Failure prediction for non-reinforced and short fiber reinforced polymers

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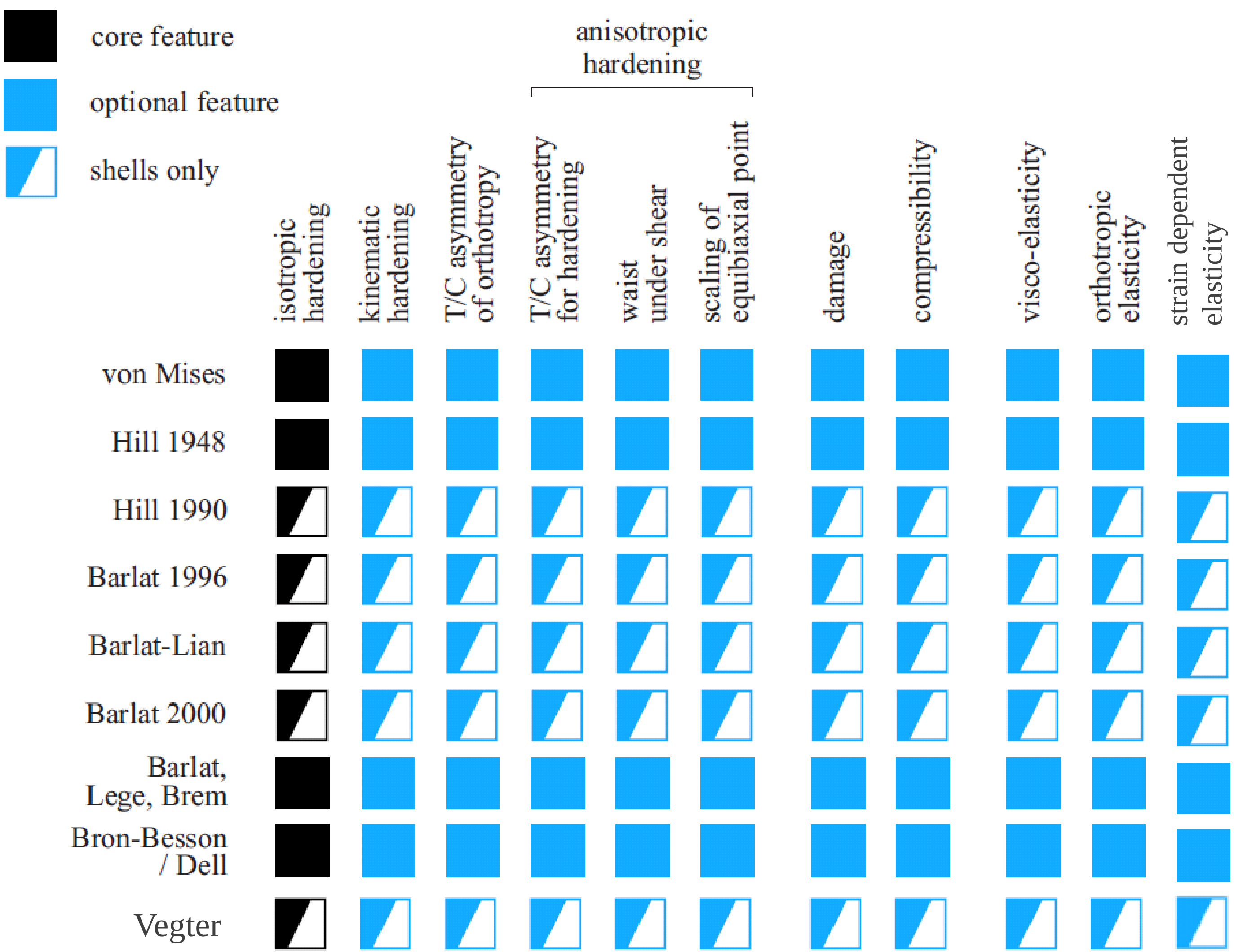
Content

MATFEM

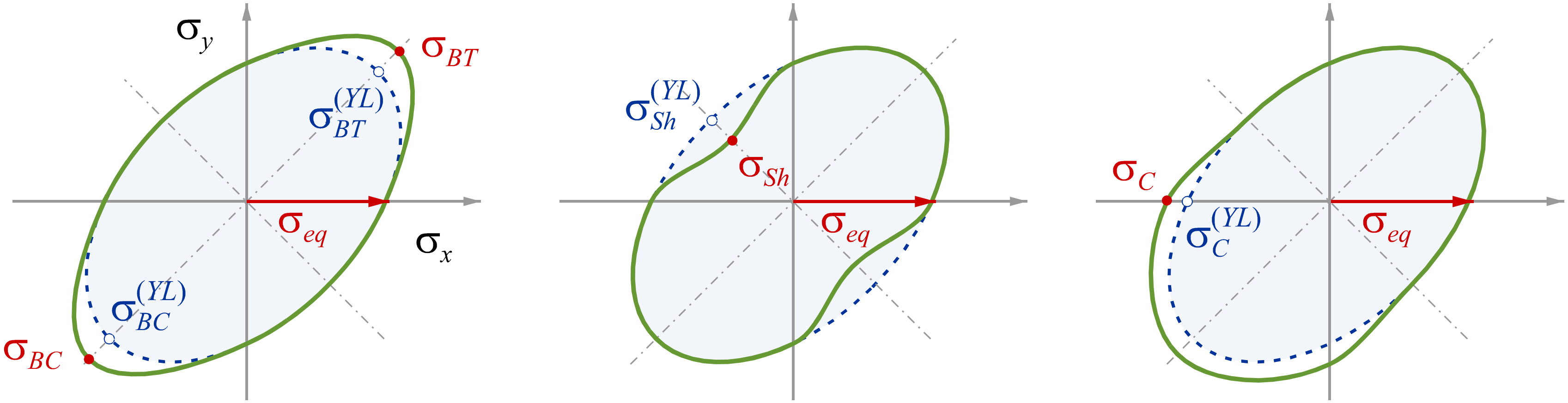
- Method
- Non-reinforced polymers
- Short fiber reinforced polymers
- Summary and outlook

- Material Model MF-GenYld+CrachFEM compatible to LS-Dyna



- Material Model MF-GenYld+CrachFEM compatible to LS-Dyna

- Yield locus modification can be done for all available yield loci in MF GenYld
- Scaled yield loci are still monotonic for yield stress and normality rule
- Reference yield locus or scaled yield locus can be used as plastic potential



Biaxial correction
Here: $b_T = b_C > 1$

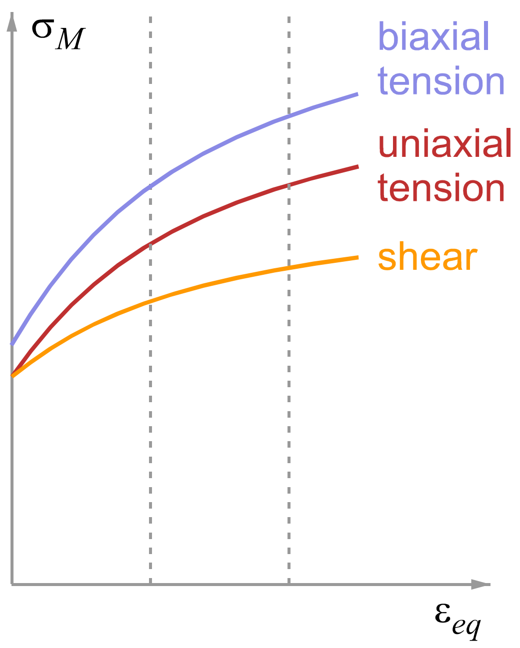
Waist for shear
Here: $a > 1$

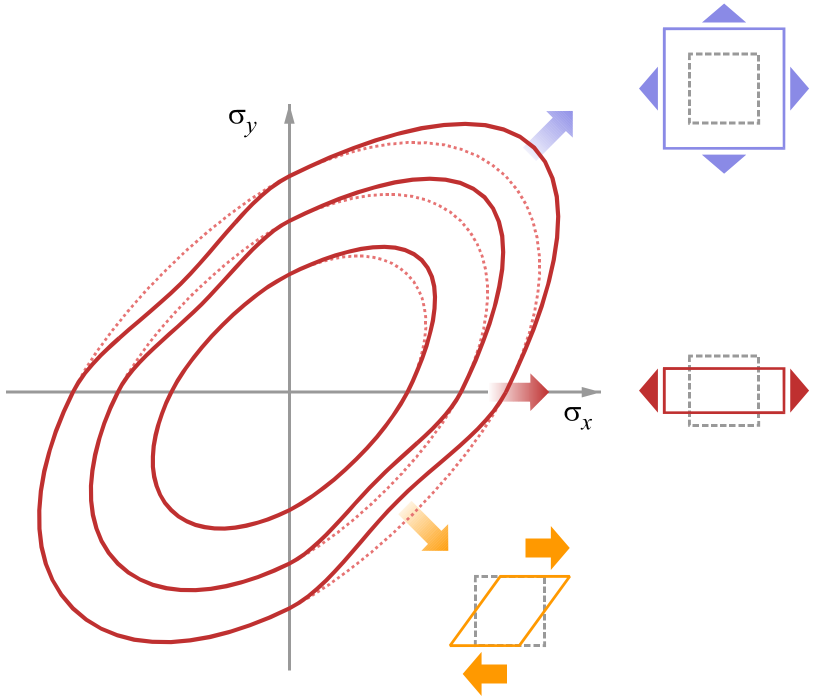
Tens./compr. asymmetry
Here: $f < 1$

$$\sigma_{eq} = \mathrm{f}^*\left(k \cdot \sigma_{ij}, q_k\right) = k \cdot \mathrm{f}^*\left(\sigma_{ij}, q_k\right)$$

