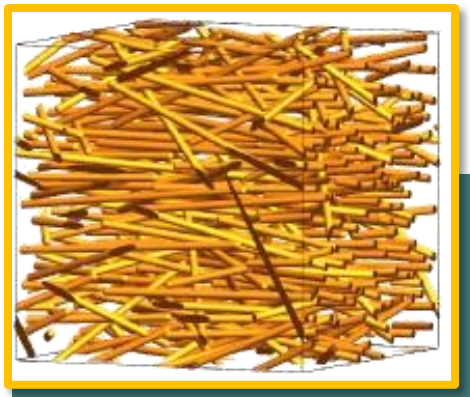
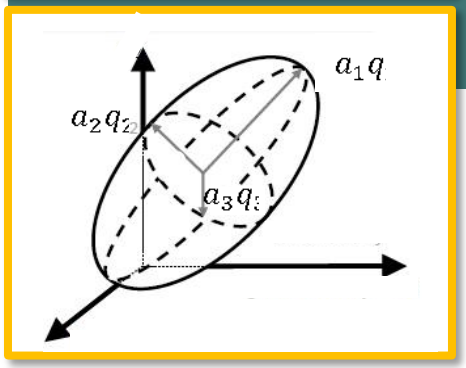
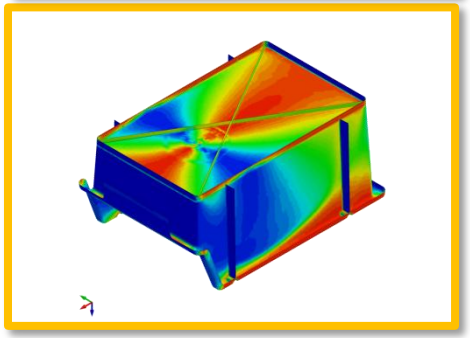






Materialmodelle zur integrativen Simulation in LS-DYNA

4a-Technologietage 2016

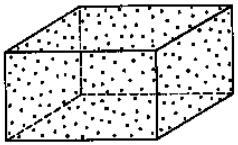
24.-26.Februar Schladming

Andrea Erhart, André Haufe,
Stefan Hartmann, Christian Liebold

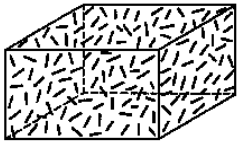
- **Motivation: Integrative simulation**
- Possibilities to model fibrous composites with LS-DYNA
- Instructions for use: Mapper and material models
- Application example

Overview

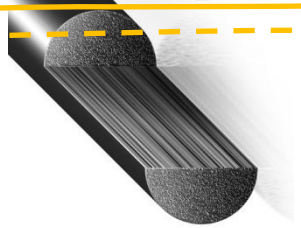
- particulate composites:



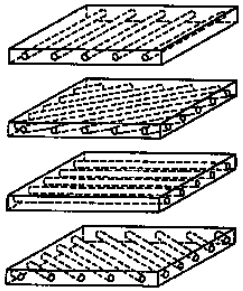
- **fibrous composites:**
  - short/long fibers:



  - continuous filaments:



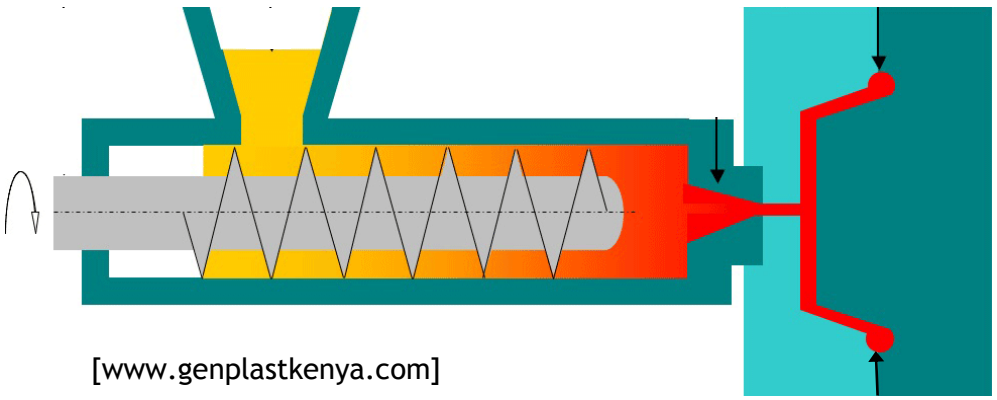
- laminated composites:



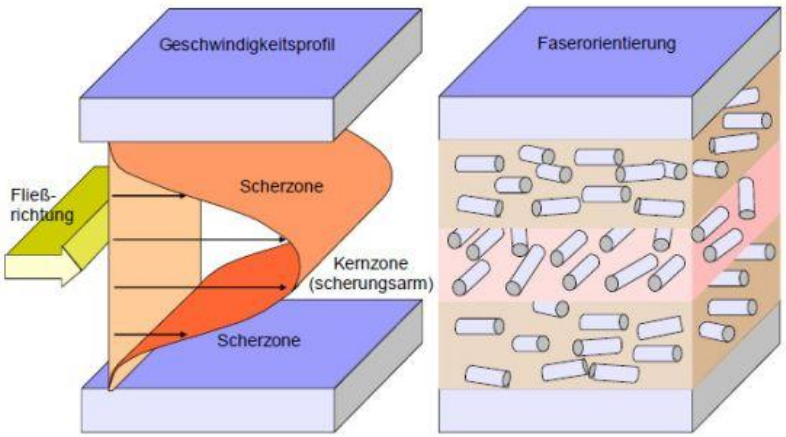
Motivation

Aim:

- Include production process in simulation model for mechanical behavior



[www.genplastkenya.com]

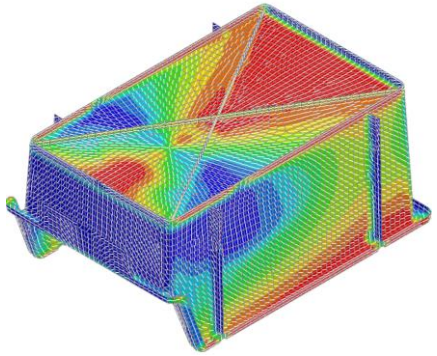


[wiki.polymerservice-merseburg.de]

Why:

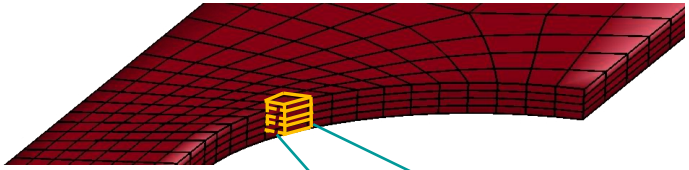
- Injection molding process induces micro-structure with 3-dimensional, local fiber orientation.
- Varying fiber orientation causes significant variation of local material stiffness combined with strong anisotropy.
- Important for reliable structural simulations to take local anisotropic material behavior precisely into account.

eigen value a_1, eigen vector $\mathbf{q}_1$



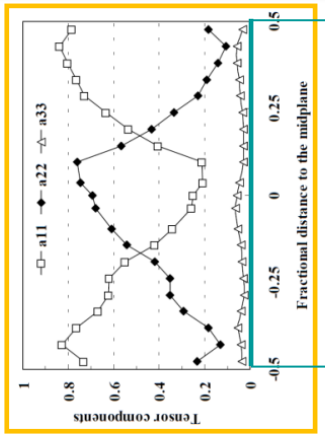
Motivation: Integrative simulation

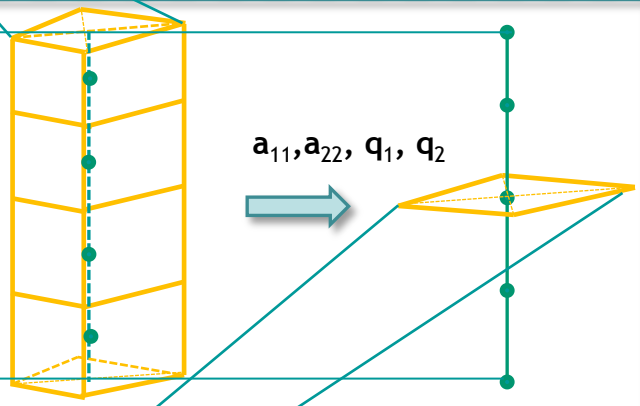
- **Injection molding simulation:**
  fiber orientation / fiber content



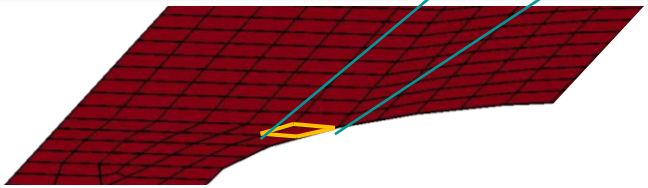
molding discretization

- **Mapping of fiber orientation tensor (main values und main directions) - fiber content**





