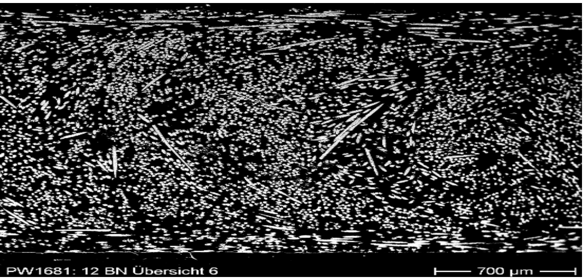
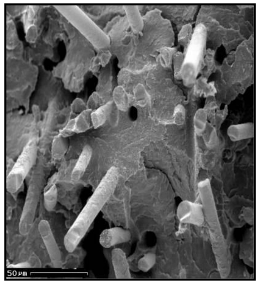


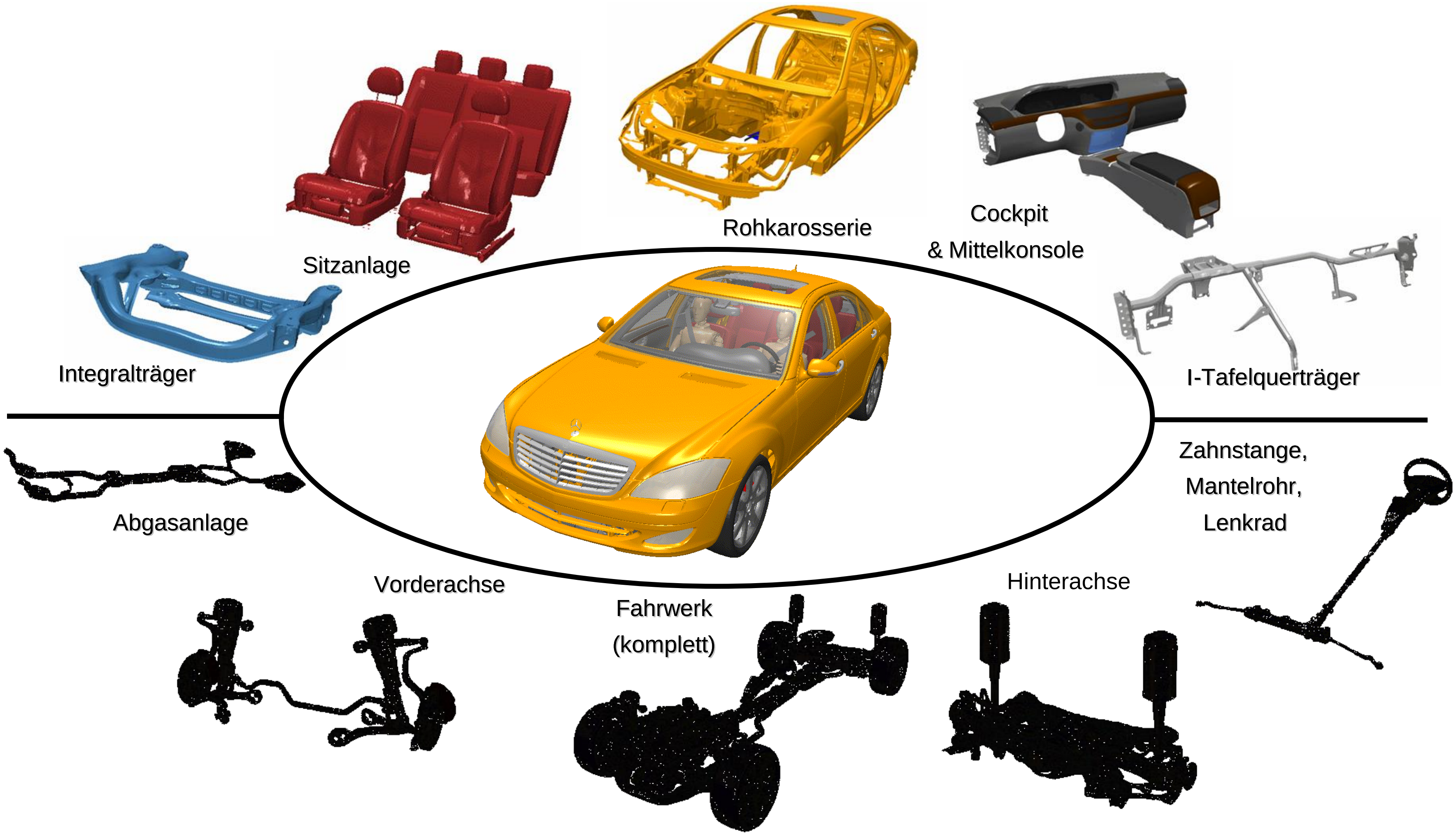


Einführung in die Charakterisierung und Modellierung von Kunststoffen: Materialmodelle in LS-DYNA

Dr. André Haufe

Crashsimulation

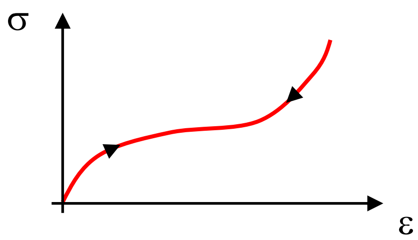
Detaillierungsgrad



Crashsimulation

Materialmodelle

Gummiartige Materialien



“Hyperelastisches Verhalten”

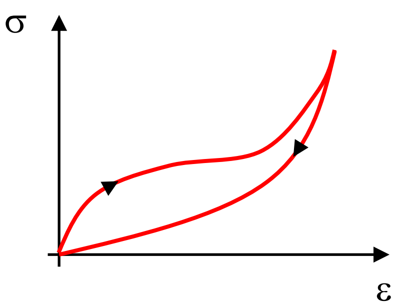
Hardy-Scheibe

Motorlager

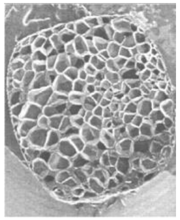
Bereifung

Kopfimpaktor

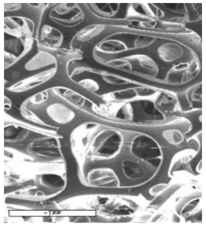
Elastische Schäume



“Hyperelastisch-Viskoses Verhalten”

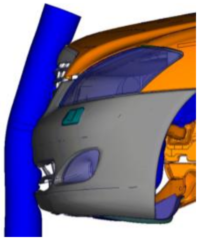


EPP-foam



PU-foam

Stoßfängerschaum (EPP, PU)

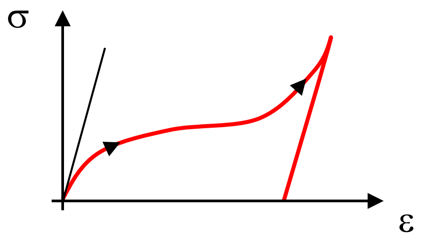


Beinimpaktor
Fußgängerschutz

Crashsimulation

Materialmodelle

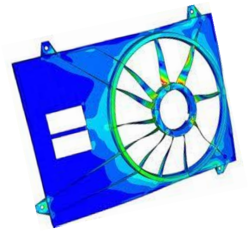
Materialien mit permanenter Verformung



“Elastisch-visko-plastisches Verhalten”

