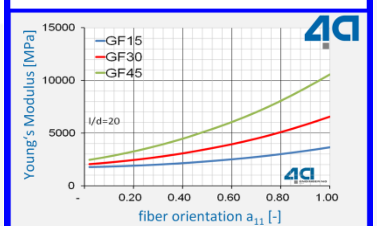
P: 3 €/kg
ρ: 1.5 g/cm³
E_1: 9500 MPa
α_1: $25\cdot10^{-6}$ 1/K
σ_y: 92 MPa
ε_B: 3%
T_G: 30 °C
a_c: 67(11) kJ/m²

H3



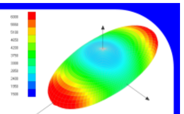
PPGF30

polypropylene short glass fiber reinforced



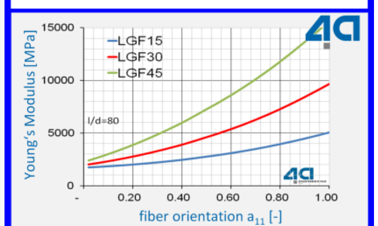
P: 2.3 €/kg
ρ: 1.1 g/cm³
E_1: 6000 MPa
α_1: $38\cdot10^{-6}$ 1/K
σ_y: 70 MPa
ε_B: 4%
T_G: -10 °C
a_c: 20(5) kJ/m²

H4



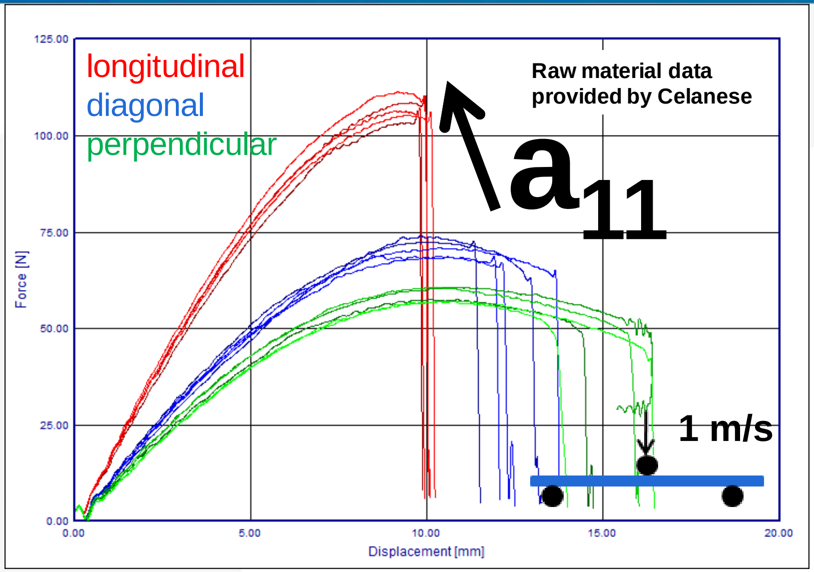
PPLGF30

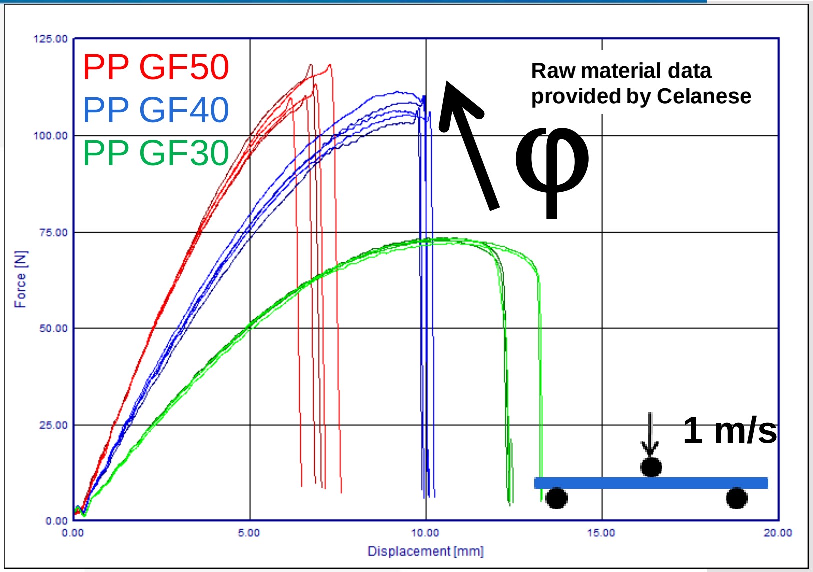
polypropylene long glass fiber reinforced

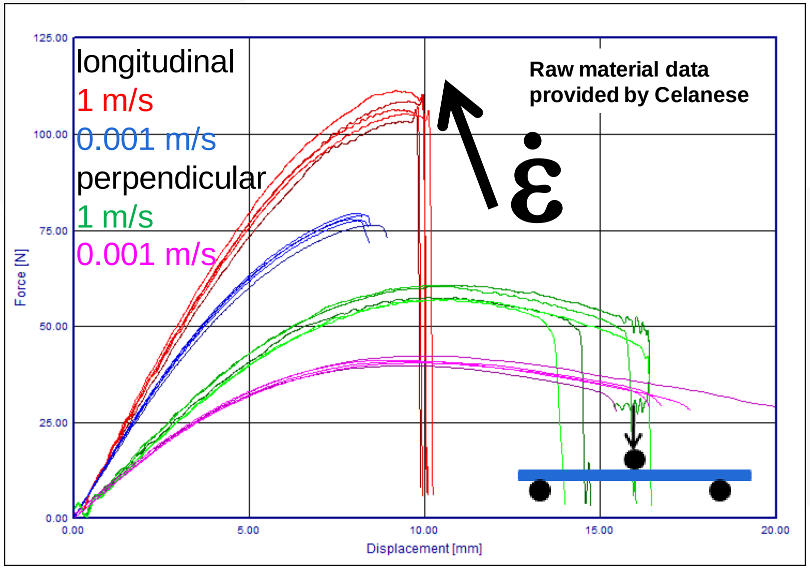


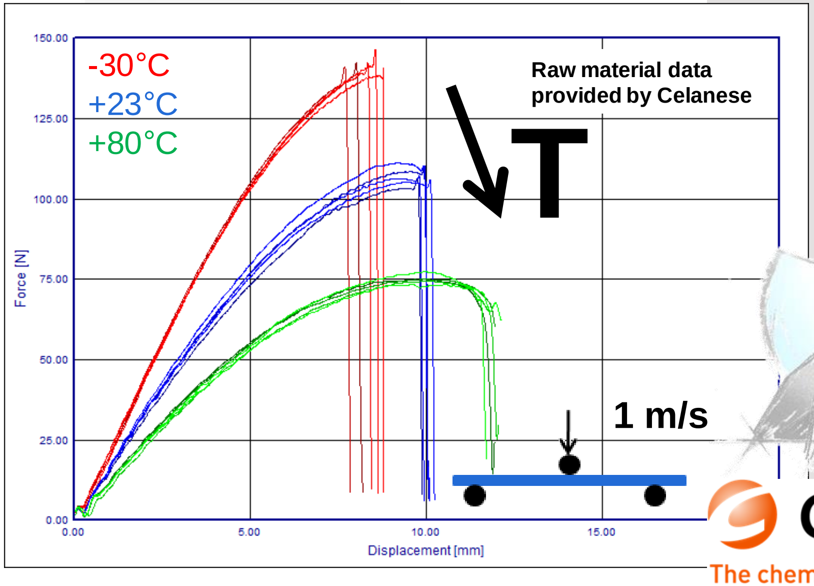
P: 2.5 €/kg
ρ: 1.1 g/cm³
E_1: 6900 MPa
α_1: $40\cdot10^{-6}$ 1/K
σ_y: 76 MPa
ε_B: 5%
T_G: -10 °C
a_c: 70(18) kJ/m²