- **Computation of homogenized (elastic) material properties**



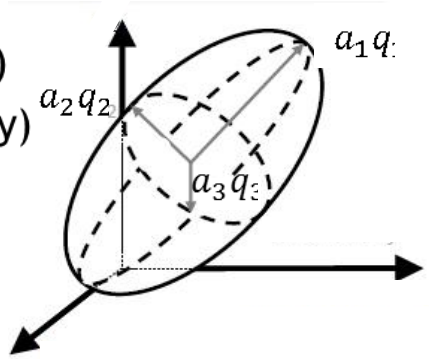
structural analysis discretization

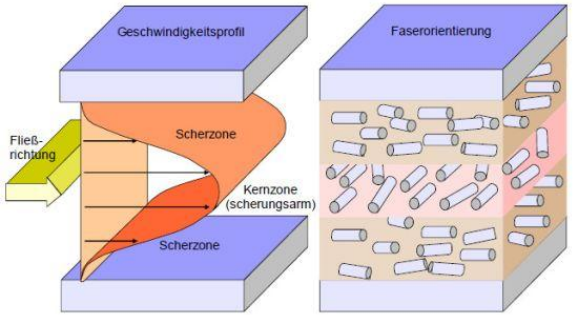
- **Structural analysis using homogenized anisotropic material model**

Motivation: Integrative simulation

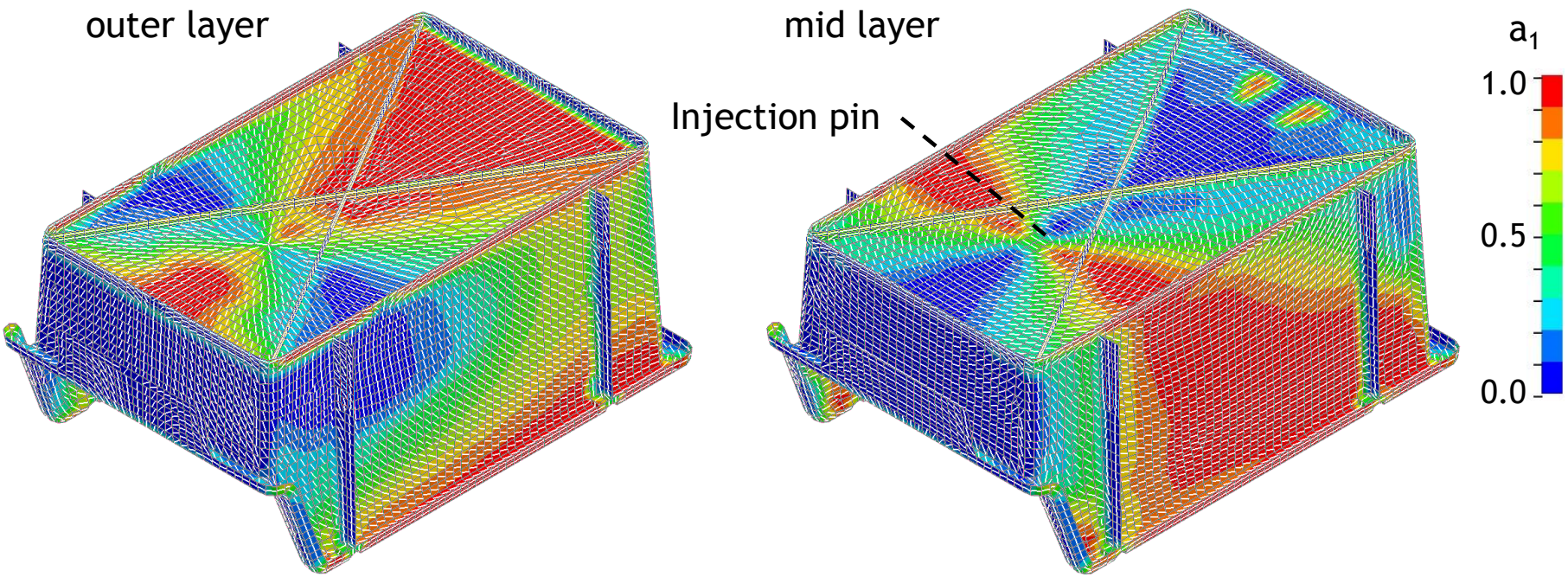
Orientation tensor 2nd order $\boldsymbol{a}$: Mapped from process simulation as

- eigenvectors $\boldsymbol{q}_i$ (main fiber directions)
- eigenvalues a_i (orientation probablity)



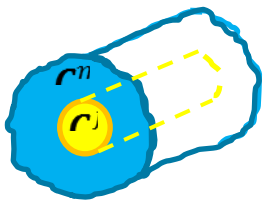


Example: "Nutini-box" eigenvalue a_1 and eigenvector q_1



Fiber orientation

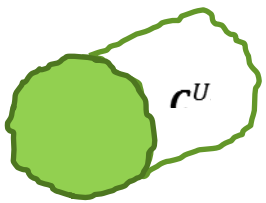
1st step: Effective properties of unidirectional (UD) composite



fiber in matrix

Analytical homogenisation:

- Eshelby + Mori-Tanaka
- empirical equations
- upper/lower bounds



equivalent homogeneous UD-medium

Eshelby + Mori-Tanaka:

strain concentration tensor:

$$\boldsymbol{A} = \left(\boldsymbol{I} + \boldsymbol{E} : \boldsymbol{S}^m : \left(\boldsymbol{C}^f - \boldsymbol{C}^m\right)\right)^{-1}$$

unidirectional stiffness matrix :

$$\boldsymbol{C}^{UD} = \boldsymbol{C}^m + \boldsymbol{v}_f\left(\boldsymbol{C}^f - \boldsymbol{C}^m\right) : \boldsymbol{A}$$

2nd step: Orientation averaging: Effective properties of (real) unaligned composite

homogenized stiffness matrix : $\boldsymbol{C}_{ijkl} = \int \boldsymbol{C}^{UD}\, \psi(\theta,\phi)\; d\Omega$

Advani&Tucker:

$$\boldsymbol{C}_{ijkl} = B_1 \boldsymbol{a}_{ijkl} + B_2\left(\boldsymbol{a}_{ij}\delta_{kl} + \boldsymbol{a}_{kl}\delta_{ij}\right) + B_3\left(\boldsymbol{a}_{ik}\delta_{jl} + \boldsymbol{a}_{il}\delta_{jk} + \boldsymbol{a}_{jl}\delta_{ik} + \boldsymbol{a}_{jk}\delta_{il}\right) + B_4\left(\delta_{ij}\delta_{kl}\right) + B_5\left(\delta_{ik}\delta_{jl} + \delta_{il}\delta_{jk}\right)$$

Closure approximation $\mathbf{a}_4$

with fiber orientation tensors: $\boldsymbol{a}_{2,ij} = \int p_i p_j\; \psi(\theta,\phi)\; d\Omega$ and $\boldsymbol{a}_{4,ijkl} = \int p_i p_j p_k p_l\; \psi(\theta,\phi)\; d\Omega$

$$B_1 = C^{UD}{}_{1111} + C^{UD}{}_{2222} - 2C^{UD}{}_{1122} - 4C^{UD}{}_{1212} \qquad B_2 = C^{UD}{}_{1122} + C^{UD}{}_{2233}$$

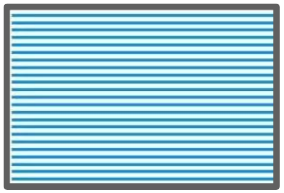
$$B_3 = C^{UD}{}_{1212} + {}^1\!/_2\,(C^{UD}{}_{2233} - C^{UD}{}_{2222}) \qquad B_4 = C^{UD}{}_{2233} \qquad B_5 = {}^1\!/_2\,(C^{UD}{}_{2222} - C^{UD}{}_{2233})$$

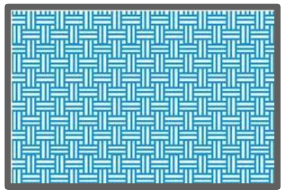
Homogenization - summary

- Motivation: Integrative simulation
- **Possibilities to model fibrous composites with LS-DYNA**
- Instructions for use: Mapper and material models
- Application example

Overview

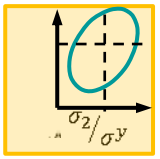
Continuous filaments / fabrics

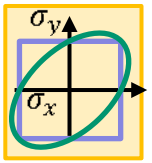




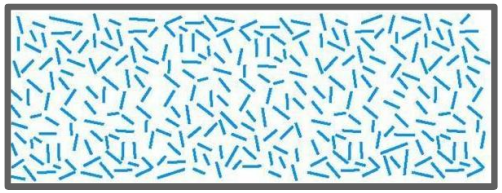
- **Non-varying anisotropy in region:** orthotropic / transversal isotropic
- One material card for part

- orthotropic elastic
- anisotropic plastic (e.g. Hill48)
- rate dependent hardening
- failure for fibrous composites (e.g. Chang-Chang,Tsai-Wu, Hashin)





long or short fibers (injection moulded)



- Local varying anisotropy
- Procedure for user: see below

Possibilities with LS-DYNA

anisotropic material models:

*MAT_002 — anisotropic / orthotropic elastic

*MAT_157 — anisotropic elastic, orthotropic plastic (Hill48)

$$\begin{bmatrix}\sigma_{11}\\ \sigma_{22}\\ \sigma_{33}\\ \sigma_{23}\\ \sigma_{31}\\ \sigma_{12}\end{bmatrix} = \begin{bmatrix} C_{11} & C_{12} & C_{13} & C_{14} & C_{15} & C_{16}\\ C_{21} & C_{22} & C_{23} & C_{24} & C_{25} & C_{26}\\ C_{31} & C_{32} & C_{33} & C_{34} & C_{35} & C_{36}\\ C_{41} & C_{42} & C_{43} & C_{44} & C_{45} & C_{46}\\ C_{51} & C_{52} & C_{53} & C_{54} & C_{55} & C_{56}\\ C_{61} & C_{62} & C_{63} & C_{64} & C_{65} & C_{66}\end{bmatrix} \begin{bmatrix}\varepsilon_{11}\\ \varepsilon_{22}\\ \varepsilon_{33}\\ \varepsilon_{23}\\ \varepsilon_{31}\\ \varepsilon_{12}\end{bmatrix}$$

material models with failure criterions for fibrous composites, that differenciate failure modes: fiber in tension, fiber in compression, matrix failure, mixed modes

*MAT_022 — orthotr.elast + Chang-Chang failure

*MAT_054 — orthotr.elast + pl.+ failure Chang-Chang

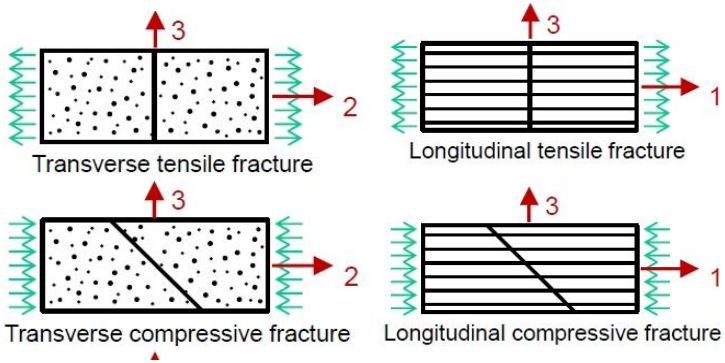
*MAT_055 — orthotr.elast + pl. + fail. f:Chang m:Tsai-Wu

*MAT_058 — orthotr.elast, damage + failure mod. Hashin

*MAT_158 — orthotr.elast, damage + failure, rate depend.

*MAT_261 — orthotr.elast, damage + failure Pinho (Puck)

*MAT_262 — orthotr.elast, damage + failure Camanho (Puck)



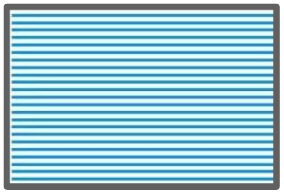
Material models for draping of fabrics / thermoplastic pre-pags:

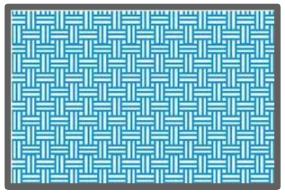
*MAT_249 — thermoplastic matrix + hyperelastic fabric (R8)

*MAT_277 — epoxy adhesive — visco-thermo-elastic, curing (from R9)

Possibilities with LS-DYNA: continuous filaments

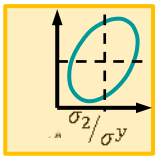
Continuous filaments / fabrics

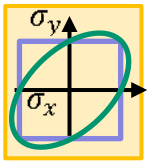




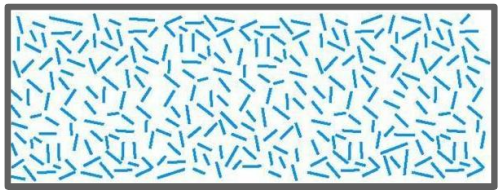
- **Non-varying anisotropy in region:** orthotropic / transversal isotropic
- One material card for part

- orthotropic elastic
- anisotropic plastic (e.g. Hill48)
- rate dependent hardening
- failure for fibrous composites (e.g. Chang-Chang,Tsai-Wu, Hashin)





long or short fibers (injection moulded)



- **Local varying anisotropy**
- Procedure for user: see below

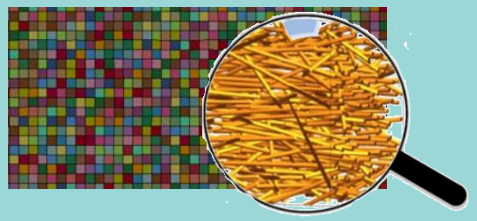
Possibilities with LS-DYNA

fiber orientation (and homogenised material data) as

input data in material card

only usefull for continuous, alligned fibers

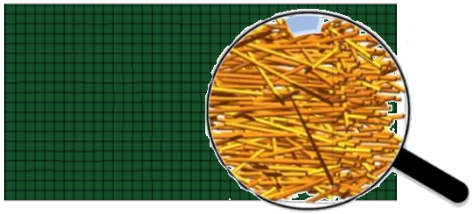
else:



inhomogeneous fiber distribution needs individual part / material card for every element

fiber orientation (and homogenised material data) as history variables. Can be initialized for each integration point individually using

*INITIAL_STRESS_SOLID / SHELL



one part / material card for whole component

***MAT_ANISOTROPIC_ELASTIC (*MAT_002)** or ***MAT_215** or

***MAT_ANISOTROPIC_ELASTIC_PLASTIC (*MAT_157)**

CARD 1	mid	ro	sigy	lcss	qr1	cr1	qr2	cr2
CARD 2	c11	c12	c13	c14	c15	c16	c22	c23
CARD 3	c24	c25	c26	c33	c34	c35	c36	c44
CARD 4	c45	c46	c55	c56	c66	R00/F	R45/G	R90/H
CARD 5	L/s11	M/s22	N/s33	s12	aopt	vp		macf
CARD 6	xp	yp	zp	a1	a2	a3		
CARD 7	v1	v2	v3	d1	d2	d3	beta	ihis=0

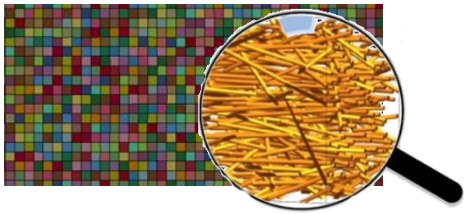
Possibilities with LS-DYNA

fiber orientation (and homogenised material data) as

input data in material card

only usefull for continuous, alligned fibers

else:



inhomogeneous fiber distribution needs individual part / material card for every element

fiber orientation (and homogenised material data) as history variables. Can be initialized for each integration point individually using

***INITIAL_STRESS_SOLID / SHELL**

one part / material card for whole component

***MAT_157 / *MAT_215:** IHIS $= 8a_3 + 4a_2 + 2a_1 + a_0$ with a_0 … a_3 each either 0 or 1

***INITIAL_STRESS_SOLID:**

NHISV $= 6a_0 + 21a_1 + 6a_2 + a_3$

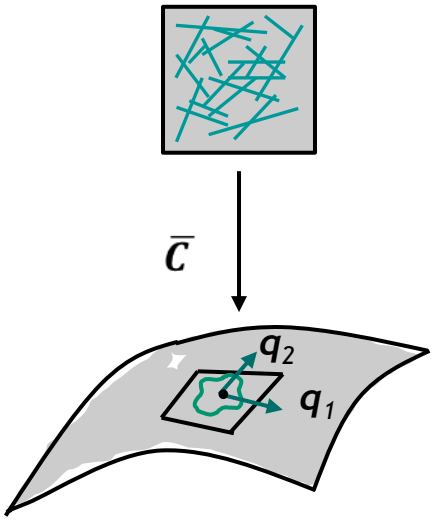
flag	description	variables	number
a_0	material directions	$\boldsymbol{q}_1,\boldsymbol{q}_2$	6
a_1	anisotropic elastic stiffness	C_{ij}	21
a_2	anisotropic plasticity	F,G,H,L,M,N	6
a_3	hardening curve	LCSS	1