MATFEM

- Material Model MF-GenYld+CrachFEM compatible to LS-Dyna

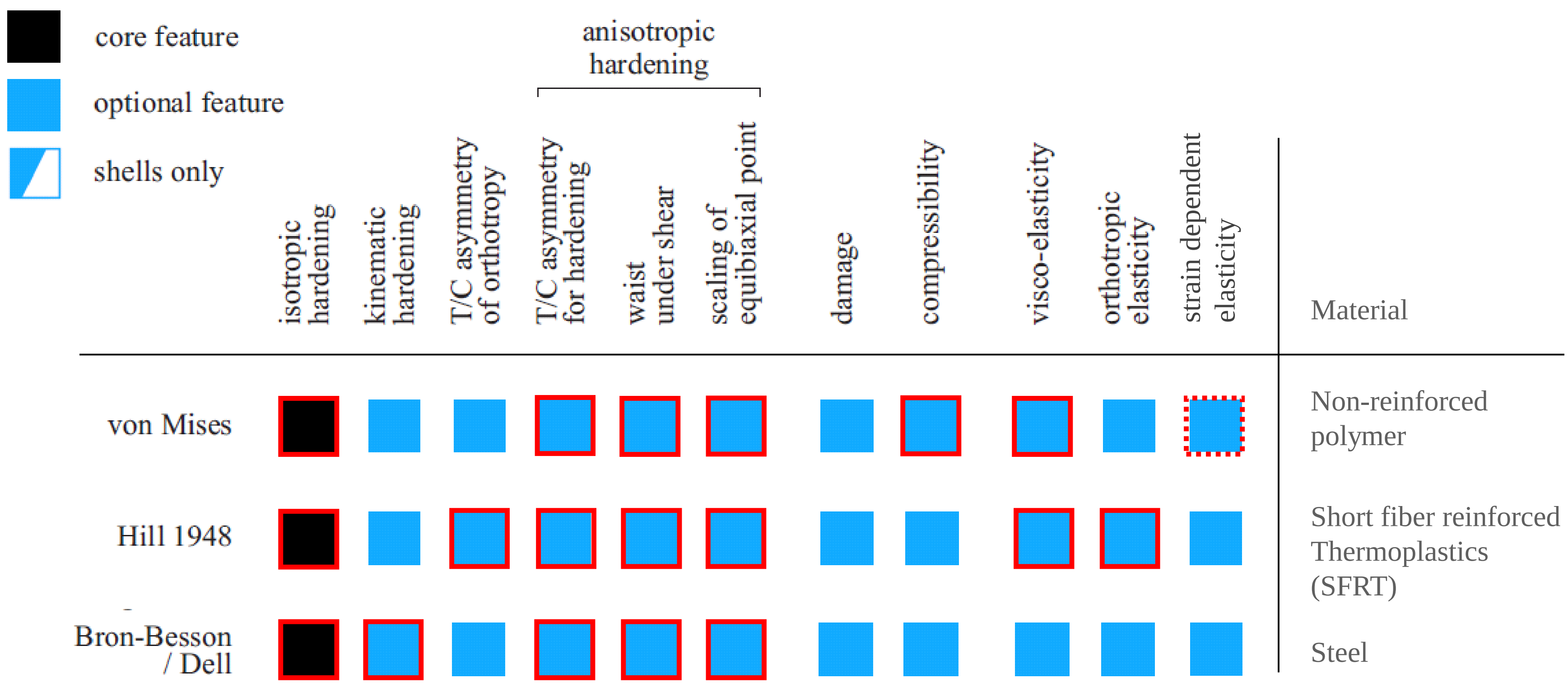




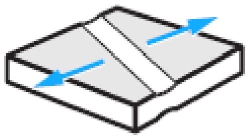
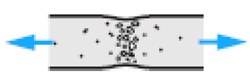
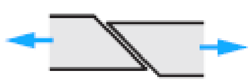
- Hardening for tension, compression shear and equibiaxial loading can be described precisely by scaling functions

MATFEM

- Material Model MF-GenYld+CrachFEM compatible to LS-Dyna



- Material Model MF-GenYld+CrachFEM compatible to LS-Dyna

			shell	solid
	Local instability (necking)	Initial FLC (approximate)	■	(1)
		Prediction with Crach	■	(1)
		Post-critical elongation	■	(1)
	Ductile normal fracture	$\varepsilon_{eq}^{**} = \varepsilon_{eq}^{**}(\eta)$	■	(2)
		$\varepsilon_{eq}^{**} = \varepsilon_{eq}^{**}(\beta)$	■	■
	Ductile shear fracture	$\varepsilon_{eq}^{**} = \varepsilon_{eq}^{**}(\theta)$	■	■

2D: shells 3D: solid elements (1) not reasonbable (2) not recommended

plastic compressibility

fracture orthotropy

Tensorial description of damage for nonlinear strain paths

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Non-reinforced polymers

MATFEM

- Experimental testing
  - Uniaxial tension
  - Tension of waisted specimens and specimens with groove
  - Biaxial tension
  - Shear
  - Compression

  - General assumption: compressibility is not strain rate dependent

- Testing – Uniaxial tension, waisted specimen, specimen with groove

Optical method of testing

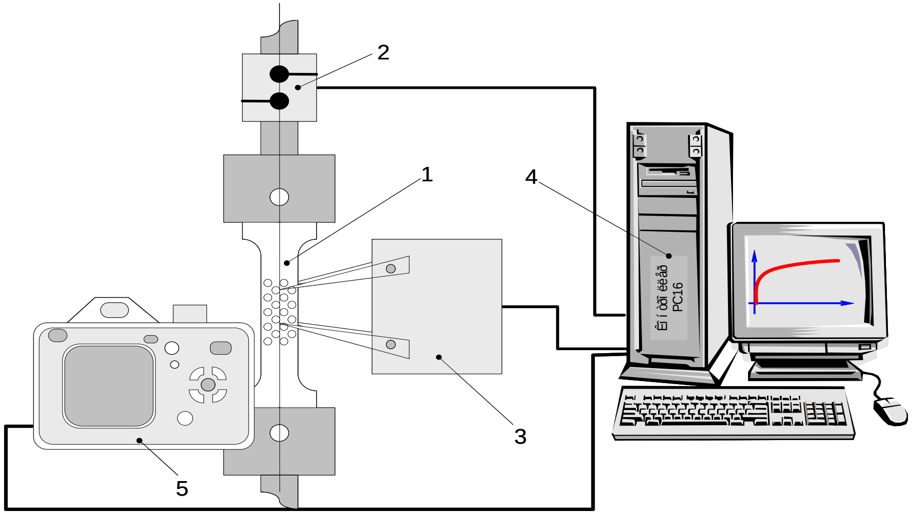
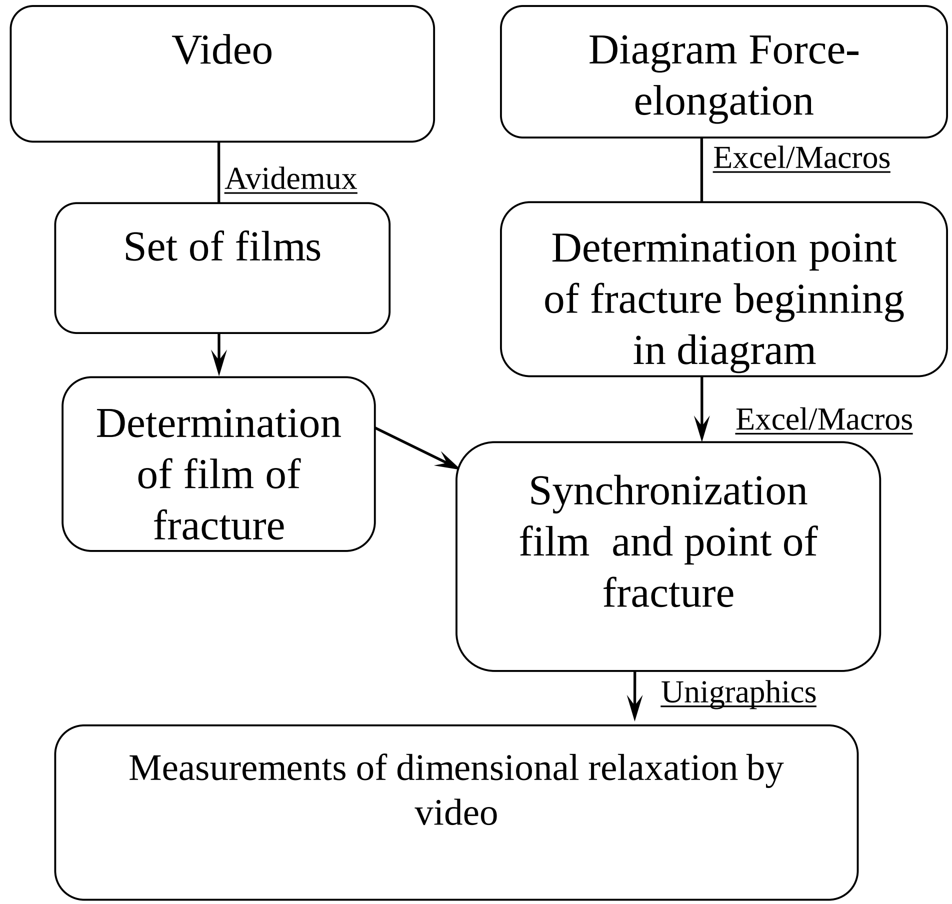


Fig.1. Scheme of optical measure of specimen deformation: 1 – specimen, 2 – force transducer, 3 – transducer of thickness decrease measure, 4 – PC-card, 5 – video-camera

Testing at MATTEST Engineering Consultants, Voronezh

Scheme of data treatment



- Experimental testing – Biaxial tension

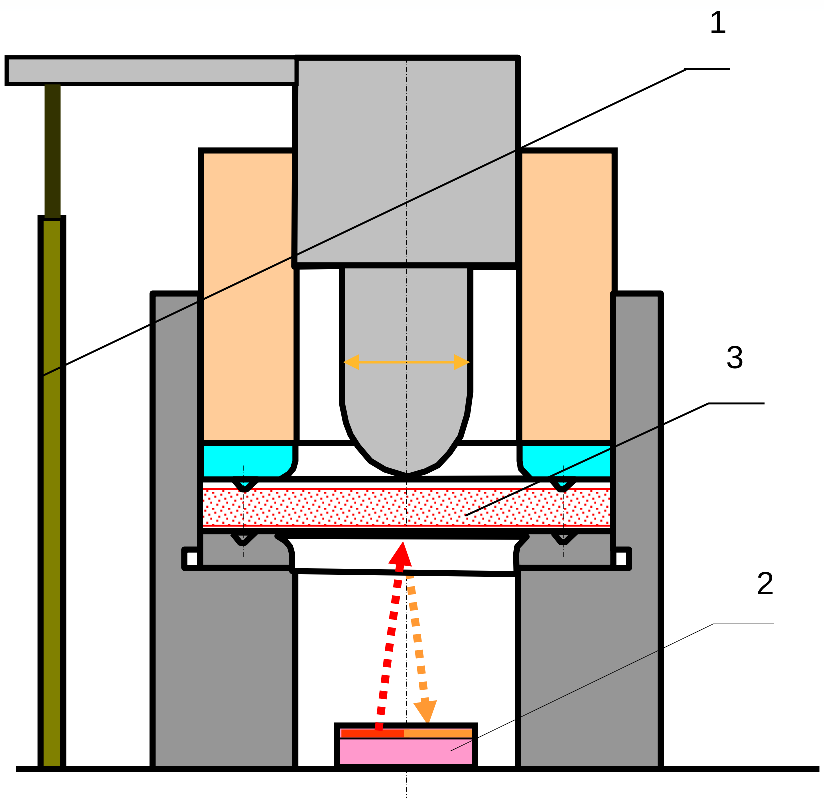


Fig.2,a. Measurement specimen thickness decrease in unibiaxial tension of polymers: 1 – transducer of elongation; 2- contactless laser transducer of elongation; 3 – specimen