Introduction
typical behavior

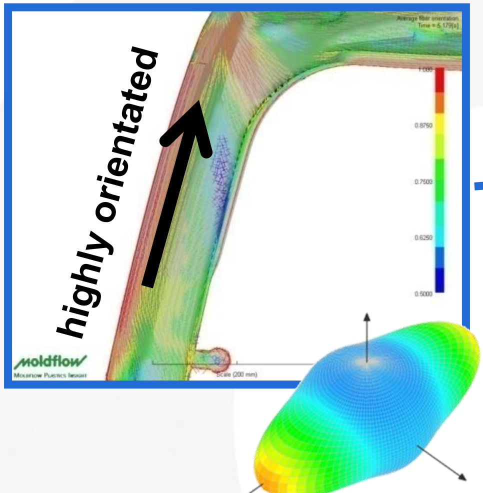




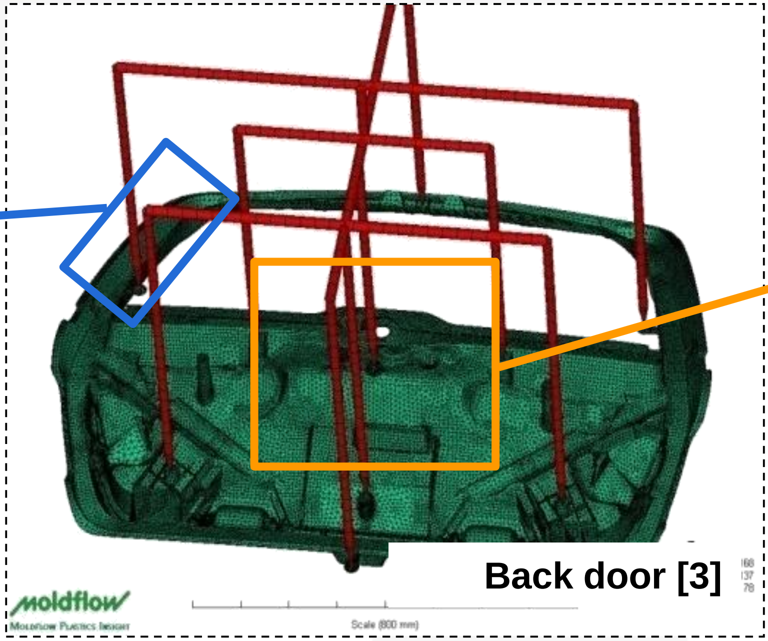


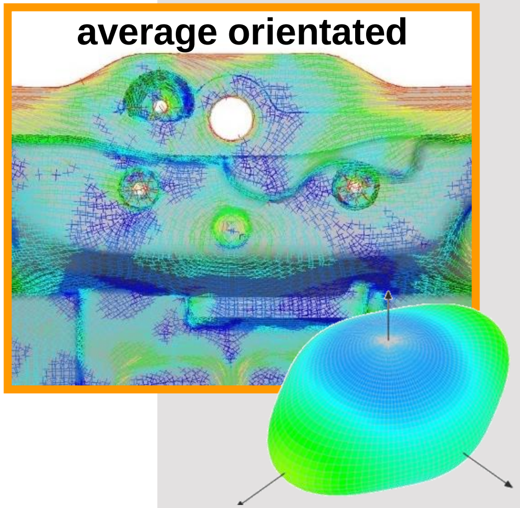


Introduction
typical SFRT

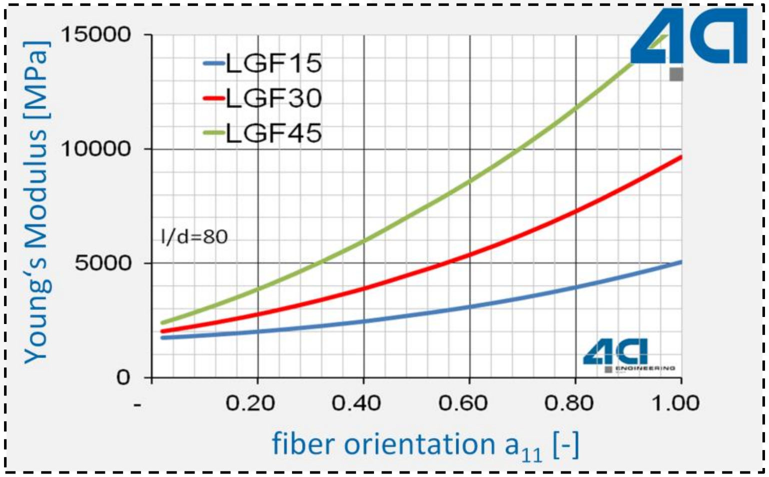


$$a_{ij} = \begin{bmatrix} 0{,}87 & 0 & 0 \\ 0 & 0{,}11 & 0 \\ 0 & 0 & 0{,}02 \end{bmatrix}$$





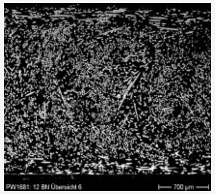
$$a_{ij} = \begin{bmatrix} 0{,}66 & 0 & 0 \\ 0 & 0{,}32 & 0 \\ 0 & 0 & 0{,}02 \end{bmatrix}$$



Simulation process chain
For injection molded parts

4a ENGINEERING GmbH

Injection molding (Moldflow, Moldex, …)

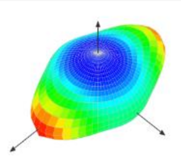


$$a_{ij} = \begin{bmatrix} 0{,}66 & 0 & 0 \\ 0 & 0{,}32 & 0 \\ 0 & 0 & 0{,}02 \end{bmatrix}$$

fiber orientation

micromechanic modeling (4a micromec, …)

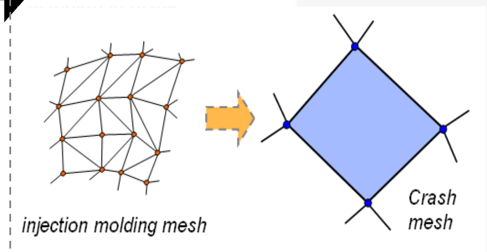
$$C = \begin{bmatrix} C_{11} & C_{12} & C_{13} & C_{14} & C_{15} & C_{16} \\ & C_{22} & C_{23} & C_{24} & C_{25} & C_{26} \\ & & C_{33} & C_{34} & C_{35} & C_{36} \\ & & & C_{44} & C_{45} & C_{46} \\ & & & & C_{55} & C_{56} \\ & & & & & C_{66} \end{bmatrix}$$



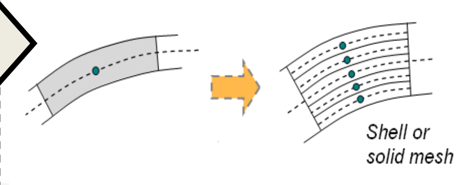
anisotropy

Mapping (4a fibermap, …)

In plane mapping



Mapping in thickness direction



Material Model

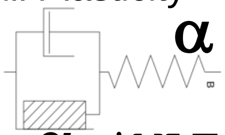
Mean Field homogenization

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

***MAT_215**

Standard Material Model

Hill Plasticity



α α ***MAT_157**

Structural Simulation

4a MICROMEC

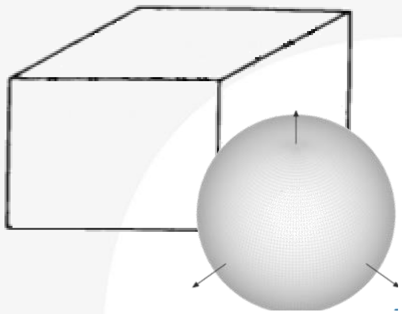
4a FIBERMAP

LSTC Livermore Software Technology Corp.

