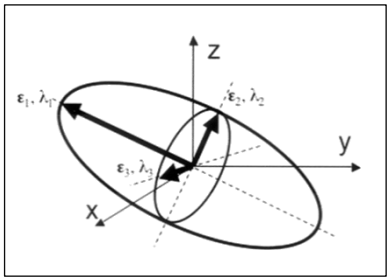

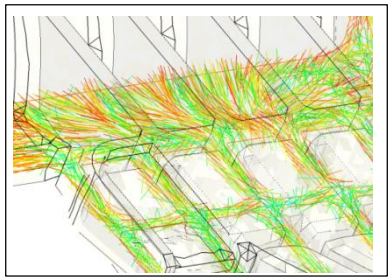

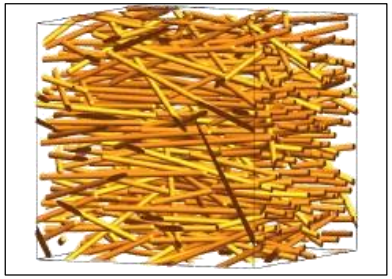

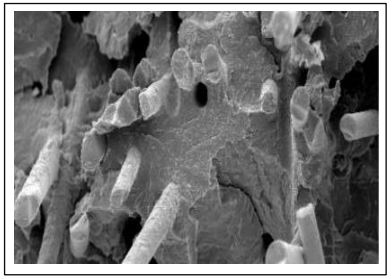

Zum aktuellen Stand der Simulation von Kunststoffen mit LS-DYNA

Dr. André Haufe
DYNAmore GmbH

DYNA*more* GmbH
Gesellschaft für
FEM-Ingenieurdienstleistungen

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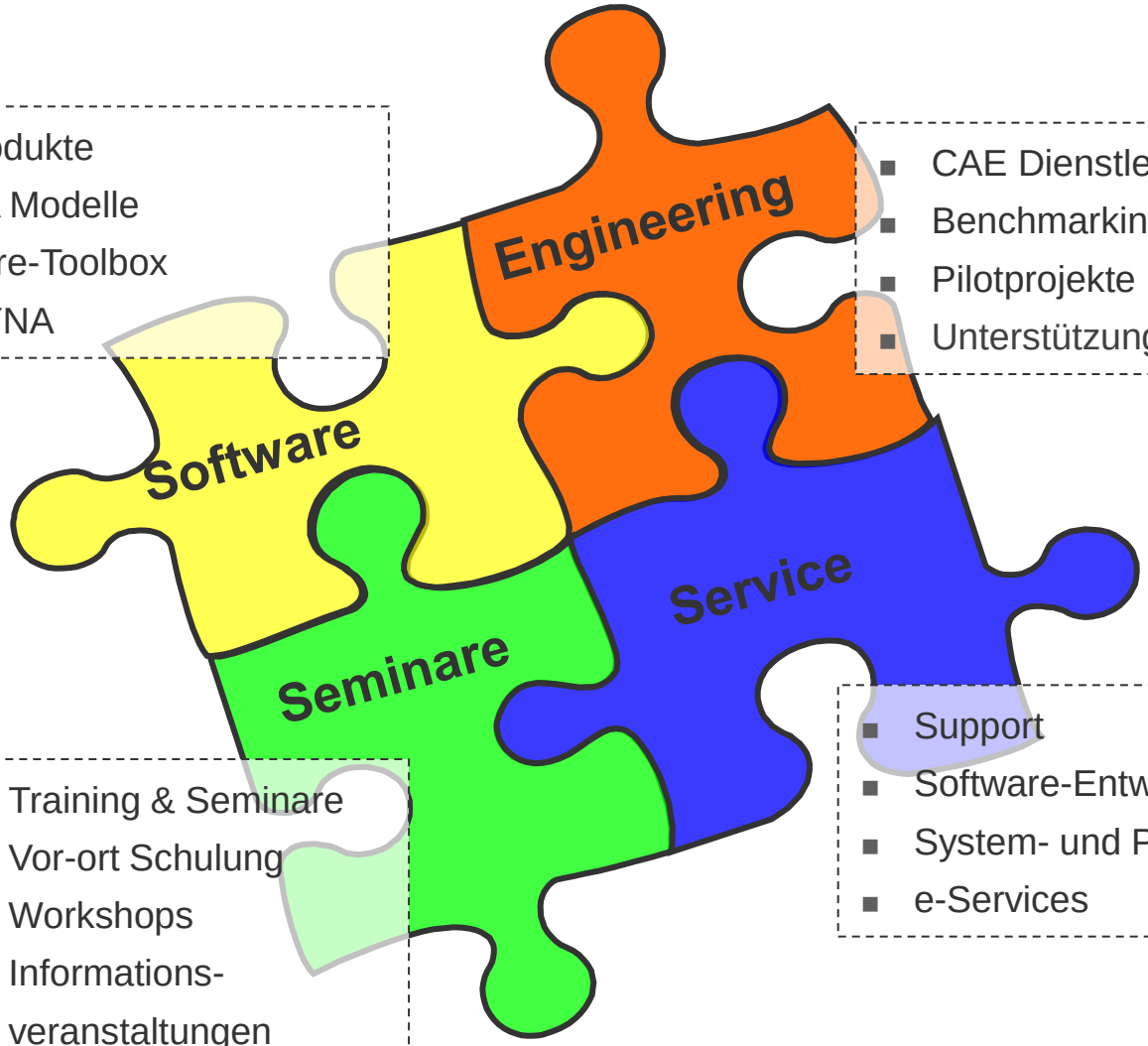
e-mail: info@dynamore.de
Internet: www.dynamore.de

Portfolio

- LSTC Produkte
- LS-DYNA Modelle
- DYNAmore-Toolbox für LS-DYNA



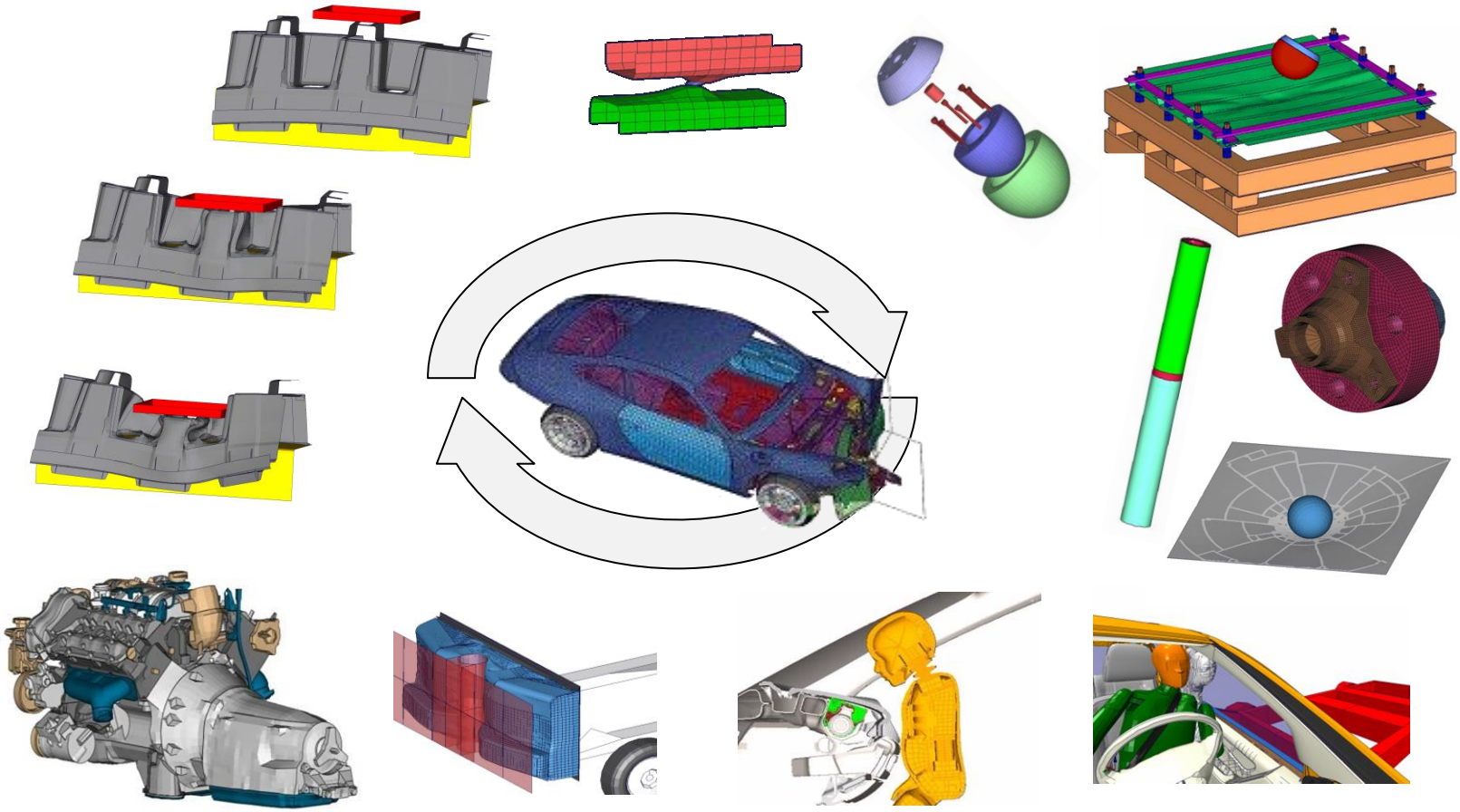
- CAE Dienstleistungen
- Benchmarking
- Pilotprojekte
- Unterstützung vor Ort

- Training & Seminare
- Vor-ort Schulung
- Workshops
- Informations-veranstaltungen

- Support
- Software-Entwicklung
- System- und Prozessintegration
- e-Services

Einsatz von Kunststoffen

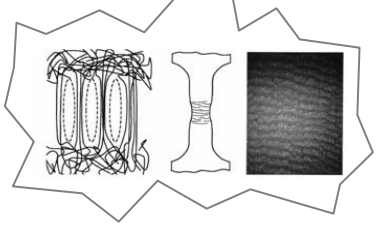
Weiterentwicklung der Werkstoffe fordert Weiterentwicklung der Berechnungsmethoden!



Validierung und Verifizierung

Identifikation

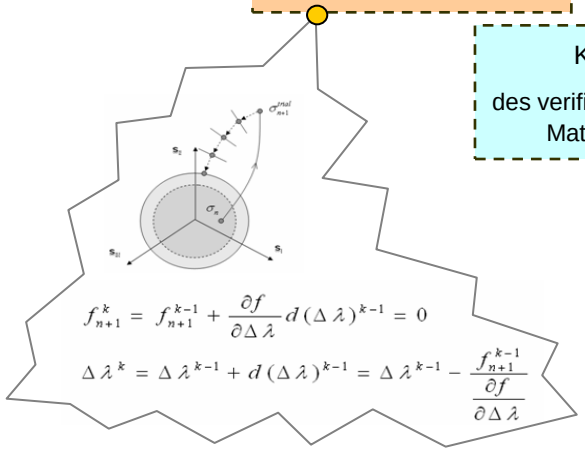
des charakteristischen Materialverhaltens



Auswahl eines vorh. Stoffgesetzes oder Implementierung

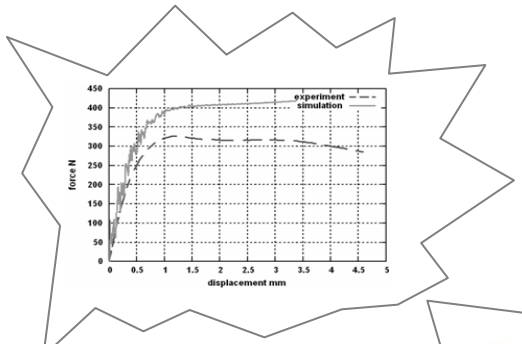
Verifikation

des Stoffgesetzes



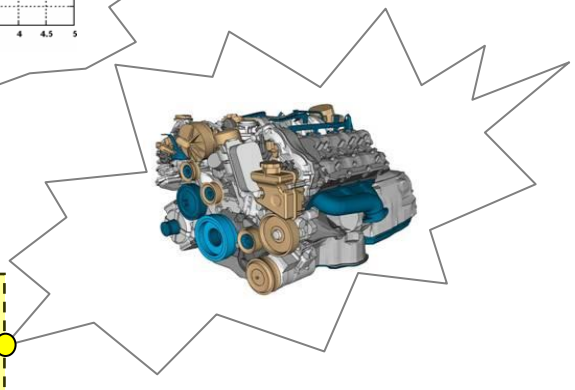
$$f_{n+1}^{k} = f_{n+1}^{k-1} + \frac{\partial f}{\partial \Delta \lambda} d(\Delta \lambda)^{k-1} = 0$$

$$\Delta \lambda^{k} = \Delta \lambda^{k-1} + d(\Delta \lambda)^{k-1} = \Delta \lambda^{k-1} - \frac{f_{n+1}^{k-1}}{\frac{\partial f}{\partial \Delta \lambda}}$$



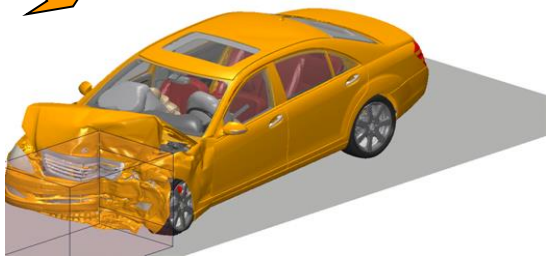
Kalibrierung

des verifizierten Models bez. Materialparameter



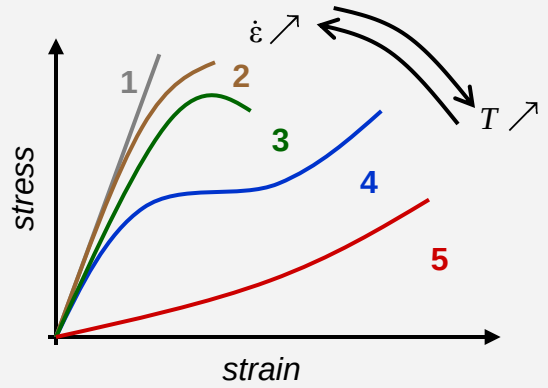
Validierung

des verifizierten und kalibrierten Modells durch Experimente

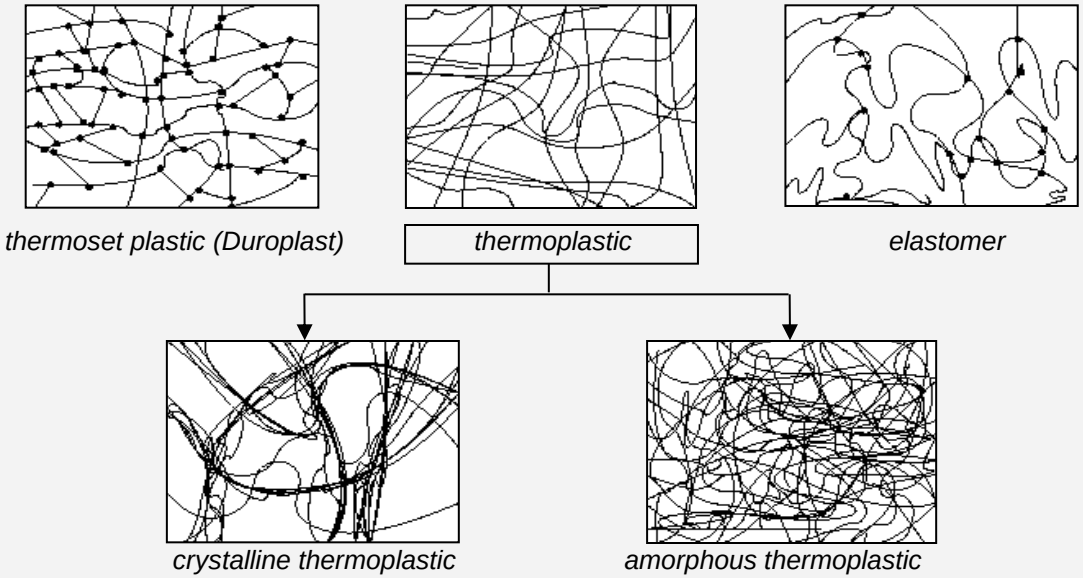


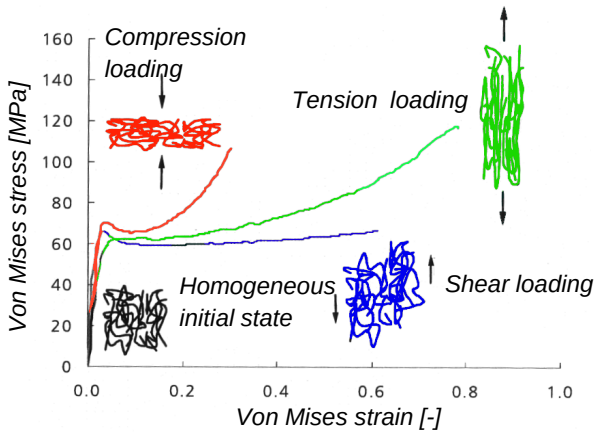
Unreinforced Polymers

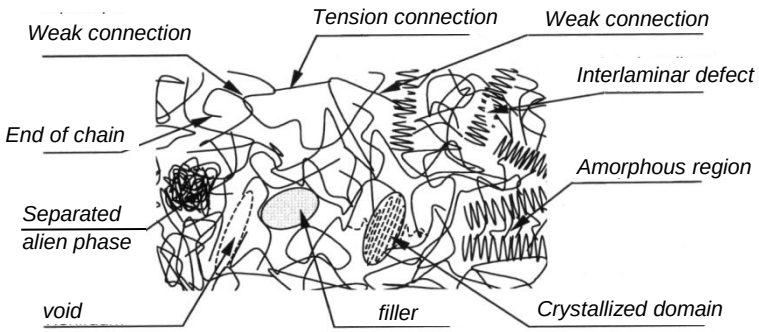
Characteristic Structure of unreinforced Plastics



1 glasslike behaviour
2 plastic or viscous flow
3 low ductility
4 high ductility
5 rubbery







[Junginger 2002]