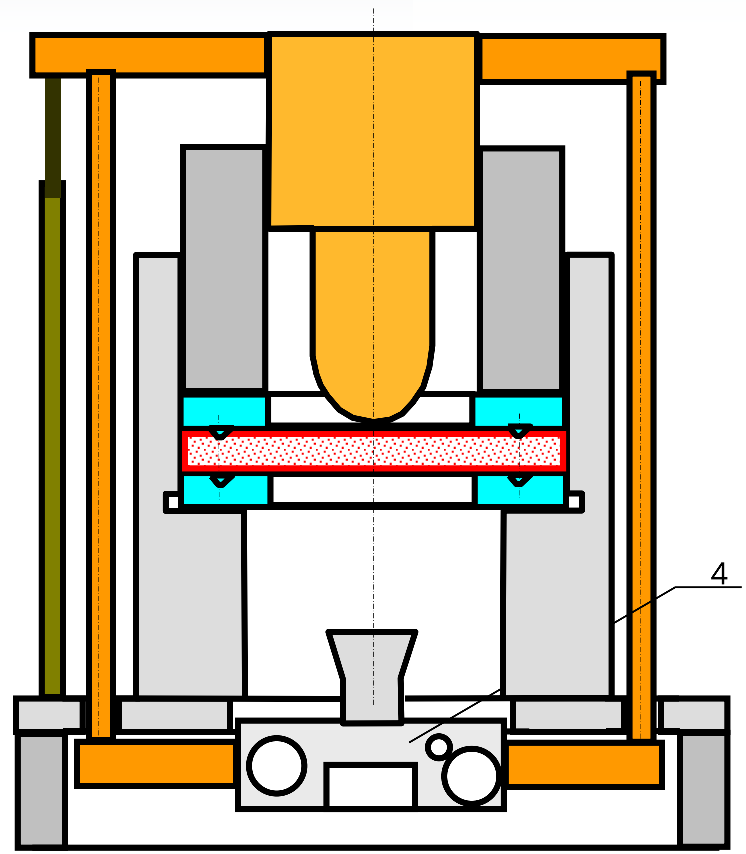


Fig.2,b. Measurement specimen grid development in unibiaxial tension of polymers: 4 - photo camera

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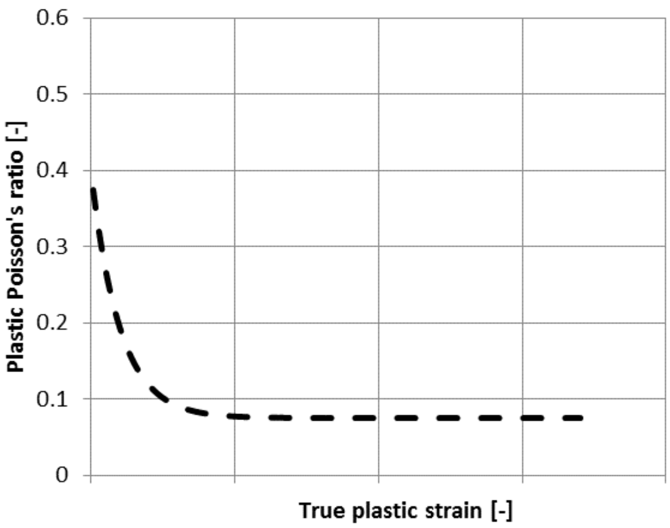
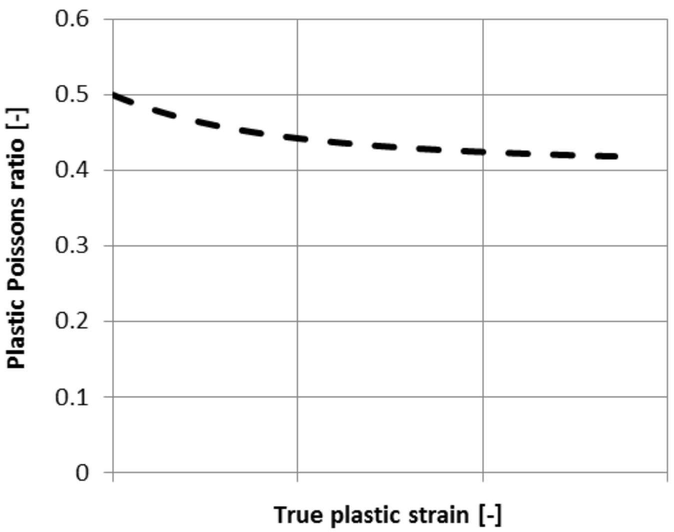
▶ Strain dependency of Poisson‘s ratio

Polymer 1



Polymer 2



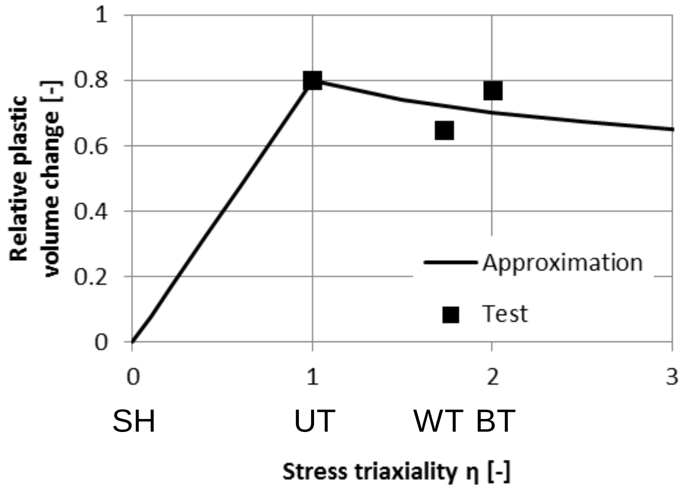
Plastic straining in cross and thickness direction can deviate significantly!

Plastic compressibility

- Plastic behaviour of thermoplastic materials can be described compressible
- Deviatoric components of plastic deformations are calculated based on the plastic ptential
- Plastic compressibility behaviour must be taken into accout for description of failure accordingly
- Equation of compressibility

$$\frac{d\varepsilon_m^p}{d\varepsilon_{eq}} = a\eta \quad \text{for } |\eta| < 1$$

$$\frac{d\varepsilon_m^p}{d\varepsilon_{eq}} = a\eta|\eta|^{-r} \quad \text{else}$$



Plastic volume change $\varepsilon_m^p = \varepsilon_x^p + \varepsilon_y^p + \varepsilon_z^p$

Stress triaxiality $\eta = \dfrac{\sigma_1 + \sigma_2 + \sigma_3}{\sqrt{\sigma_1^2 + \sigma_2^2 + \sigma_3^2 - \sigma_1\sigma_2 - \sigma_2\sigma_3 - \sigma_3\sigma_1}}$

Parameter r is a material parameters

Equivalent plastic strain based on plastic work ε_{eq}

Parameter a is strain dependent

Plastic compressibility

- Determination of function a(ε_{eq}) based on flat specimen with strain measurement in longitudinal direction, cross direction and thickness direction

- Based on the increments of plastic straining

$$d\varepsilon_x^p = d\varepsilon_x - d\sigma_x / E \qquad d\varepsilon_y^p = d\varepsilon_y + \mu\, d\sigma_x / E \qquad d\varepsilon_z^p = d\varepsilon_z + \mu\, d\sigma_x / E$$

the averaged current plastic Poisson's ratio is calculated

$$\mu_p = -\frac{d\varepsilon_y^p + d\varepsilon_z^p}{2 d\varepsilon_x^p}$$

μ elastic Poissons ratio

- For the uniaxial tensile test it is valid

$$d\varepsilon_m^p = (1 - 2\mu_p) d\varepsilon_{eq}$$

η = 1

- Therefore

$$a = 1 - 2\mu_p$$

- For the determination of exponent r test results from the waisted tensile test as well as the Erichsen test are used

▶ Plastic compressibility

Material Card

```
$   FRELIM     DTMIN        NF     VELSC    RSTRAT
         1    1e-029      2000         1     0.001         0         0         0
$ EL_YOUNG  EL_POISS  EL_BULKM  EL_SHEAR  EL_ORTHO  EL_SHRCO
         a         b         c         d       910  0.833333         0         0
$ PL_HARDE  PL_ORTHO  PL_ISKIN  PL_ASYMM  PL_WAIST  PL_BIAXF  PL_COMPR  PL_DAMAG
      1000         0         0      1009      1010      1011       999         0
$ NF_CURVE  NF_PARAM  NF_POSTC  SF_CURVE  SF_PARAM  SF_POSTC
      1012      1016      1017      1018         0         0         0         0
$ CR_HARDE  CR_ORTHO  CR_ISKIN  CR_POSTC  CR_PARAM  CR_CHECK             MF_INIT
         0         0         0         0         0         0         0         0
```

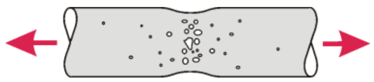
- Plastic Poisson's ratio μ_p is defined versus equivalent plastic strain for tension and compression

$$\mu_p = \mu_s + \mu_1 \exp(-p_1 \varepsilon_{eq}^p) + \mu_2 \exp(-p_2 \varepsilon_{eq}^p)$$

	Curve	PL_COMPR
	1	model
	2	assoc
	3	n
Tension	4	μ_1
	5	μ_2
	6	μ_{sat}
	7	p_1
	8	p_2
Compression	9	μ_1
	10	μ_2
	11	μ_{sat}
	12	p_1
	13	p_2
	14	r
	15	c

▶ Material Model MF-GenYld+CrachFEM compatible to LS-Dyna

Normal fracture



$$\varepsilon^{**}(\eta)$$

$$\eta = \frac{-3 \cdot p}{\sigma_M}$$

$$\varepsilon_{eq}^{**} = d_0 \exp(-c\eta) + d_1 \exp(c\eta)$$

$$\varepsilon_{eq}^{**} = \frac{\varepsilon_{NF}^{+} \sinh\left(c \cdot (\eta^{-} - \eta)\right) + \varepsilon_{NF}^{-} \sinh\left(c \cdot (\eta - \eta^{+})\right)}{\sinh\left(c \cdot (\eta^{-} - \eta^{+})\right)}$$