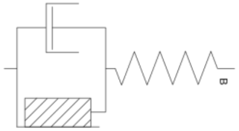
LS-DYNA®

DYNA MORE

Plastics

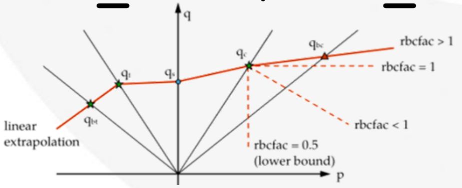


***MAT_024**



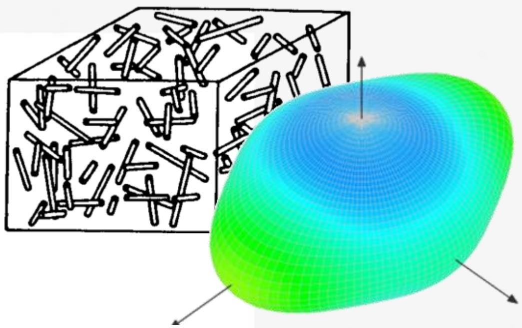
- quick & dirty
- mises plasticity

***MAT_187 (*MAT_124)**



SHELL or TET10

SFRT / LFRT



***MAT_002** α

- orthotropic elastic

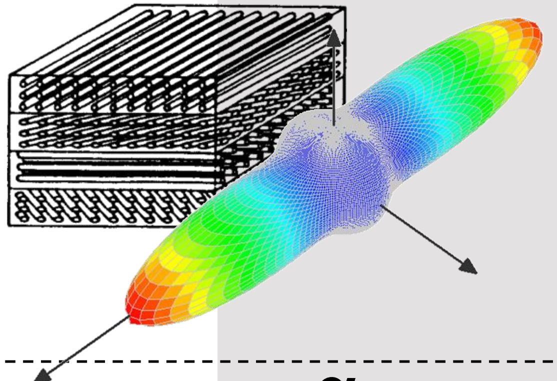
***MAT_157**

α α

- orthotropic
- elastic viscoplastic
- Hill plasticity

INITIAL_STRESS

Composite



***MAT_022/** α

***MAT_054/058**

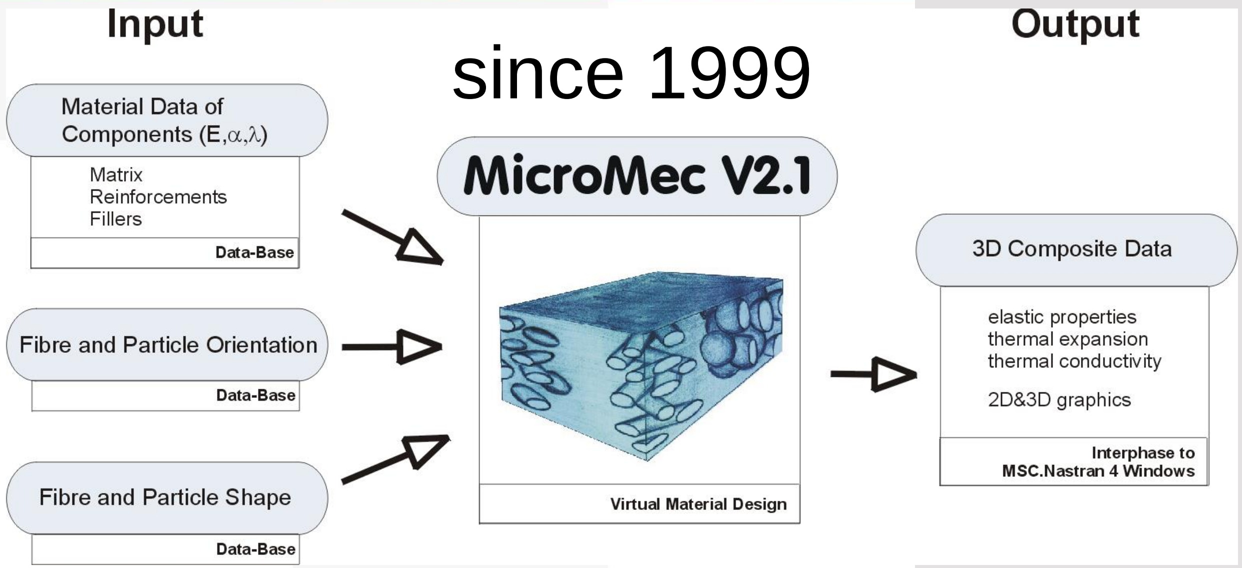
- orthotropic elastic
- Damage

COMPOSITE (PLY)

α – orientation dependent

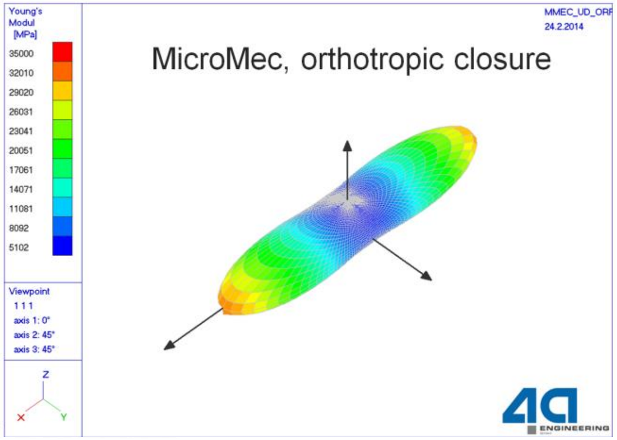
*MAT_215 - *MAT_4A_MICROMEC
mean field homogenization

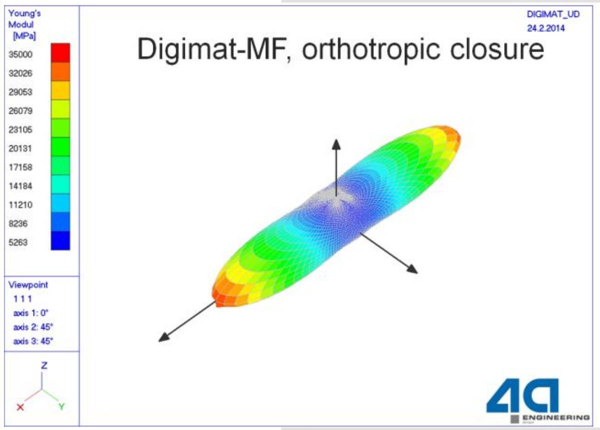
Standalone product



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

C...composite, F...fiber, M...matrix





Comparison by University of Leoben **[Berer2014]**

*MAT_215 - *MAT_4A_MICROMEC
mean field homogenization

4a MICROMEC

Standalone product

Library

4a IMPETUS

***MAT_157**

calculate parameter for constitutive law

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

C...composite, F...fiber, M...matrix

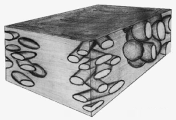
160223_006 | Material | Designvariablen | Layers

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

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]
y_scalematrix0	3.076	[1]

*MAT_215 - *MAT_4A_MICROMEC
mean field homogenization

MICROMEC



Standalone product

Library→4a impetus

usermaterial

Main Framework
Mori Tanaka Mean Field Theory

Composite stresses, strains (i)
↓
Matrix stresses, strains → **Yield condition**
↓
Fiber stresses, strains
↓
Failure, Damage Criteria
↓
Composite stresses, strains (i+1)

plug able
possible extensions other plasticity formulations, ...

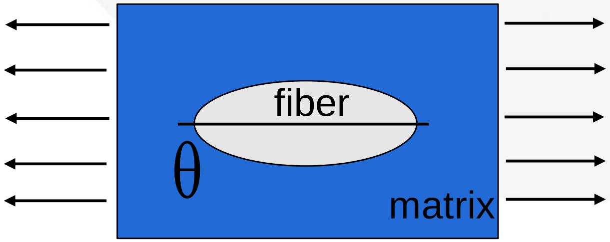
→ J2 Plasticity
Isotropic Harding

Table Lookup or Parameter Setup

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

C...composite, F...fiber, M...matrix

assumption elliptical inclusion
(Eshelby Tensor)



$$\Delta\varepsilon^C \Rightarrow \Delta\varepsilon^M, \left(\Delta\varepsilon^F\right)$$

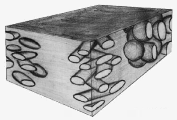
$$\Delta\varepsilon^M = \frac{1}{\varphi\overline{B}_i + (1-\varphi)I}\Delta\varepsilon^C$$

$$\Delta\varepsilon^M \Rightarrow E_M^T, \Delta\varepsilon^M{}_{pl}, \Delta\sigma^M$$

$$\overline{B}_{i+1} = f\left(fo^{(4)}, E_M^T, {}^{l}\!/\!_{d}\right)$$

$$\overline{A} = S^F\,\overline{B}_{i+1}C^M$$

$$\Delta\sigma^C = \left[\varphi\overline{A} + (1-\varphi)I\right]\Delta\sigma^M$$



MICROMEC

Standalone product

Library→4a impetus

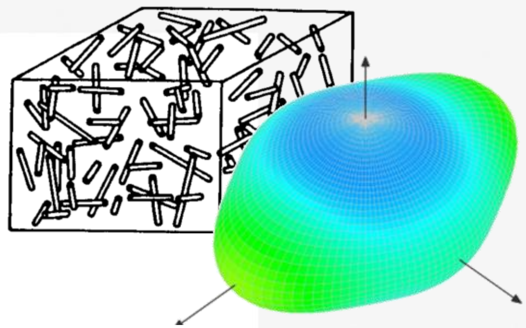
usermaterial

*MAT_4A_MICROMEC

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

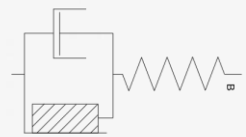
C...composite, F...fiber, M...matrix

SFRT / LFRT



***MAT_215**

matrix:



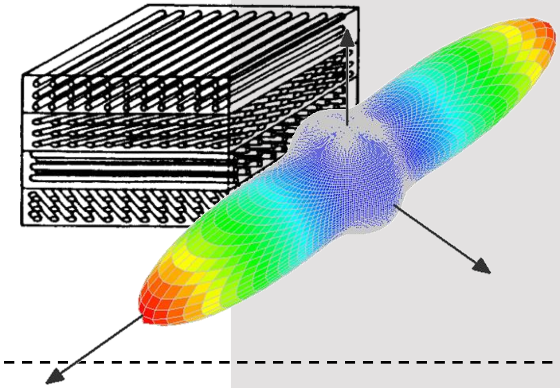
- isotropic elastic viscoplastic (like MAT_024)

fiber:

- isotropic elastic

INITIAL_STRESS

Composite



***MAT_215**

matrix:

- isotropic elastic

fiber:

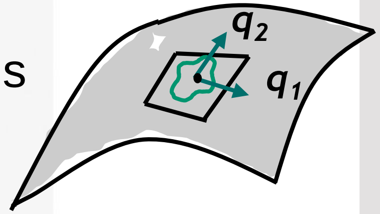
- transversal isotropic elastic

COMPOSITE (PLY)

CARD 1: General Options / Parameter

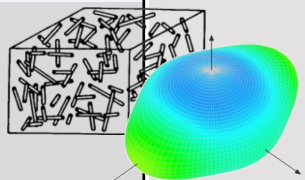
CARD 2-3: Element orientation*

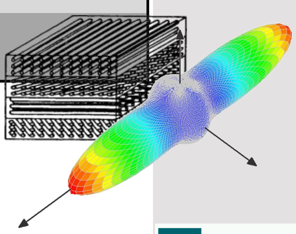
analog to LSDYNA standard anisotropic material cards



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

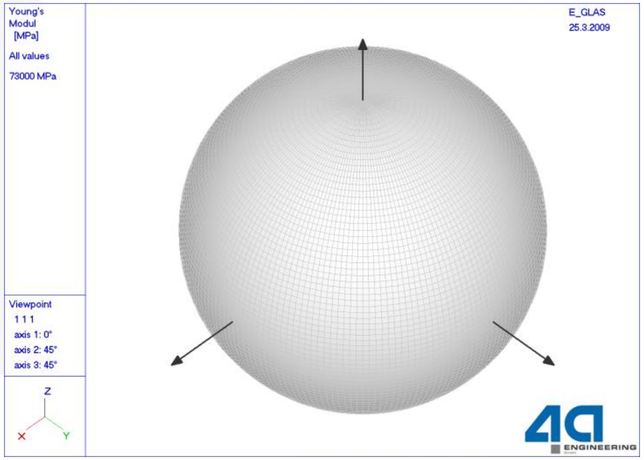
*may be overwritten by
`*INITIAL_STRESS_SHELL/SOLID`