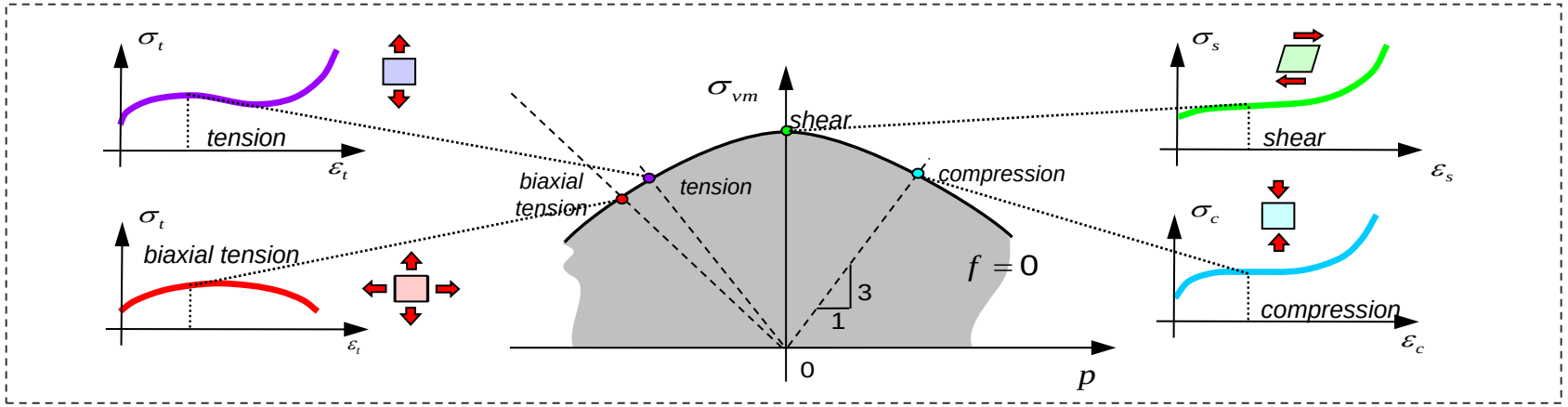
Some material laws for visco-plasticity in LS-DYNA

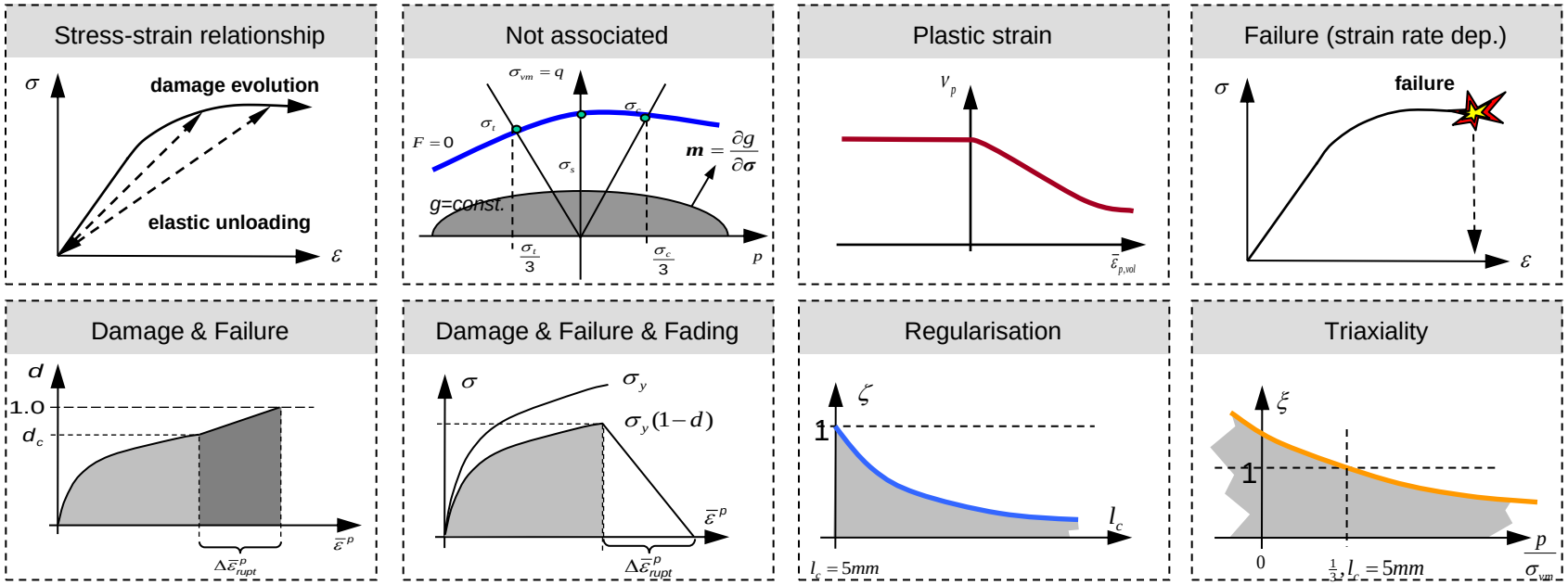
No.	Keyword	Formulation	Input
24,123	MAT_PIECEWISE_LINEAR_PLASTICITY	isotropic, el-pl, von Mises strain rate	LC table
81, 82	MAT_PLASTICITY_WITH_DAMAGE	isotropic, el-pl damage strain rate	LC LC table
89	MAT_PLASTICITY_POLYMER	isotropic, el-pl strain rate	LC parameter
141	MAT_STRAIN_RATE_SENSITIVE_ POLYMER	isotropic, el-pl strain rate	parameter parameter
168	MAT_POLYMER	isotropic, el-pl strain rate, isochoric	parameter Parameter
193	MAT_DRUCKER_PRAGER	isotropic, el-pl strain-rate plastic compressibility	LC parameter parameter
187	MAT_SAMP-1	isotropic, el-pl strain rate damage plastic compressibility	LC table LC LC

New!

Unreinforced Polymers

Overview on SAMP-1 (#187)

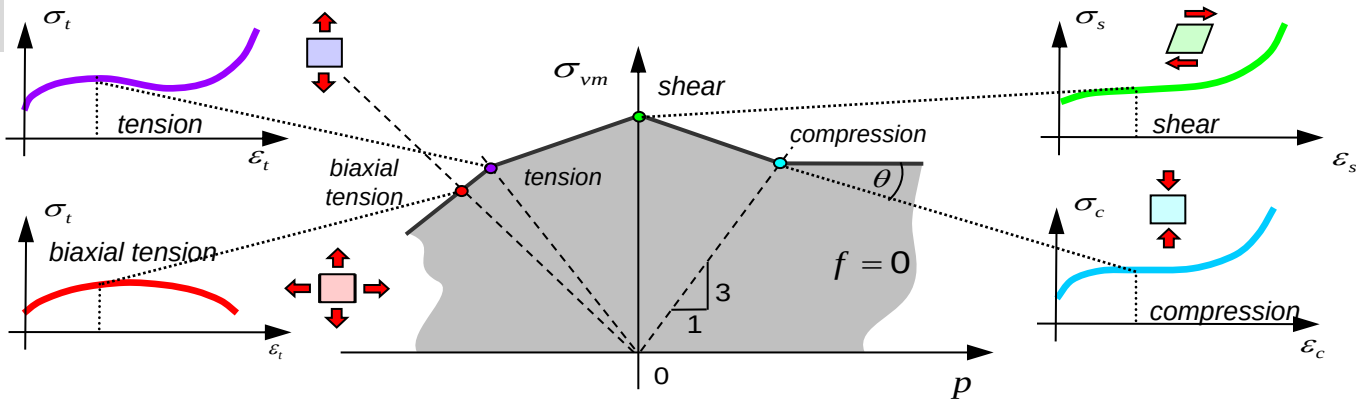




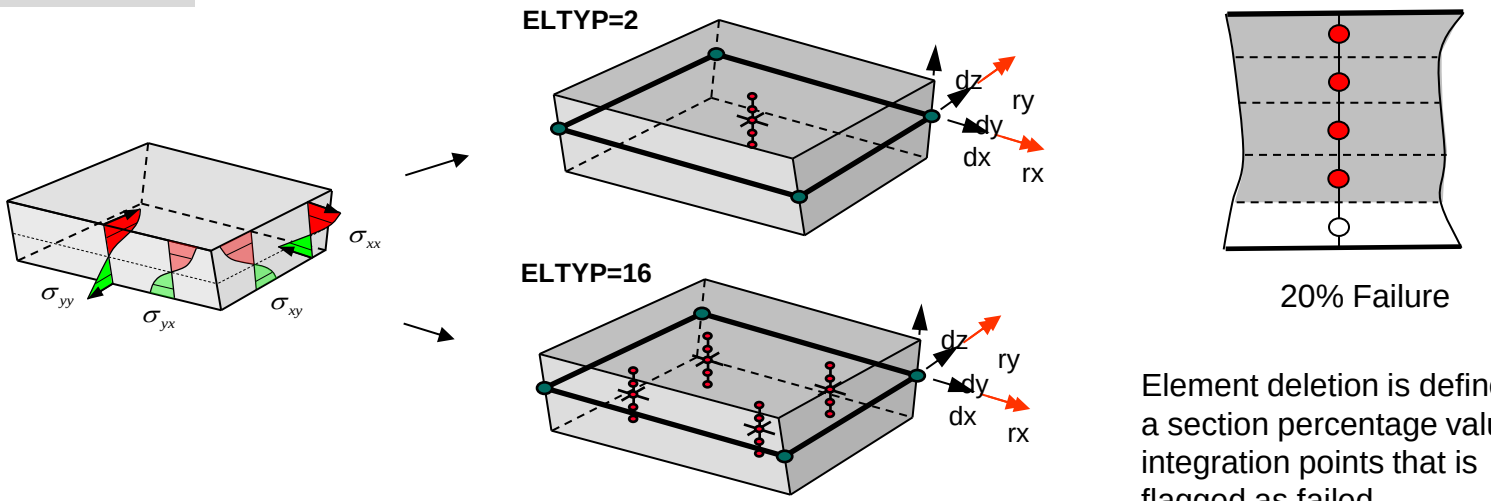
Unreinforced Polymers

Overview on SAMP-1 (#187): Mature options

RBCFAC



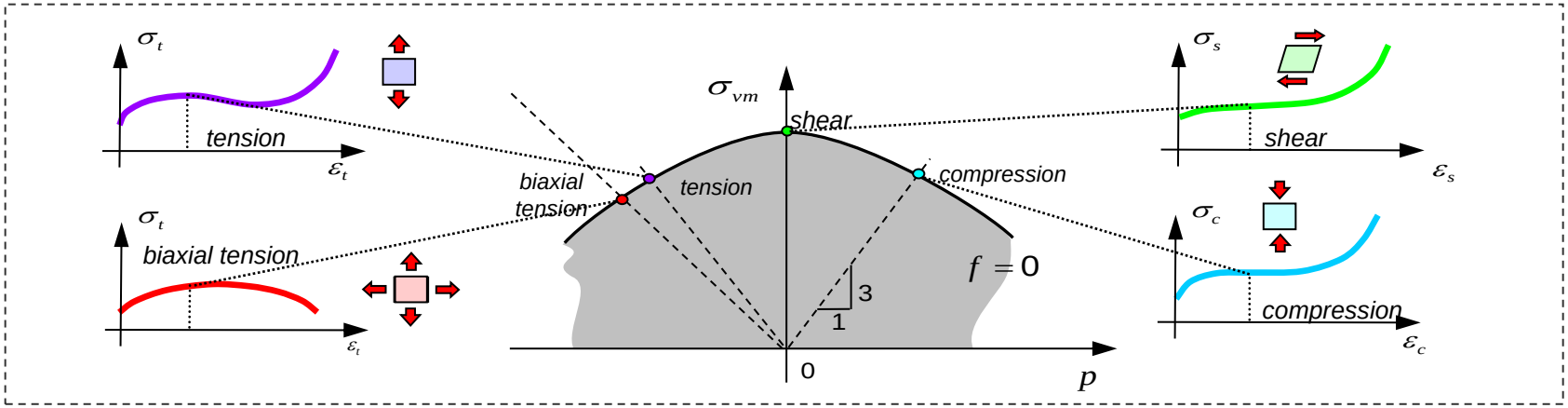
NUMINT<0



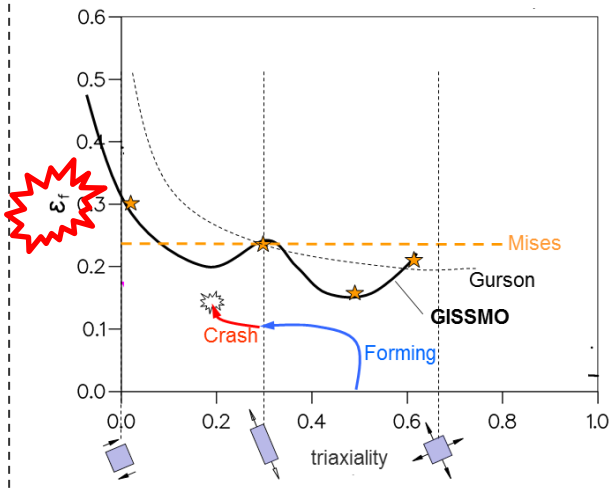
Element deletion is defined via a section percentage value of integration points that is flagged as failed

Unreinforced Polymers

Overview on SAMP-1 (#187): New options



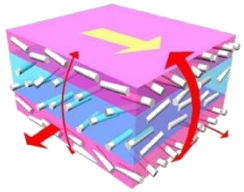
Combining MAT_187 and GISSMO



New!

- GISSMO is driven by a monotonic ascending variable: the equiv. plastic strain stored in hisv(0).
- The new option allows the definition of any history variable to be the driving force of GISSMO. I.e. SAMP my deliver volumetric plastic strain on hisv(6) and this may be used to drive damage in GISSMO (used for crazing!).
- Usage: DMGTYP=YYYX
  with X=1 and YYY=hisv(YYY)
- Next release will be able to use multiple GISSMO-cards with reference to one material model. This will allow different hisv-driven failure criteria to act on the same material.

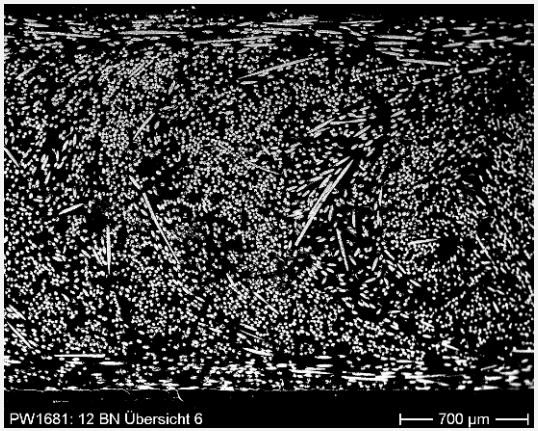

Kunststoffe + Simulation
Strategien der Materialmodellierung für unverstärkte Thermoplaste auf Basis von Zug- und Biegeversuchen
Veronika Effinger[1], Andreas Hirth[2], Anja Förderer[1]
24.02.2014
[1]DYNAmore GmbH, Sindelfingen
[2]Daimler AG, Sindelfingen
kunststoffe + SIMULATION
08. und 09. April 2014 in München
Der Branchentreff zur Bauteil-optimierung!

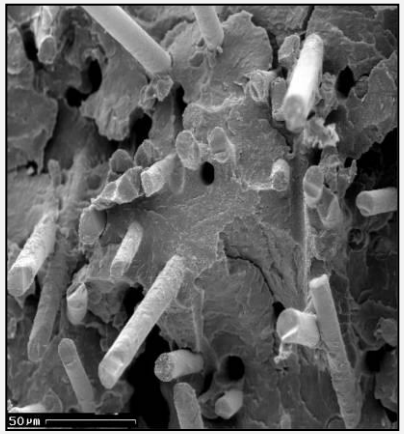


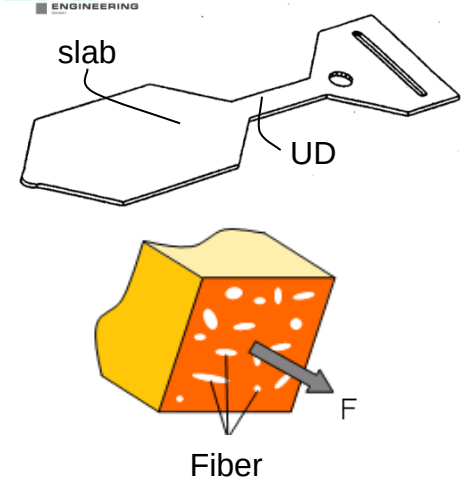
Reinforced Polymers

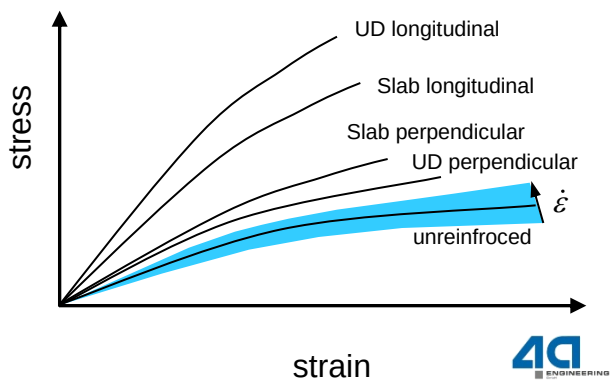
Characteristic Structure of reinforced Plastics

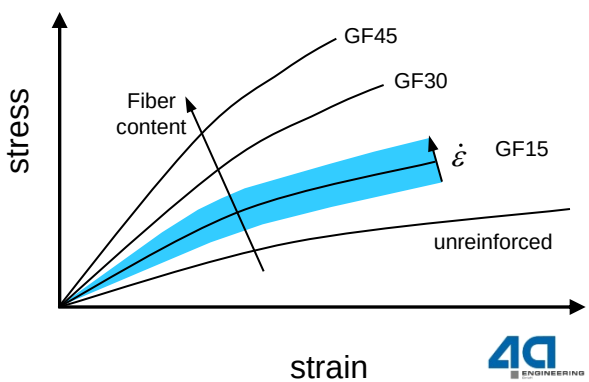
Fiber **size** and **geometry** have significant influence on the part performance.
Orthotropic properties increase with increasing fiber content while at the same time the effect of strain rate diminishes due to the less content of matrix material.