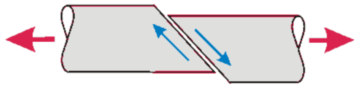
$$\varepsilon^{**}(\beta)$$

$$\beta = \frac{1 - s_{NF} \cdot \eta}{v}$$

$$v = \frac{\sigma_1}{\sigma_M}$$

$$\varepsilon_{eq}^{**} = d \cdot e^{q \cdot \beta}$$

Shear fracture



$$\varepsilon^{**}(\theta)$$

$$\theta = \frac{1 - k_{SF} \cdot \eta}{w}$$

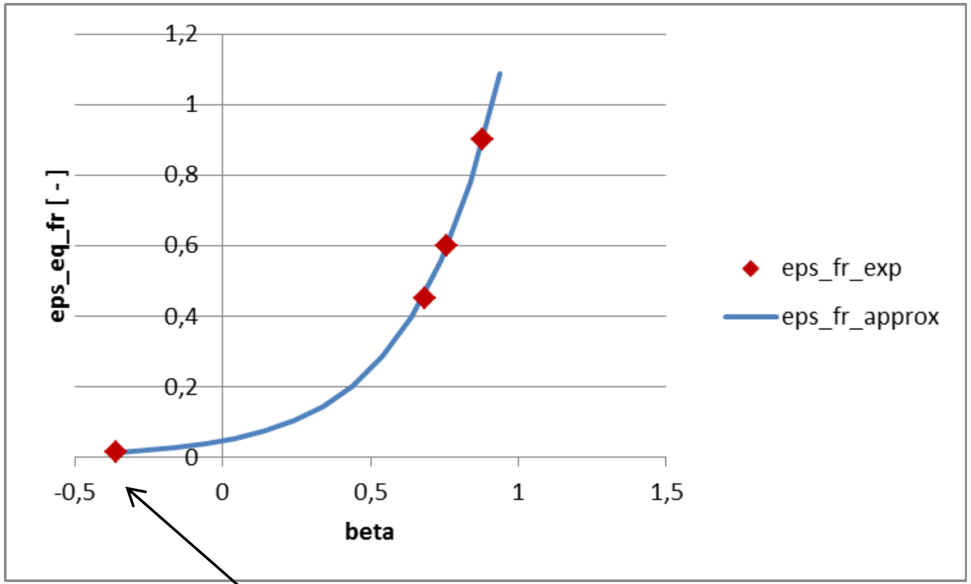
$$w = \frac{\tau_{max}}{\sigma_M}$$

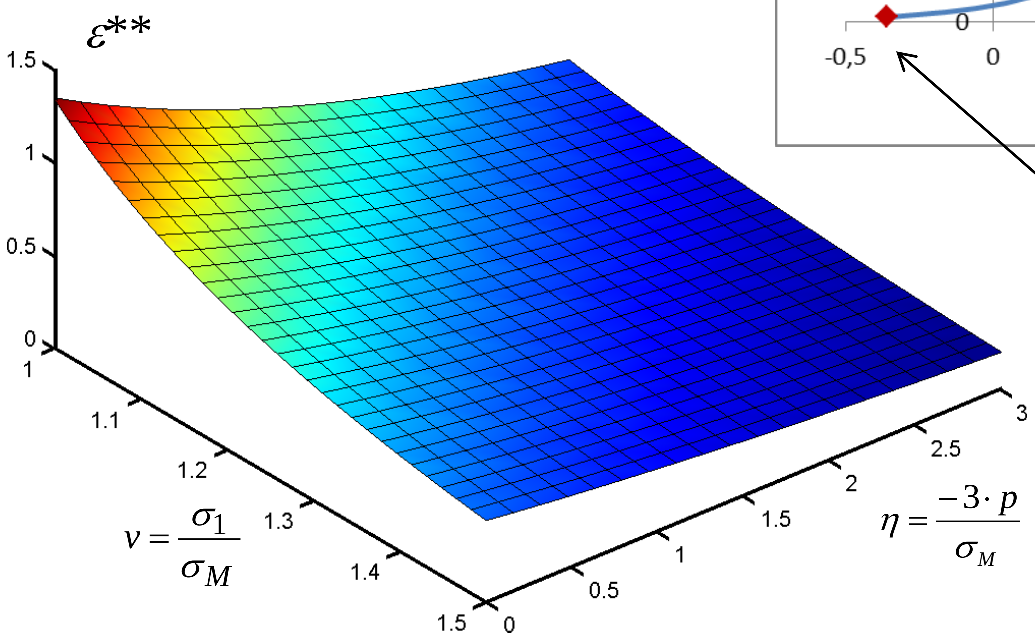
$$\varepsilon_{eq}^{**} = e_0 \exp(-f\theta) + e_1 \exp(f\theta)$$

$$\varepsilon_{eq}^{**} = \frac{\varepsilon_{SF}^{+} \sinh\left(f(\theta - \theta^{-})\right) + \varepsilon_{SF}^{-} \sinh\left(f(\theta^{+} - \theta)\right)}{\sinh\left(f(\theta^{+} - \theta^{-})\right)}$$

- Material Model MF-GenYld+CrachFEM compatible to LS-Dyna

- Approximation of experiments with beta-model for ductile normal fracture; optimization by variation of parameters (right)
- Derived 3D fracture surface for ductile normal fracture (below)



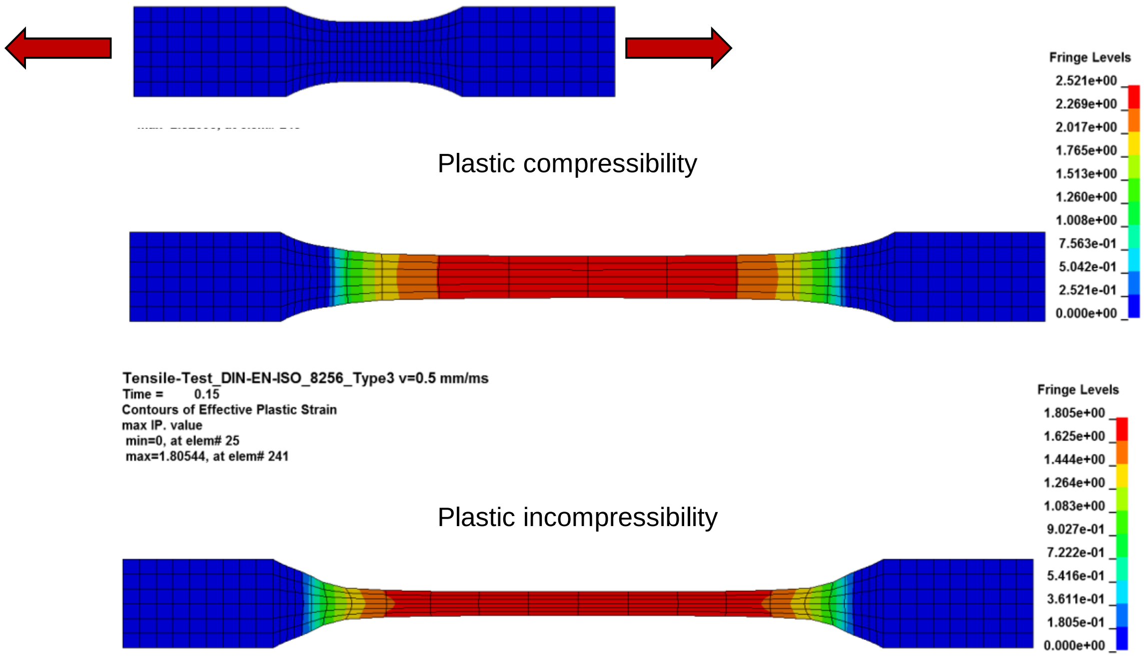


triaxial tension for β = -3s

Plastic compressibility of polymers

- Plastic Poisson's ratio μpl is defined versus equivalent plastic strain for tension and compression
- A geometrical equivalent plastic strain is used as an input for the fracture models

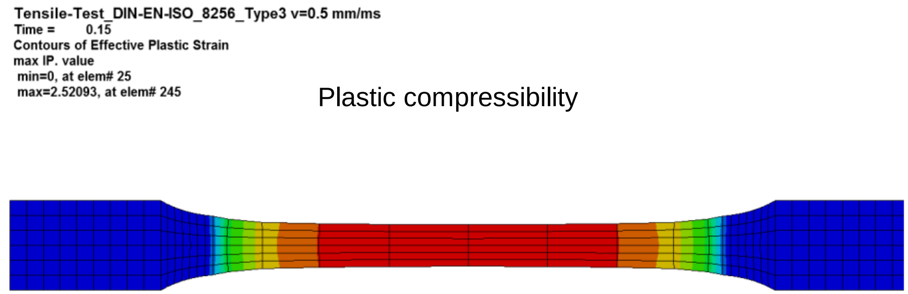
$$\varepsilon^{**} = \int \sqrt{2 d\boldsymbol{\varepsilon}^{p} : d\boldsymbol{\varepsilon}^{p} / 3} = \int \sqrt{2\left(d\varepsilon_1^{p2} + d\varepsilon_2^{p2} + d\varepsilon_3^{p2}\right)/3}$$

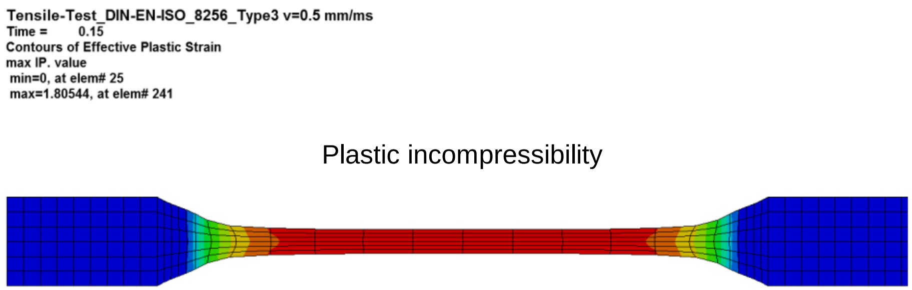


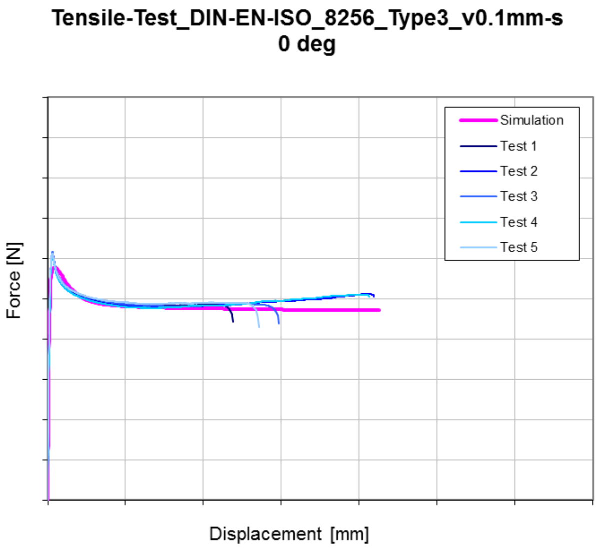
- Approach with plastic incompressibility gives similar force–deflection curves as model with plastic compressibility as long as assumption is used consequently during data preparation
- However geometry (width and thickness of uniaxial tensile specimen) is predicted wrong with plastic incompressibility for large deformation