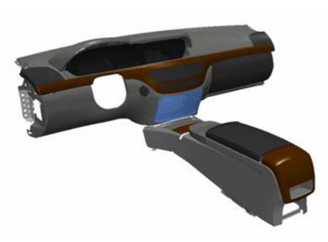
Metallische Bleche

Leichtmetalle



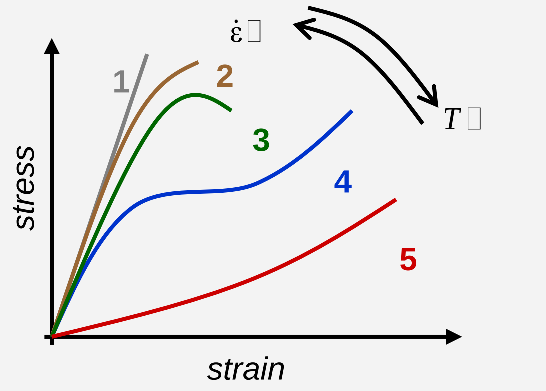
Kunststoffe

Hochfeste Stähle

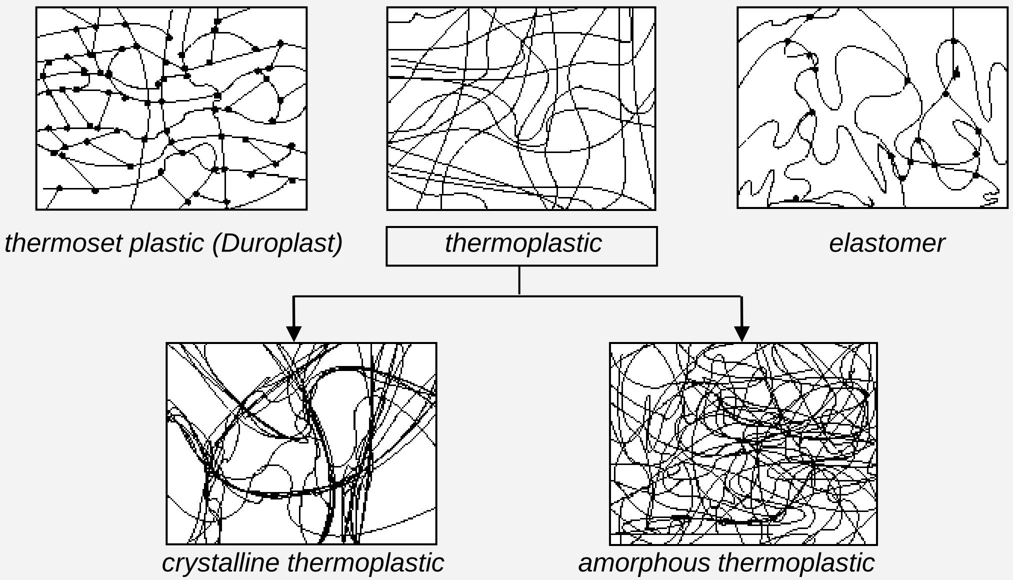


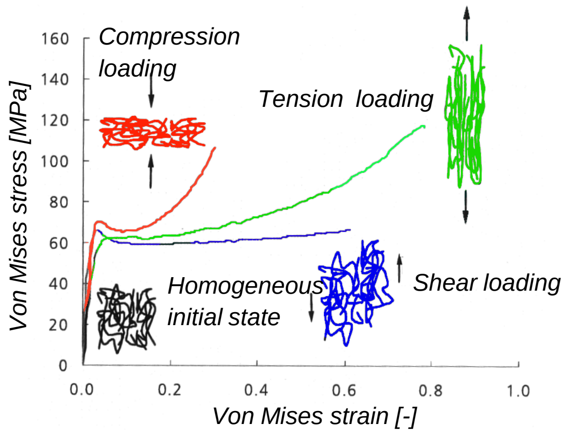
Kunststoffe/Schäume

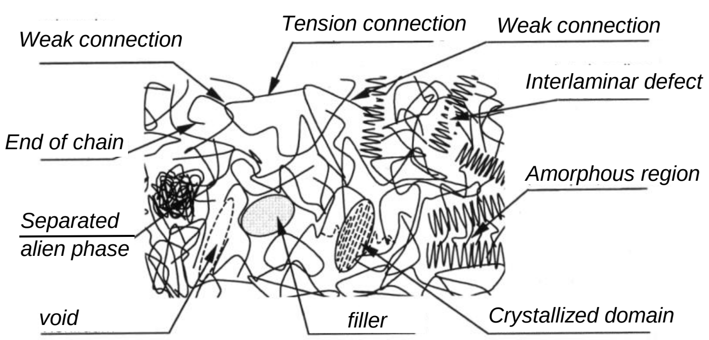
Characteristic Structure of Plastics



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







[Junginger 2002]

Selected material laws for polymers in LS-DYNA

Plasticity based models

MAT_24 , MAT_123, MAT_124 MAT_89 and MAT_187

Neo Hooke / Arruda-Boyce

MAT_168

Process chain

MAT_002_ANIS

Composites

MAT_54 and MAT_58

Material #24 and #123

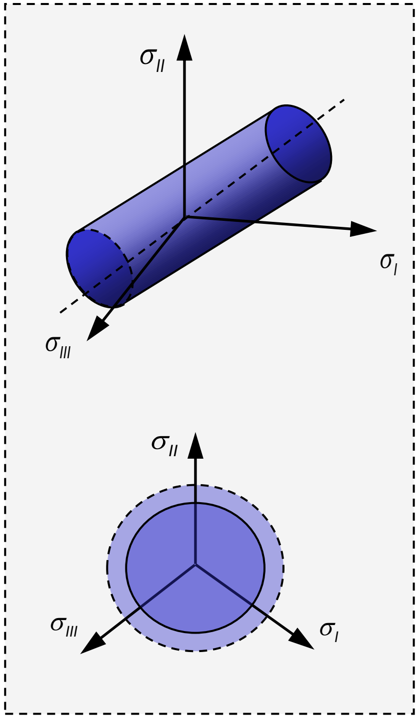
Unreinforced Polymers

Quick solution with MAT_24/123

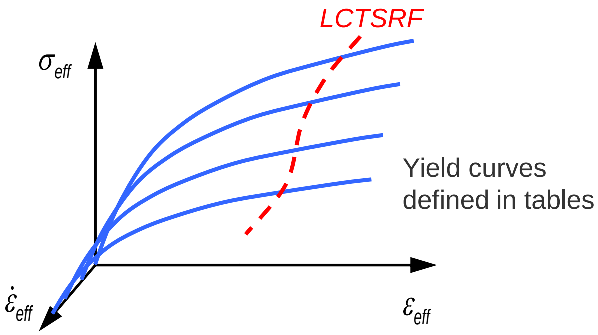
- Standard von Mises Material Model

$$F \equiv 0 = \sqrt{3J_2} - \bar{\sigma}_y(\bar{\varepsilon}^{pl})$$

- Known (and sometimes acceptable) drawbacks:
  - No visco-elastic response
  - Plastic response is isochoric
  - Isotropic hardening
  - No damage model
  - Basic failure criteria, but may be extended with MAT_ADD_EROSION



- Strain rate dependent failure by thinning curve definition



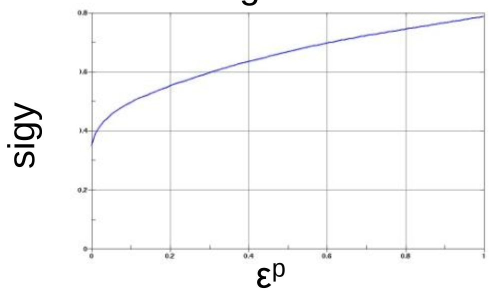
Material #124

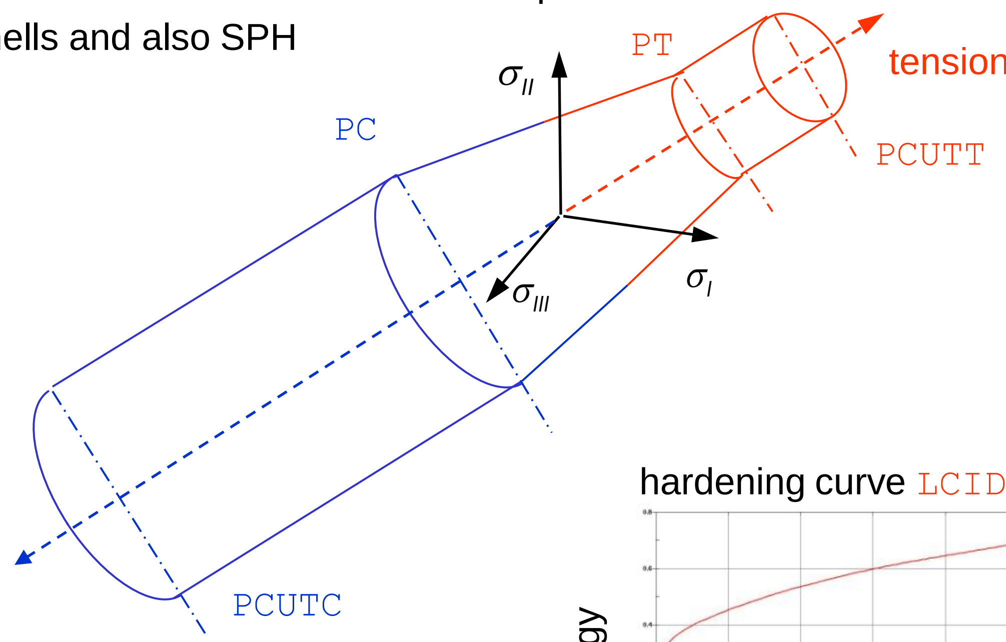
Unreinforced Polymers

Quick solution with MAT_124 (MAT_PLASTICITY_COMPRESSION_TENSION)