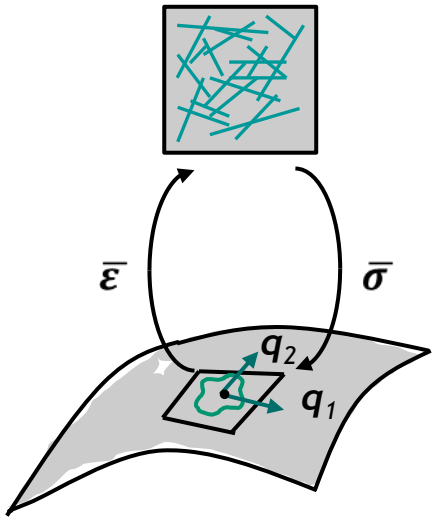
***INITIAL_STRESS_SHELL:**

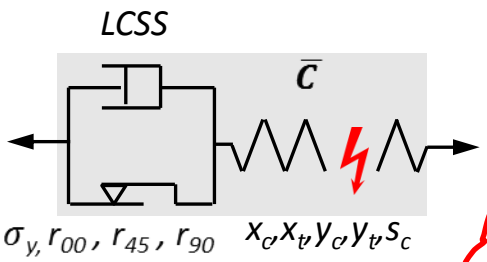
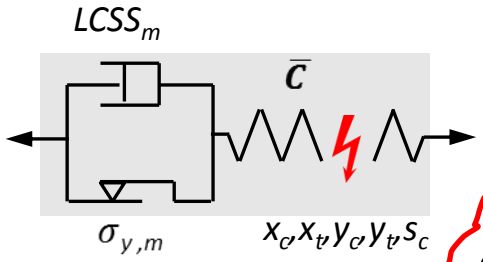
NHISV $= 2a_0 + 21a_1 + 3a_2 + a_3$

flag	description	variables	number
a_0	material directions	q_1,q_2	2
a_1	anisotropic elastic stiffness	C_{ij}	21
a_2	anisotropic plasticity	r_{00},r_{45},r_{90}	3
a_3	hardening curve	LCSS	1

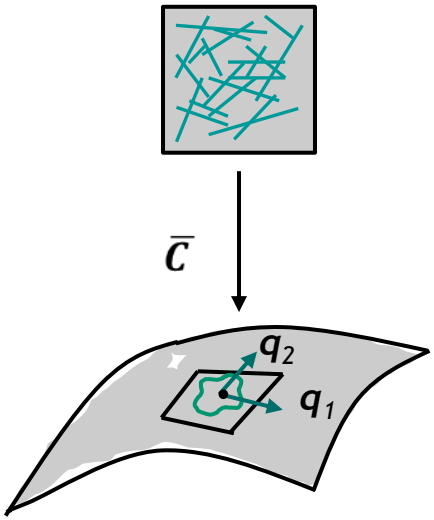
Possibilities with LS-DYNA

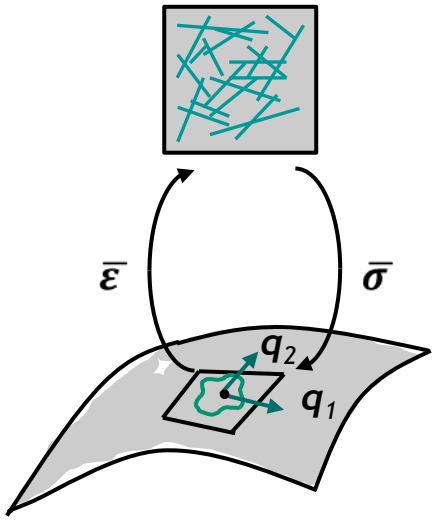




homogenised elastic (+ *MAT_ADD_EROSION)	**homogenised elastic - macroscopic visco-plastic** (+ *MAT_ADD_EROSION)	**homogenised elastic-visco-plastic with fiber-/matrix-failure**
 $\bar{C} = \begin{bmatrix} C_{11} & C_{12} & C_{13} & 0 & 0 & 0 \\ C_{12} & C_{22} & C_{23} & 0 & 0 & 0 \\ C_{13} & C_{23} & C_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & C_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & C_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & C_{66} \end{bmatrix}$	 from R8.1	 planned from R9
***MAT_002 *MAT_157 *MAT_215** solids, shells	***MAT_157** (*MAT_ANISOTROPIC _ELASTIC_PLASTIC) solids, shells	***MAT_215** (*MAT_4A_MICROMEC) solids, shells

Possibilities with LS-DYNA: short fibers





homogenised elastic (+ *MAT_ADD_EROSION)		homogenised elastic - macroscopic visco-plastic (+ *MAT_ADD_EROSION)	homogenised elastic-visco-plastic with fiber-/matrix-failure
fiber orientation and homogenisation with **DYNAmap**	fiber orientation with **DYNAmap** homogenisation with ***MAT_215**	fiber orientation and elastic homogenisation with **DYNAmap** from R8.1	fiber orientation with **DYNAmap** homogenisation with ***MAT_215** planned from R9
***MAT_157**	***MAT_215**	***MAT_157** (*MAT_ANISOTROPIC_ELASTIC_PLASTIC)	***MAT_215** (*MAT_4A_MICROMEC)

Possibilities with LS-DYNA: short fibers

- Motivation: Integrative simulation
- Possibilities to model fibrous composites with LS-DYNA
- **Instructions for use: Mapper and material models**
- Application example

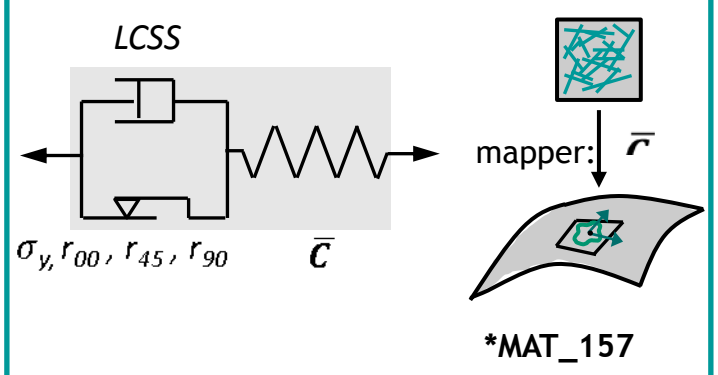
Overview

ab R8.1

*MAT_ANISOTROPIC_ELASTIC_PLASTIC (*MAT_157)

- material card is input of user
- elastic **homogenization done with DYNAmap**
  → c11 … c66 in *INITIAL_STRESS_SHELL
- aopt=0: q1 and q2 in *INITIAL_STRESS_SHELL
- evaluation of **ihis=3** see above
- for damage / failure: *MAT_ADD_EROSION
  from R9: Tsai-Wu failure criterion

homogenised elastic - macroscopic visco-plastic



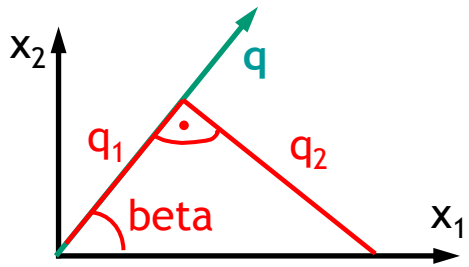
$CARD 1	mid 1	ro 1.52E-06	sigy 0.018	lcss 999	qr1	cr1	qr2	cr2
$CARD 2	C11	C12	C13	C14	C15	C16	C22	C23
$CARD 3	C24	C25	C26	C33	C34	C35	C36	C44
$CARD 4	C45	C46	C55	C56	C66	R00 0.95	R45 0.8	R90 1.0
$CARD 5	s11	s22	s33	s12	aopt 0	vp		macf
$CARD 6	xp	yp	zp	a1	a2	a3		
$CARD 7	v1	v2	v3	d1	d2	d3	beta	ihis 3

Instructions for use

*INITIAL_STRESS_SHELL is generated automatically by DYNAmap

	$CARD 1	eid 1	nplane 1 or 4	nthick e.g. 5	nhisv 23	ntensr	large	nthhint	nthhisv
Integration point 1	$CARD 2	t 0.0e+00	sigxx 0.0	sigyy 0.0	sigzz 0.0	sigxy 0.0	sigyz 0.0	sigzx 0.0	eps 0.0
	$CARD 3	q1 8.84e-01	q2 1.09e-01	C11 1.1e+01	C12 4.9e+00	C13 2.4e+00	C14 0.0e+00	C15 0.0e+00	C16 0.0e+00
	$CARD 4	C22 4.6e+00	C23 8.6e-01	C24 0.0e+00	C25 0.0e+00	C26 0.0e+00	C33 4.3e+00	C34 7.2e-01	C35 0.0e+00
	$CARD 5	C36 0.0e+00	C44 1.5e+00	C45 0.0e+00	C46 0.0e+00	C55 5.6e-01	C56 0.0e+00	C66 8.7e-01	
IP 2	$CARD 6	t -0.9062	sigxx 0.0	sigyy 0.0	sigzz 0.0	sigxy 0.0	sigyz 0.0	sigzx 0.0	eps 0.0

For shells:
Material direction (main fiber orientation): Only first eigenvector necessary:
described by direction $q_1 = cos\beta, \quad q_2 = sin\beta$



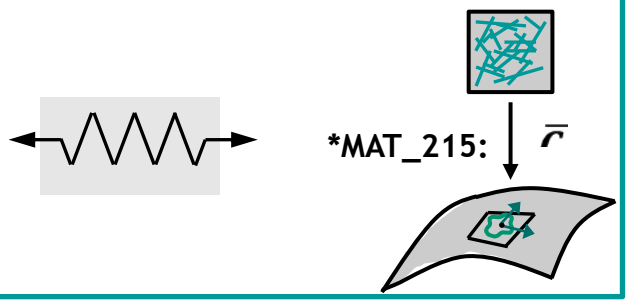
Instructions for use

planned from R9

*MAT_215 (mmopt=1.0)