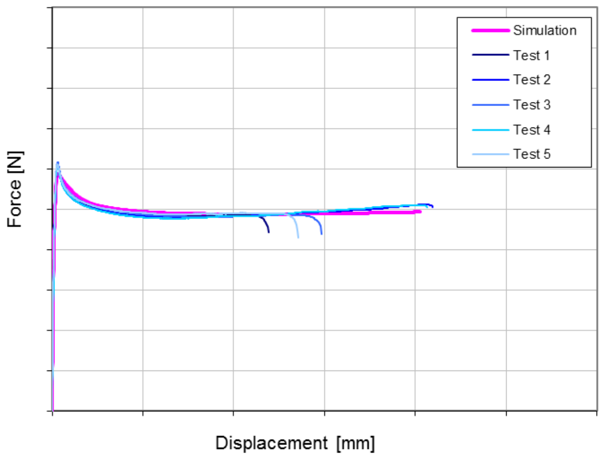
MATFEM

- Plastic compressibility of polymers









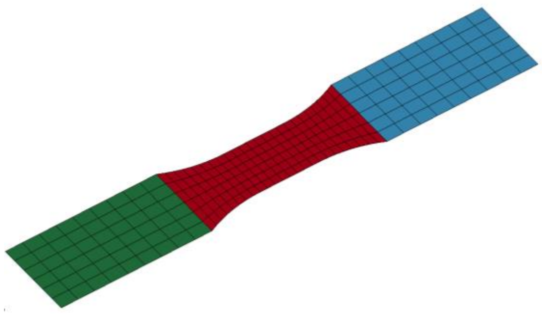
Non-reinforced polymers

MATFEM

► Plastic compressibility of polymers

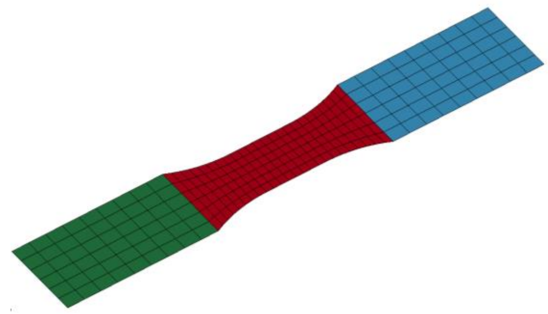
Tensile-Test_DIN-EN-ISO_8256_Type3

Test Speed: 0.1mm/s



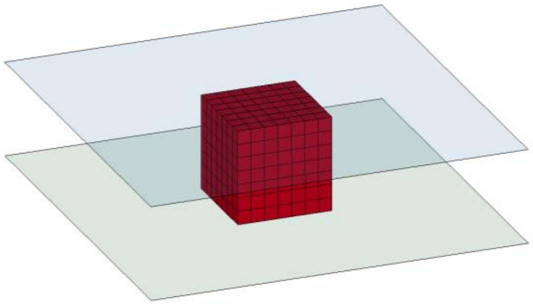
Tensile-Test_DIN-EN-ISO_8256_Type3

Test Speed: 2000 mm/s



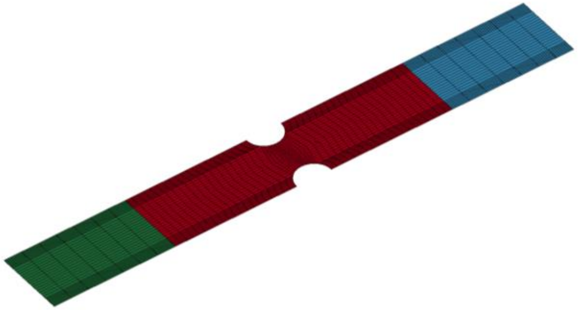
Compression-Test_DIN-EN-ISO_604

Test Speed: 0.05 mm/s



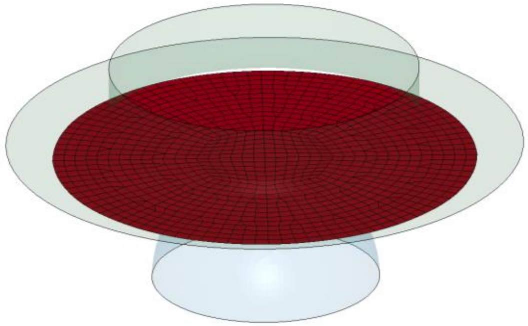
Waisted-Tensile-Test

Test Speed: 0.05 mm/s



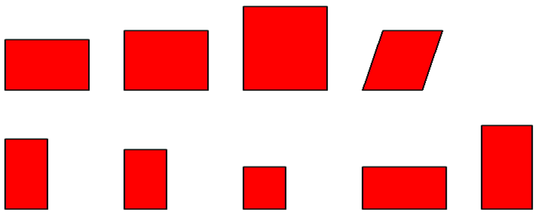
Erichsen-Test

Test Speed: 0.5 mm/s



Sigle-Element-Test

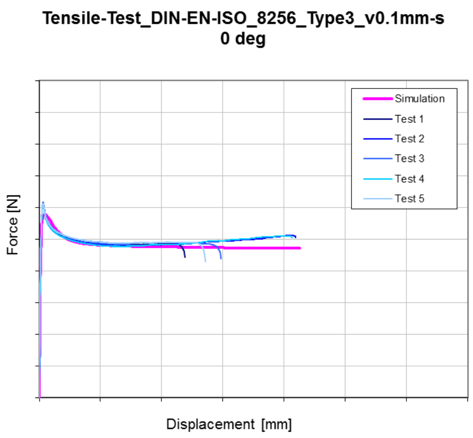
Strain Rate: qasi static - dynamic

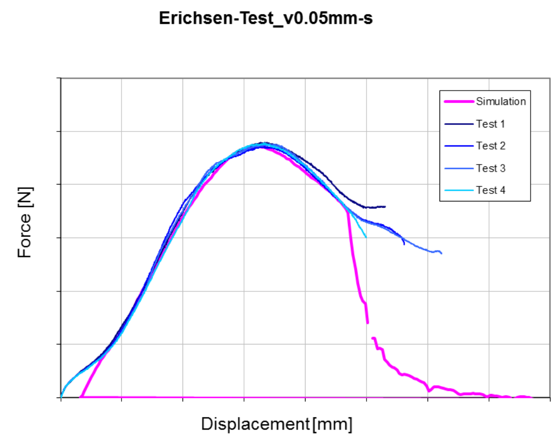


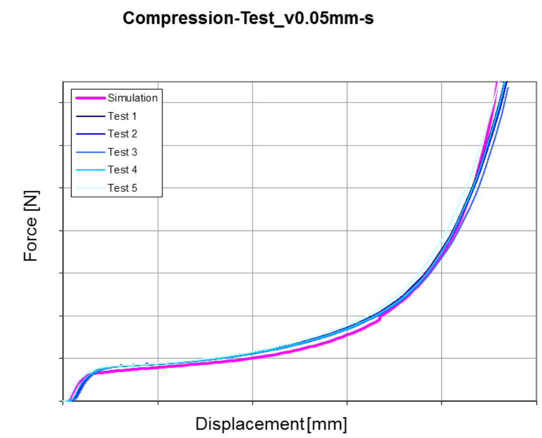
Non-reinforced polymers

▶ Plastic compressibility of polymers

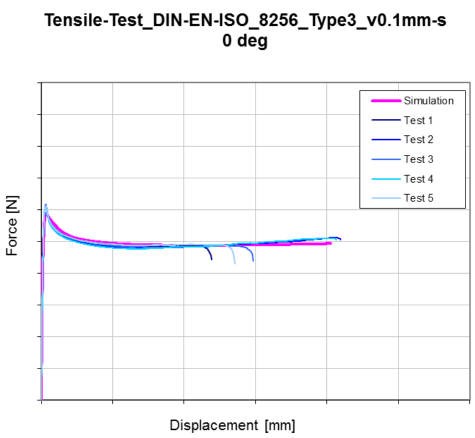
Plastic compressibility

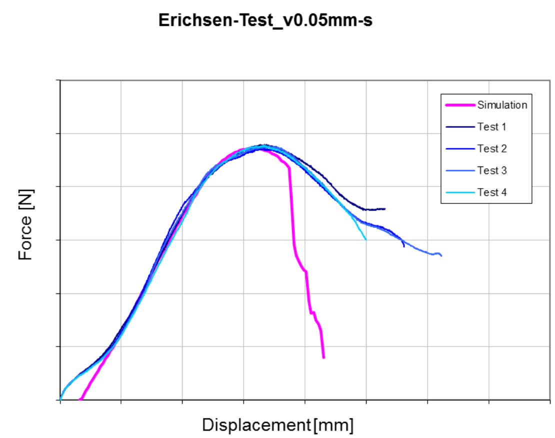


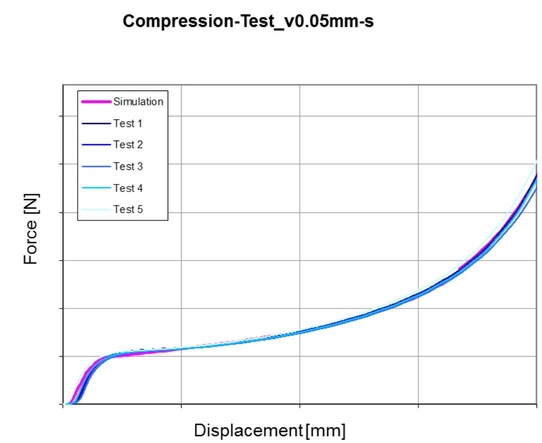




Plastic incompressibility

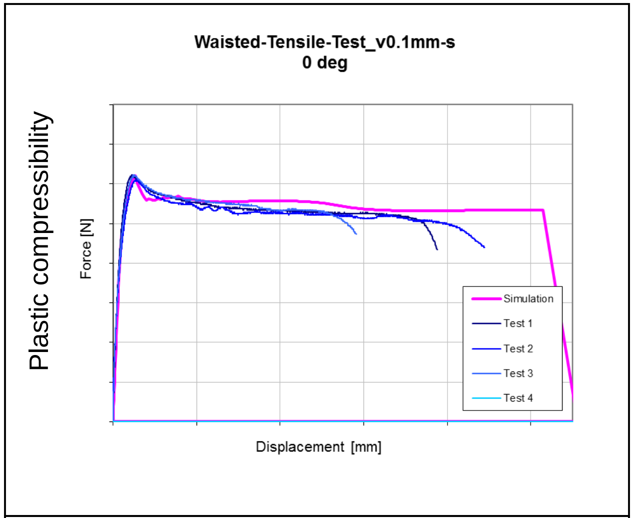


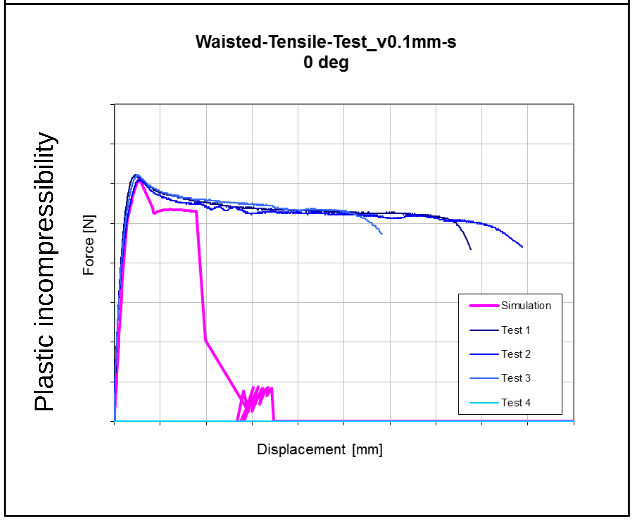




MATFEM

- Plastic compressibility of polymers

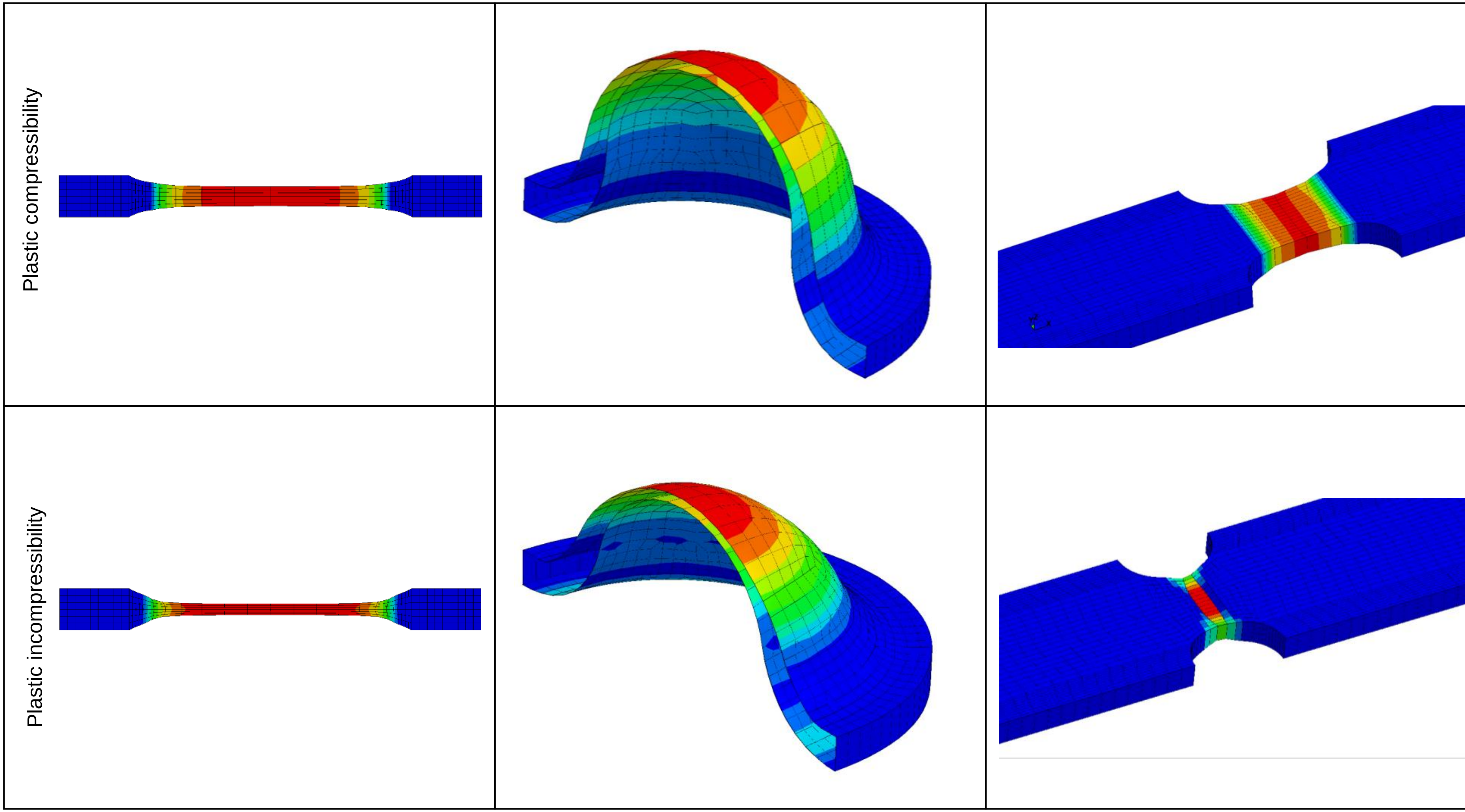




Non-reinforced polymers

MATFEM

- Plastic compressibility of polymers



- Discussion