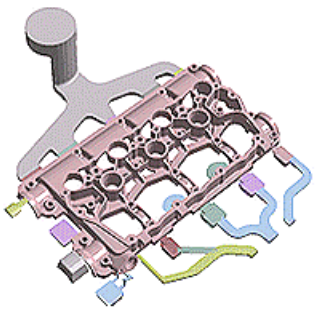


Fiber Reinforced Polymers

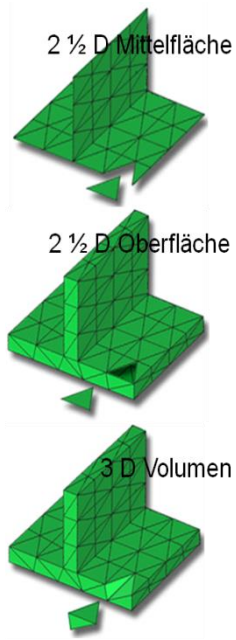
Detailed approach: Locally anisotropic model

Taking process chain into account

Injection molding



SIGMASOFT, Moldflow, Moldex, CADmold etc.



Fiber content & orientation

Mapping

SCAImapper

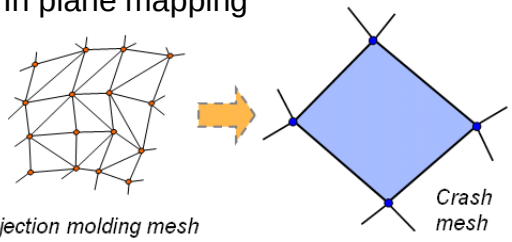
or

DYNAmap

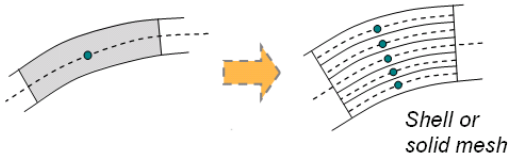
or

Whatever tool you find useful.

In plane mapping

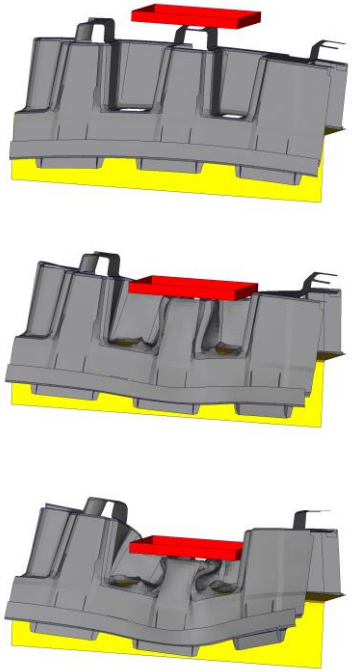


Mapping in thickness direction



Crash analysis

With calibrated anisotropic plasticity model including damage & failure



Un/reinforced Polymers / Process chain

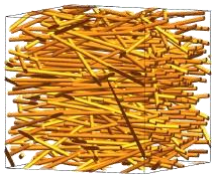
Anisotropic elastic solution with MAT_002_ANIS

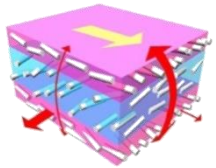
New!

- Hyperelastic (total) formulation using Green-Lagrange strain $\mathbf{E}$

$$\boldsymbol{\sigma} = J^{-1}\mathbf{F}\cdot\mathbf{S}\cdot\mathbf{F}^T = J^{-1}\mathbf{F}\cdot\mathbf{C}\cdot\mathbf{E}\cdot\mathbf{F}^T$$

- Elastic-anisotropic behavior, stiffness matrix with 21 independent coefficients:





Generation of constitutive data

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

- Several possibilities to define material directions, e.g. AOPT, ELEMENT_SOLID_ORTHO, …
- Use invariant node numbering is recommended → *CONTROL_ACCURACY: INN=4

- No plasticity, no damage, no failure (but: brittle failure possible via *MAT_ADD_EROSION)

*MAT_(ANISO)TROPIC_ELASTIC

New!

CARD #1	mid	ro	c11	c12	c22	c13	c23	c33
CARD #2	c14	c24	c34	c44	c15	c25	c35	c45
CARD #3	c55	c16	c26	c36	c46	c56	c66	aopt
CARD #4	xp	yp	zp	a1	a2	a3	macf	ihis
CARD #5	v1	v2	v3	d1	d2	d3	beta	ref

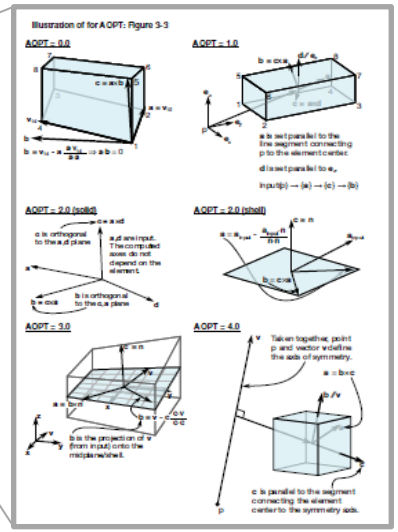
- C_{ij}: constants in the 6x6 anisotropic constitutive matrix $\sigma_{ij} = C_{ijkl}\varepsilon_{kl}$

*MAT_(ANISO)TROPIC_ELASTIC

New!

CARD #1	mid	ro	c11	c12	c22	c13	c23	c33
CARD #2	c14	c24	c34	c44	c15	c25	c35	c45
CARD #3	c55	c16	c26	c36	c46	c56	c66	aopt
CARD #4	xp	yp	zp	a1	a2	a3	macf	ihis
CARD #5	v1	v2	v3	d1	d2	d3	beta	ref

- C_{ij}: constants in the 6x6 anisotropic constitutive matrix $\sigma_{ij} = C_{ijkl}\varepsilon_{kl}$
- AOPT: usual options to define the material's coordinate system

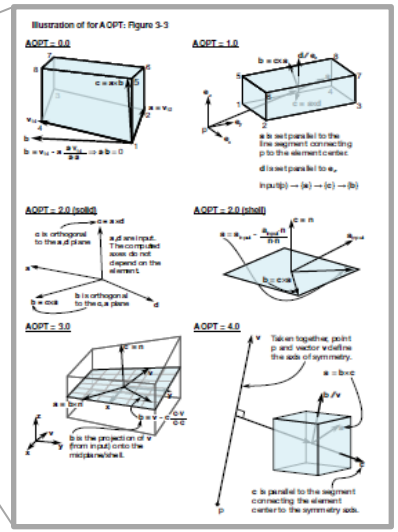


*MAT_(ANISO)TROPIC_ELASTIC

New!

CARD #1	mid	ro	c11	c12	c22	c13	c23	c33
CARD #2	c14	c24	c34	c44	c15	c25	c35	c45
CARD #3	c55	c16	c26	c36	c46	c56	c66	aopt
CARD #4	xp	yp	zp	a1	a2	a3	macf	ihis
CARD #5	v1	v2	v3	d1	d2	d3	beta	ref

- C_{ij}: constants in the 6x6 anisotropic constitutive matrix $\sigma_{ij} = C_{ijkl}\varepsilon_{kl}$
- options defining the material's coordinate system
- ihis: flag for element-wise definition of the stiffness tensor with *INITIAL_STRESS_SOLID
  This allows mapping of locally anisotropic data.



*INITIAL_STRESS_SOLID

New!

CARD #1	eid	nint	nhisv	large	iveflg	ialegp	nthint	nthhsv
CARD #2	sigxx	sigyy	sigzz	sigxy	sigyz			
CARD #3	sigzx	eps	hisv1	hisv2	hisv3			
CARD #4	hisv4	hisv5	hisv6	hisv7	hisv8			
CARD #5	hisv9	hisv10	hisv11	hisv12	hisv13			
CARD #6	hisv14	hisv15	hisv16	hisv17	hisv18			
CARD #7	hisv19	hisv20	hisv21					

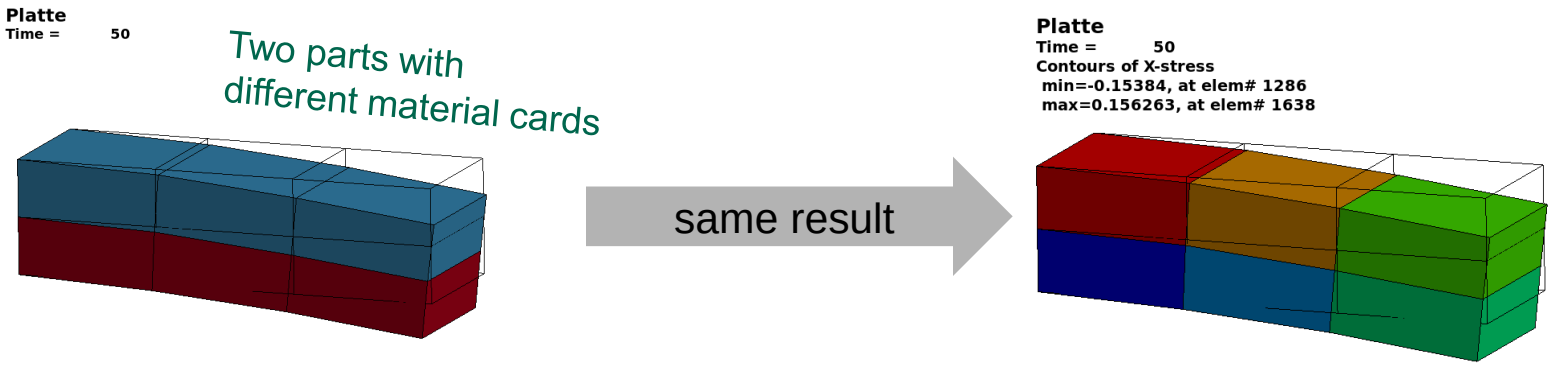
- The parameters C_{ij} are written onto the history variables per integration point.
- Setting `ihisv=21` in MAT_002 will take into account the fully anistropic stiffness tensor (e.g. hisv#1 – hisv#21 have to be defined in DYNAIN for instance)

Un/reinforced Polymers / Process chain

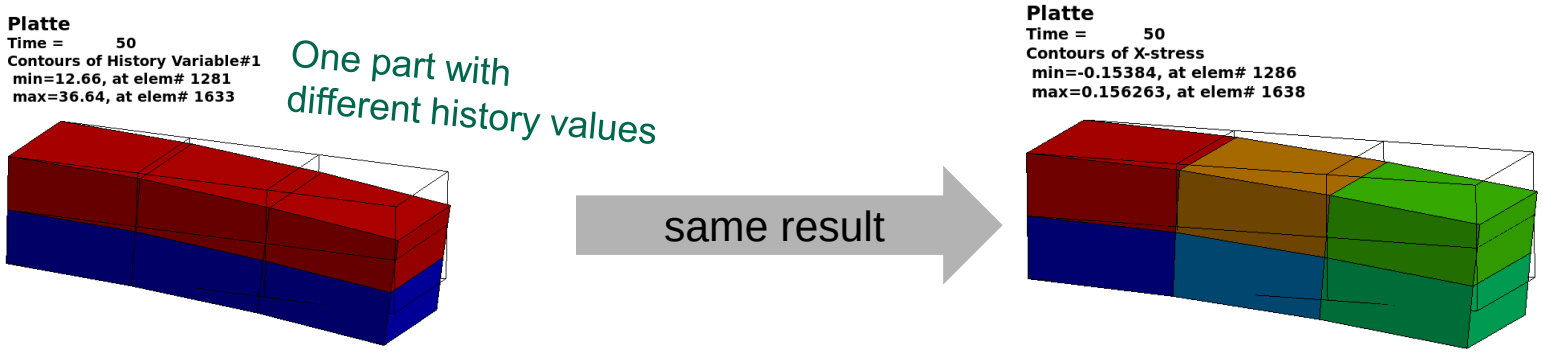
Anisotropic elastic solution with MAT_002_ANIS

- Two options to define the 21 material constants:

1) **Directly in material card**: small bending test



2) **Initialization with *INITIAL_STRESS_SOLID**: small bending test

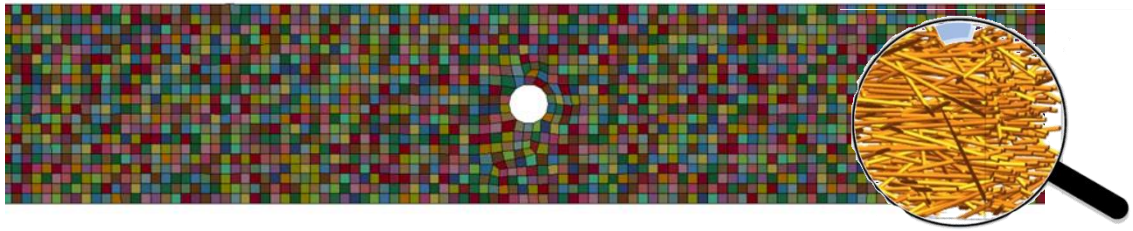


Un/reinforced Polymers / Process chain

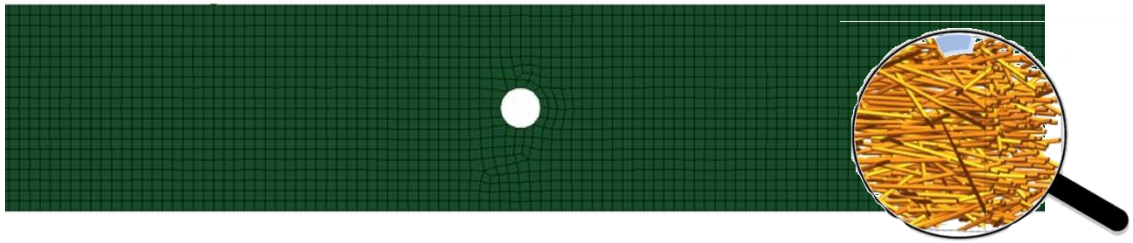
Anisotropic elastic solution with MAT_002_ANIS

- Two options to define the 21 material constants:

1) **Directly in material card**.
   Drawback: inhomogeneous distribution (e.g. from previous short fiber filling simulation) in component needs individual part definition for every element



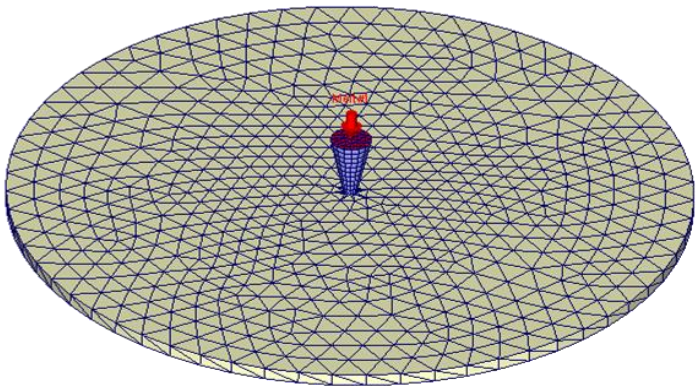
2) **Initialization with *INITIAL_STRESS_SOLID (new option in next Release R7.1)**
   Only one part definition for whole component. Anisotropic coefficients are part of material‘s history field and can therefore be initialized for each integration point individually.

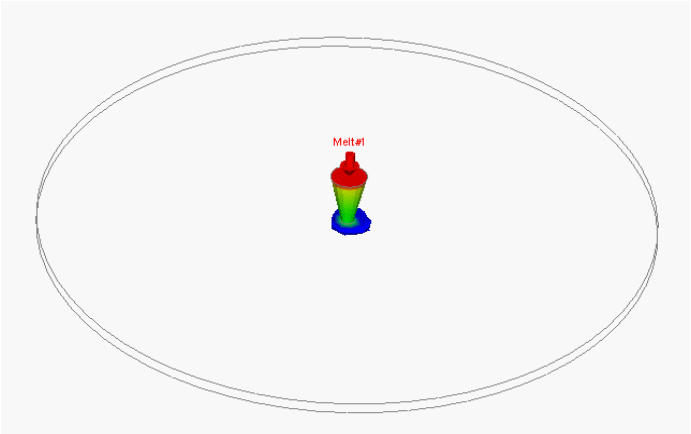


Results from Infiltration

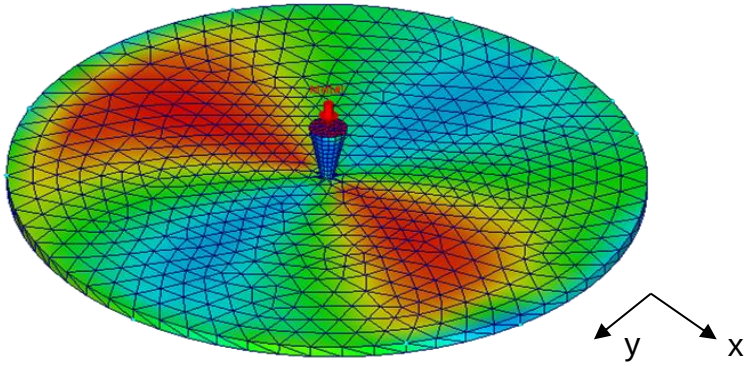
Mapping example

- Small test example – simple plate, filling performed with Moldex3D

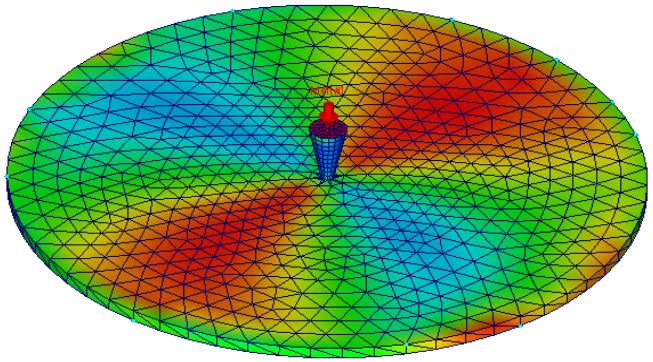




- Resulting orientations



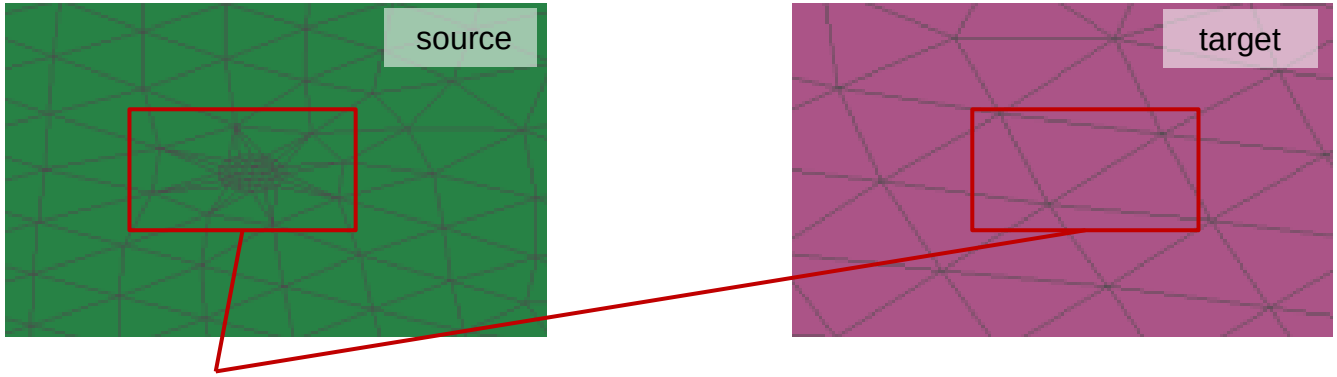
x-orientation



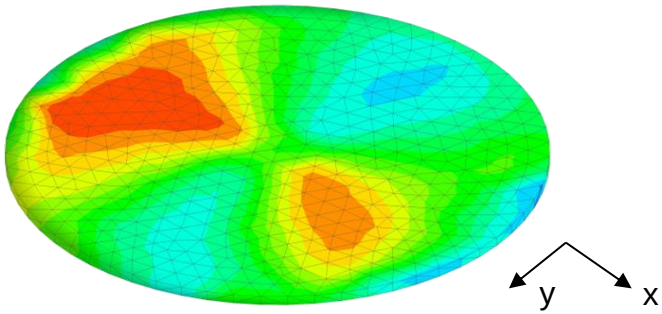
y-orientation

Mapping for further simulations (current development)