CARD 5: fiber material

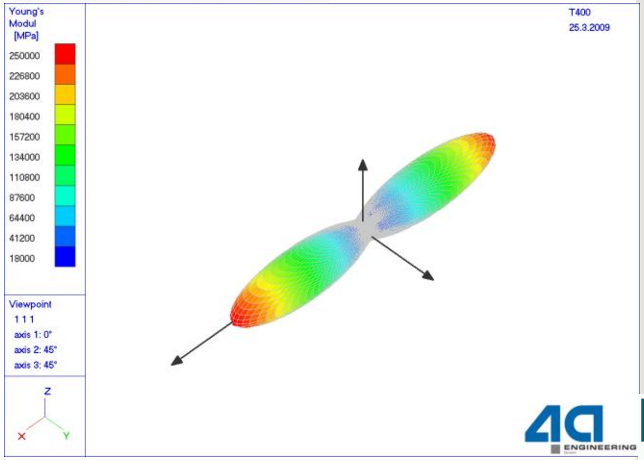
Standard values from literature

Card 5	1	2	3	4	5	6	7	8
FIBER	ROF	EL	ET	GLT	PRTL	PRTT		
UNITS	kg/mm^3	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)



CARD 7-8: matrix material

from material characterization (e.g. 4a impetus MPIP)

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

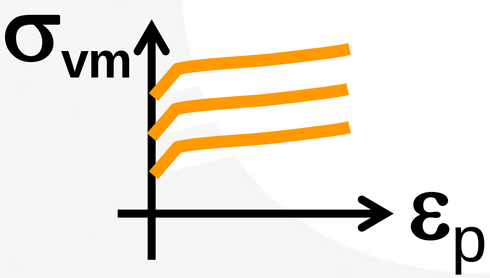
4a ENGINEERING GmbH

CARD 9: matrix material tables

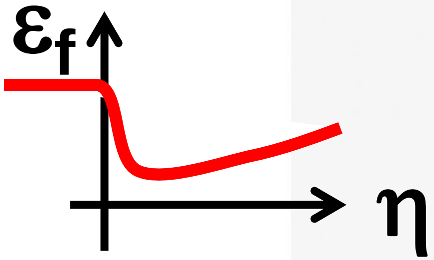
Card 9	1	2	3	4	5	6	7	8
Variable	LCIDT				LCDI	UPF		
Type	F				F	F		
Default	0				0	0.0		

LCIDT	Effective stress (Table)
LCDI	Damage initiation (Table)
UPF	Damage evolution parameter

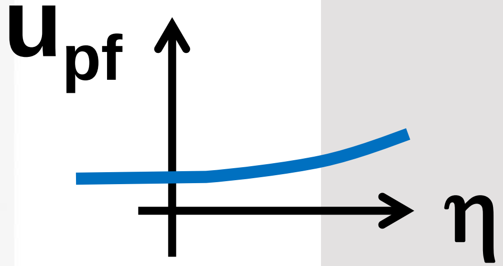
Hardening



Damage Initiation

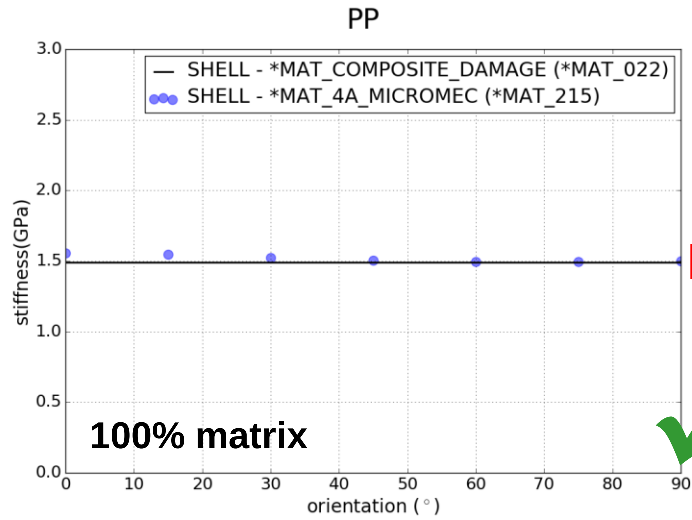


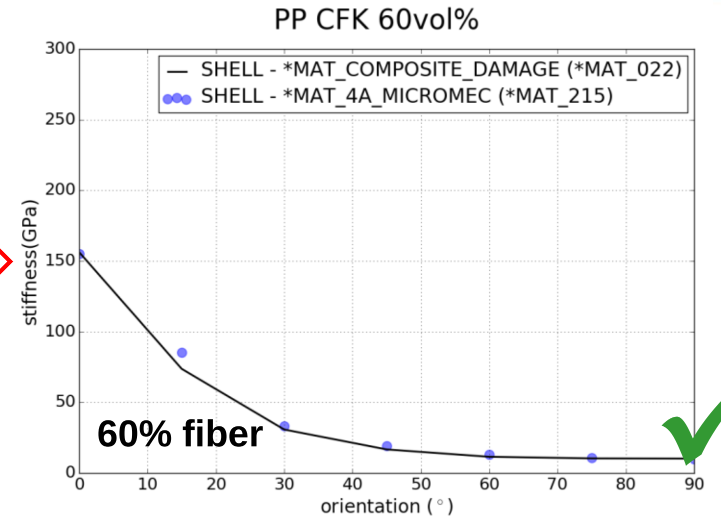
Damage Evolution

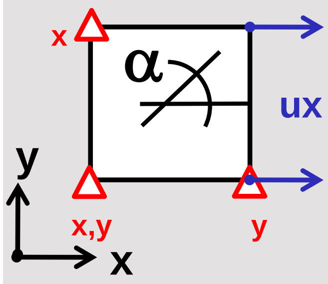


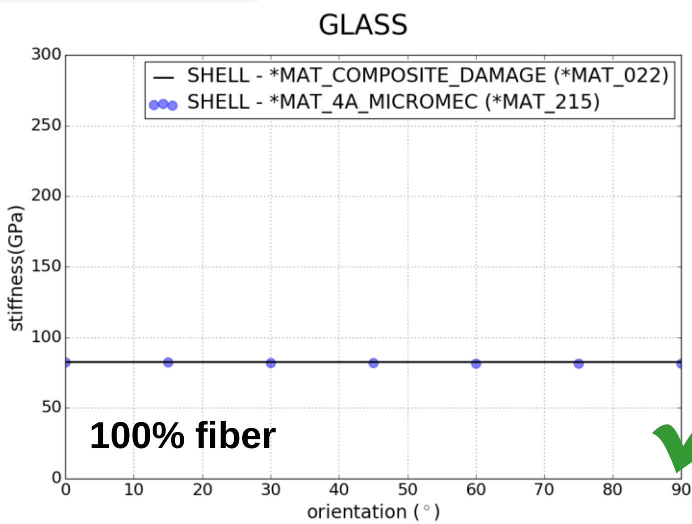
DYNA MORE

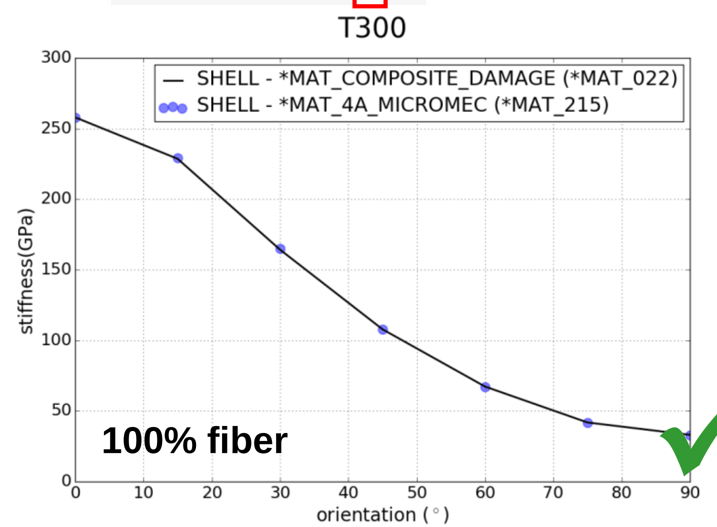
*MAT_215 - *MAT_4A_MICROMEC
Verification – 1-Element tension test