  - In general the force deflection behavior can be described with comparatively good accuracy assuming plastic incompressibility (there are exceptions exceptions) as long as the assumption of plastic incompressibility is used consequently during data preparation (elasto-plastic behaviour and failure behavior)
  - However geometry (especially the thickness of specimen) is predicted wrong with plastic incompressibility for large deformation
  - Increased thinning can initiate early strain localization if plastic Poisson's at saturation is low; this can cause a too early failure prediction
  - Significant anisotropy of plastic straining can occur
  - Model for plastic compressibility used within this investigation can be combined with all available orthotropic yield locus functions

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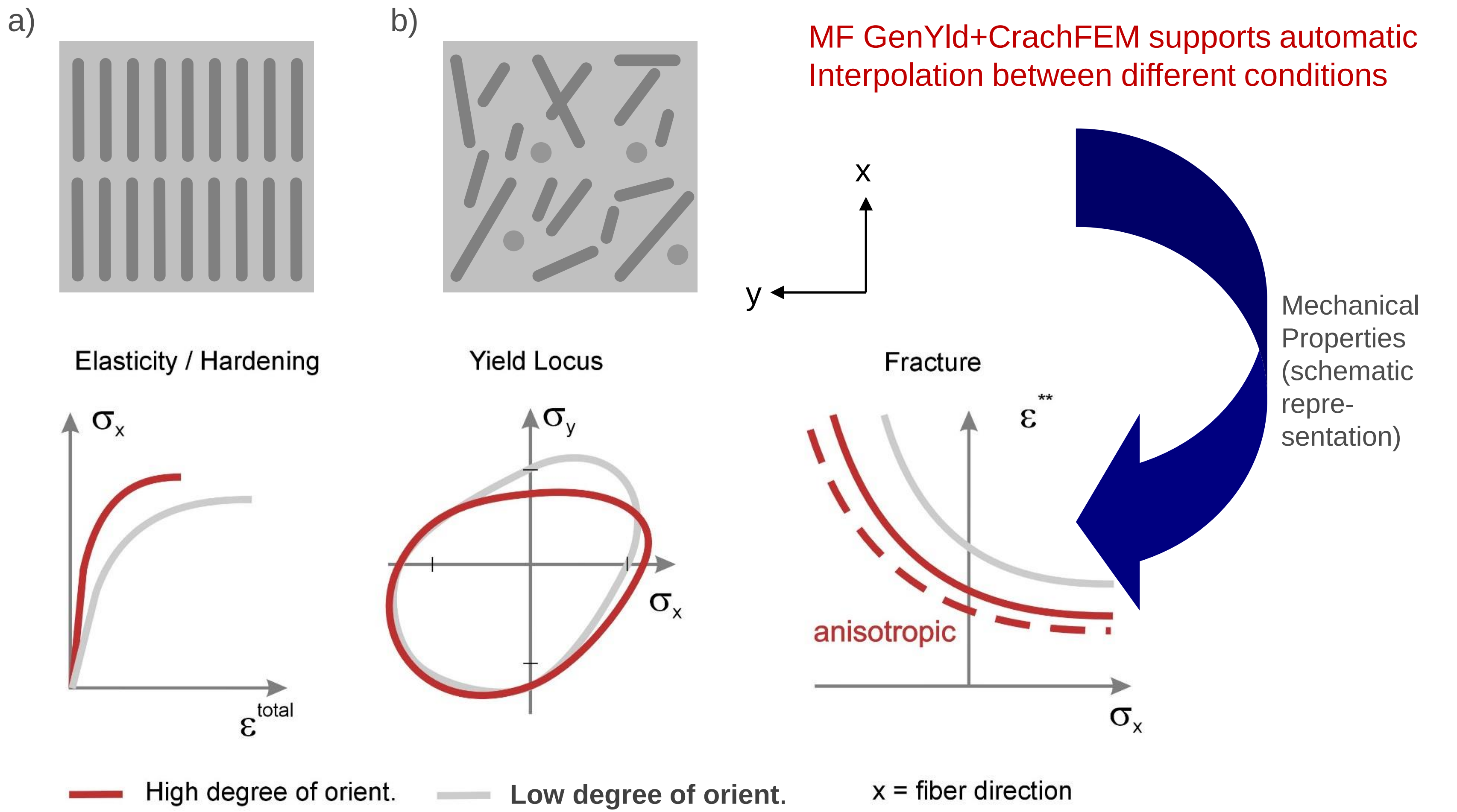
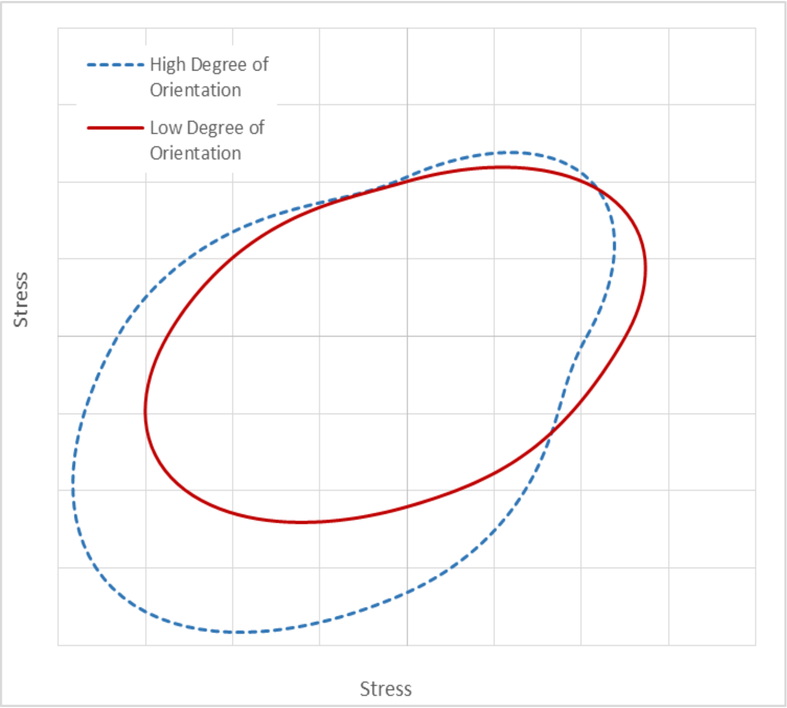
- Degree of fiber orientation
  - Extremal conditions for one fiber density: a) Highly oriented fibers (maximum degree of anisotropy) / b) Randomly distributed fibers (isotropic)



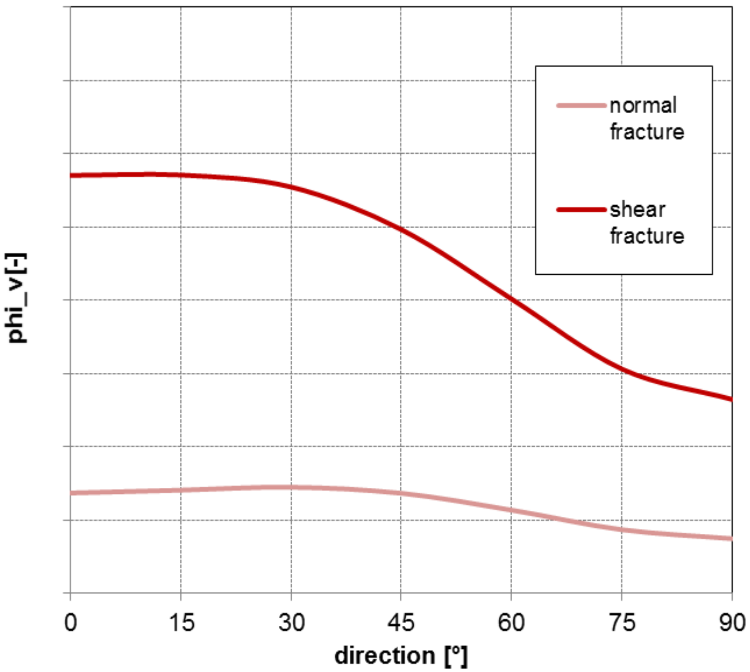
MATFEM

- Degree of fiber orientation
  - Example

Yield locus



Anisotropy of fracture



▶ Anisotropy of fracture

Fracture anisotropy denotes the dependence of the fracture strain on the fracture surface orientation.