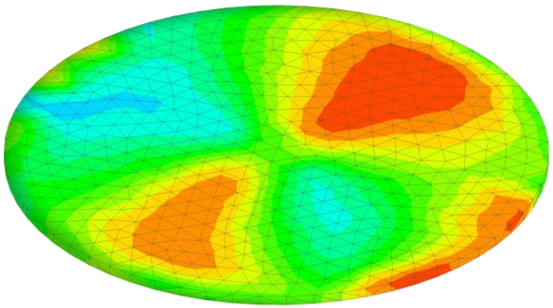
- Comparison btw. source and target mesh



- Biggest difference btw. meshes at the inlet
- Mapping results:



x-orientation



y-orientation

Outlook: Initialization IP-wise for *MAT_ANISOTROPIC_ELASTIC_PLASTIC

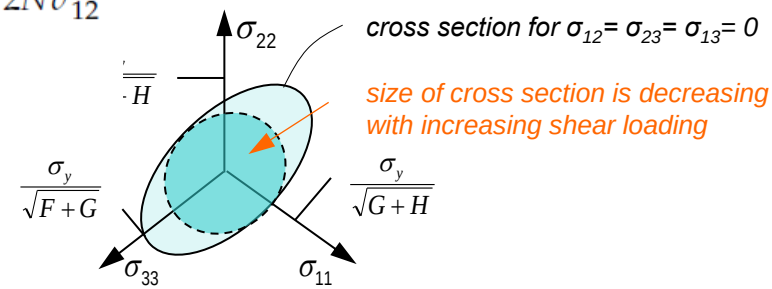
Outlook!

MAT_157 = MAT_002 + MAT_103

- Anisotropic elastic solution with MAT_002_ANIS as stated before
- Plasticity is based on Hill criteria:

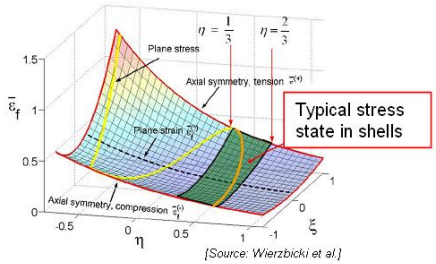
$$F(\sigma_{22}-\sigma_{33})^2 + G(\sigma_{33}-\sigma_{11})^2 + H(\sigma_{11}-\sigma_{22})^2 + 2L\sigma_{23}^2 + 2M\sigma_{31}^2 + 2N\sigma_{12}^2 = \left[\sigma(\varepsilon_{\text{eff}}^p, \dot{\varepsilon}_{\text{eff}}^p)\right]^2$$

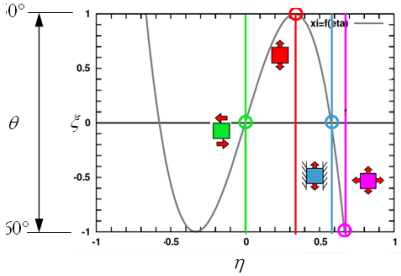
- Initialization via DYNAIN-file, hence possibility of mapping orientation data and constitutive parameters from mould simulation

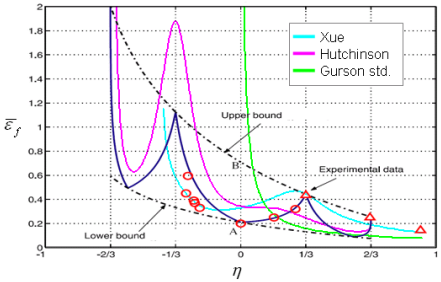


damage + failure part

- GISSMO
  or DIEM or else…
- Or any combination!







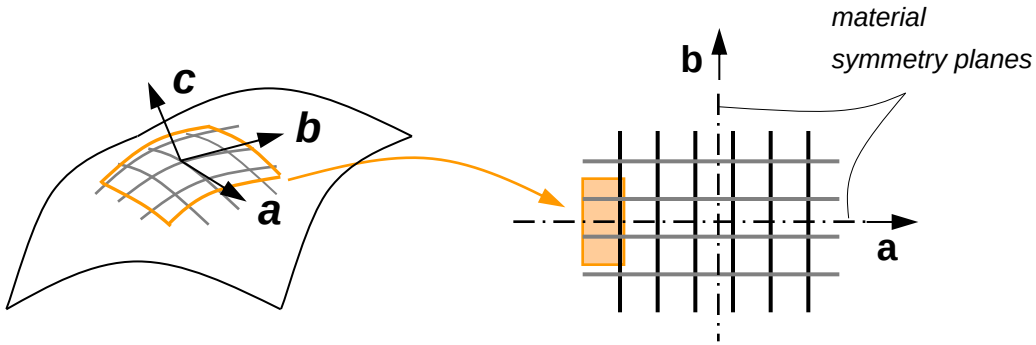
Fiber Reinforced Polymers

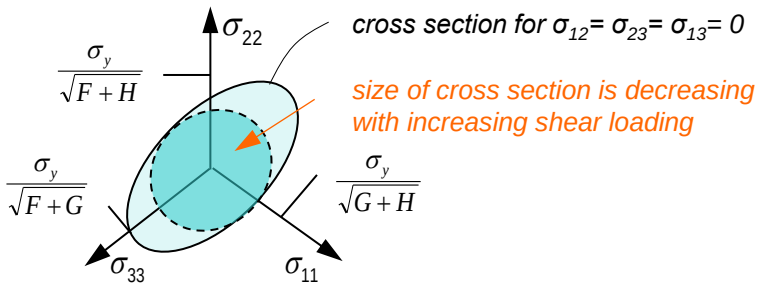
Quick (!) solution with orthotropic material + failure model

MAT_ORTHO_ELASTIC_PLASTIC (#108) + MAT_54 + MAT_ADD_EROSION (GISSMO, DIEM)

elastic + plastic part

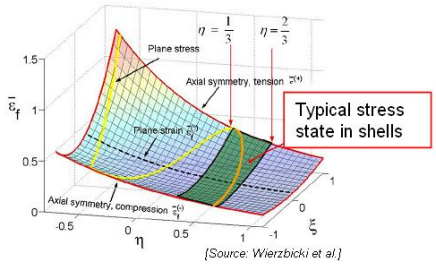
- elastic **and** plastic behavior is orthotropic
- Plastic yield surface is Hill 1948 (others also available)

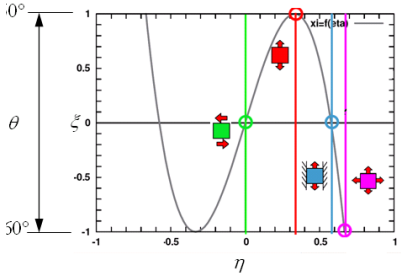


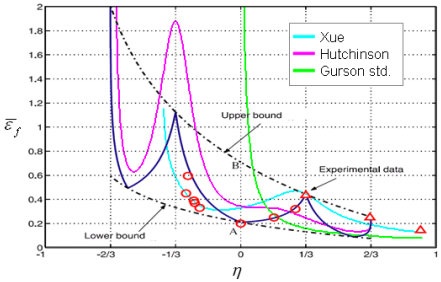


damage + failure part

- GISSMO
  or DIEM or else…
- Or any combination!







Fiber Reinforced Polymers

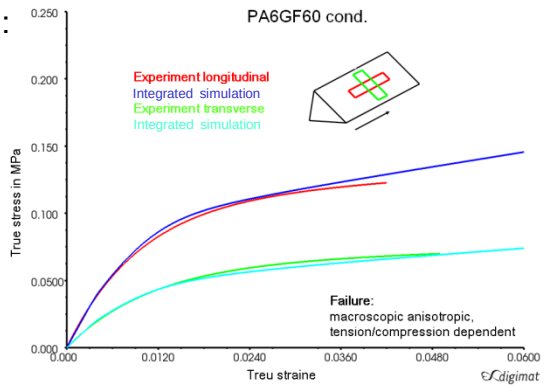
Model calibration exemplified on PA6GF60

DAIMLER

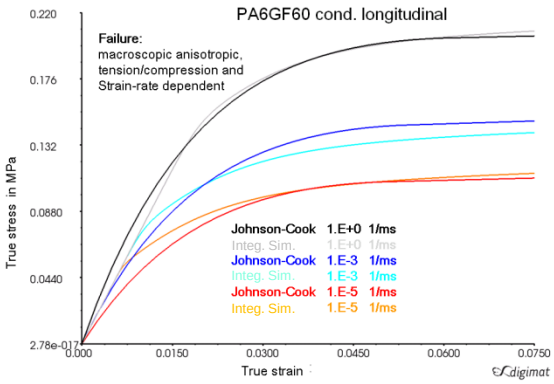
[Diss. J.Schöpfer]

True stress-strain input

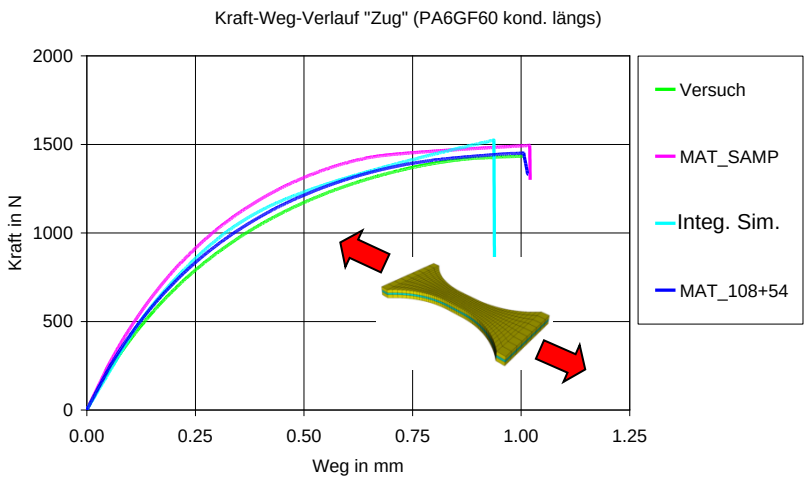
Elasto-plastic model:

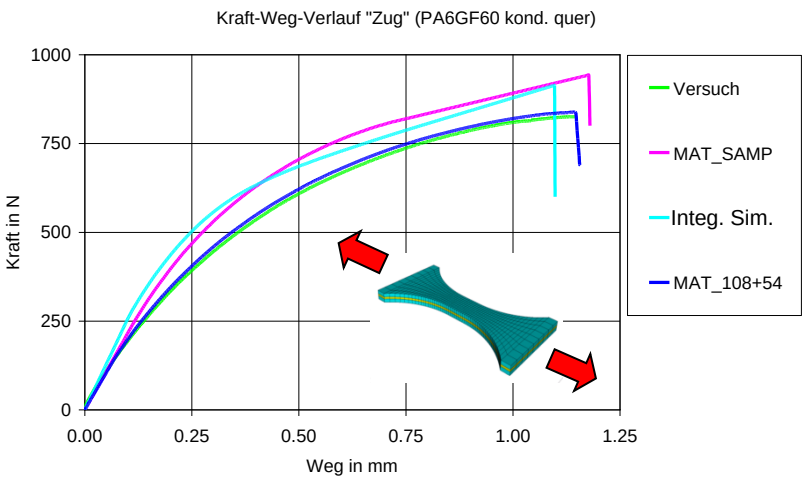


Elasto-visco-plastic model:
(strain rate dependent)



Tension test calibration results



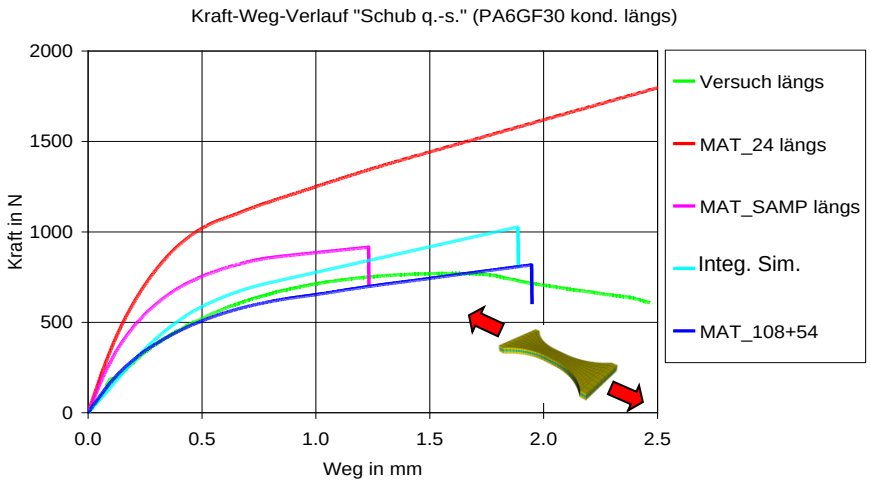


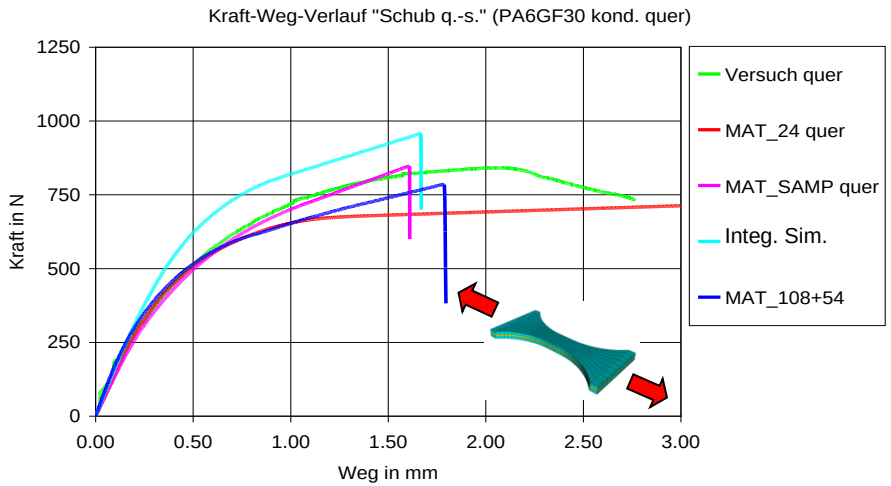
Fiber Reinforced Polymers

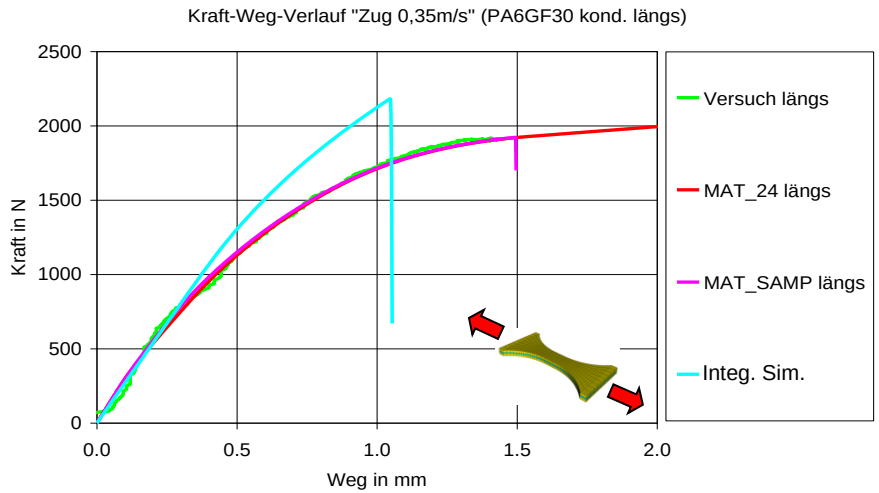
Calibration results (tension & shear) PA6GF30

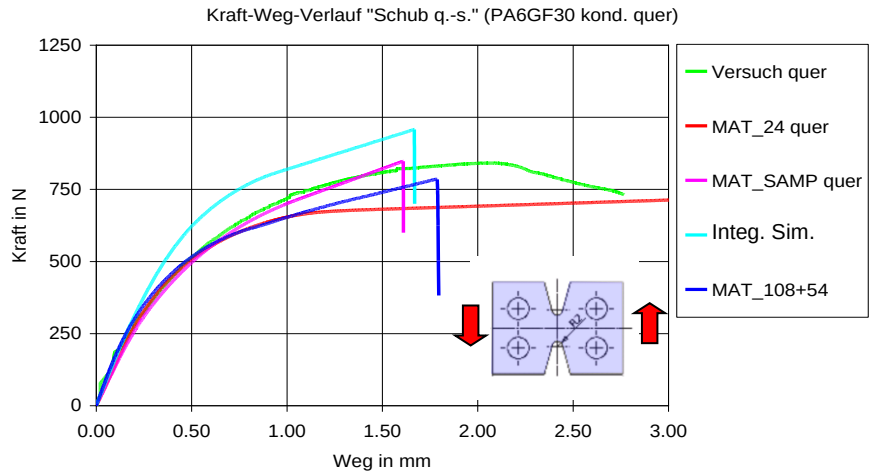
DAIMLER

[Diss. J.Schöpfer]







