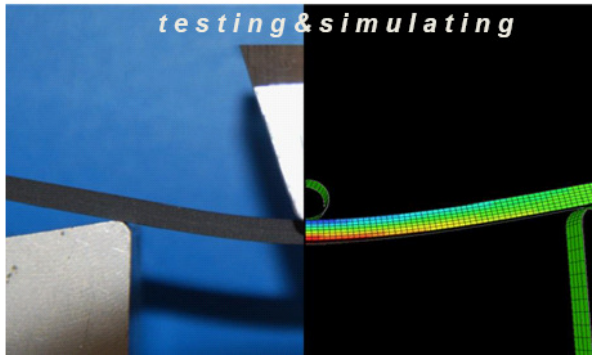
Technologietag

Kunststoffe

Prüfen und Simulieren

11.- 12. März 2010

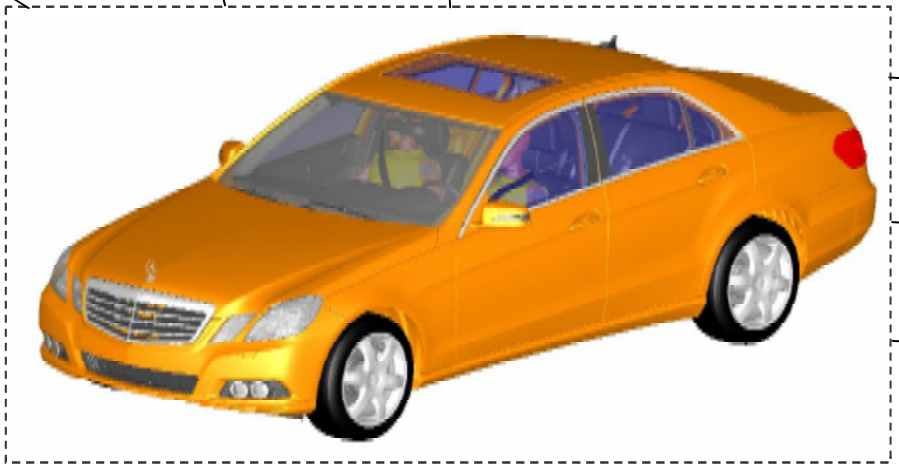


Neuerungen und einige Gedanken zu Materialmodellen für Kunststoffe in LS-DYNA

Dr. André Haufe

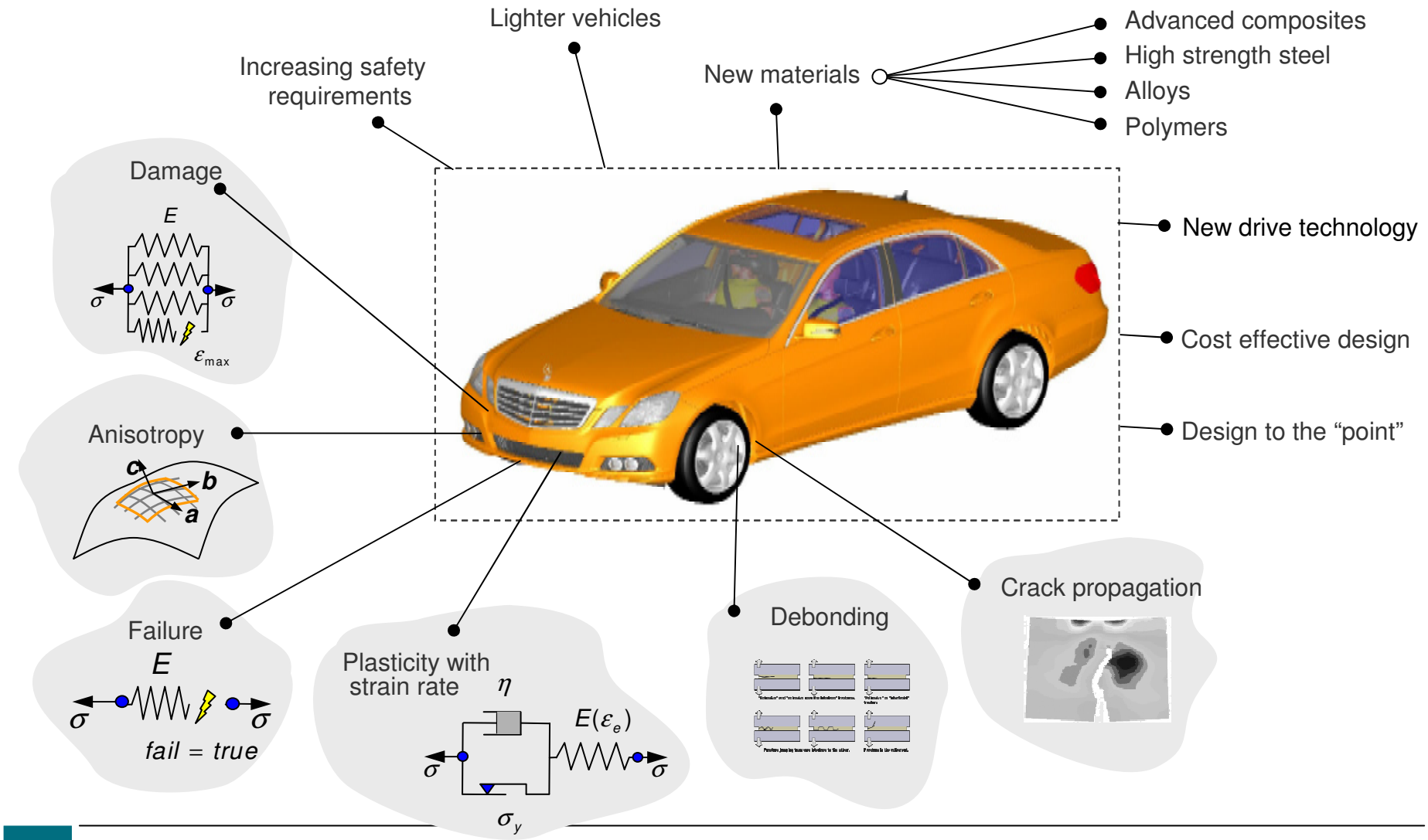
DYNA MORE