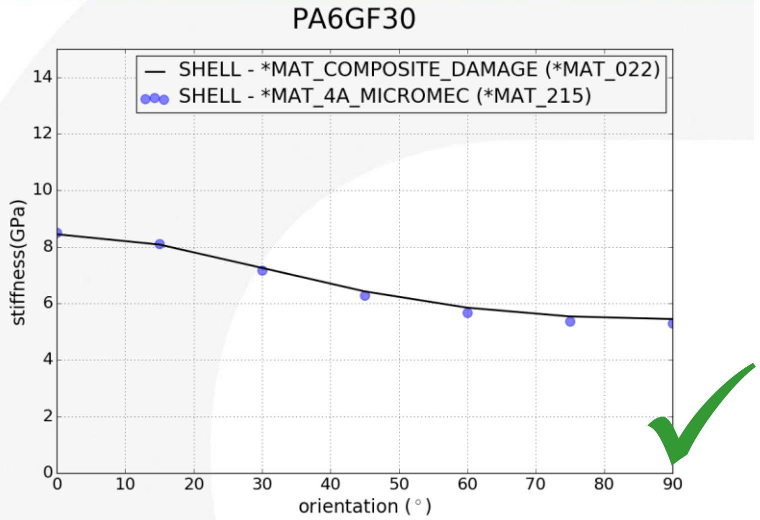


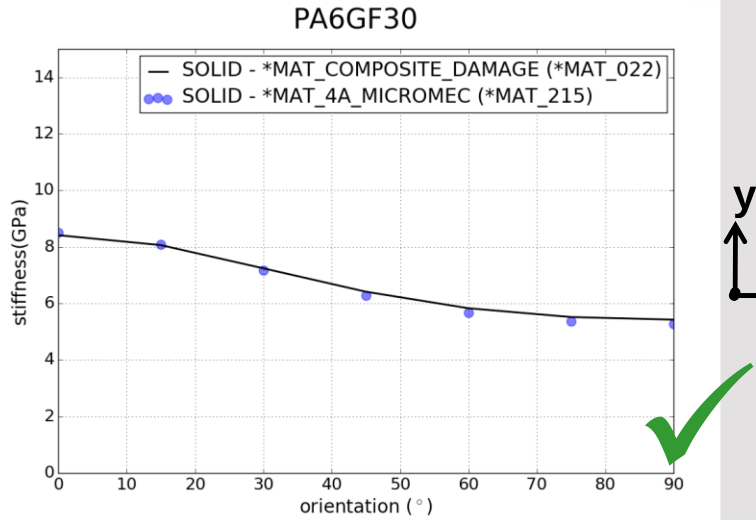


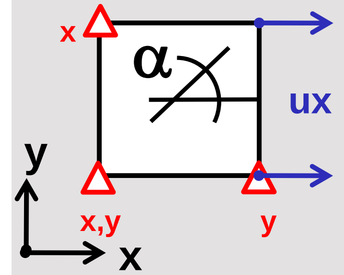


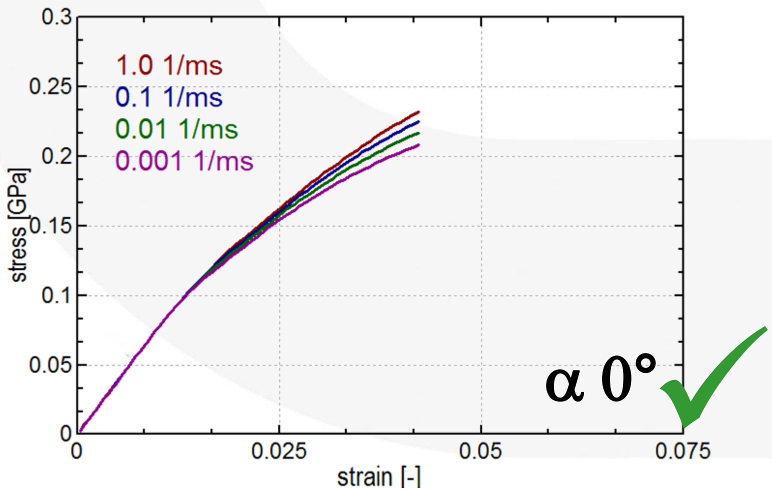


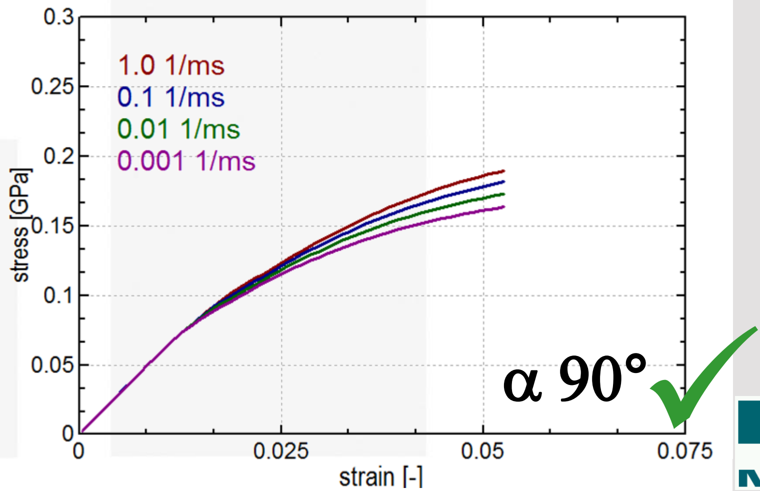
*MAT_215 - *MAT_4A_MICROMEC
Verification – 1-Element tension test



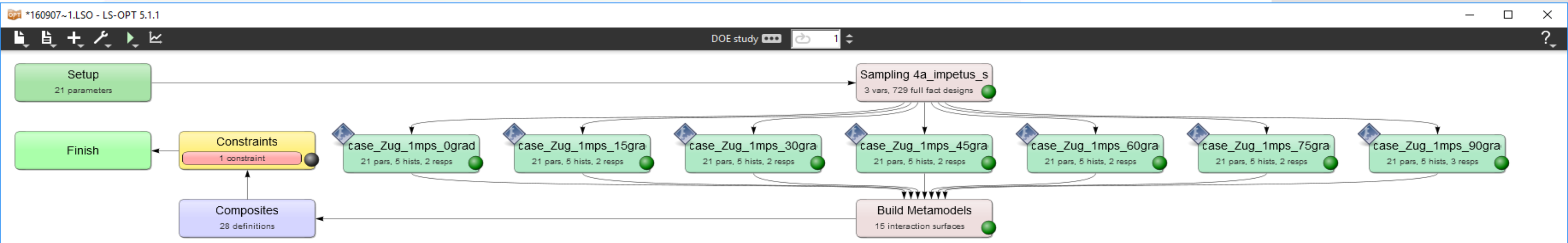








*MAT_215 - *MAT_4A_MICROMEC
Verification – 1-Element tension test



DOE with LS-OPT:

MATRIX: PP

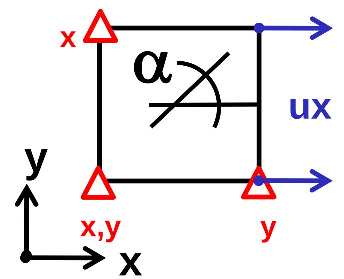
FIBER: GLASS

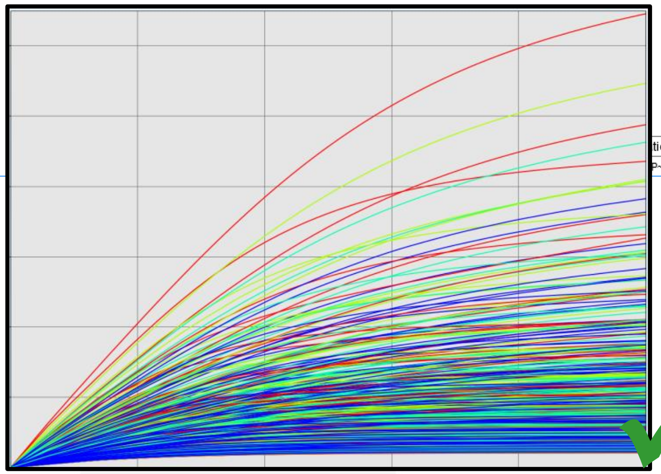
FVF: -0.05;-0.15;-0.20;-0.25;-0.30;-0.35;-0.40;-0.50;-0.60