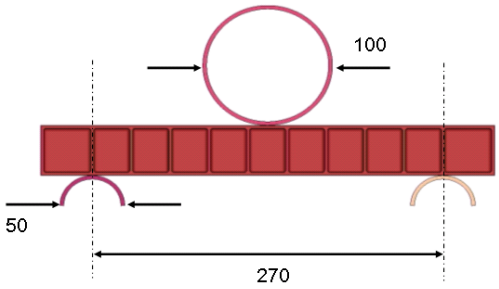


Fiber Reinforced Polymers

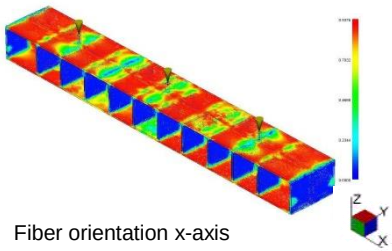
Quasi static three point bending test of PA6GF30

DAIMLER

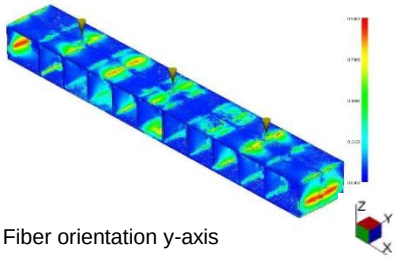
[Diss. J.Schöpfer]



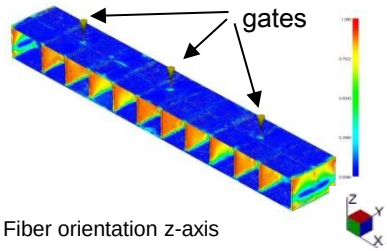
Mould simulation results



Fiber orientation x-axis

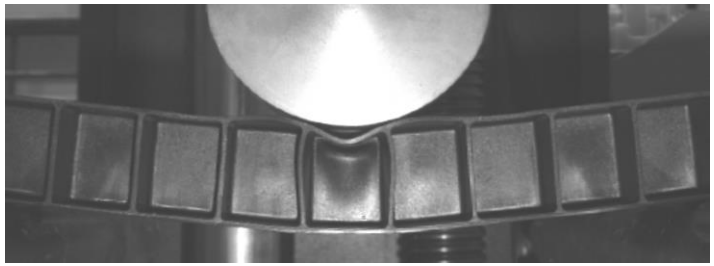


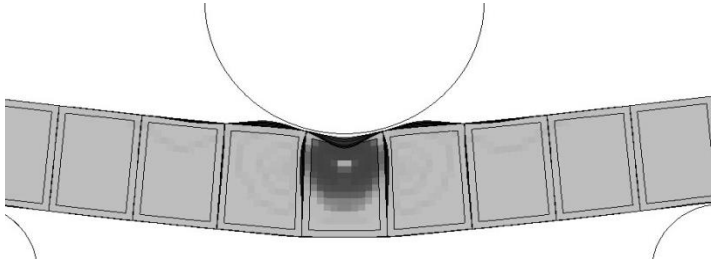
Fiber orientation y-axis



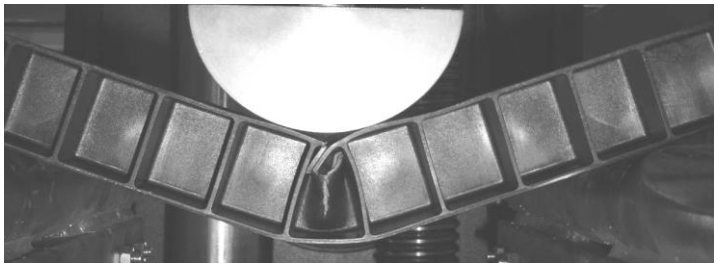
Fiber orientation z-axis

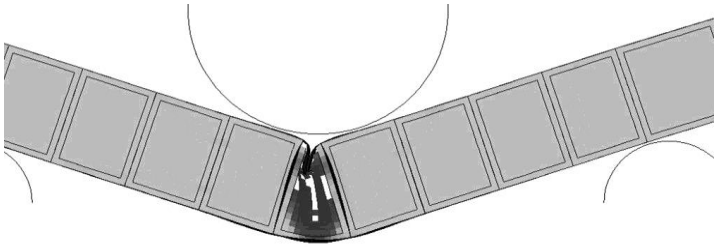
15mm punch travel





40mm punch travel



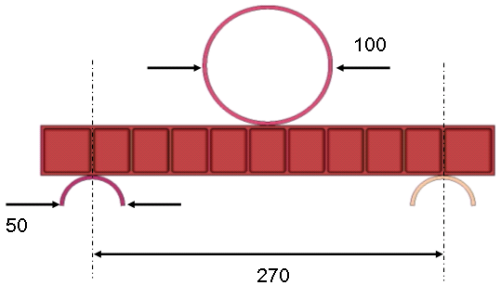


Fiber Reinforced Polymers

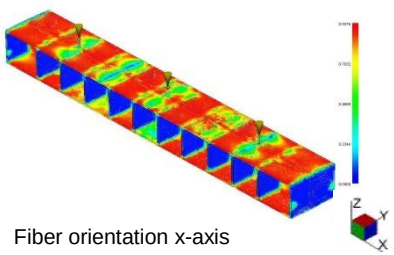
Quasi static three point bending test of PA6GF30

DAIMLER

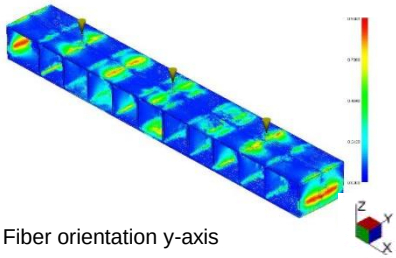
[Diss. J.Schöpfer]



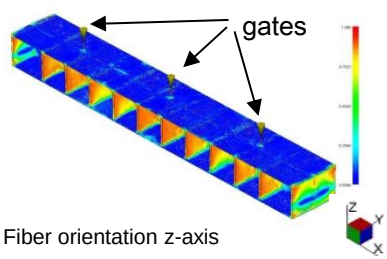
Mould simulation results



Fiber orientation x-axis

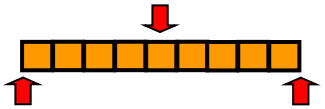


Fiber orientation y-axis

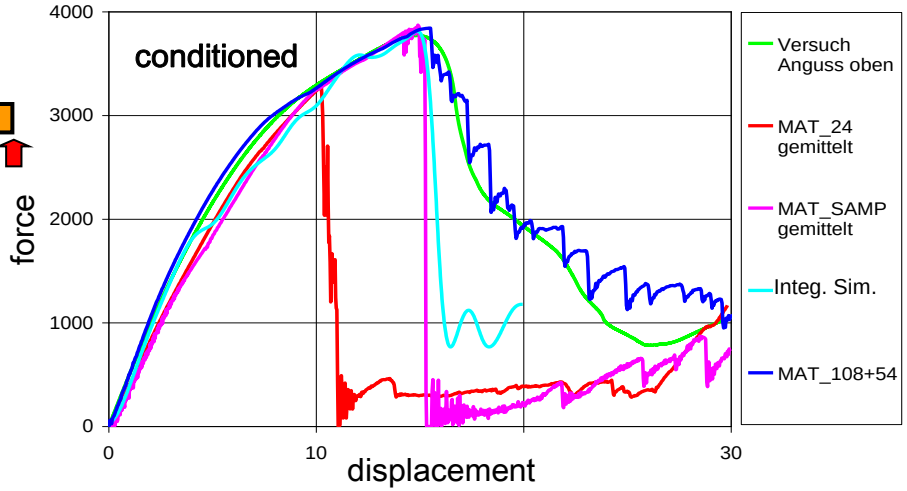


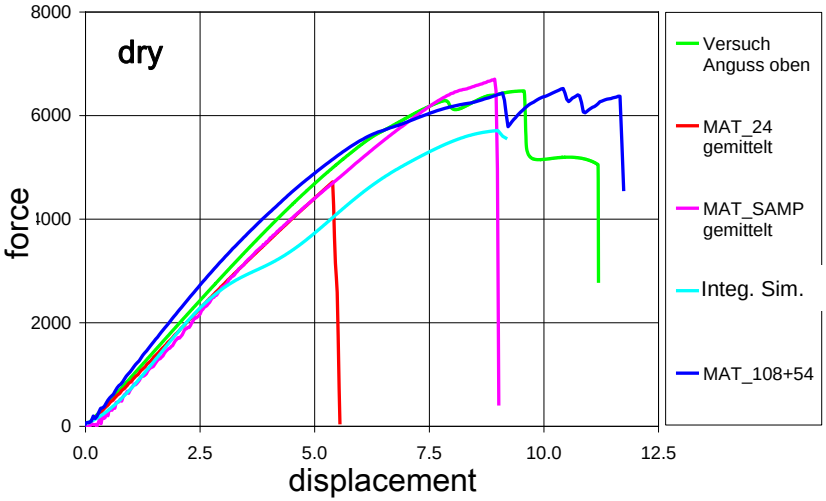
Fiber orientation z-axis

Comparison of test vs. simulation



Standard orientation



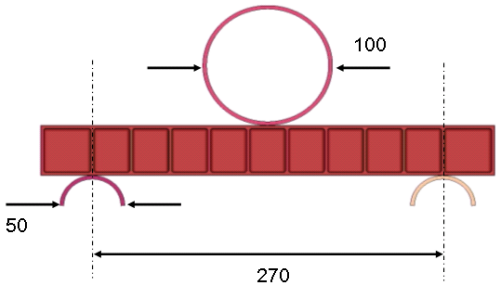


Fiber Reinforced Polymers

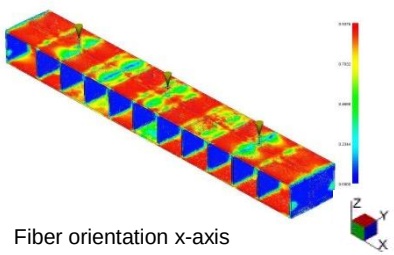
Quasi static three point bending test of PA6GF30

DAIMLER

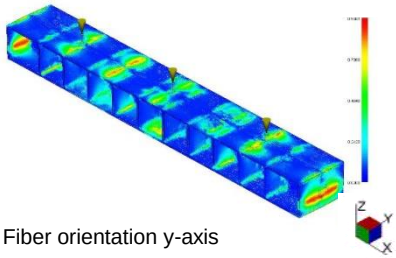
[Diss. J.Schöpfer]



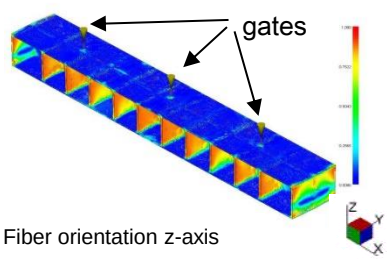
Mould simulation results



Fiber orientation x-axis

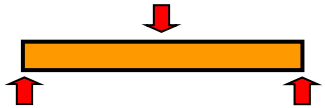


Fiber orientation y-axis

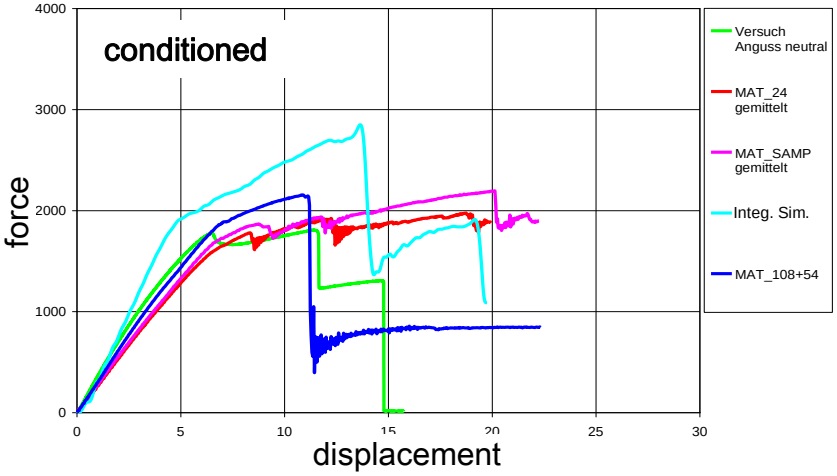


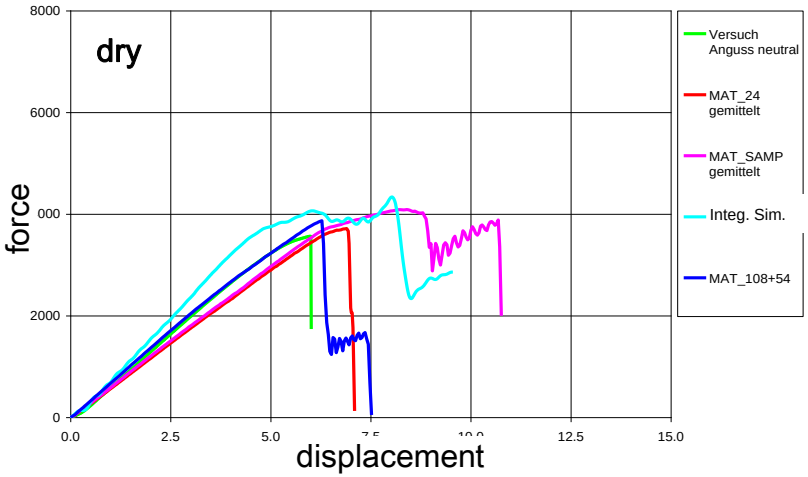
Fiber orientation z-axis

Comparison of test vs. simulation



Orientation rotated 90°

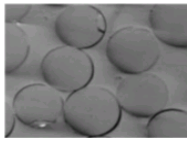
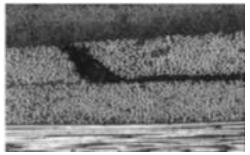
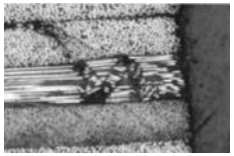


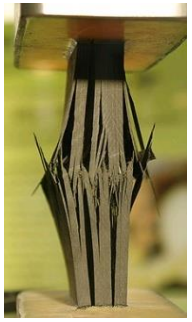


Composites

Target: Predict serviceability in crashworthiness

➡ Crushing/cracking/delamination/buckling on different length scales…



[μm] micro — sub-ply — [mm] — meso — [cm] macro — Length scale

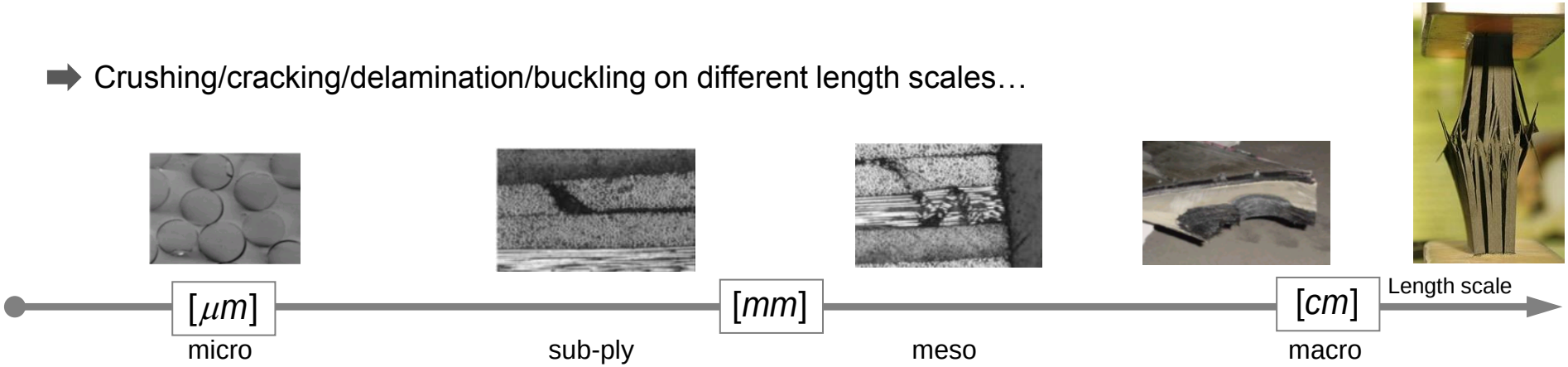
➡ Optimal product design? New approaches in CAE necessary!

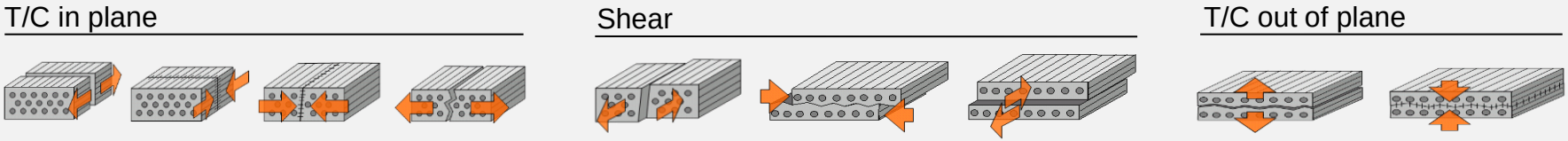
Steel/Aloy
Isotropic
Elasto plastic
Ductile

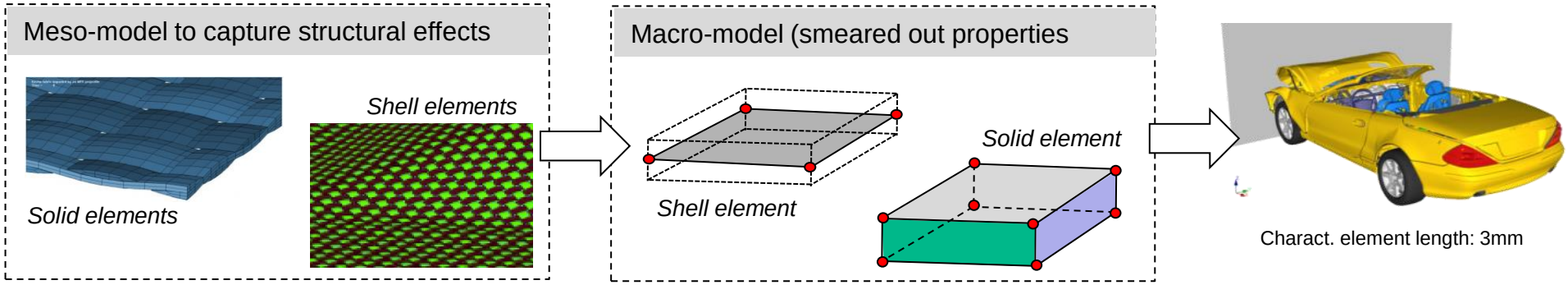
CFRP
Anisotropic
Stacked laminate
Elastic
Brittle failure

Target: Predict serviceability in crashworthiness

➡ Crushing/cracking/delamination/buckling on different length scales…

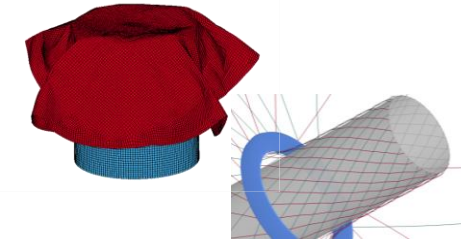


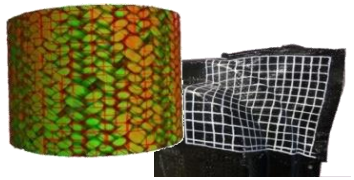




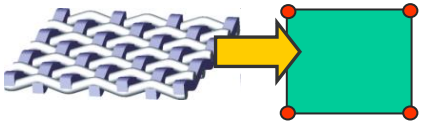
… only possible if process simulation is predictively solved!