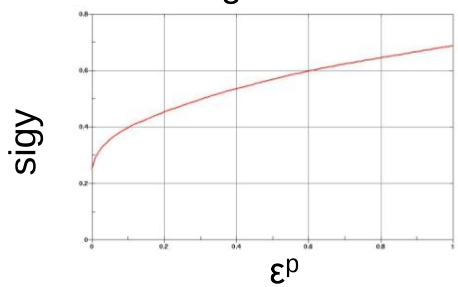
- Isotropic visco-elasto/visco-plastic material model with the possibility to define different yield stress - effective plastic strain behavior in compression and tension
- Visco-elastic response by a 6 term Maxwell mode Prony-series
- Visco-plastic effect by Cowper-Symonds or strain rate scaling function
- Failure can be defined by a critical plastic strain or minimum time step
- Applicable for solids, shells, thick shells and also SPH
- Useful for metals and polymers

hardening curve LCIDC





hardening curve LCIDT

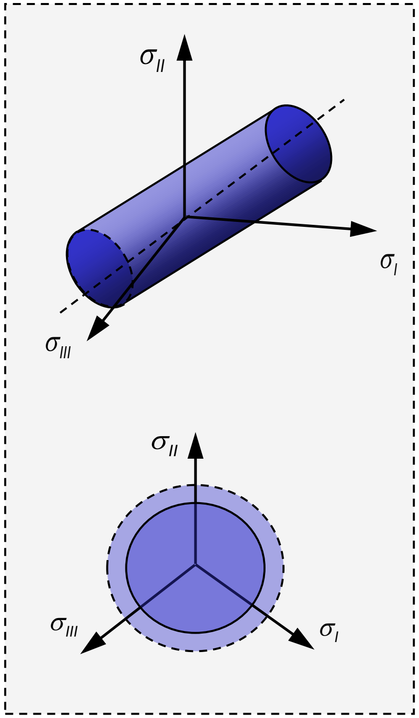


Material #89

Unreinforced Polymers

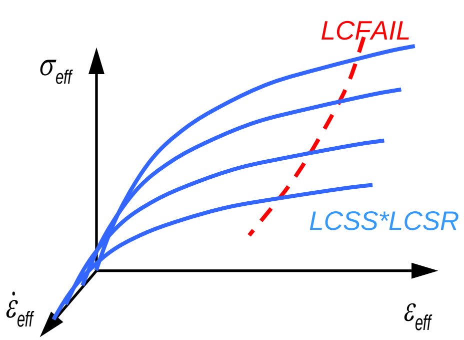
Quick solution with MAT_PLASTICITY_POLYMER

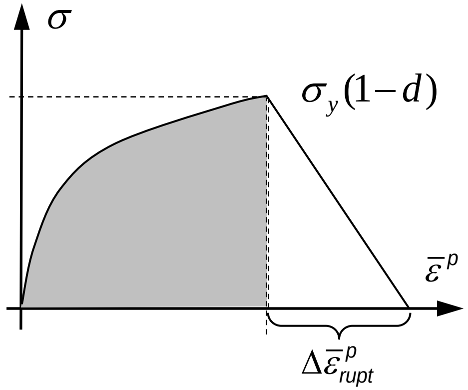
- Standard von Mises Material Model (MAT_PLASTICITY_POLYMER)
  $F \equiv 0 = \sqrt{3J_2} - \bar{\sigma}_y(\bar{\varepsilon}^{pl})$
  - Formulated in effective stress versus total effective strain



- Known (and sometimes acceptable) drawbacks:
  - No visco-elastic response
  - Plastic response is isochoric
  - Isotropic hardening

- Strain rate dependent failure by curve definition
- Rupture strain is 10% of failure strain

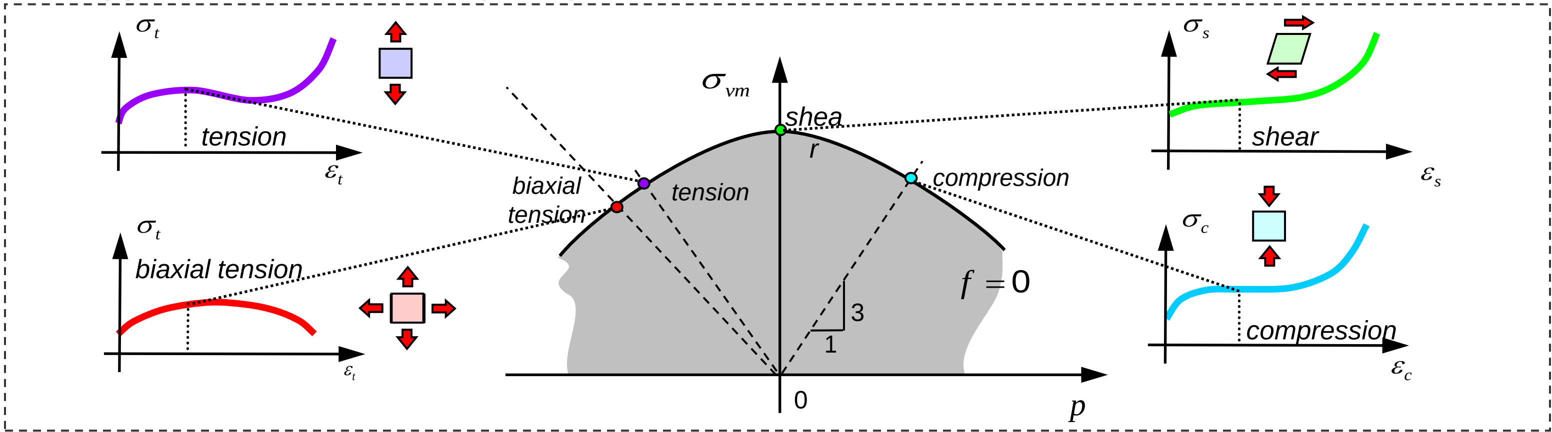




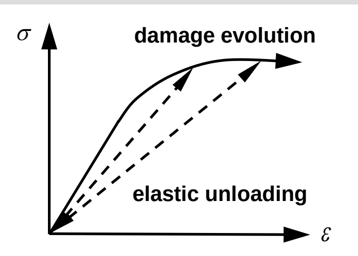
Material #187

Unreinforced Polymers

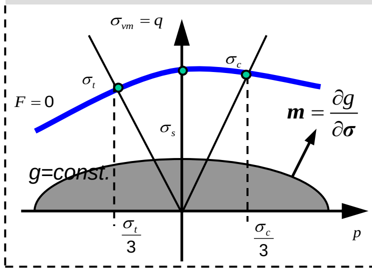
Detailed approach with SAMP-1 (#187)