FL: 100;200;500;1000

A11: 0.6;0.7;0.8;0.9

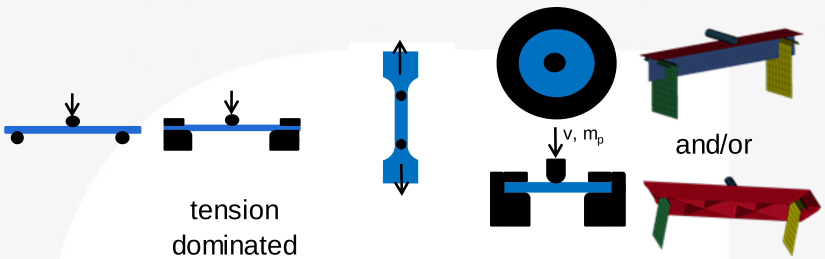
α: 0°;15°;30°;45°;60°;75°;90°

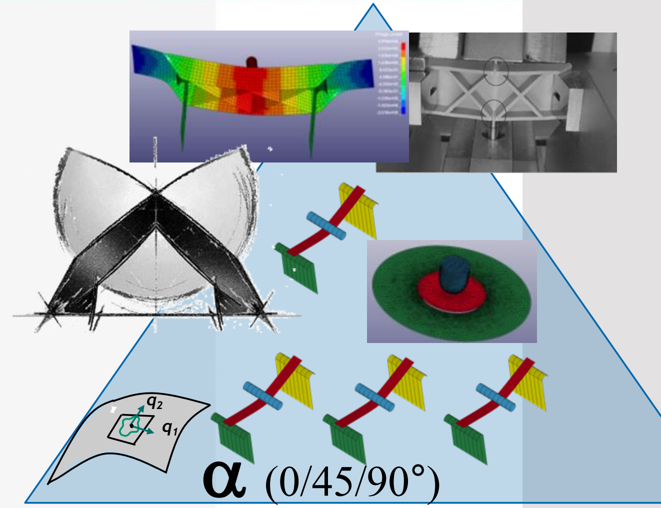




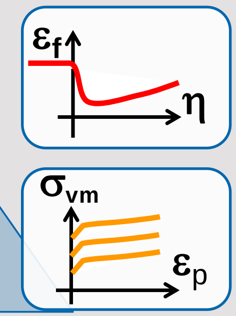
RUNS without an Error

*MAT_215 - *MAT_4A_MICROMEC
Material characterization

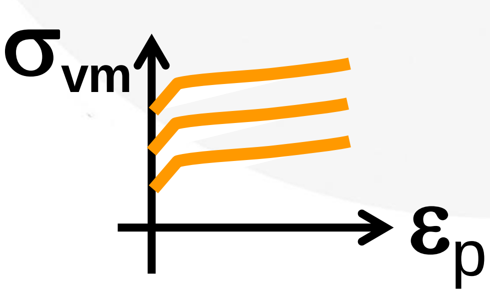


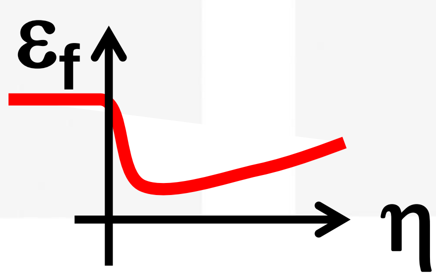


component validation



	bending		tension dominated bending		tension		puncture		validation		
	static	dynamic		dynamic	static	dynamic	static	dynamic	static	dynamic	comment
**MAT_024*	☑	☑									Materialcard for each direction
**MAT_157 *MAT_215*	☑	☑		☑	☑		☑	☑	☑	☑	µCT

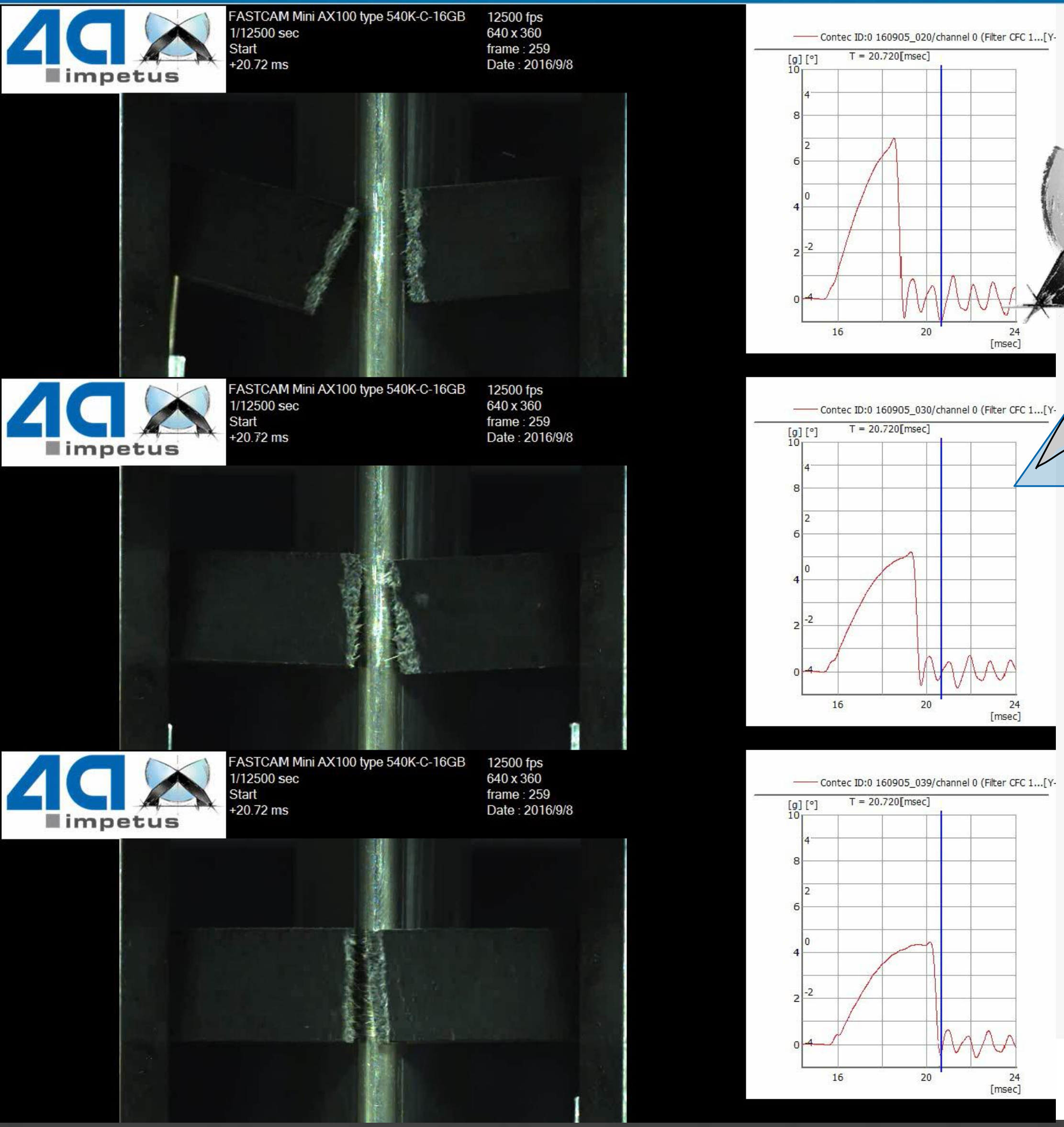


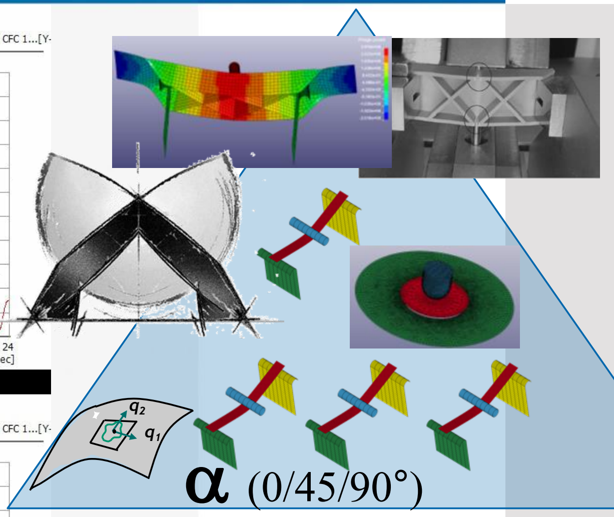


Upcoming ISO
Plate 120 x 80 x 2 mm

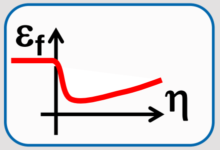
injected samples

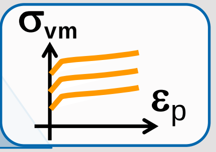
*MAT_215 - *MAT_4A_MICROMEC
Material characterization