It is assumed that the fracture strains are orthotropic, i.e. that they are symmetrical about three mutually perpendicular symmetry planes at an arbitrary orientation to the anisotropy axes x, y and z. It is additionally assumed that the fracture strain can be expressed as a product of two functions:

$$\varepsilon^{**} = \varepsilon_x^{**} w(C_x, C_y, C_z)$$

It is difficult to measure a fracture diagram for a fixed direction (e.g. for the rolling direction), because the fracture surface does not necessarily develop on the perpendicular plane. For this reason the fracture diagrams are usually determined for the direction with minimum fracture strain:

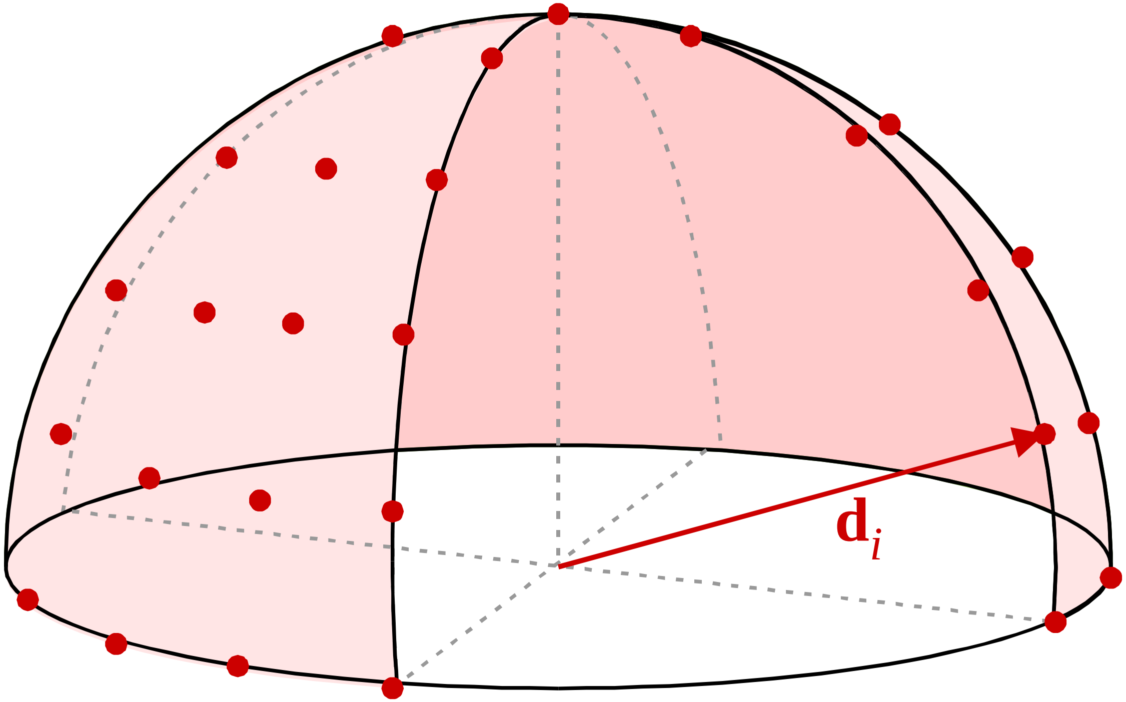
$$\varepsilon^{**} = \varepsilon_{\min}^{**} w(C_x, C_y, C_z) / w_{\min}$$

The anisotropy function is described by the following equation:

$$w = \frac{a_{xy}(1-C_z^2)^{2n} + a_{yz}(1-C_x^2)^{2n} + a_{xz}(1-C_y^2)^{2n}}{(1-C_z^2)^{2n} + (1-C_x^2)^{2n}(1-C_y^2)^{2n}}$$

a_{xy}, a_{yz}, a_{zx} depend on the normal onto the fracture plane

- Anisotropy of fracture



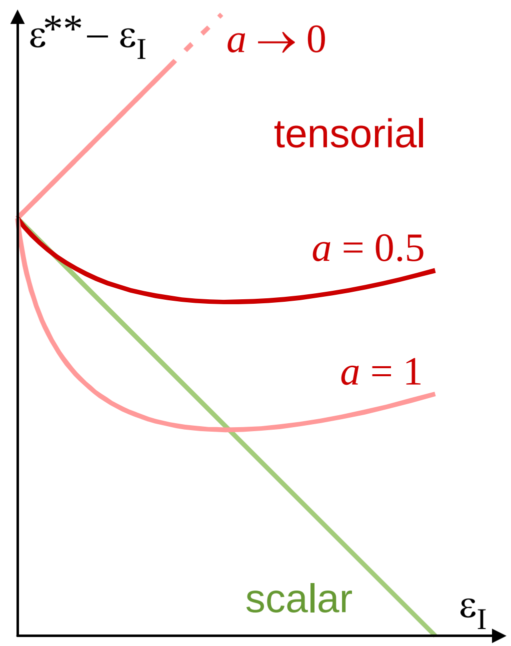
New approach to fracture:

Various discrete directions are probed for the maximum fracture risk:

$$\varepsilon^{**} = \min_{i=1}^{n} \varepsilon^{**}(\mathbf{d}_i)$$

MATFEM

▶ Tensoriell damage accumulation



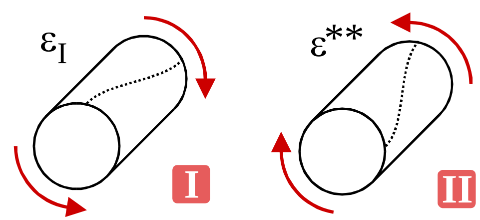
Damage accumulation

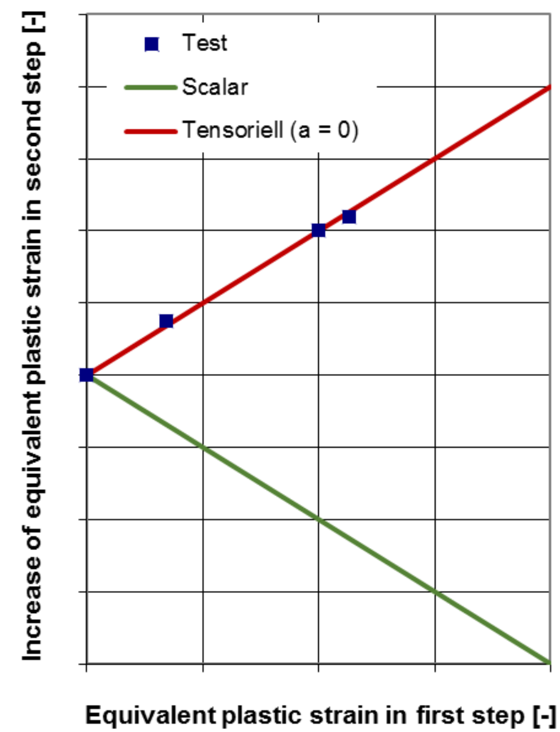
Tensorial

$a \to 0$	linear
$a = 1$	quadratic
$a = 0$	default: $a = 0.5$

Scalar:

$a < 0$	(as flag)