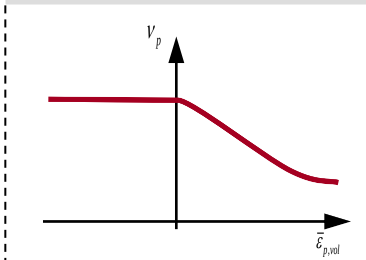
Stress-strain relationship



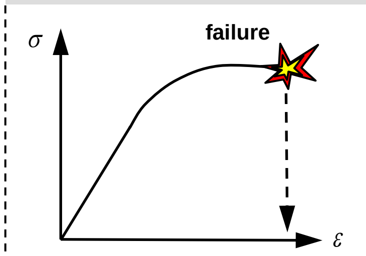
Not associated



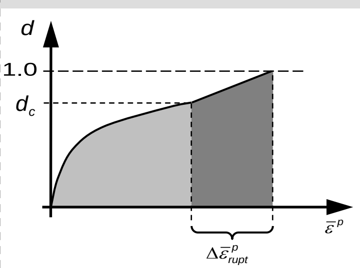
Plastic strain



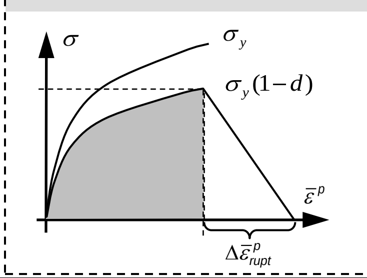
Failure



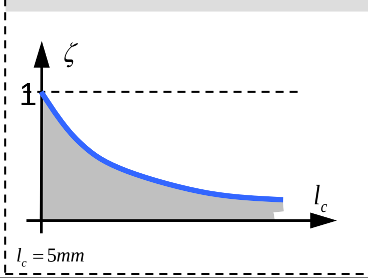
Damage & Failure



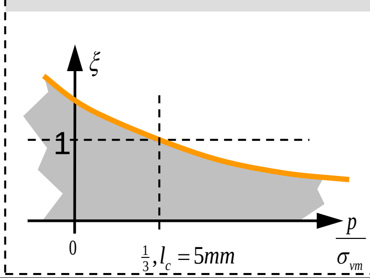
Damage & Failure & Fading



Regularisation



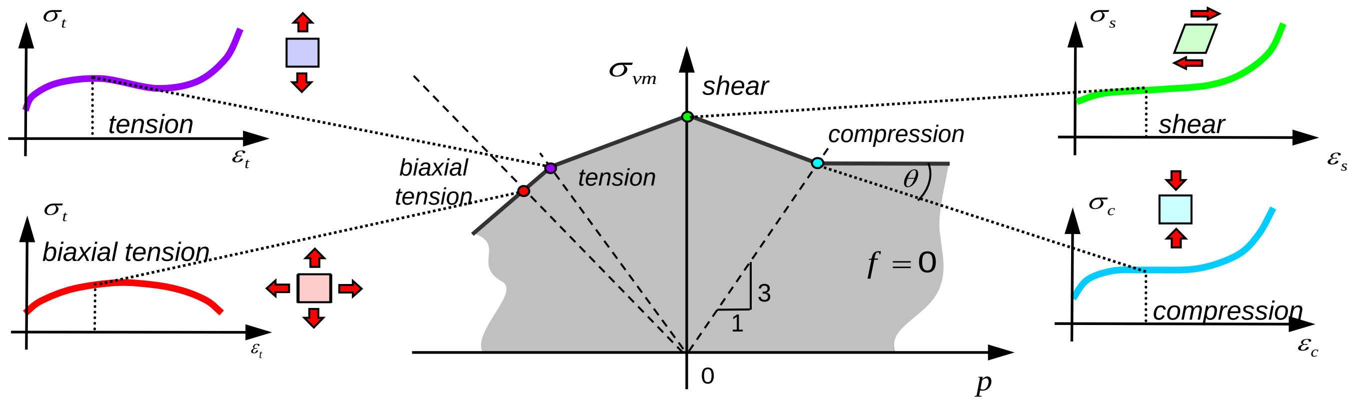
Triaxiality

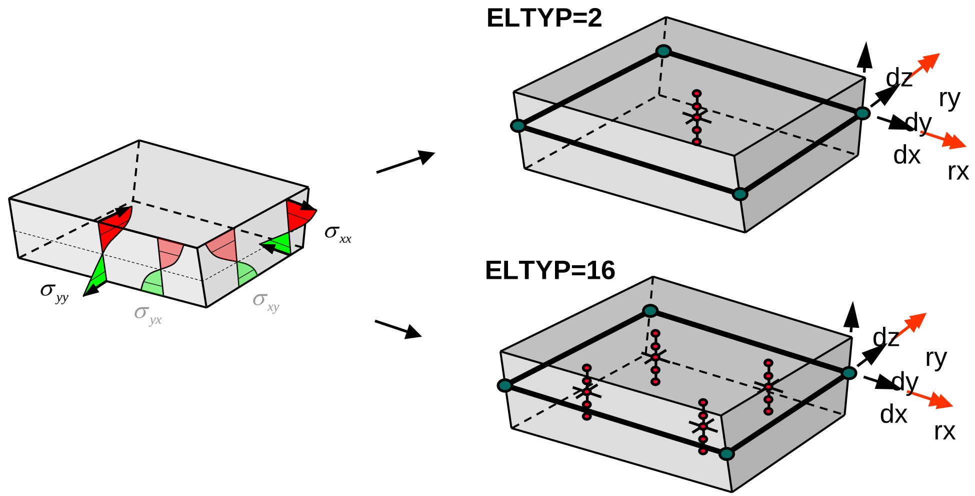


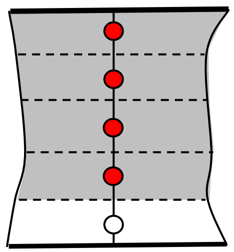
Unreinforced Polymers

Detailed approach with SAMP-1 (#187)

RBCFAC to switch on multi-linear yield surface







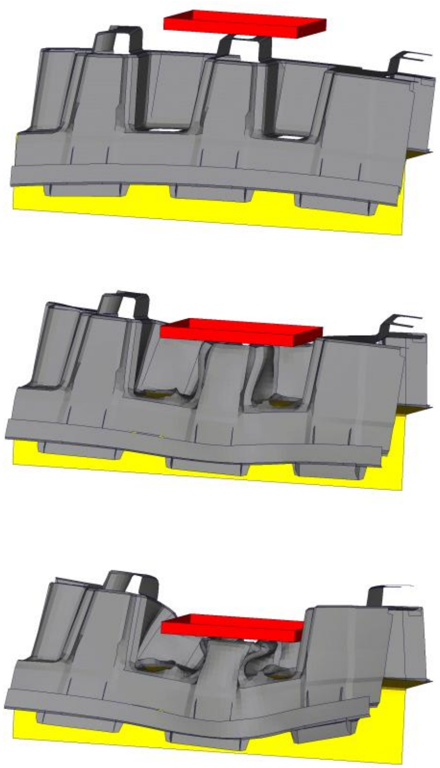
20% Failure

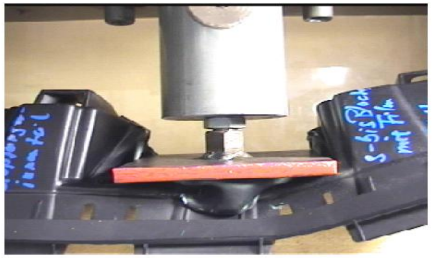
Element deletion is defined via a section percentage value of integration points that is flagged as failed

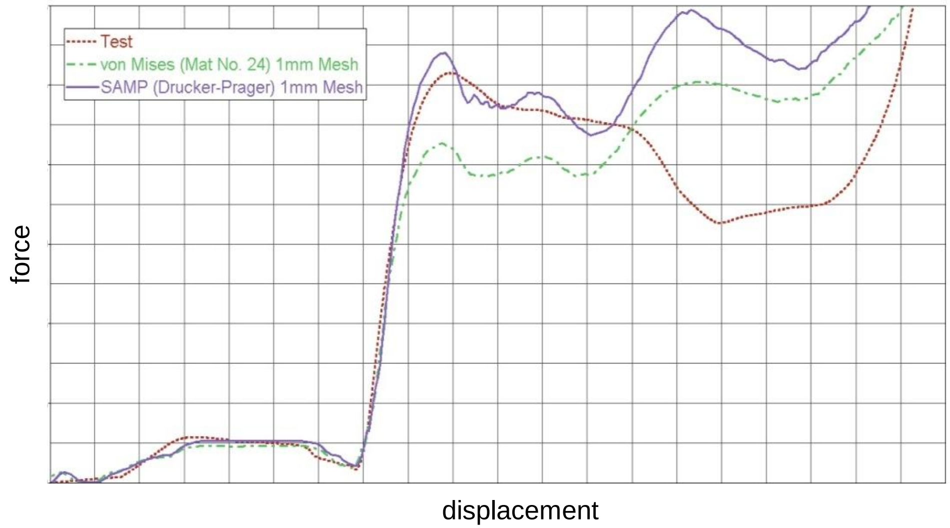
Unreinforced Polymers

Detailed approach with SAMP-1 (#187)

Typical behaviour for thermoplastics: material cards that are fitted for uniaxial tension yield a too soft response under bending and compression. Hence different yield curves under compression and tension are necessary!!