- Know fiber influence (orientation) and matrix properties on relevant length scale
  - producibility simulation
  - Measurements





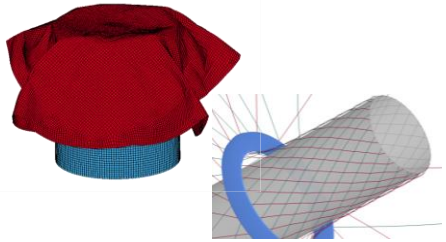
- Homogenize and map data to target length scale



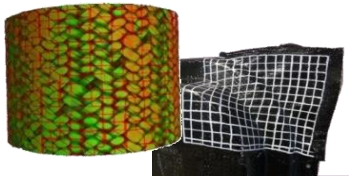
- Find suitable (predictive) models on that scale!

… only possible if process simulation is predictively solved!

- Know fiber influence (orientation) and matrix properties on relevant length scale
  - producibility simulation



  - Measurements



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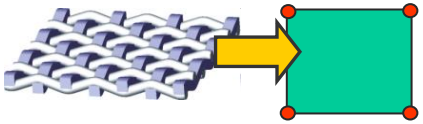

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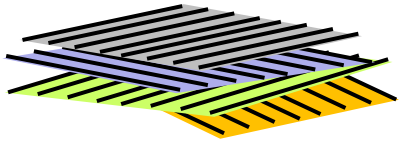


Producibility

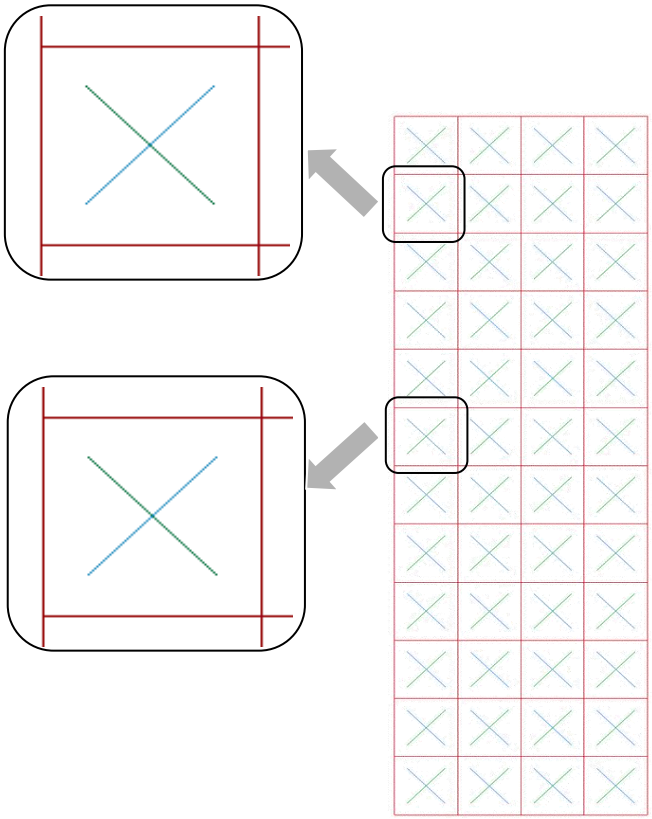
New model for draping

(available in R7.1 as MAT_249)

Thermoplastic pre-pregs – fiber contribution

New!

- Anisotropic and hyperelastic material definition
- Discretization with shell elements, where the fiber families are represented by vectors stored at the integration points
  - Its initial orientation $\vec{m}_i^0$ is an input parameter
  - current configuration is given as $\vec{m}_i = \underline{F}\vec{m}_i^0$
- Behavior under compression / tension
  - Elongation can easily be computed using the current length λ_i of vector $\vec{m}_i$
  - Load curve defines stresses for given λ_i
- Shear response
  - Based on the angle between neighboring fibers
  - Load curve defines stresses for given angle



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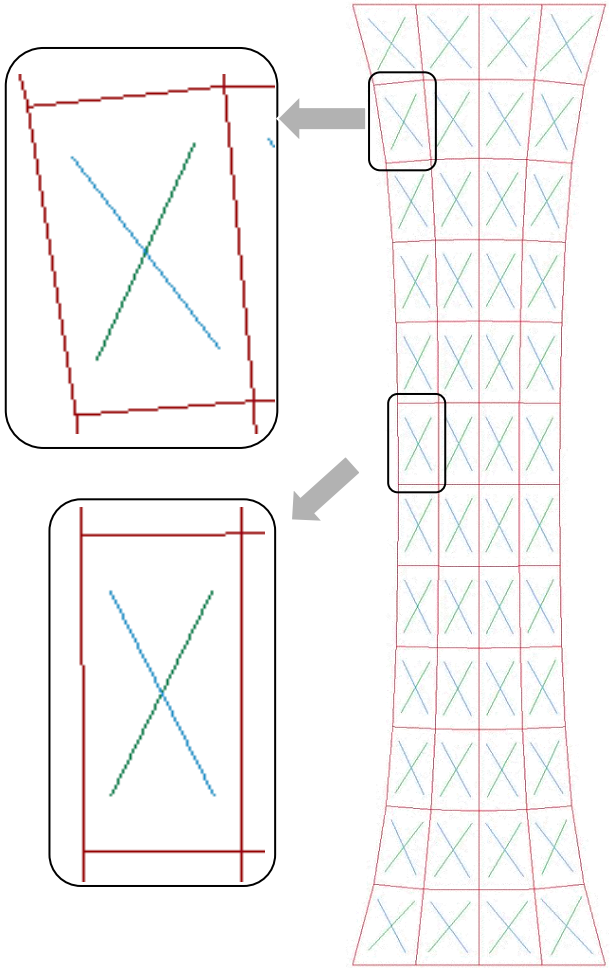
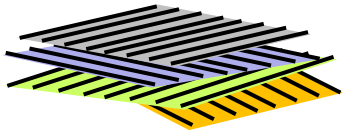
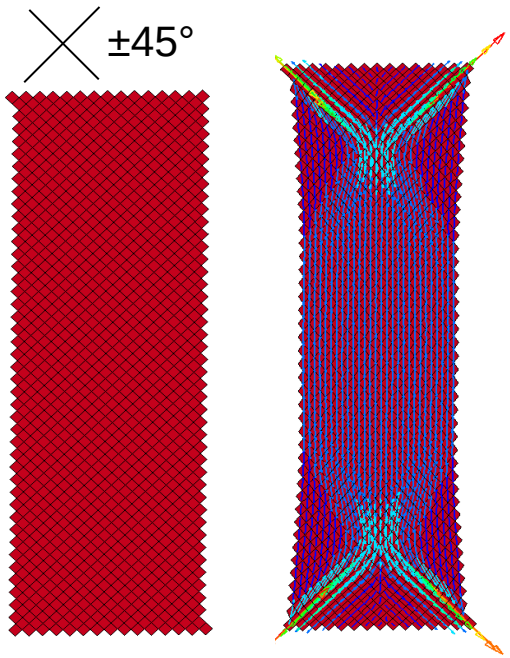


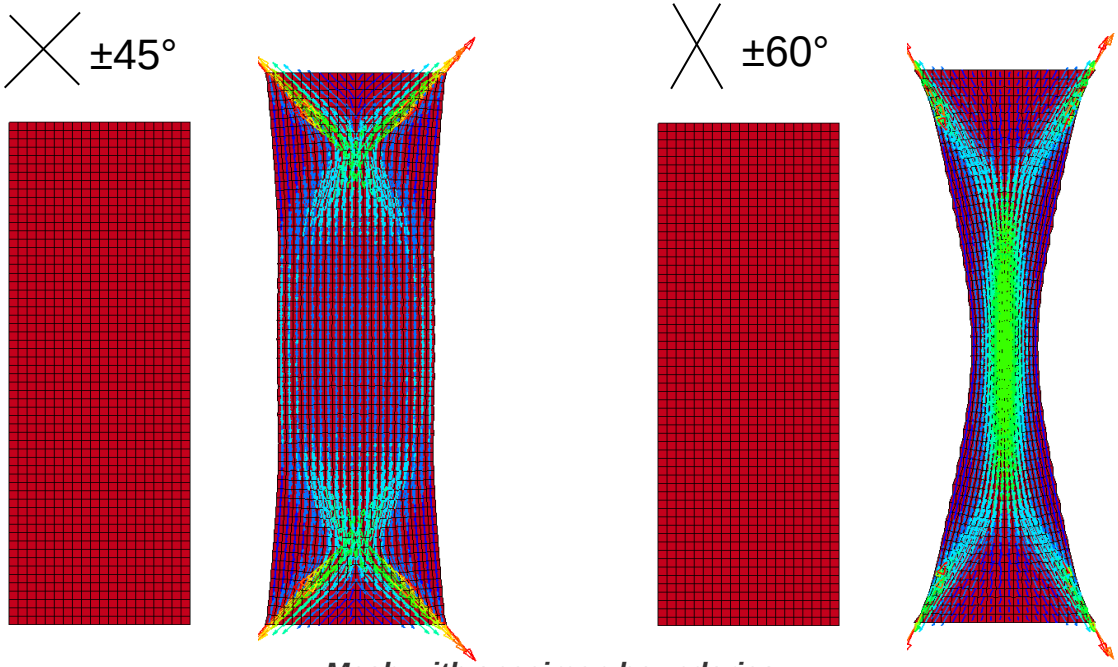
Tensile test specimen



- Prescribed motion of top nodes
- Arrows indicate the principal stresses



Mesh aligned with fiber directions

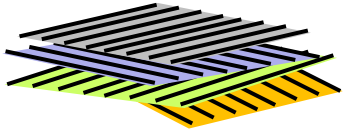


Mesh with specimen boundaries

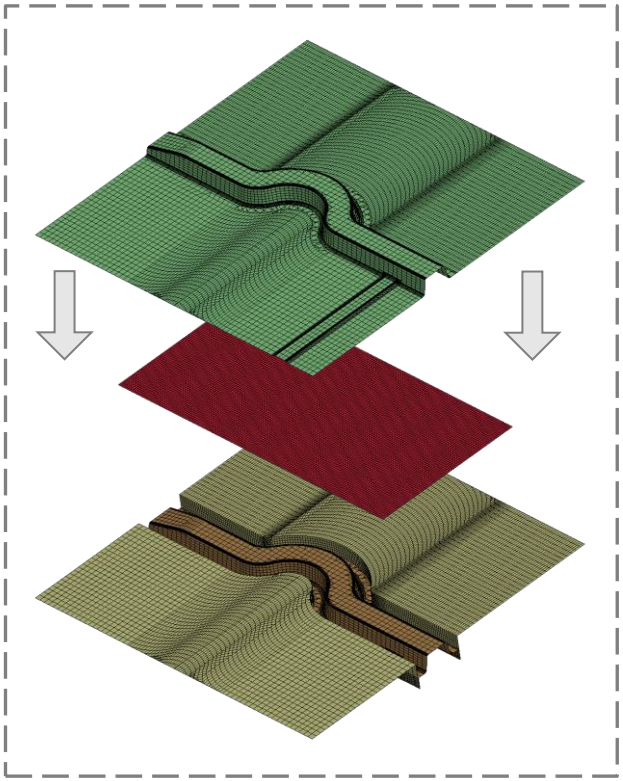
Results show that

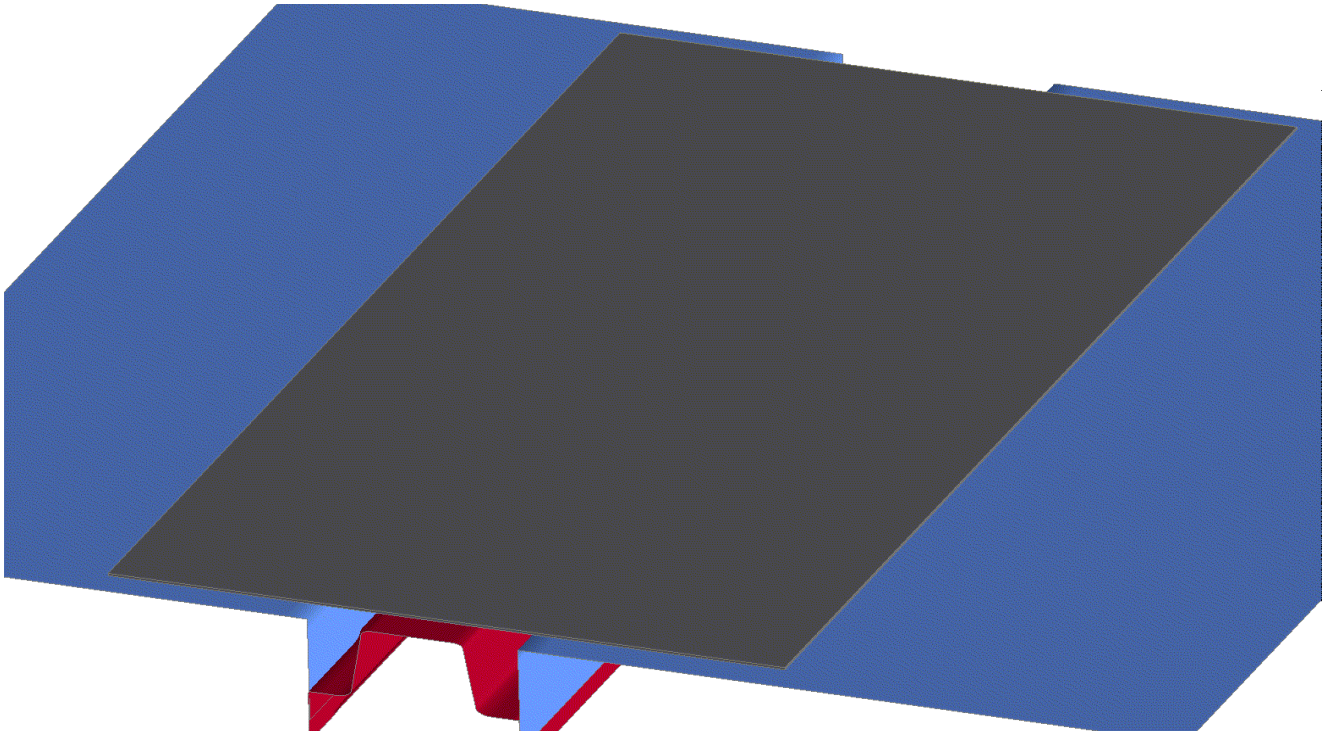
- stress orientations are independent of element orientations
- material definition accounts correctly for anisotropic (non-orthotropic) material behavior

Draping example: Rail



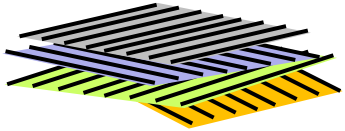
Process simulation



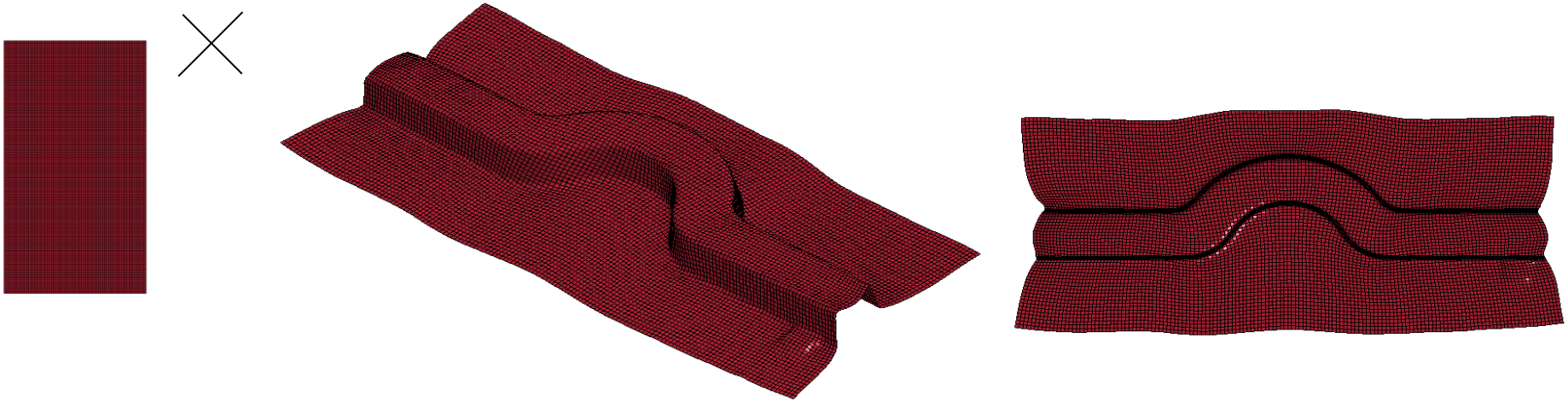


[geometry provided by Benteler-SGL]