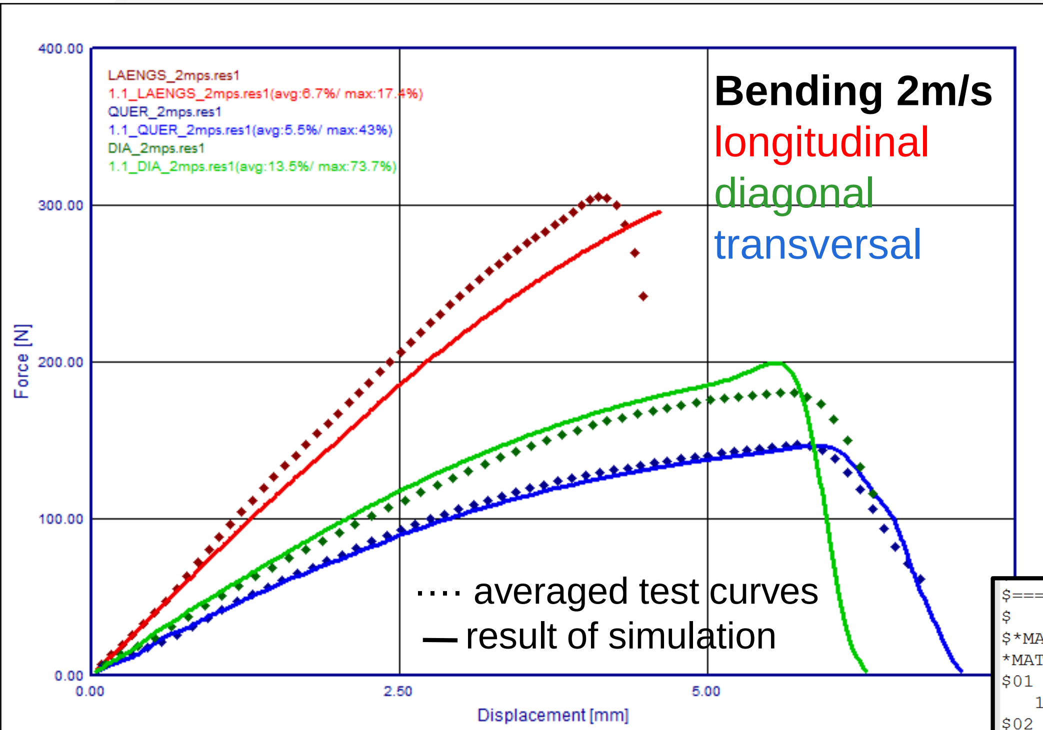


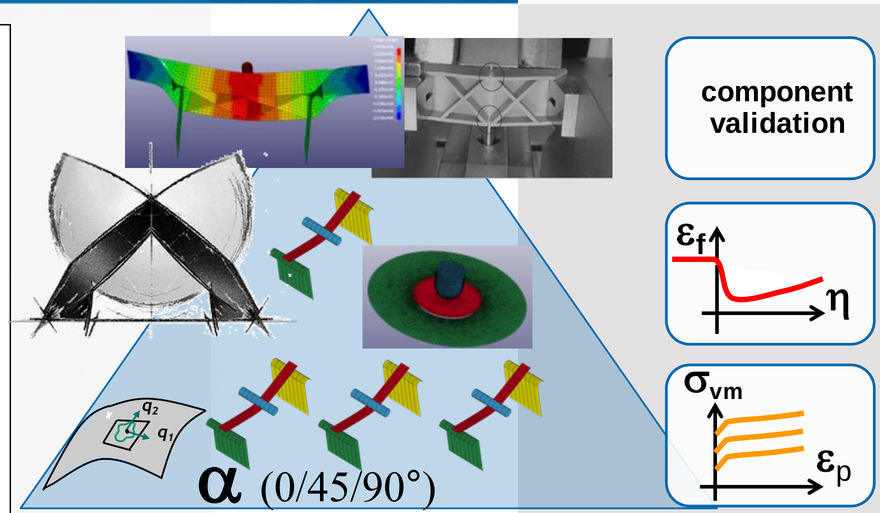
component validation





*MAT_215 - *MAT_4A_MICROMEC
Material characterization

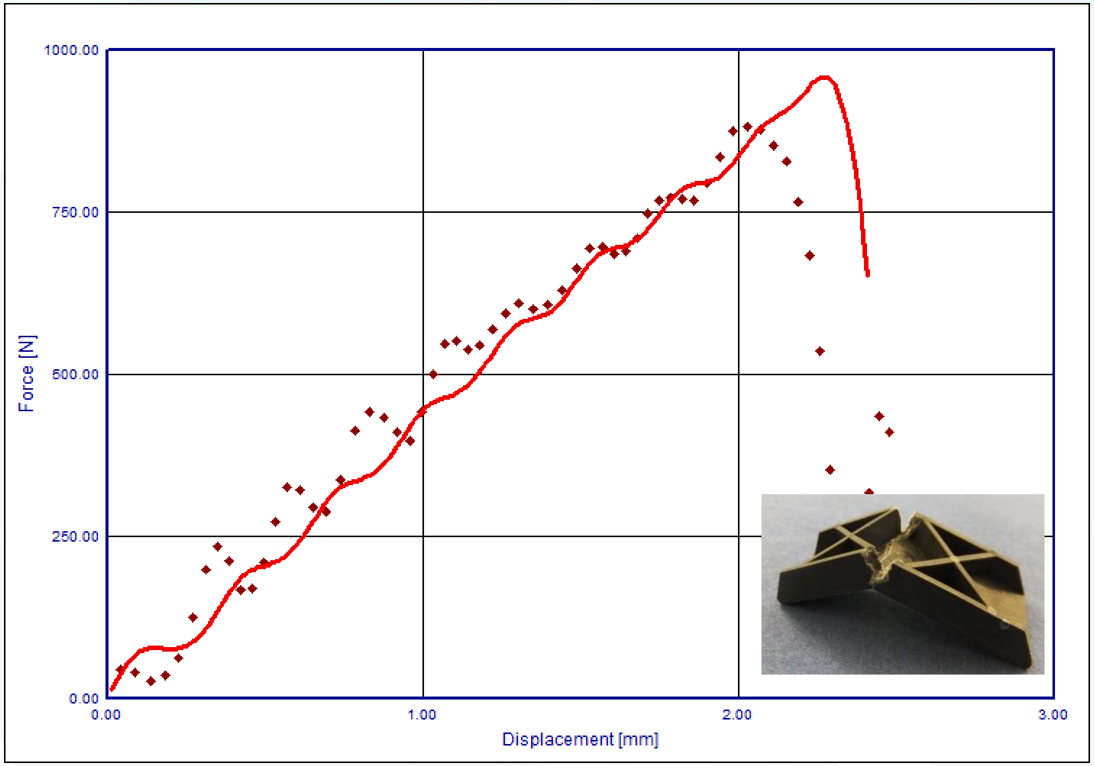


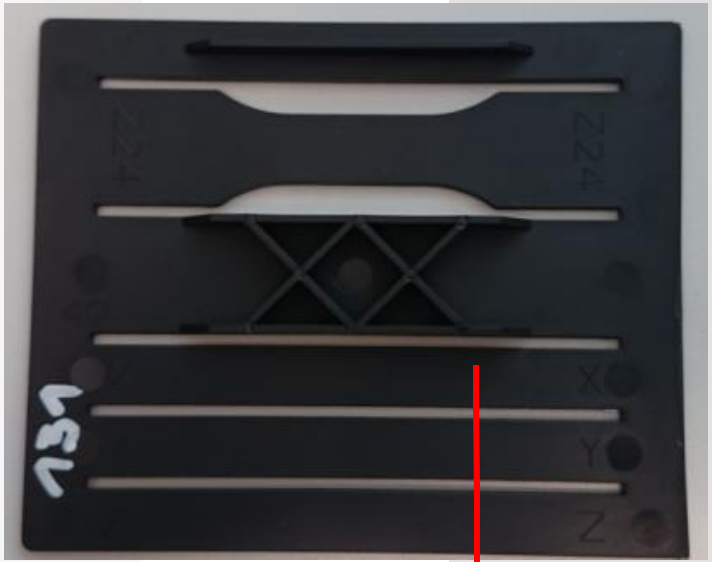


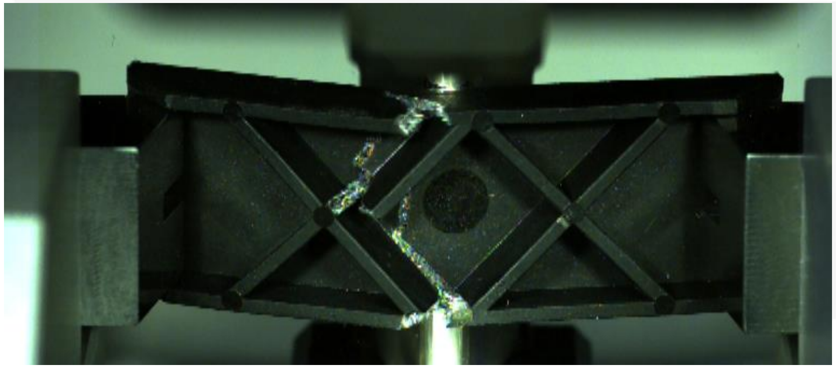

```
$========================================================================================
$
$*MAT_215
*MAT_4A_MICROMEC
$01     mid     mmopt      bupd        --        --     failm     failf    NUMINT
    1000000       1.0      0.01                              1.        0.      -65.
$02    aopt      macf        xp        yp        zp        a1        a2        a3
          0         0       0.0       0.0       0.0       1.0       0.0       0.0
$03      v1        v2        v3        d1        d2        d3      beta        --
        0.0       0.0       0.0       0.0       0.0       1.0        0.
$04     fvf        --        fl        fd        --       a11       a22        --
       .115                 53.       1.0                  .7       .25
$05     rof        el        et       glt      prtl      prtt        --        --
2.5899e-09    70000.    70000.    28759.     0.217     0.217
$06      xt        --        --        --        --        --    SLIMXT    NCYRED
      2800.                                                        0.01        10
$07     rom         e        pr        --        --        --        --        --
    9.1e-10     1500.       0.3
$08   sigyt     etant        --        --      eps0         c

$09    LCST        --        --        --      LCDI       UPF
    1000000                                 1000020  -1000026
$========================================================================================
```

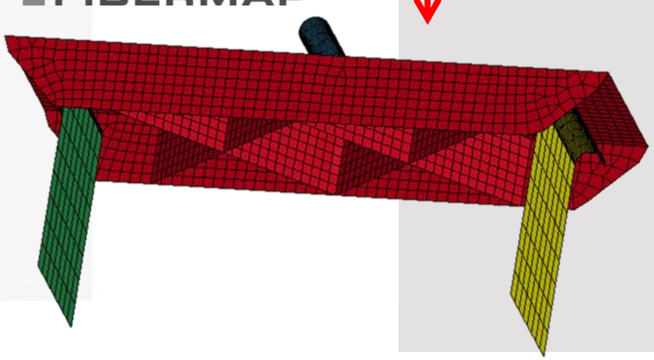
Case study Doublecrossrib
Using *MAT_215