- material card is input of user
- elastic **homogenization done** *once* **within *MAT_215**
- fiber orientation tensor: main values a11,a22, and main material direction q1,q2 evaluated by mapper and written to *INITIAL_STRESS_SOLID/SHELL
- for solids and shells

homogenised elastic



$CARD 1	mid 1	mmopt 1	fmf 0.2			method 1.-8.		mini	homogenization
$CARD 2	fupd	bupd	corlc				failm	failf	material main direction
$CARD 3	aopt	macf	xp	yp	zp	a1	a2	a3	alternative: *INITIAL_STRESS_SOLID/SHELL
$CARD 4	v1	v2	v3	d1	d2	d3	beta		
$CARD 5	rof	el	et	glt	prtl	prtt	al	at	fiber properties
$CARD 6	xc	xt	yc	yt	sc				
$CARD 7	gtyp	r1	r2	r3	a11	a22	ca		fiber geometry
$CARD 8	rom	e	pr	am					matrix material
$CARD 9	sigyt	etant	sigyc	etanc	eps0	c			
$CARD 10	lcidt	lcidc							

Instructions for use

*INITIAL_STRESS_SHELL is generated automatically by DYNAmap

	$CARD 1	eid 1	nplane 1 or 4	nthick e.g. 5	nhisv 17	ntensr	large	nthhint	nthhisv
Integration point 1	$CARD 2	t 0.0e+00	sigxx 0.0	sigyy 0.0	sigzz 0.0	sigxy 0.0	sigyz 0.0	sigzx 0.0	eps 0.0
	$CARD 3							q1 -5.2e-01	q2 -8.5e-01
	$CARD 4								a11 8.84e-01
	$CARD 5	a22 1.09e-01							
Integration point 2	$CARD 6	t -0.9062	sigxx 0.0	sigyy 0.0	sigzz 0.0	sigxy 0.0	sigyz 0.0	sigzx 0.0	eps 0.0
	$CARD 7	see *SECTION_SHELL						q1 ..	q2 ..
	$CARD 8								a11 ..
	$CARD 9	a22 ..							
IP 3 … 5	$CARD 10 - 21	t -0.5385	sigxx ..	sigyy ..	sigzz ..	sigxy ..	sigyz ..	sigzx ..	eps ..
	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮

Instructions for use

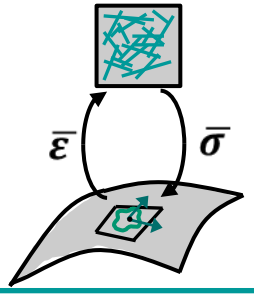
planned from R9

*MAT_215 (mmopt=2.0)

- material card is input of user
- elasto-plastic **homogenization done within *MAT_215**
- fiber orientation tensor by mapper and written to *INITIAL_STRESS_SOLID
- for solids

homogenised elastio-plastic

*MAT_215:



$CARD 1	mid 1	mmopt 2	fmf 0.2			method		mini	homogenization
$CARD 2	fupd	bupd	corlc				failm	failf	material main direction
$CARD 3	aopt	macf	xp	yp	zp	a1	a2	a3	alternative: *INITIAL_STRESS_SOLID
$CARD 4	v1	v2	v3	d1	d2	d3	beta		
$CARD 5	rof	el	et	glt	prtl	prtt	al	at	fiber properties
$CARD 6	xc	xt	yc	yt	sc				
$CARD 7	gtyp	r1	r2	r3	a11	a22	ca		fiber geometry
$CARD 8	rom	e	pr	am					matrix material
$CARD 9	sigyt	etant	sigyc	etanc	eps0	c			
$CARD 10	lcidt	lcidc							

Instructions for use

mapper DYNAmap:

- transfers fiber orientation tensor from Moldflow mid-plane/3D onto structural analysis meshes (solid or shell) → a11, a22, **q1, q2**
- can be used for elastic homogenization of the stiffness parameters C11 – C66

mapping info file:

```
$#----------------------------
$# Main mapping definition
$#----------------------------
FIBERMAP=MOLDFLOW3D-SHELL
$#----------------------------
$# Activate transformation
$#----------------------------
TRANSFORMATION=YES
MoveSRCTo=-124.7885 0.0 -0.0124
RotateSRCAngle=45.0
RotateSRCAxis=Z
TransformBack=YES
WriteTransformedMesh=NO
```

main mapping parameter – for SFRP:
- Moldflow3D → Shell
- Moldflow → Shell

activate transformation:
- specimen → moldflow-component → specimen

relation for transformation

flag to write additional output file of transformed mesh

```
$#----------------------------
$# In- and output meshes
$#----------------------------
SourceFile=…/CC32-Volumen-3D_scaled.key
TargetFile=specimen_2mm.inc
MappingResult=specimen_45deg_2mm_mapped_3D_FolgarTucker.inc
OrientationFile=…/CC32-A0001-3D-FolgarTucker_auto.xml
$#TransformedMeshFile=specimen_0deg_2mm_mapped_trans.inc
$#----------------------------
$# Target - PIDs
$#----------------------------
NumberOfTARLayers=5
NumberOfTARInPlaneIPs=1
MapStress=YES
TargetThickness=2.5
MapMainDir=NO
```

moldflow mesh (LS-DYNA format)

target mesh (LS_DYNA format)

mapping result file

moldflow result file (mid-plane/3D)

optional filename for transformed source file

number of through thickn. Integr. points

fully or under-integrated shell elements

flag initialize HISV-output

thickness of target mesh

output of main axis of orientation tensor in *ELEMENT_SHELL_COMPOSITE with AOPT=0

```
$#----------------------------
$# Mapping-Options
$#----------------------------
ALGORITHM=ClosestPoint
TargetMaterialModel=157
HomogenizationMethod=Mori-Tanaka#3
ClosureApproximation=hybrid_A
E11F=72.000
E22F=72.000
RHOF=2.54E-06
PRBAF=0.22
PRCBF=0.22
G12F=29.510
EM=2.6
RHOM=1.086E-06
PRM=0.39
AspectRatio=25
FiberVolumeFraction=30
InclusionShape=Spheroidal
```

flag for search algorithm

*MAT_157 → homogenization by mapper

elastic homogenization method:

- Halpin-Tsai
- Tandon-Wenig
- Voigt
- Kukuri
- Mori-Tanaka #1 - #3c

closure-approximation:

- linear
- quadratic
- hybrid_A & hybrid_B

inclusion and matrix elastic material properties for homogenization

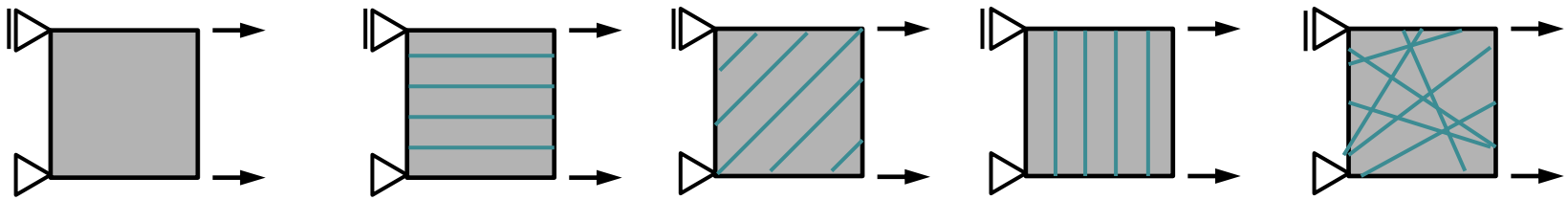
inclusion shape :

- spherical
- needle
- disc

- Motivation: Integrative simulation
- Possibilities to model fibrous composites with LS-DYNA
- Instructions for use: Mapper and material models
- **Application example**

Overview

***MAT_4a_micromec (*MAT_215): stress-strain-behavior** (looking at 1 integration point)



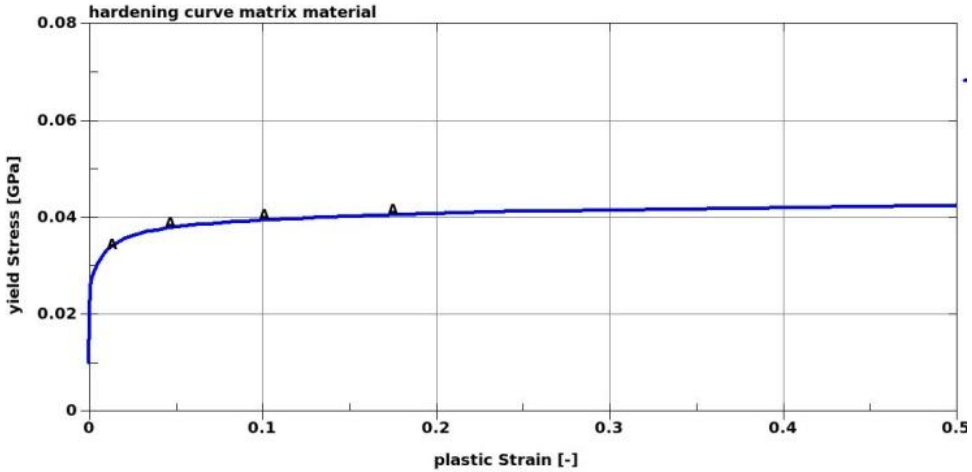
→ **Material properties:**

Fiber material:

- E11f = E22f = 72.0 GPa
- prBA = prCB = 0.20
- rhof = 2.58E-06 kg/mm^3
- apect ratio (L/d) = 25
- fiber volume fraction = 40%

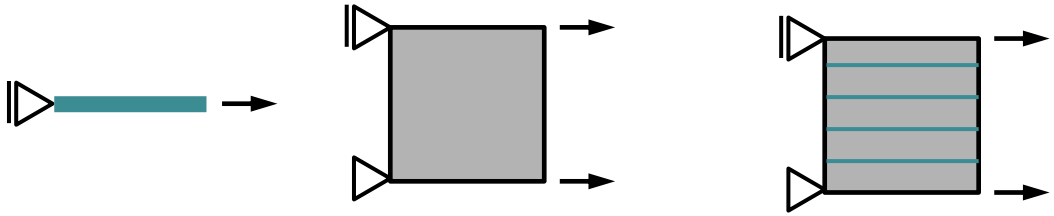
Matrix material:

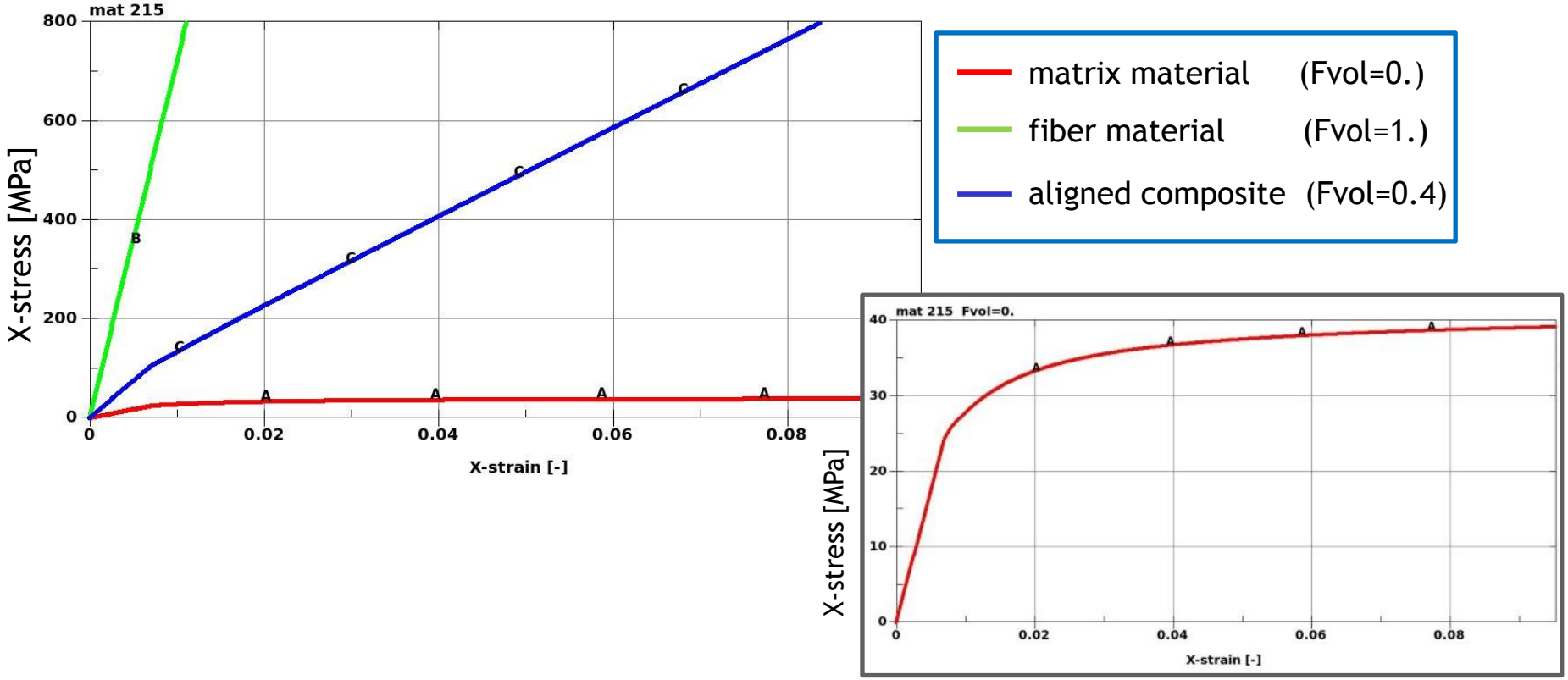
- EM = 3.5GPa
- prM = 0.32
- rhom = 1.2E-06 kg/mm^3



*MAT_215 (stress-strain behavior)

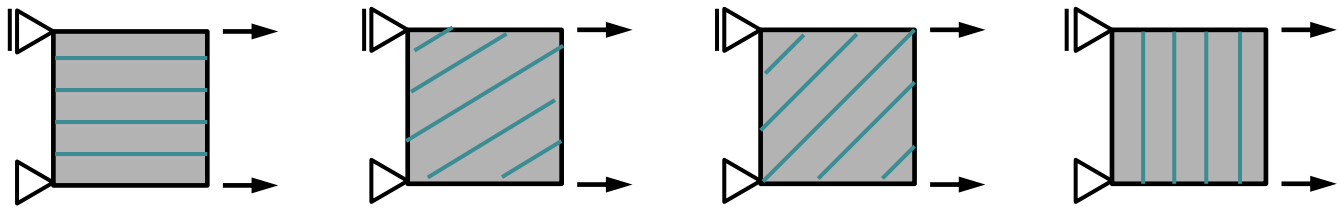
→ **matrix material - fiber material - composite**

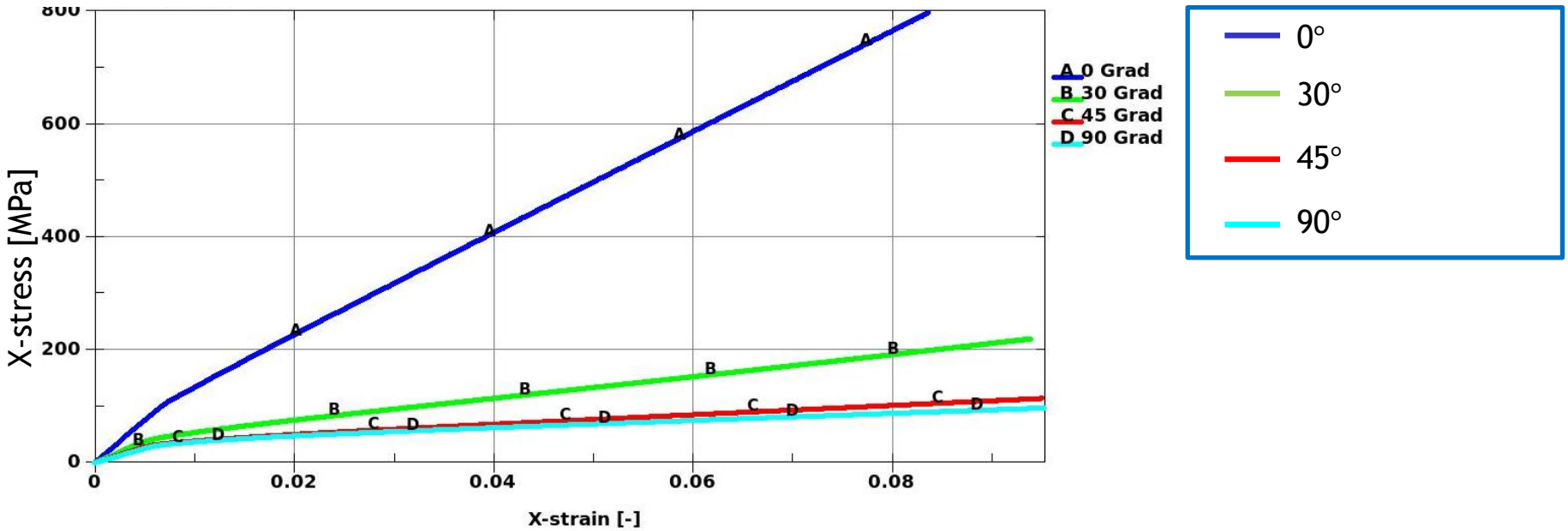




*MAT_215 (stress-strain behavior)