[Kolling, Feucht, DuBois, Haufe, 2006-2009, Courtesy Daimler AG]

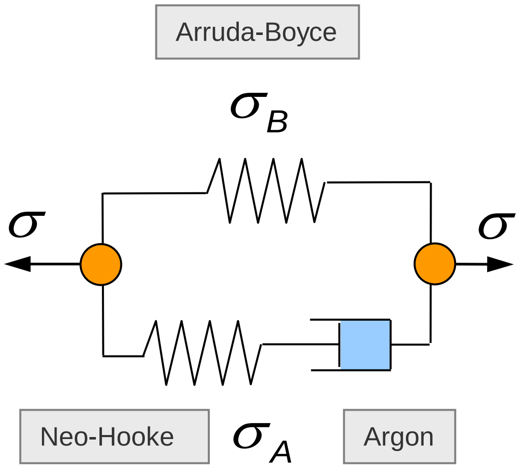
Material #168

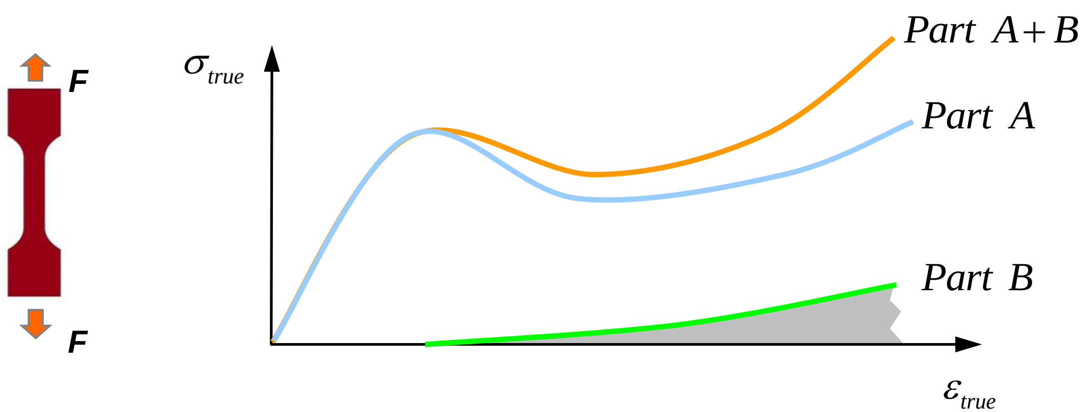
Unreinforced Polymers

Detailed approach with MAT_POLYMER (#168) by Boyce et al.

- Currently only available for solid elements
- Two parallel mechanisms to describe deformations and derive stresses

Partial model A:	Neo-Hooke for elastic spring Argon model for plastic part
Partial model B:	Arruda-Boyce for network stiffness of polymers



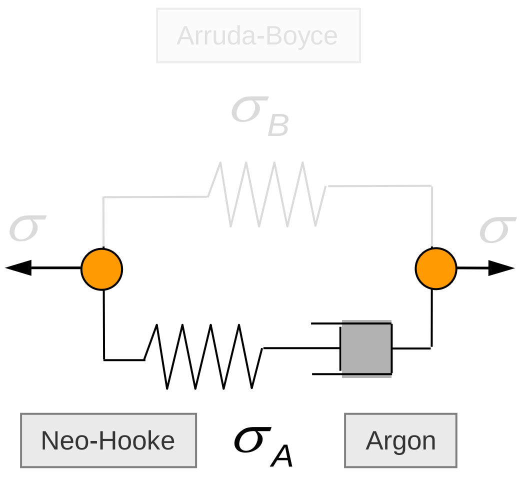


Deformation tensor: $\mathbf{F} = \mathbf{F}_A = \mathbf{F}_B$ corresponding final stresses $\boldsymbol{\sigma} = \boldsymbol{\sigma}_A + \boldsymbol{\sigma}_B$

Unreinforced Polymers

Detailed approach with MAT_POLYMER (#168) by Boyce et al.

Partial model A:	Neo-Hooke for elastic spring Argon model for plastic part



Intermolecular barrier to deformations due to relative movements between molecules.

Multiplicative decomposition of elastic and plastic part of deformation tensor: $\mathbf{F}_A = \mathbf{F}_A^e \cdot \mathbf{F}_A^p$

Velocity gradient: $\mathbf{L}_A = \dot{\mathbf{F}}_A \cdot \mathbf{F}_A^{-1} = \mathbf{L}_A^e + \mathbf{L}_A^p$

Rate of deformation (el. & pl.): $\mathbf{L}_A^e = \mathbf{D}_A^e + \mathbf{W}_A^e = \dot{\mathbf{F}}_A^e \cdot (\mathbf{F}_A^e)^{-1}$

$$\mathbf{L}_A^p = \mathbf{D}_A^p + \mathbf{W}_A^p = \mathbf{F}_A^e \cdot \dot{\mathbf{F}}_A^p \cdot (\mathbf{F}_A^p)^{-1} \cdot (\mathbf{F}_A^e)^{-1} = \mathbf{F}_A^e \cdot \overline{\mathbf{L}}_A^p \cdot (\mathbf{F}_A^e)^{-1}$$

elastic

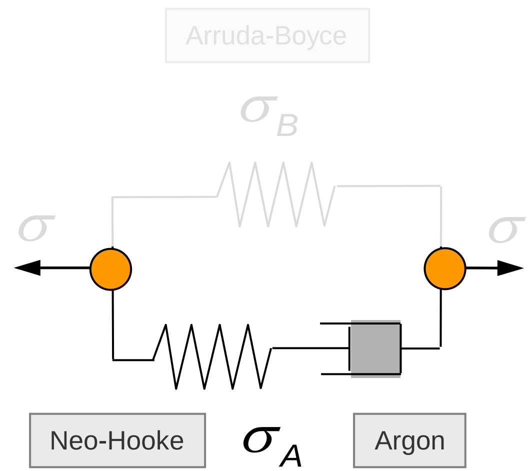
Neo-Hooke for elastic part: $\boldsymbol{\tau}_A = \lambda_0 \ln J_A^e \,\mathbf{I} + \mu_0 (\mathbf{B}_A^e - \mathbf{I})$ with $\mathbf{B}_A^e = \mathbf{F}_A^e \cdot \mathbf{F}_A^{eT}$ (left Cauchy-Green)

and $J_A^e = \sqrt{\det \mathbf{B}_A^e} = J_A$ (Jacobian)

Unreinforced Polymers

Detailed approach with MAT_POLYMER (#168) by Boyce et al.

Partial model A:	Neo-Hooke for elastic spring Argon model for plastic part



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Rate of deformation (el. & pl.):
$$\mathbf{L}_A^e = \mathbf{D}_A^e + \mathbf{W}_A^e = \dot{\mathbf{F}}_A^e \cdot (\mathbf{F}_A^e)^{-1}$$

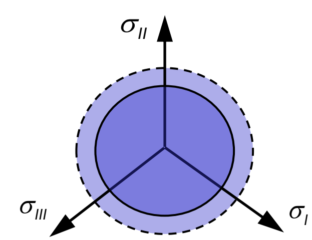
$$\mathbf{L}_A^p = \mathbf{D}_A^p + \mathbf{W}_A^p = \mathbf{F}_A^e \cdot \dot{\mathbf{F}}_A^p \cdot (\mathbf{F}_A^p)^{-1} \cdot (\mathbf{F}_A^e)^{-1} = \mathbf{F}_A^e \cdot \bar{\mathbf{L}}_A^p \cdot (\mathbf{F}_A^e)^{-1}$$

elastic

Flow rule $\mathbf{L}_A^p = \dot{\gamma}_A^p \mathbf{N}_A$ with $\mathbf{N}_A = \frac{1}{\sqrt{2}\,\tau_A} \boldsymbol{\tau}_A^{dev}, \quad \tau_A = \sqrt{\frac{1}{2} \mathrm{tr}\left(\boldsymbol{\tau}_A^{dev}\right)^2}$

and $\dot{\gamma}_A^p = \dot{\gamma}_{0A} \exp\left[-\frac{\Delta G \left(1 - \tau_A / s\right)}{k\theta} \right]$

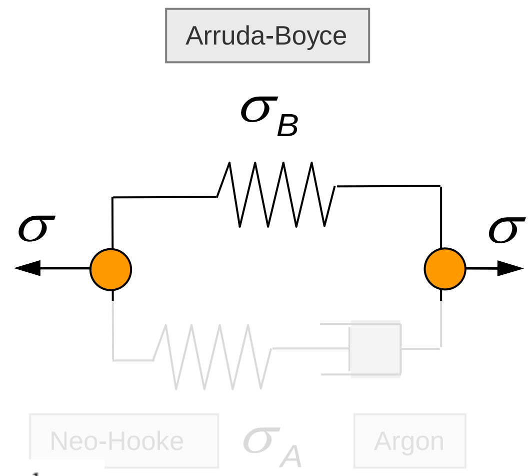
Plastic multiplier, thermal activated where shear resistance **s** is dependent on stress triaxiality.