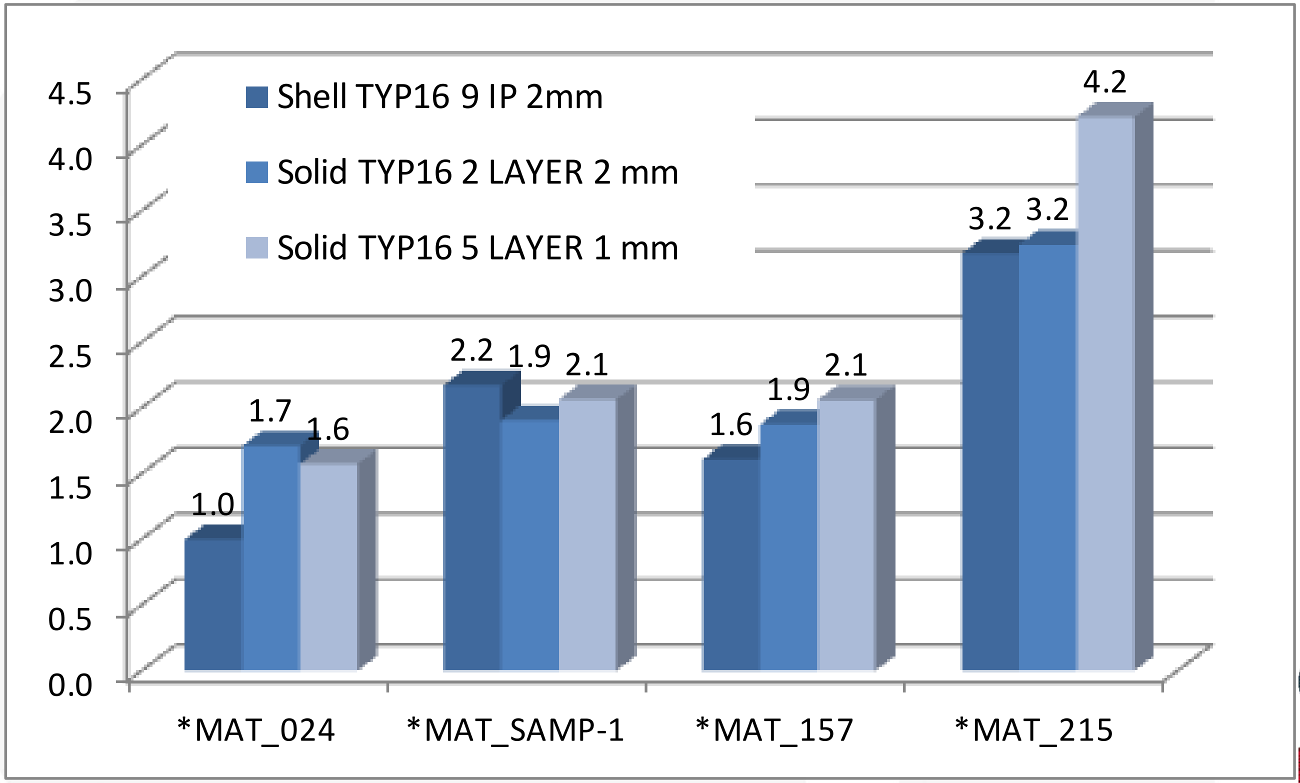


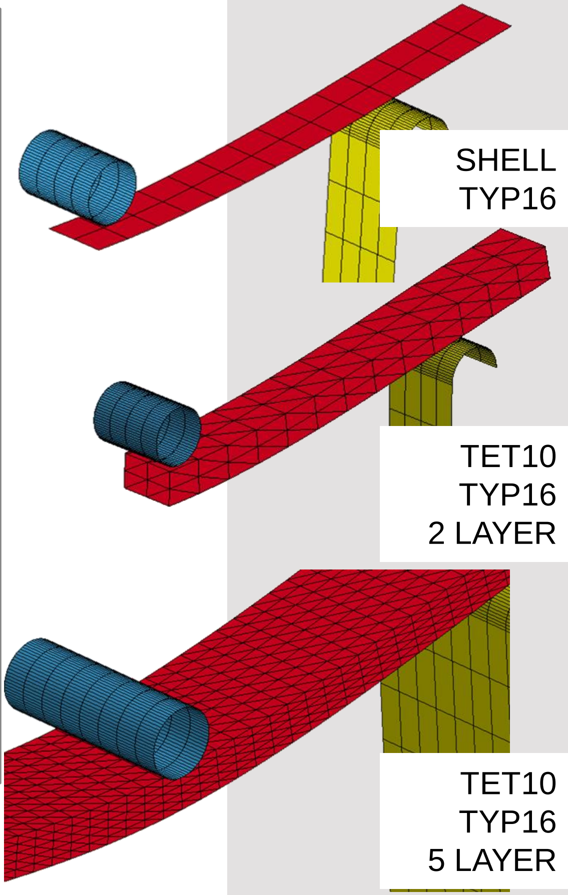


FIBERMAP



*MAT_215 - *MAT_4A_MICROMEC
CPU TIME per integration point (SMP 1 CPU)





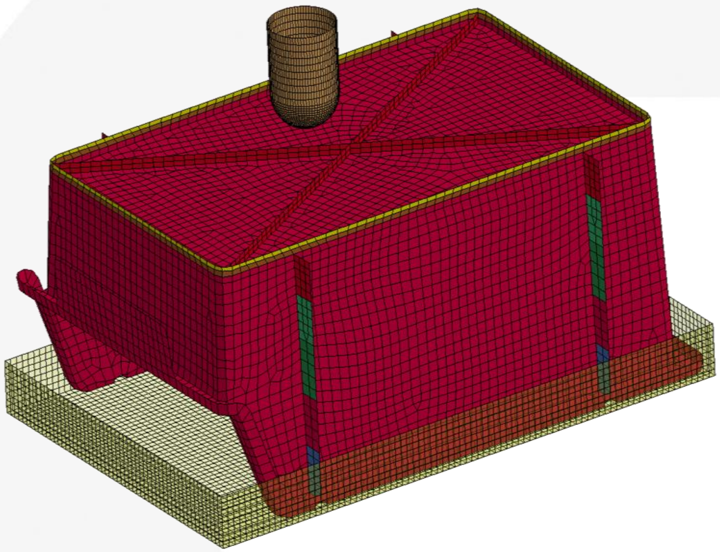
- **`*MAT_215` - possible improvements**
  - timestep calculation (conservative implementation)
  - compiler options – Optimizations for Cluster
  - ...

Summary

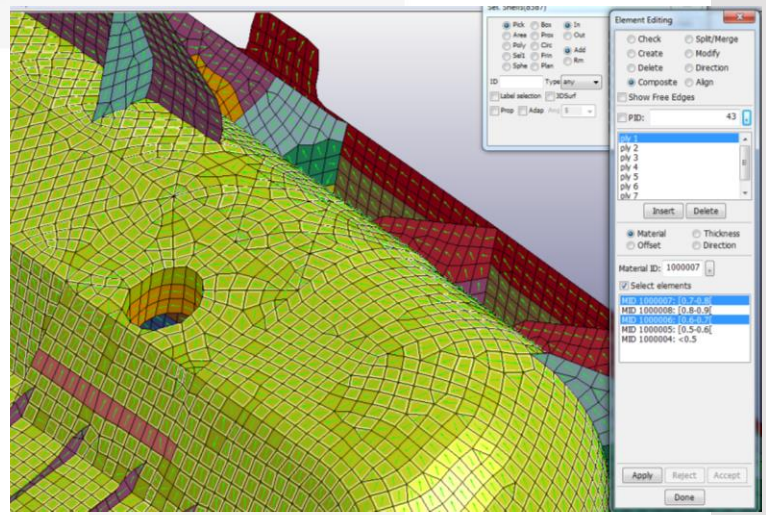
	*MAT_157	*MAT_215
Solver	implicit/explicit R9/R8	Explicit R10
CPU TIME vs. *MAT_024	2x slower	4x slower
Material model	Composite (HILL)	Mean Field Homogenization
Material model parameters	at least 20	at least 10
Failure/Damage	Composite properties	Matrix and Fiber criteria
Mapping	Material properties	Fiber orientation & content, aspect ratio
Ease to use	-*	+

*** Check input not really possible**

Outlook
ongoing testing / validations



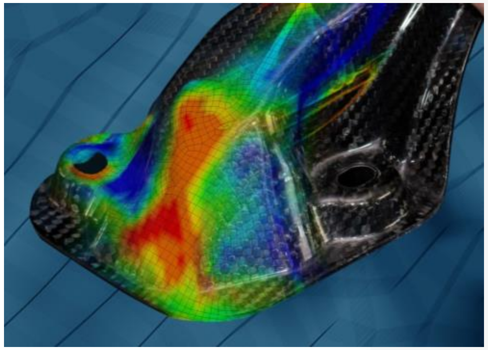
Nutini Box [4] [5]



Airbag [FAT Arbeitskreis]

and hopefully many of your applications …

Thank you for your attention!



14th TECHNOLOGIETAG

23.- 24. March 2017
in Schladming, Austria

„Light weight applications & Composites"
More information: *http://technologietag.4a.co.at/*

Literature

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[2] H. Staack, A. Koukal (Audi AG) – *Anforderungsgerechte Materialund Bruchmodellierung für die Fahrzeugsicherheit,* 4a Technologietag 2016 (Link)

[3] P. Reithofer, B. Jilka, A. Fertschej (4a engineering GmbH) – *4a micromec für die integrative Simulation faserverstärkter Kunststoffe,* NAFEMS Deutschsprachige Konferenz 2014, Bamberg (Link)

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