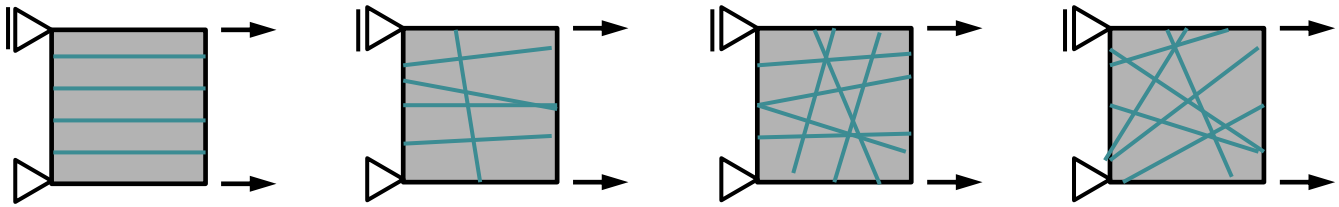
→ **Varying fiber orientation:**

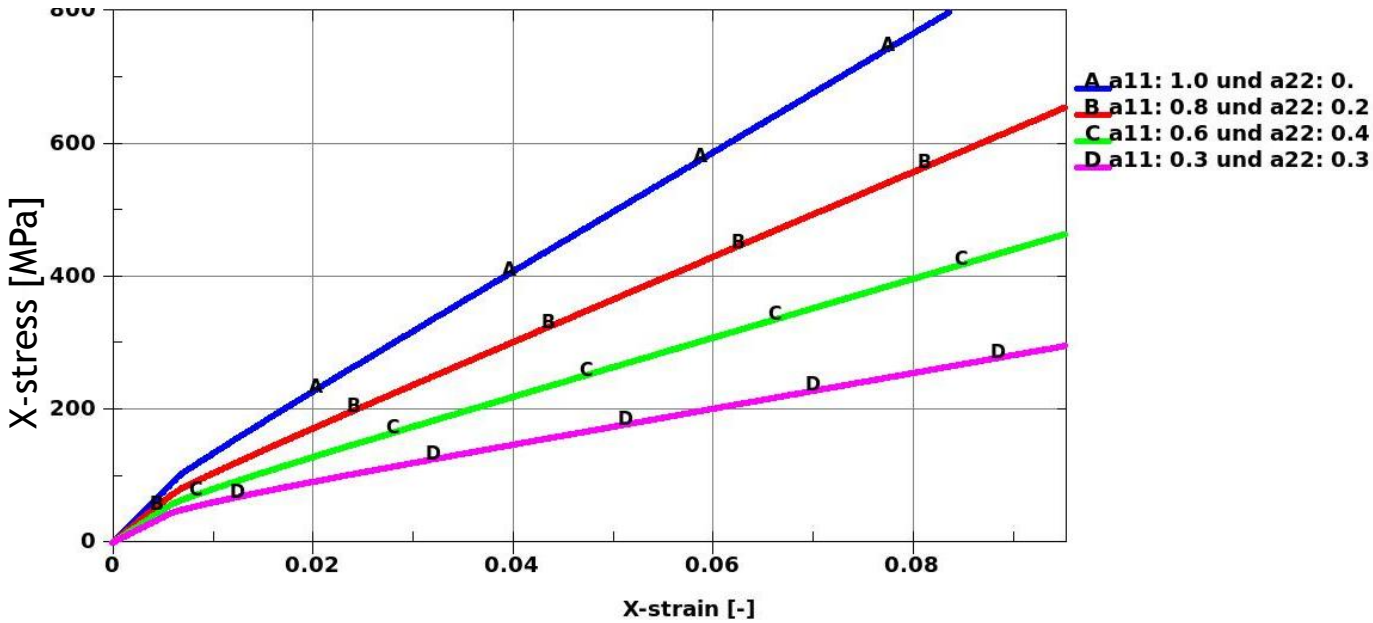




*MAT_215 (stress-strain behavior)

→ **Varying fiber distribution:**

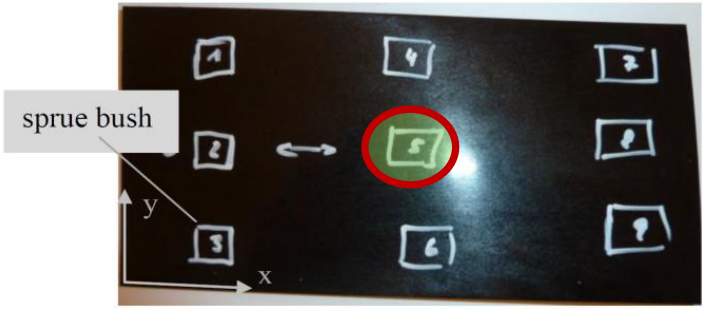


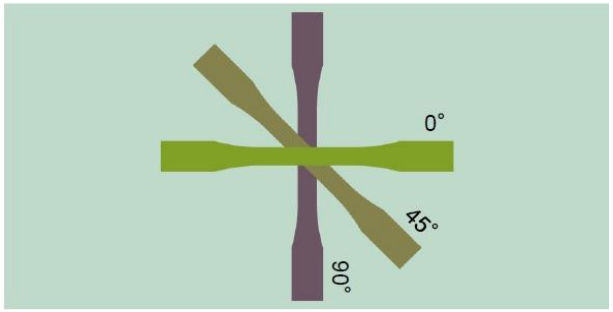


- a11=1, a22=0.
- a11=0.8, a22=0.2
- a11=0.4, a22=0.4
- a11=a22=0.333

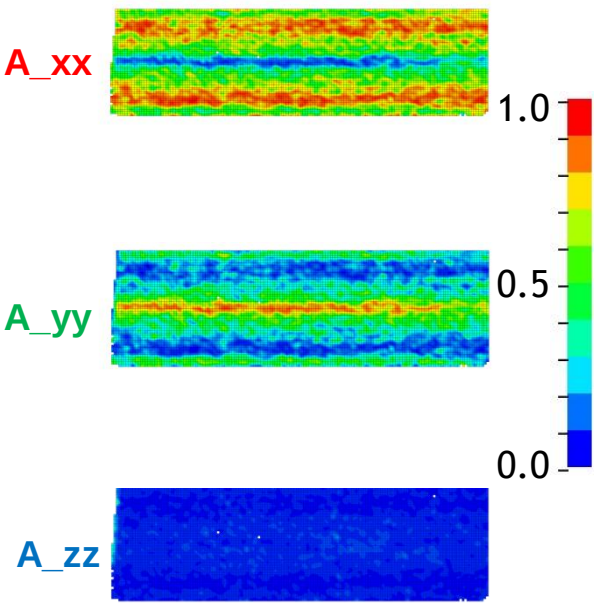
*MAT_215 (stress-strain behavior)

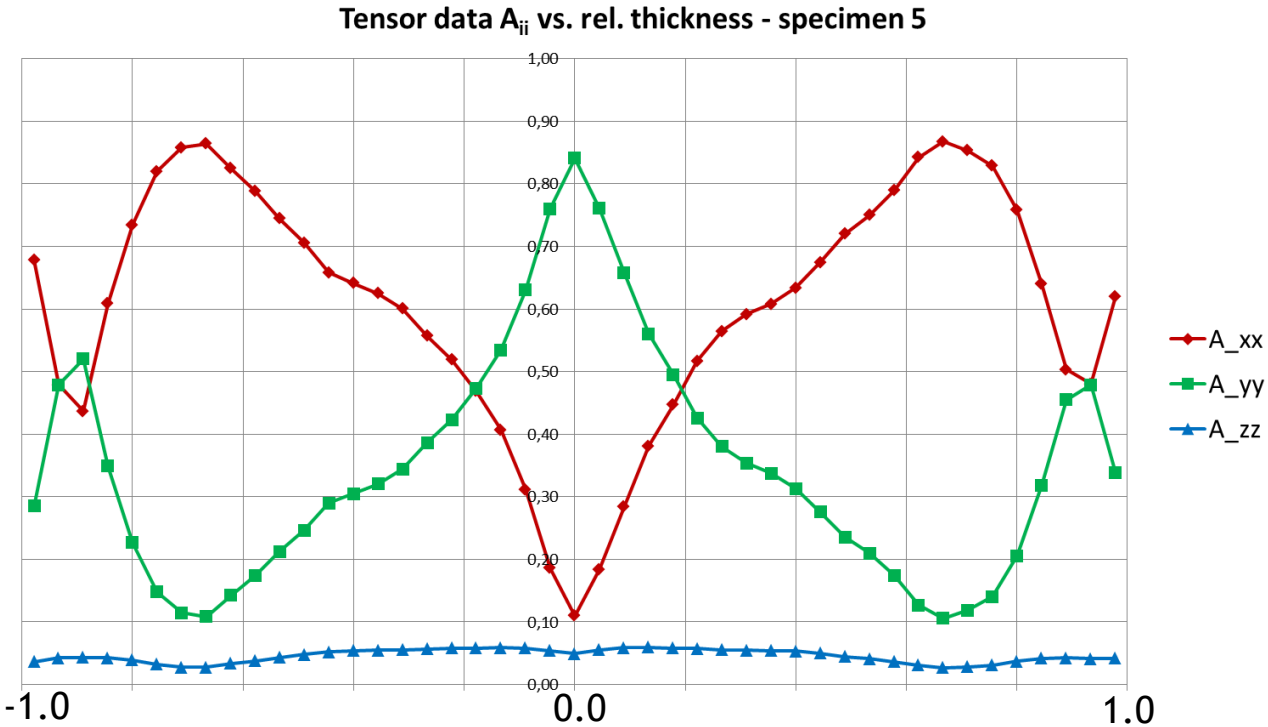
- **Tensile specimen** in 0°, 45°, 90° cut out in middle of injection moulded plate