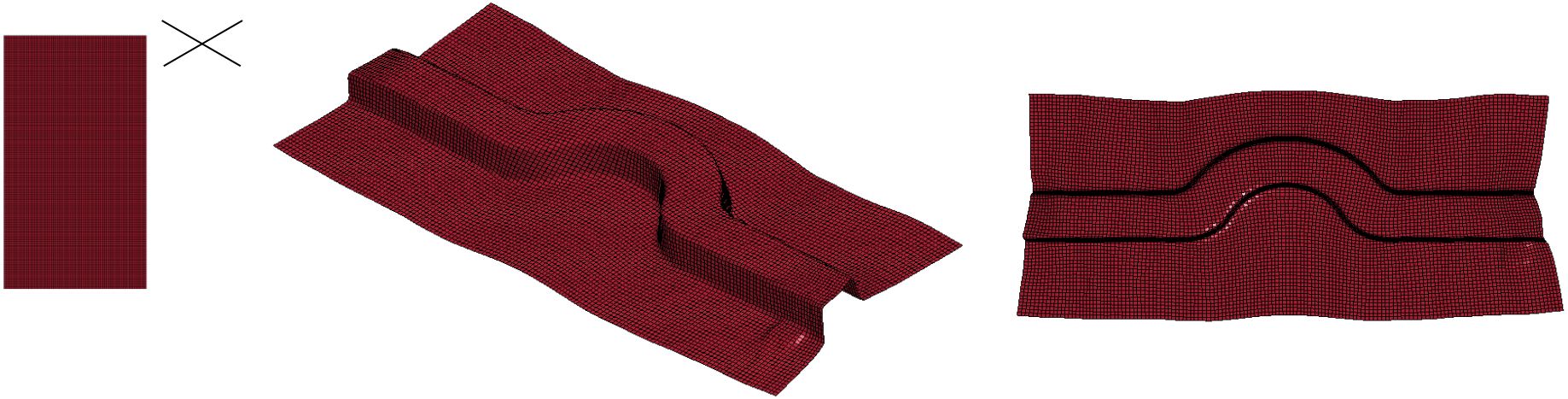
Draping example: S-Rail



Fiber angle ±45°, final state



Fiber angle ±60°, final state



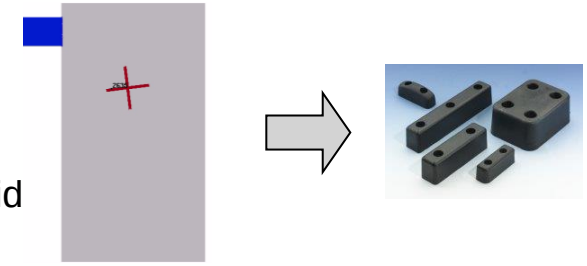
Producibility

New thermo-mechanical model

(available in R7.1 as MAT_249)

Thermoplastic pre-pregs – process overview

- Properties of thermoplastic matrix material
  - At high temperature, molten material behaves like a viscous fluid
  - At low temperature, material can be described as an elastio-plastic solid

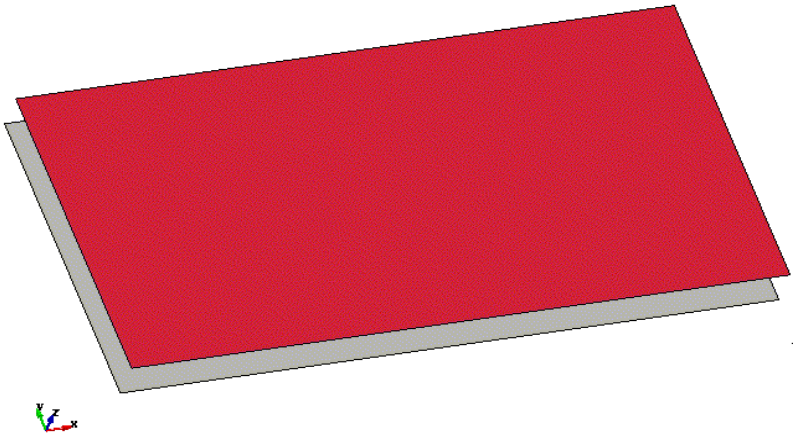


- Process overview

heating | positioning | forming | cooling | final part

- Process is reversible as often no chemical curing occurs

- Relatively short cycle times can be realized

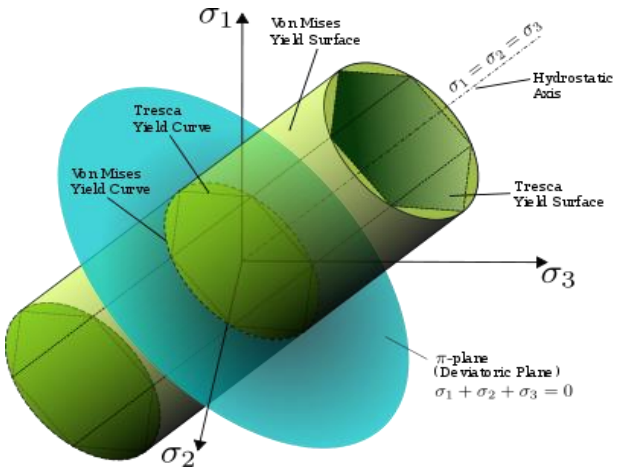


Thermoplastic pre-pregs – constitutive aspects

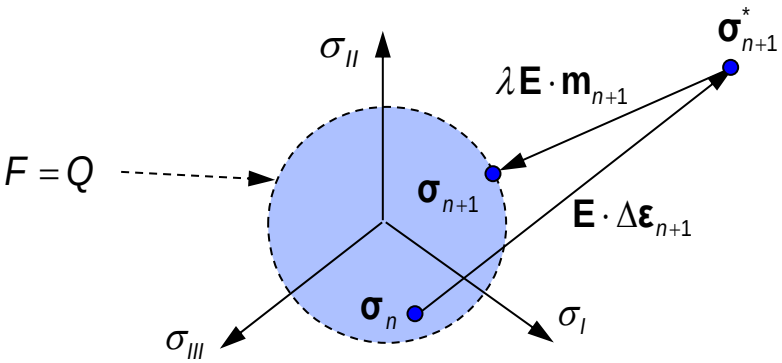
- Additive split for matrix and fiber contributions

- Matrix formulation
  - Elastic properties are defined with load curves w.r.t. to temperature
  - Van-Mises yield criterion is implemented
  - Yield stress is given by load tables w.r.t.
    - Temperature
    - Equivalent plastic strain

  - Return-mapping algorithm
  - If dependency on first stress invariant is seen necessary appropriate modifications may be done.



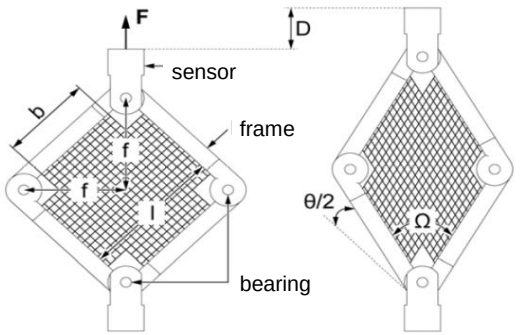
[source: www.wikipedia.de]

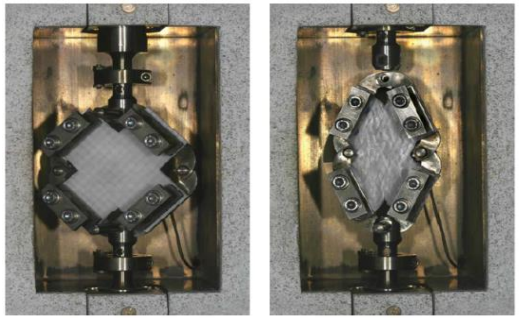


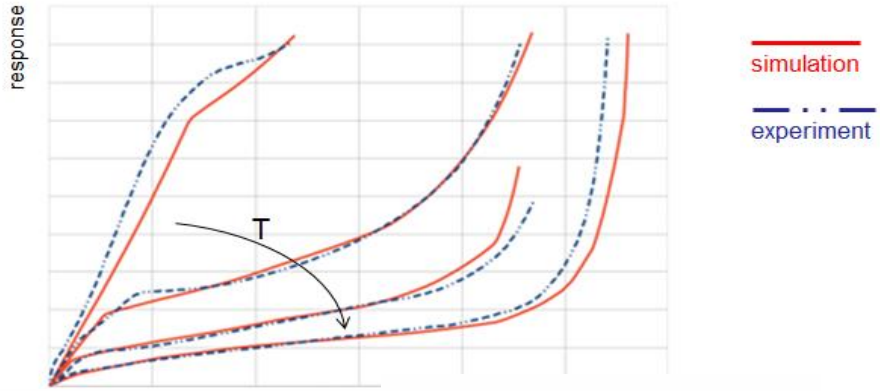
Thermoplastic pre-pregs – picture frame test

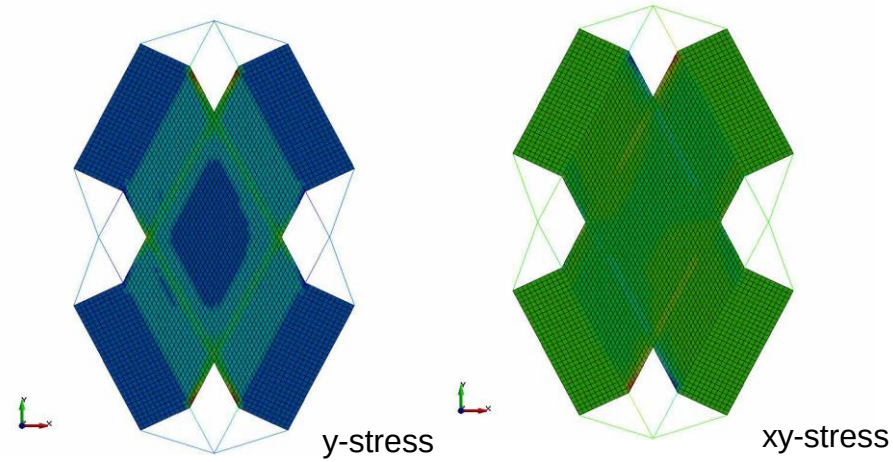
- Standard experimental set-up to characterize shear behavior

- Results show significant temperature dependence
  - At low temperature, matrix material dominates
  - At high temperature, equivalent to dry fabric materia



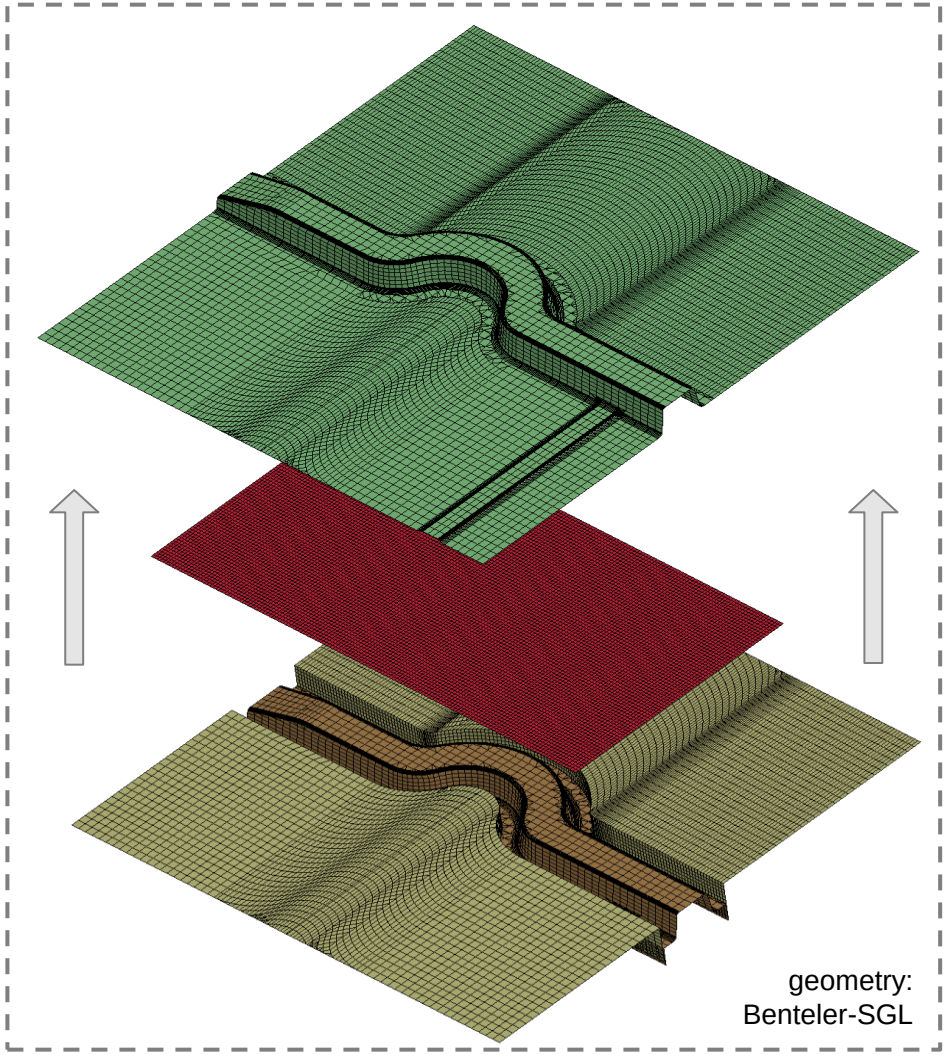






Thermoplastic pre-pregs – Stamping

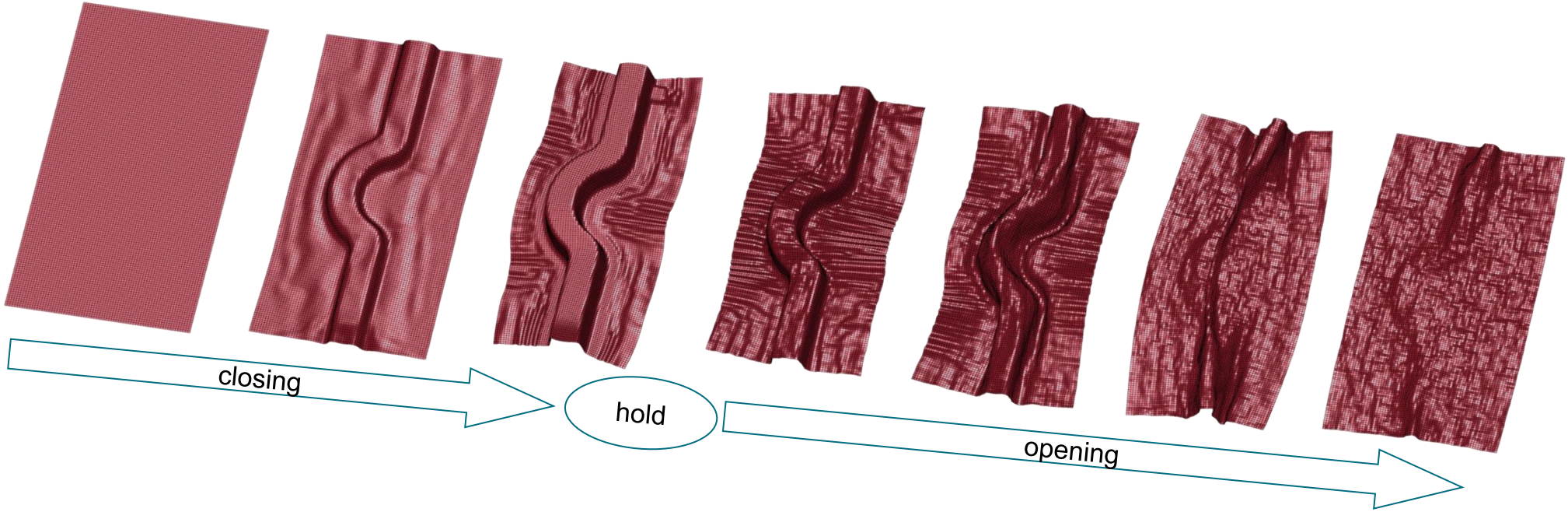
- Tool is closed within 80ms,
  kept closed for 3ms, and
  opened within 56.5ms (time is scaled)
- Thermo-mechanical coupling
  between working piece and tools
  can be included
- Material parameters for matrix and
  textile from picture frame test
- 2 fiber families
  - ±45°
  - Woven structure



Thermoplastic pre-pregs – Stamping

- Closing and opening at a constant temperature of 225°C (molten phase of matrix material)

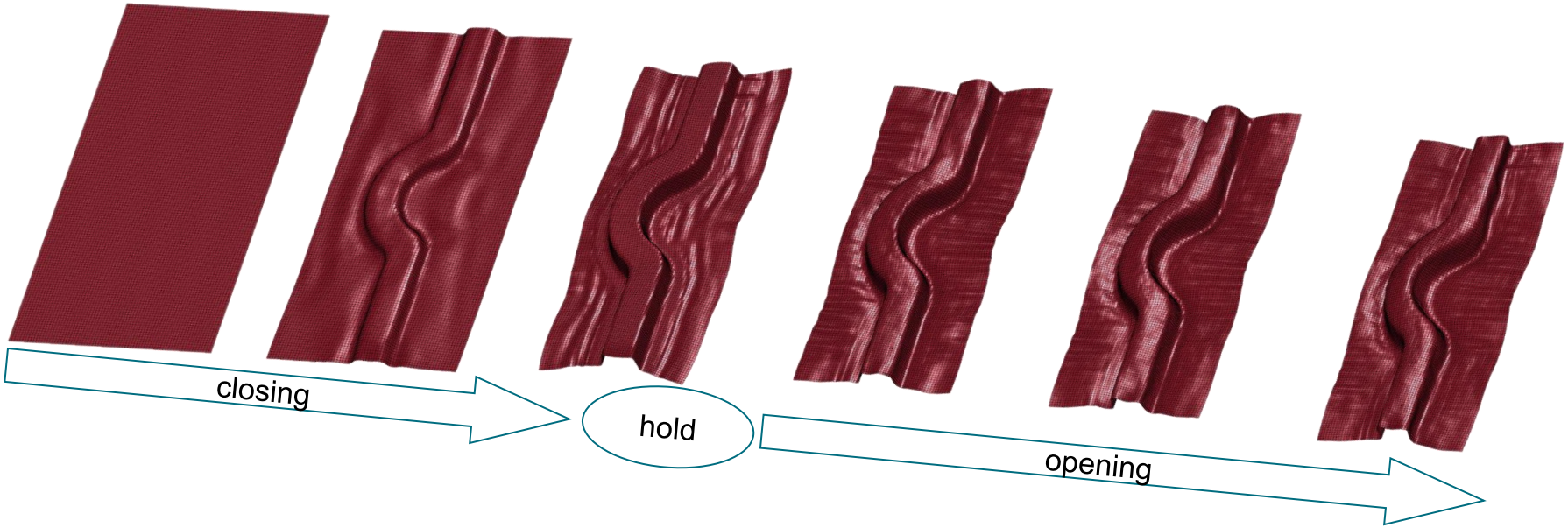
- Deformation is governed by properties of the fabric
  - Very low plastic deformations induced
  - Many wrinkles form