Unreinforced Polymers

Detailed approach with MAT_POLYMER (#168) by Boyce et al.

Partial model B:	Arruda-Boyce for network stiffness of polymers



Viscous part is neglected: $\mathbf{F}_B = \mathbf{F}_B^N$

Stress-stretch relation: $\boldsymbol{\tau}_B = \frac{nk\theta}{3} \frac{\sqrt{N}}{\bar{\lambda}_N} \mathcal{L}^{-1}\left(\frac{\bar{\lambda}_N}{\sqrt{N}}\right)(\bar{\mathbf{B}}_B^N - \bar{\lambda}_N^2 \mathbf{I})$

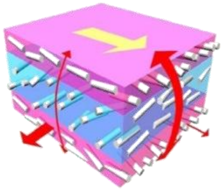
Chain density: n
Number of rigid links: N

with $\bar{\mathbf{B}}_B^N = \bar{\mathbf{F}}_B^N \cdot \bar{\mathbf{F}}_B^{NT}$, $\bar{\mathbf{F}}_B^N = J_B^{-1/3}\,\mathbf{F}_B^N$, $J_B = \det \mathbf{F}_B^N$, $\bar{\lambda}_N = \left[\frac{1}{3} \operatorname{tr} \bar{\mathbf{B}}_B^N\right]^{\frac{1}{2}}$

Rate of molecular relaxation: $\mathbf{L}_B^F = \dot{\gamma}_B^F \mathbf{N}_B$ $\quad \mathbf{N}_B = \frac{1}{\sqrt{2}\,\tau_B} \boldsymbol{\tau}_B^{dev}$, $\quad \tau_B = \sqrt{\frac{1}{2} \boldsymbol{\tau}_B^{dev} : \boldsymbol{\tau}_B^{dev}}$

where the rate of relaxation is: $\dot{\gamma}_B^F = C\left(\frac{1}{\bar{\lambda}_F - 1}\right)\tau_B$

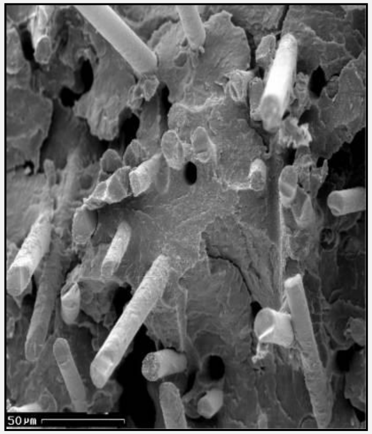
with $\bar{\lambda}_F = \left[\frac{1}{3} \operatorname{tr}\left(\mathbf{F}_B^F \left\{\mathbf{F}_B^F\right\}^T\right)\right]^{\frac{1}{2}}$

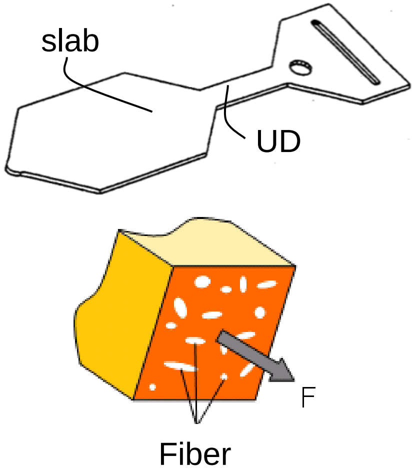


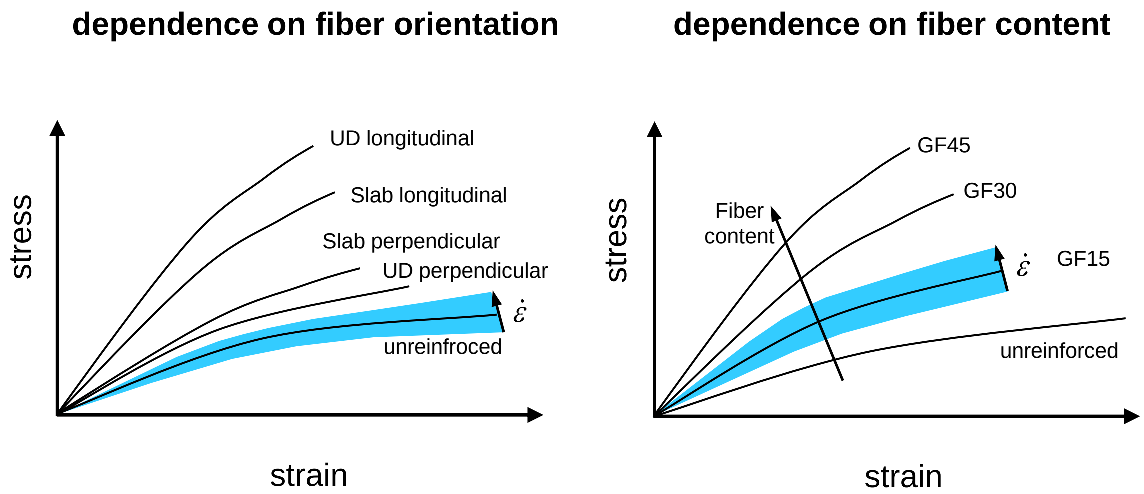
Short Fiber Reinforced Polymers

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.





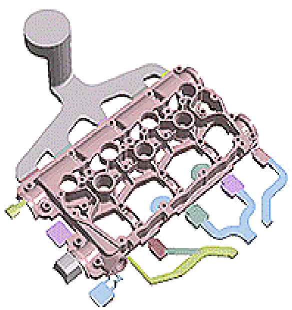


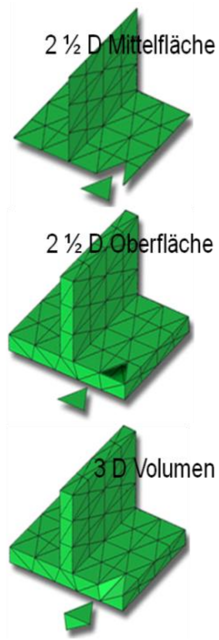
Fiber Reinforced Polymers

Detailed approach: Locally anisotropic model

Taking process chain into account

Injection molding





SIGMASOFT, Moldflow, Moldex, CADmold etc.

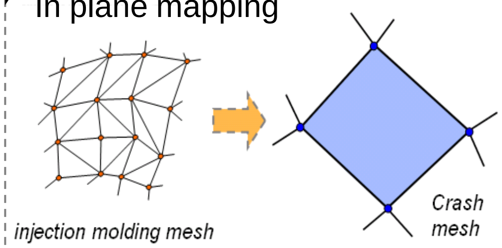
Fiber content & orientation

Mapping

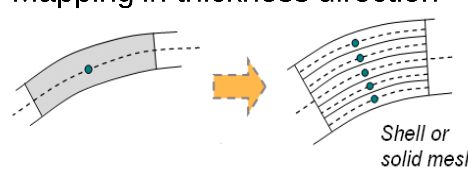
SCAImapper

or **LS-DYNA**

In plane mapping

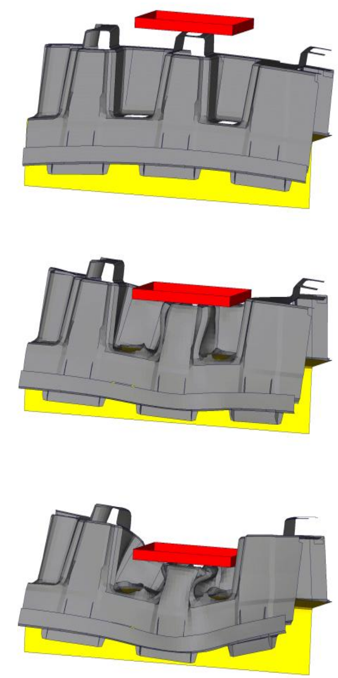


Mapping in thickness direction



Crash analysis

With calibrated anisotropic plasticity model including damage & failure



Un/reinforced Polymers / Process chain

Anisotropic elastic solution with MAT_002_ANIS

- 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:

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

- Several possibilities to define material directions, e.g. AOPT, ELEMENT_SOLID_ORTHO, … (use invariant node numbering! → *CONTROL_ACCURACY: INN=4)

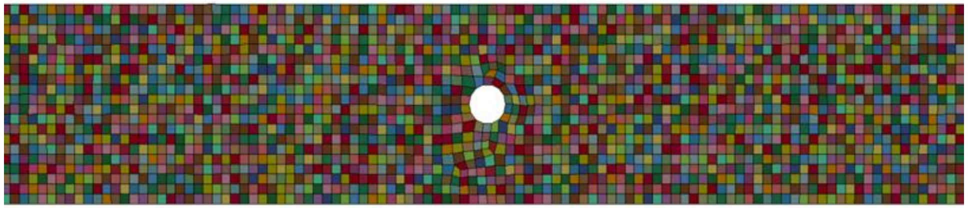
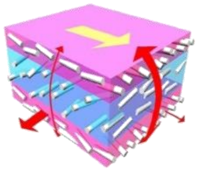
- No plasticity, no damage, no failure (but: brittle failure possible via *MAT_ADD_EROSION)

Un/reinforced Polymers / Process chain

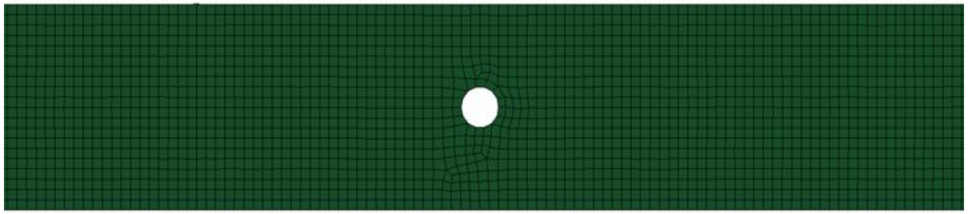
Anisotropic elastic solution with MAT_002_ANIS

- 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.

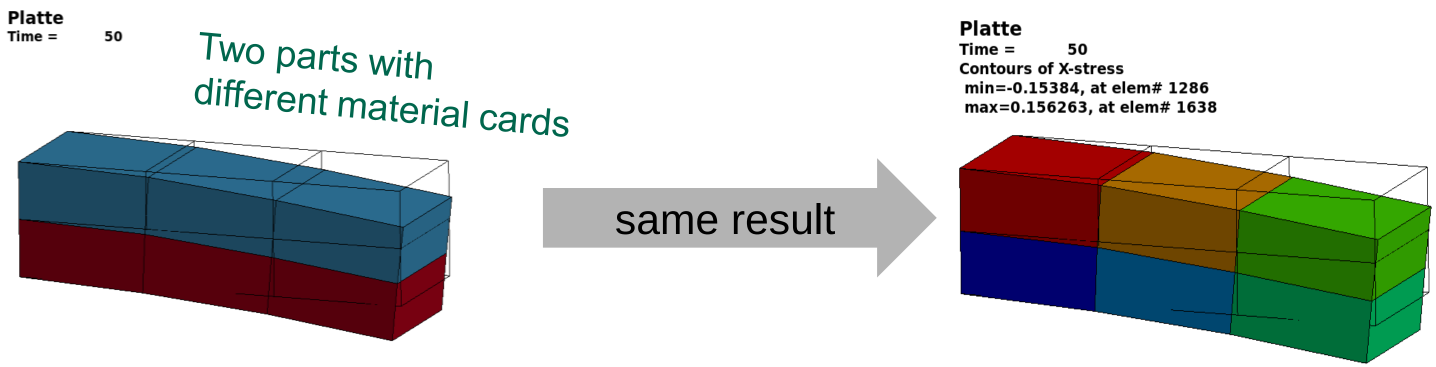


Un/reinforced Polymers / Process chain

Anisotropic elastic solution with MAT_002_ANIS

- Two options to define the 21 material constants:

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



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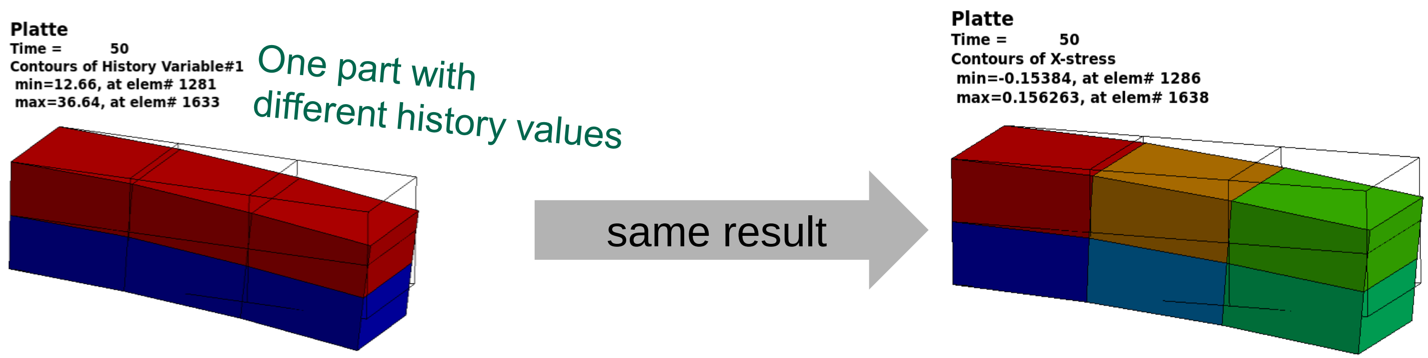
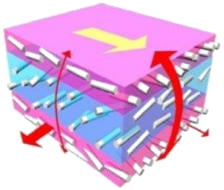
2) **Initialization with *INITIAL_STRESS_SOLID**: small bending test





Long or Endless Fiber Reinforced Polymers

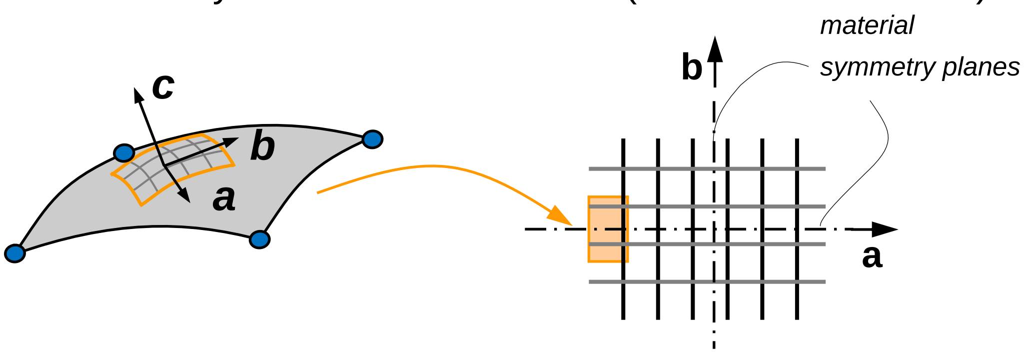
Fiber Reinforced Polymers

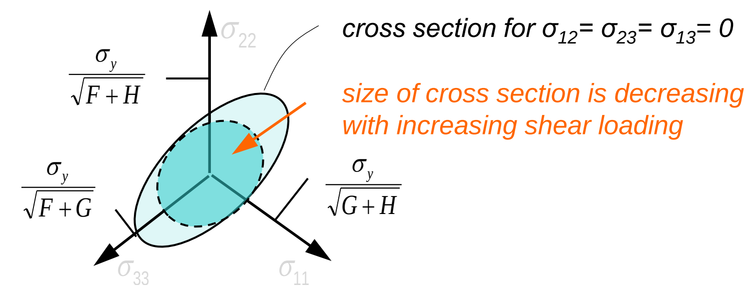
Quick (!) solution with orthotropic material + failure model