- **Fiber orientation of 0°- specimen over thickness:**





Tensile test

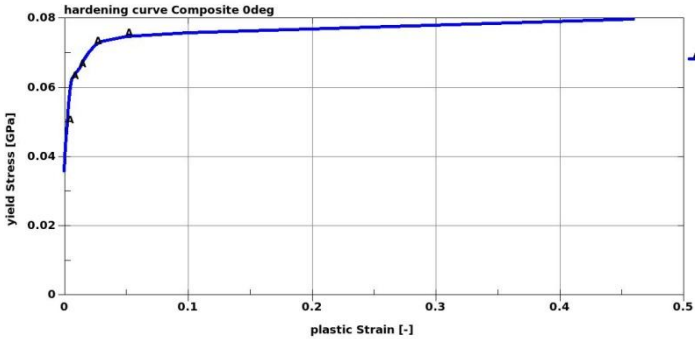
- **Experimental tensile tests** carried out by DYNAmore (here: quasi-static loading)
- **Simulations of tensile test:**

material properties:

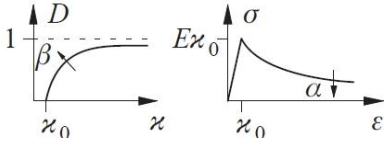
Fiber material:
- E11f = E22f = 72.0 Gpa
- prBA = prCB = 0.22
- rhof = 2.54E-06 kg/mm^3
- apect ratio (L/d) = 25
- fiber volume fraction = 20%

Matrix material:
- EM = 2.6GPa
- prM = 0.29
- rhom = 1.086E-06 kg/mm^3

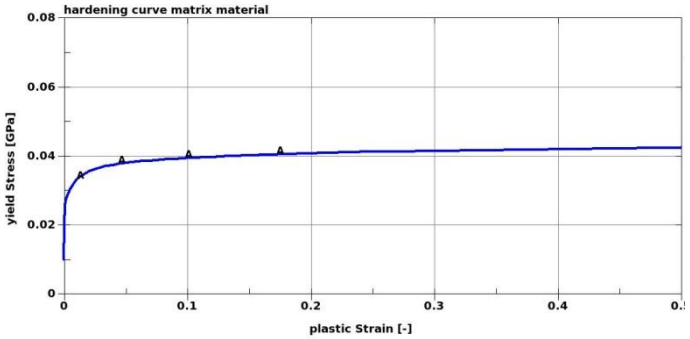
- ***MAT_ANISOTROPIC_ELASTIC_PLASTIC (*MAT_157):**
- elastic properties homogenized by DYNAmap: Mori-Tanaka + hybrid CA
- (macroscopic) hardening curve fitted:



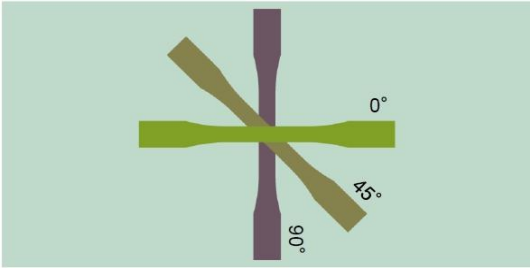
- ***MAT_4A_MICROMEC (*MAT_215):**
- elastoplastic matrix + exponential damage (kappa0=0.002, alpha=0.2,beta=0.8)

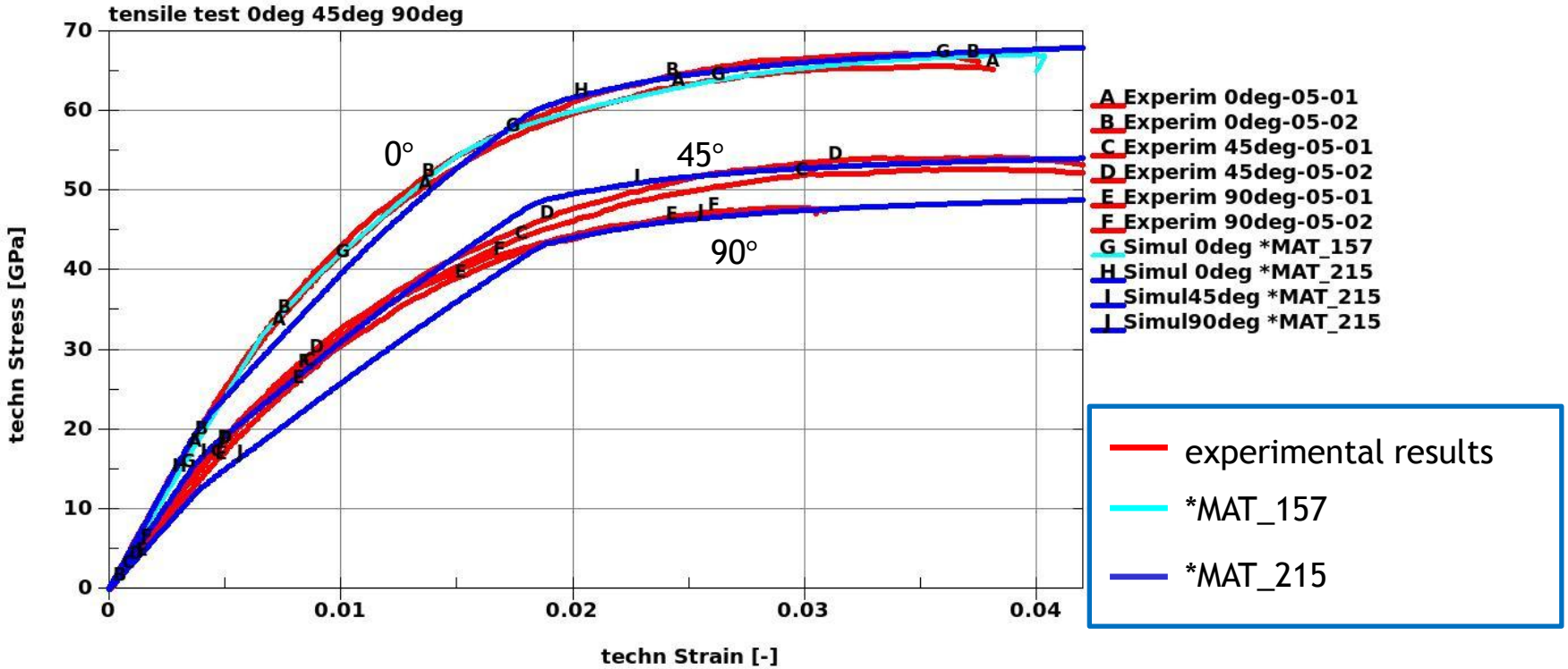


- hardening curve matrix material:

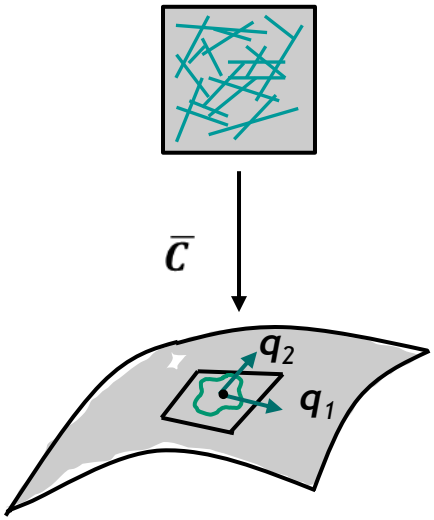


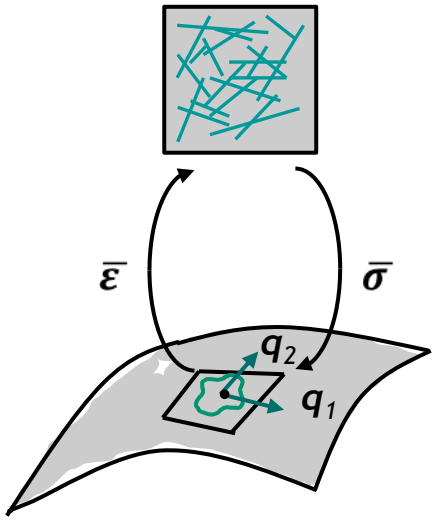
Tensile test





Tensile test





homogenised elastic (+ *MAT_ADD_EROSION)			homogenised elastic - macroscopic visco-plastic (+ *MAT_ADD_EROSION)	homogenised elastic-visco-plastic with fiber-/matrix-failure
***MAT_002**	***MAT_157**	***MAT_215**	***MAT_157** (*MAT_ANISOTROPIC _ELASTIC_PLASTIC)	***MAT_215** (*MAT_4A_MICROMEC)
available	available	from R9	from R8.1	planned from R9
solids shells	solids shells	solids shells	solids shells	solids shells

Download of new releases: ftp-server Kundenzugang: ftp.dynasupport.de (R8.1.: 1.Quartal R9: 3.Quartal 2016)

Summary - material models moulded composites