Thermoplastic pre-pregs – Stamping

- Closing and opening at a constant temperature of 210°C

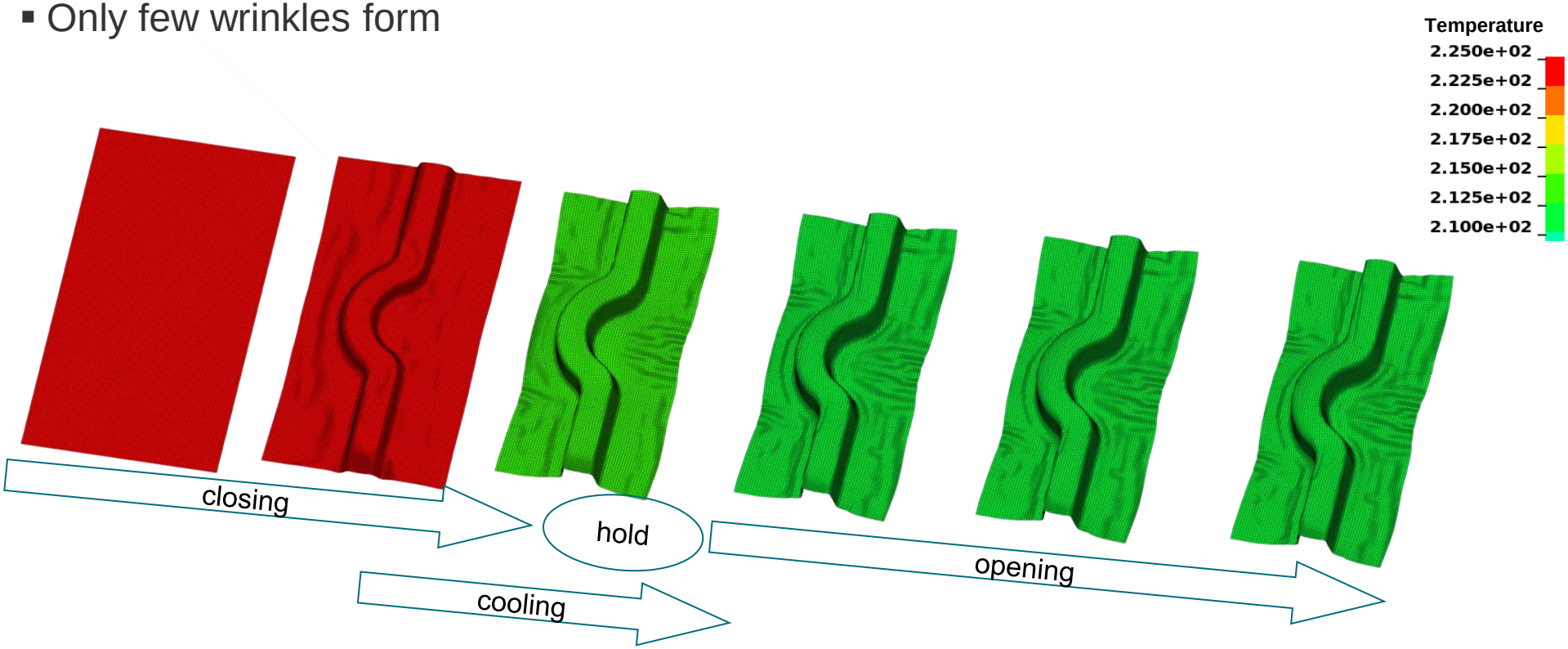
- Matrix shows elasto-plastic behavior
  - Plastic deformations are induced
  - Still significant influence of fiber orientations on deformation pattern
  - Significant spring-back

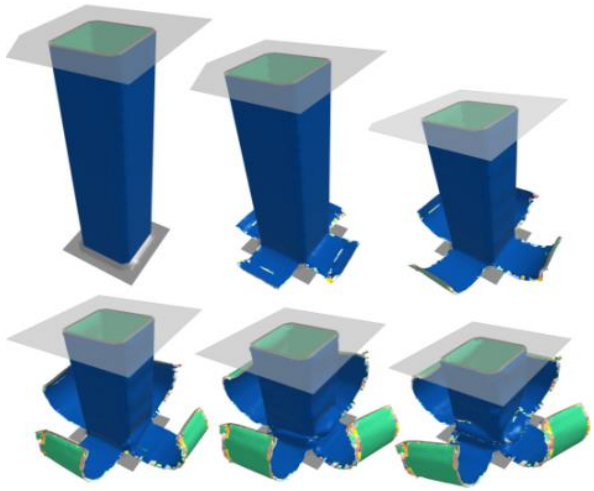


Thermoplastic pre-pregs – Stamping

- 225°C up to t=70 ms, then cooling down (13 ms) to 210°C
- Opening at a constant temperature of 210°C

- Significantly reduced spring-back
- Only few wrinkles form



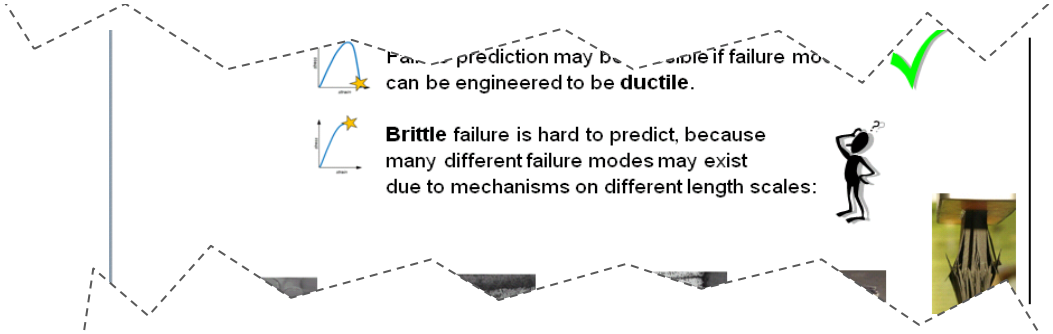


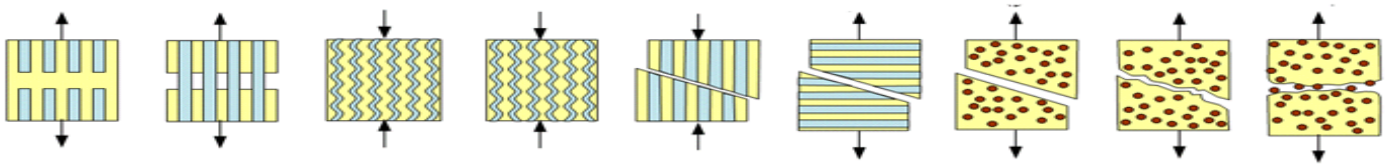
Serviceability

Crashworthiness

(New models in R7.1)

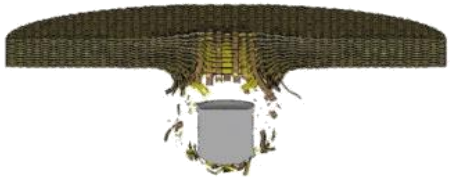
The challenge to predict failure in crashworthiness





Modeling complex failure modes…

on same length scale
(detailed model)



Simple failure criteria
will often do!

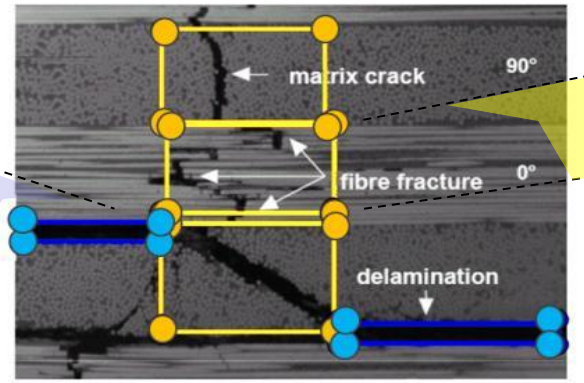
on higher length scale
(smeared model)

Complex failure criteria
necessary!

Modeling failure: Interlaminar vs. intralaminar

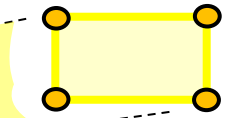
Interlaminar (between laminae):

Risc of delamination modeled by cohesive elements or tiebreak contacts



[Camanho]

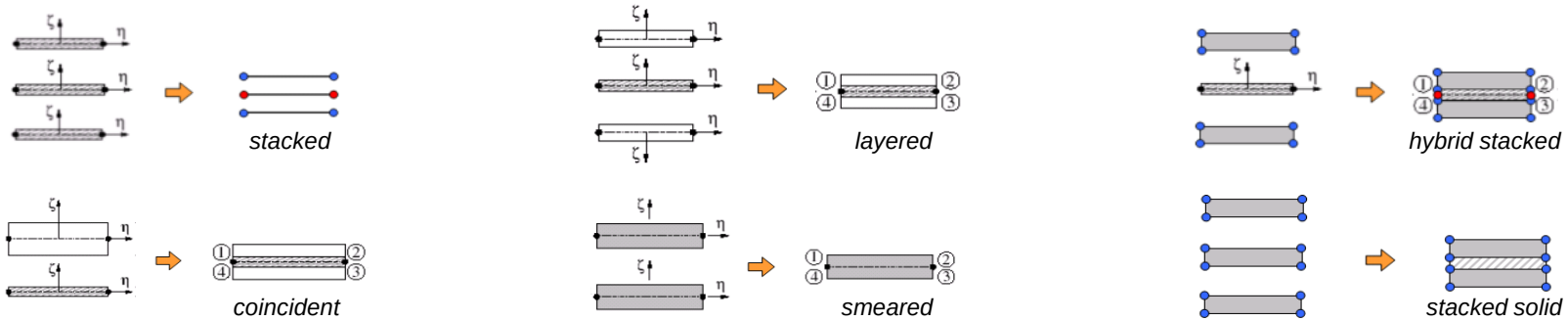
Intralaminar (within one lamina):



Element: layered (thick/thin) shell or one solid for each layer

Material: elasto(plastic) material models with damage behavior

➡ Element size in crashworthiness models is 1-2 orders of magnitude bigger, hence damage and failure cannot be described in detail. A smeared approach is unavoidable.



LS-DYNA: Recent developments

New!

Constitutive models for composite structures

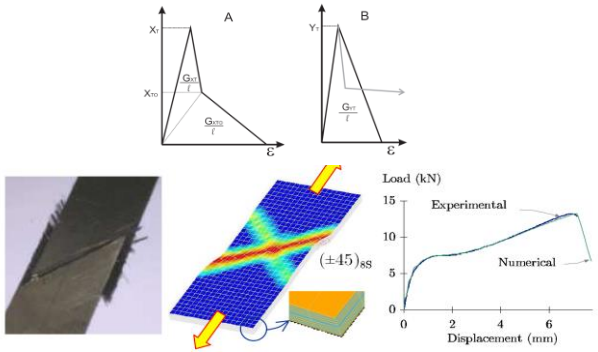
***MAT_Camanho (Continuum-Damage-Model)**

- ✓ plane stress
- ✓ coupled failure criteria
- ✓ bi-linear softening law based on fracture toughness
- ✓ 1D-plasticity-model (mixed hardening) for in-plane shear behavior

***MAT_Pinho (Continuum-Damage-Model)**

- ✓ 3D-stress space
- ✓ coupled failure criteria
- ✓ complex 3D-fibre kinking model
- ✓ linear softening law based on fracture toughness
- ✓ 1D-plasticity-model (mixed hardening) in in-plane shear behavior

Damage models with softening properties. Usable for inter- and intra-laminar modeling.



Implemented in collaboration with Daimler AG.
Available since LS-DYNA R7.

Options for composite (part) modeling (LS-DYNA 971 R6)

***PART_Composite**

Easier definition of lay-ups in part-section by just defining MATID, thickness and orientation.

***ELEMENT_(t)shell_composite**

Same input scheme as in *PART_Composite but on element level.
Useful to define different lay-ups within one part (elementwise definition of lay-up).

Features of Pinho/Camanho

New!

	***MAT_262** (Camanho)	***MAT_261** (Pinho)
	Failure criterion based on plane stress assumption	Failure criterion may use 3D-stress state
Fiber tension	Maximum strain criterion	Maximum stress criterion
Fiber compression	Use constant fiber misalignment angle based on shear and longitudinal compressive strength	Complex 3D-fiber kinking model, expensive search for controlling fracture plane
Matrix failure: transverse tension	Use constant fiber misalignment angle based on shear and longitudinal compressive strength	Complex 3D-fiber kinking model, expensive search for controlling fracture plane
Matrix failure: transv. compression/shear	Assume constant fracture plane angle (i.e. 53°)	Search for controlling fracture plane
In-plane shear treatment	1D-plasticity model with combined (iso/kin) linear hardening	1D-plasticity model with combined (iso/kin) hardening based on DEFINE_CURVE
Damage evolution	Bi-/linear damage based on fracture toughness	Linear damage based on fracture toughness

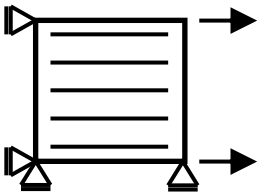
Comparison of the material models

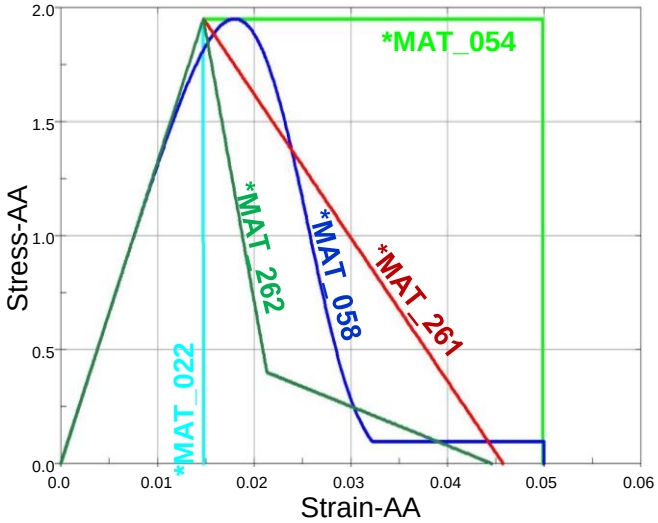
1-Element-Test, Single-Layer (‚SHELL‘, ELFORM=2)

New!

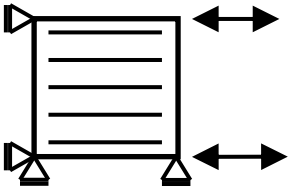
Material Parameter: EA= 132.0 [kN/mm²]
XT= 1.95 [kN/mm²]
XC= 1.35 [kN/mm²]
… and more …. (model dependent)

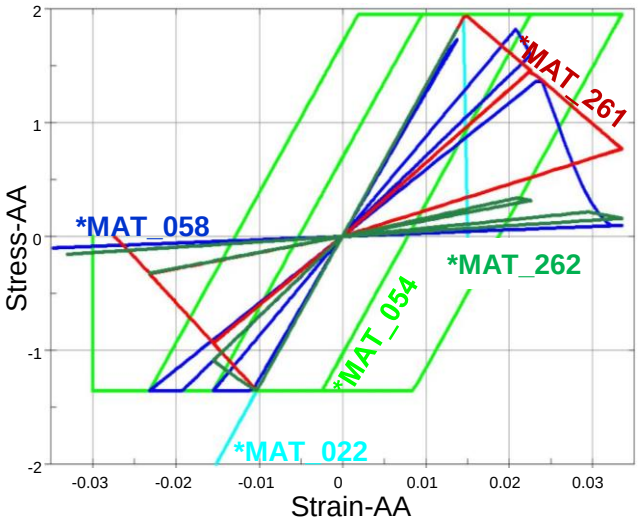
Fiber tensile load (A-E)



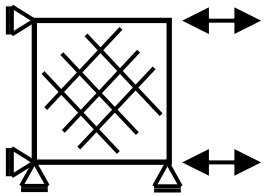


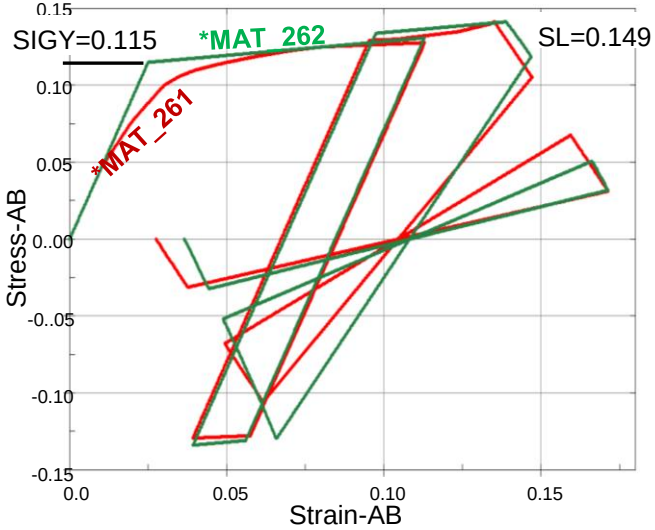
Fiber cyclic load (A-K)

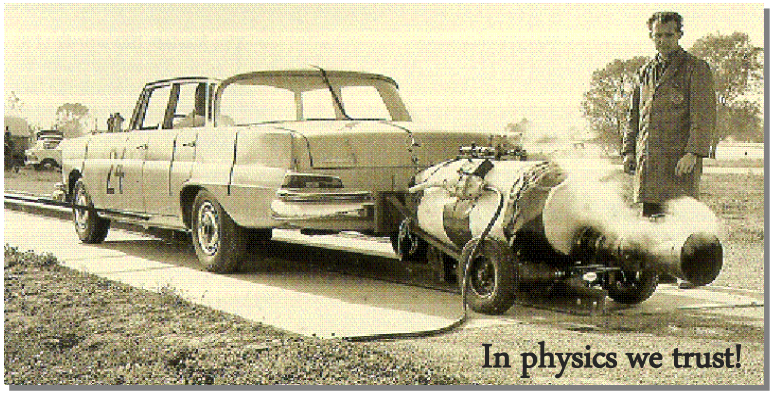




Cyclic test with a +/- 45° layup (A.M)







FIN

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