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

elastic + plastic part

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

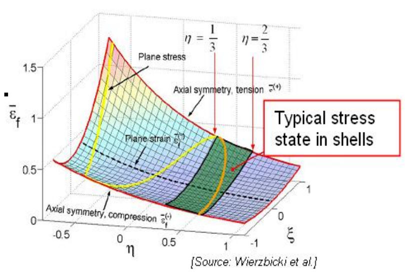


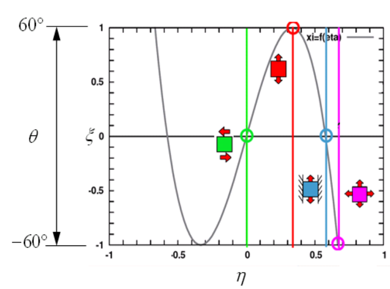


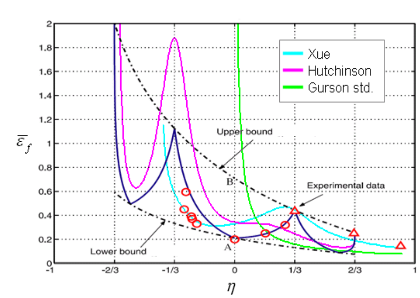
damage + failure part

- GISSMO

  or DIEM or else…







Material #83

Low and medium density foam

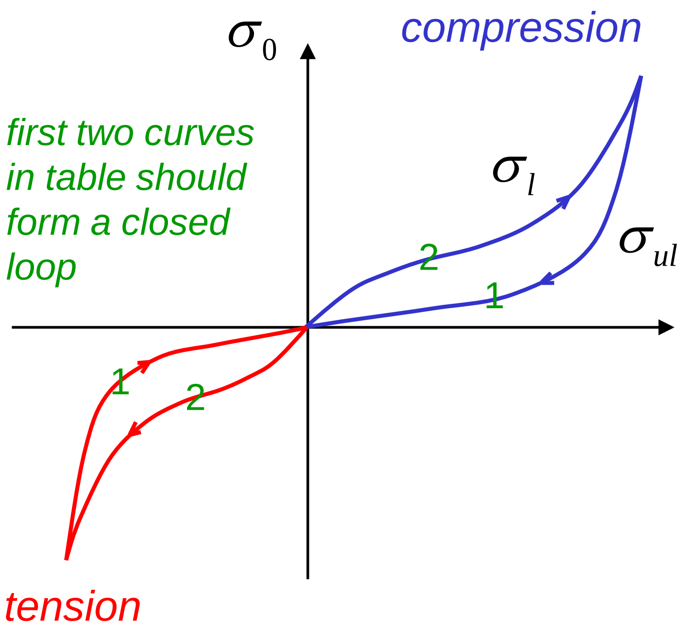
MAT_FU_CHANG_FOAM (#83)

- Used for low and medium density foams
- Visco-elastic model, similar to Mat #57
- Input of nominal stress versus nominal strain curves or alternatively via function parameters
- Rate effects are taken into account via table definition
- Distinguish between engineering and true strain rate
- Input of tensile stress strain curve; be aware of the fact that negative values represent tension (TFLAG)!
- If the LCID-option is used, the provided data is split into 100 equidistant points (from -eps to +eps, including the origin)
- Use of strain rate evolution flag
- Additional input of load curve describing pressure versus volumetric strain

Low and medium density foam

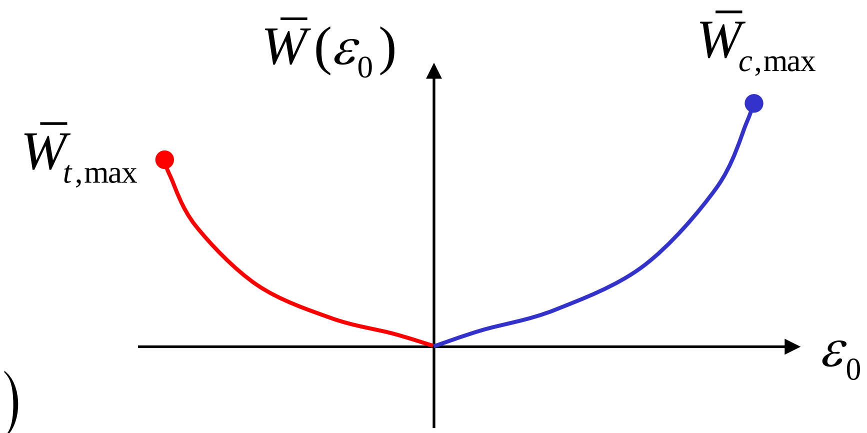
MAT_FU_CHANG_FOAM (#83)

Generate energy – strain curve from (quasistatic) stress – strain curve



ε_0

$$\bar{W}(\varepsilon_0) = \int_0^{\varepsilon_0} \sigma_l \,\mathrm{d}\varepsilon$$



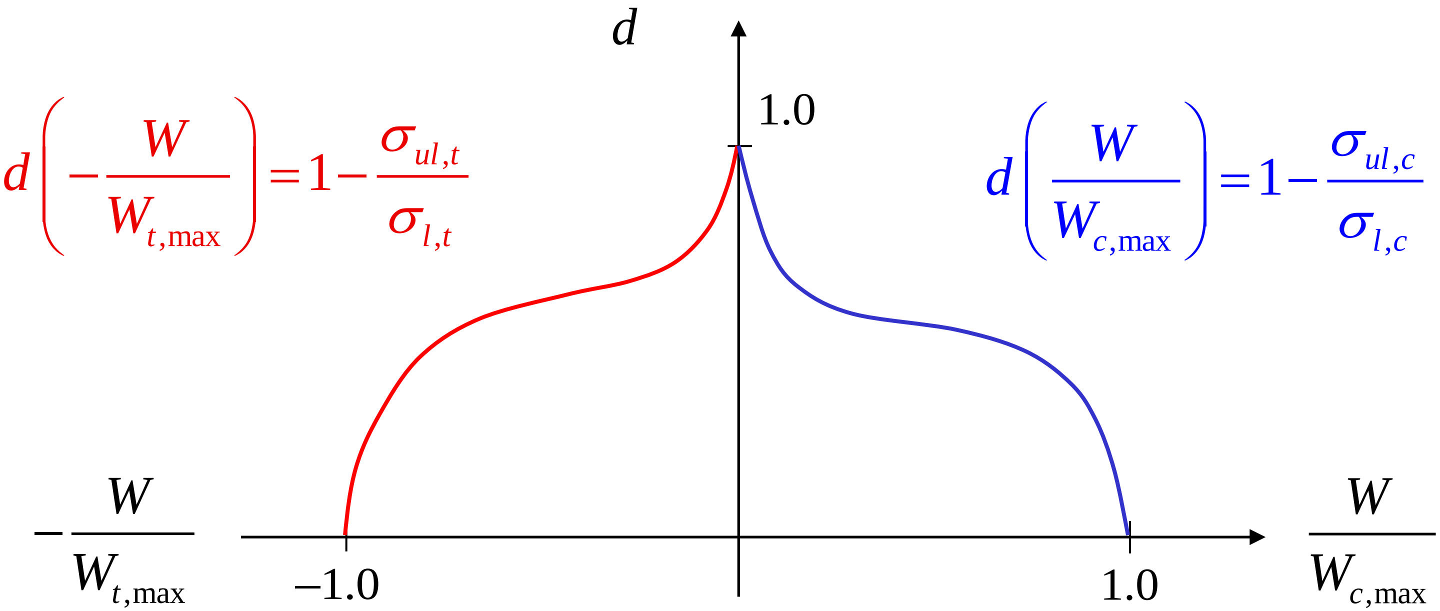
Numerical integration (trapezoidal):

$$\bar{W}_{n+1} = \bar{W}_n + \tfrac{1}{2}\left(\sigma_{0,n} + \sigma_{0,n+1}\right)\left(\varepsilon_{0,n+1} - \varepsilon_{0,n}\right)$$

Low and medium density foam

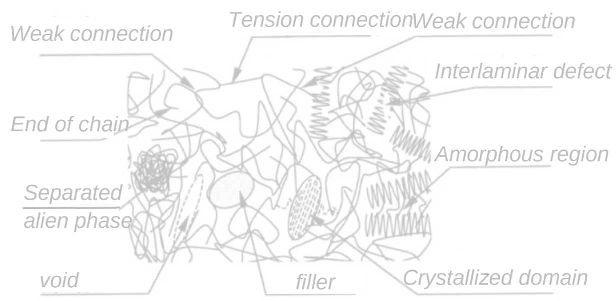
MAT_FU_CHANG_FOAM (#83)

Generate damage – energy ratio curve from stress – strain curve



energy is set negative in tension before damage is evaluated !

➡ *unloading path under uniaxial tension and compression is fitted exactly*



Thank you for your attention.

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