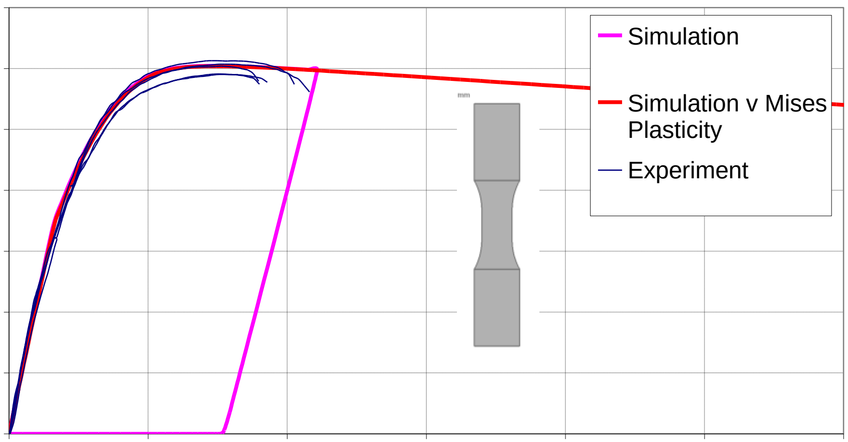


▶ Linear tensorial damage accumulation is suitable

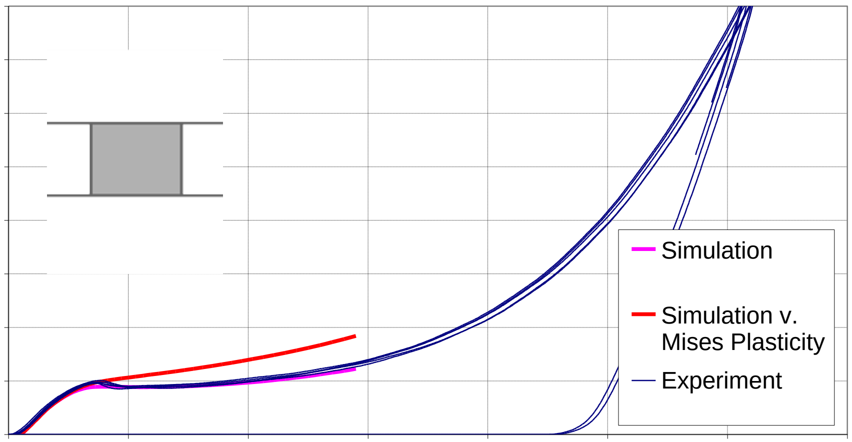
MATFEM

▶ The highly oriented state

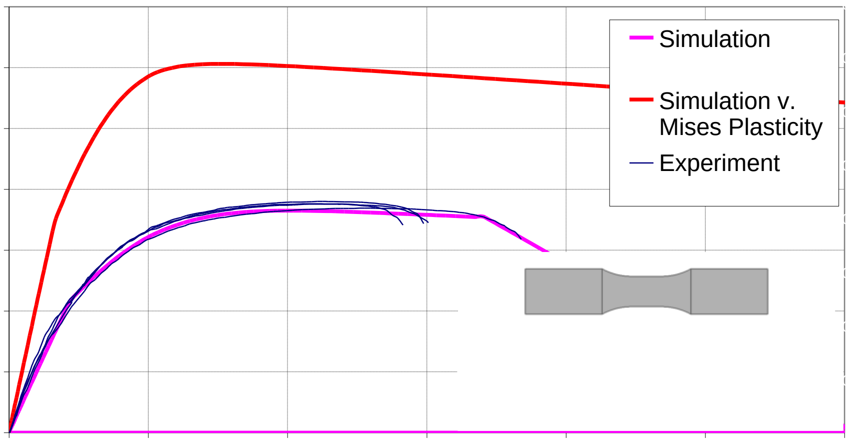
Uniaxial Tension / quasi-static / 0°



Compression / quasi static / 0°

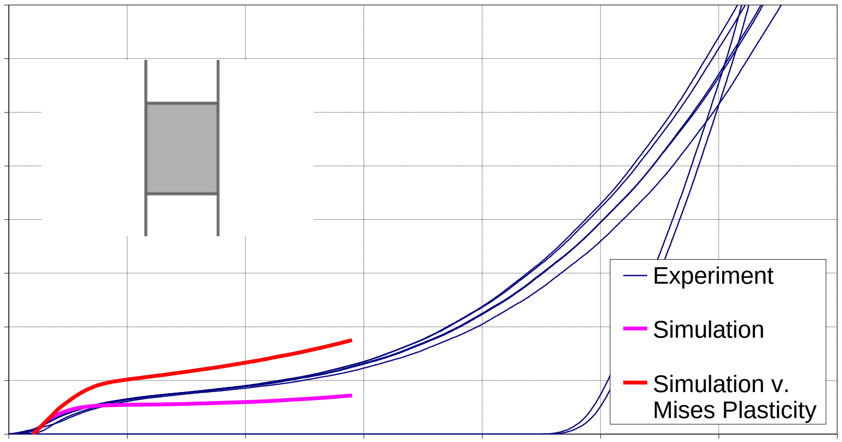


Uniaxial Tension / quasi static / 90°



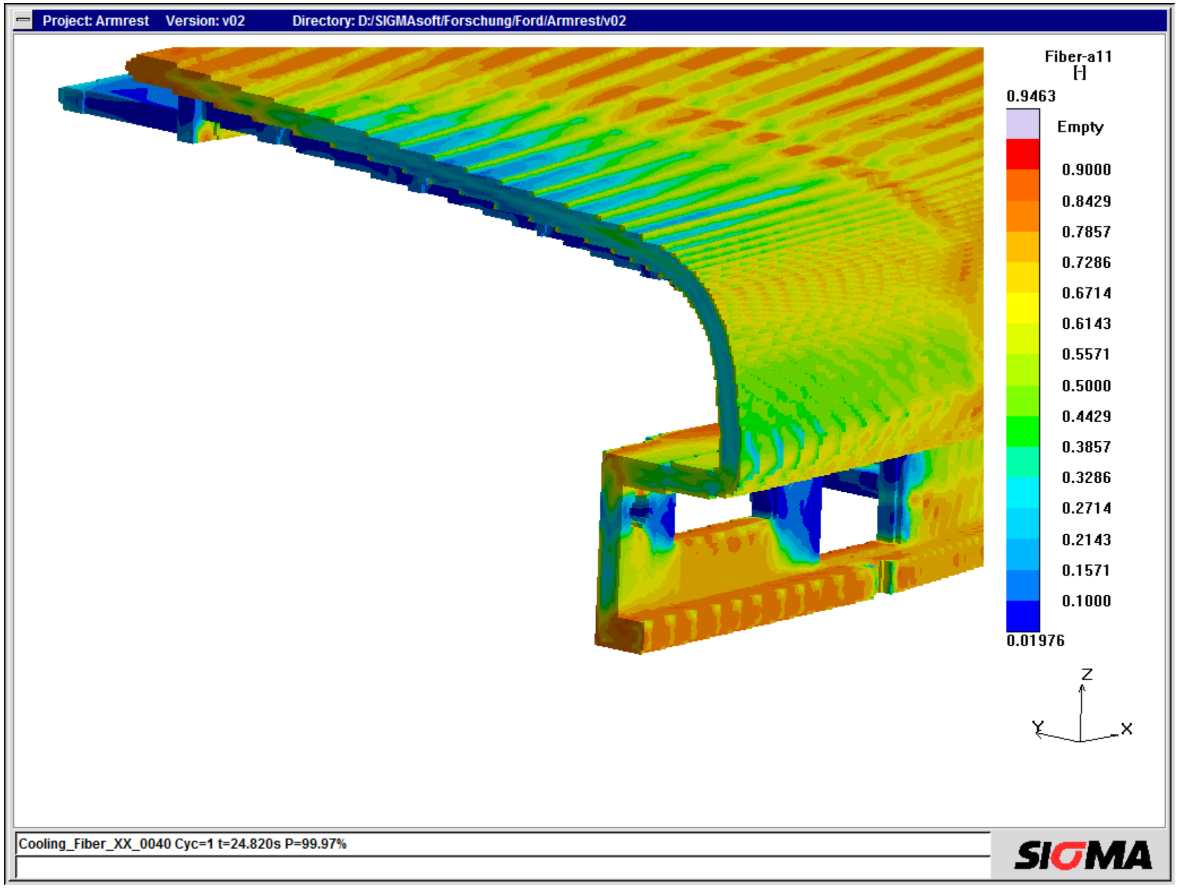
Displacement

Compression / quasi static / 90°



Displacement [mm]

- Component simulation
  - Tensor of fiber orientation as a result of mould-filling simulation

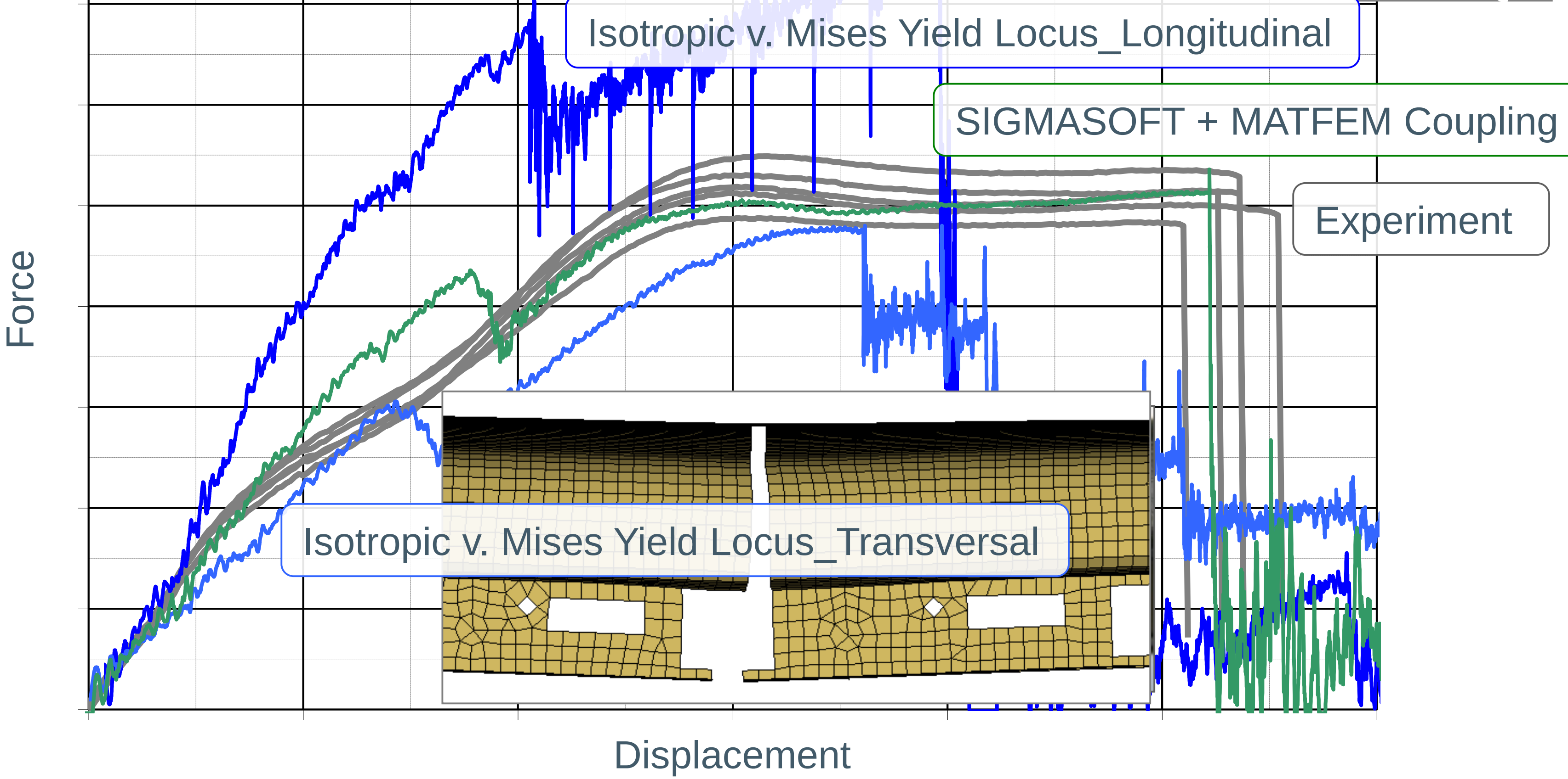


Strong gradients in fiber orientation:

anisotropic part properties

Source: M. Franzen, G. Oberhofer, M. Thornagel, Advanced Modeling of Fiber Reinforced Thermoplastics for Crash Applications under Consideration of the Injection Molding Process; Proceedings of Crashmat 2012, 9-10 May 2012

- Component simulation
  - Tensor of fiber orientation as a result of mould-filling simulation



Source: M. Franzen, G. Oberhofer, M. Thornagel, Advanced Modeling of Fiber Reinforced Thermoplastics for Crash Applications under Consideration of the Injection Molding Process; Proceedings of Crashmat 2012, 9-10 May 2012

- Discussion
  - In case of short fiber reinforced polymers the anisotropy of fracture is significant in case of the highly oriented state
  - For a correct failure prediction a good representation of the state of deformation is essential

Content

MATFEM

- Method
- Non-reinforced polymers
- Short fiber reinforced polymers
- Summary and outlook

Summary and outlook

MATFEM

- For a correct failure prediction a good representation of the state of deformation is essential
- If plastic compressibility is taken into account in the elasto-viscoplastic material model than plastic compressibility must be taken into account for the characterization of failure behaviour as well
- In case of short fiber reinforced polymers the anisotropy of fracture is significant in case of the highly oriented state
- The degree of fiber orientation can be taken into account by defining different material states