Introduction



- Increasing safety requirements
- Lighter vehicles
- New materials
  - Advanced composites
  - High strength steel
  - Alloys
  - Polymers
- New drive technology
- Cost effective design
- Design to the “point”

Introduction



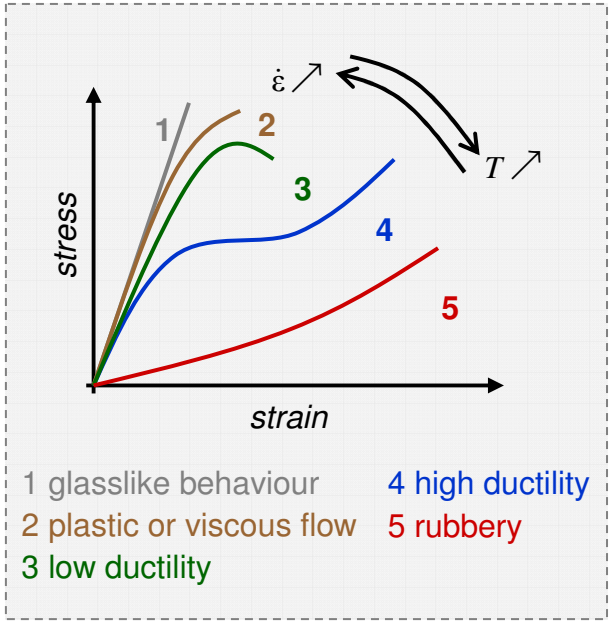
Introduction: Summary!

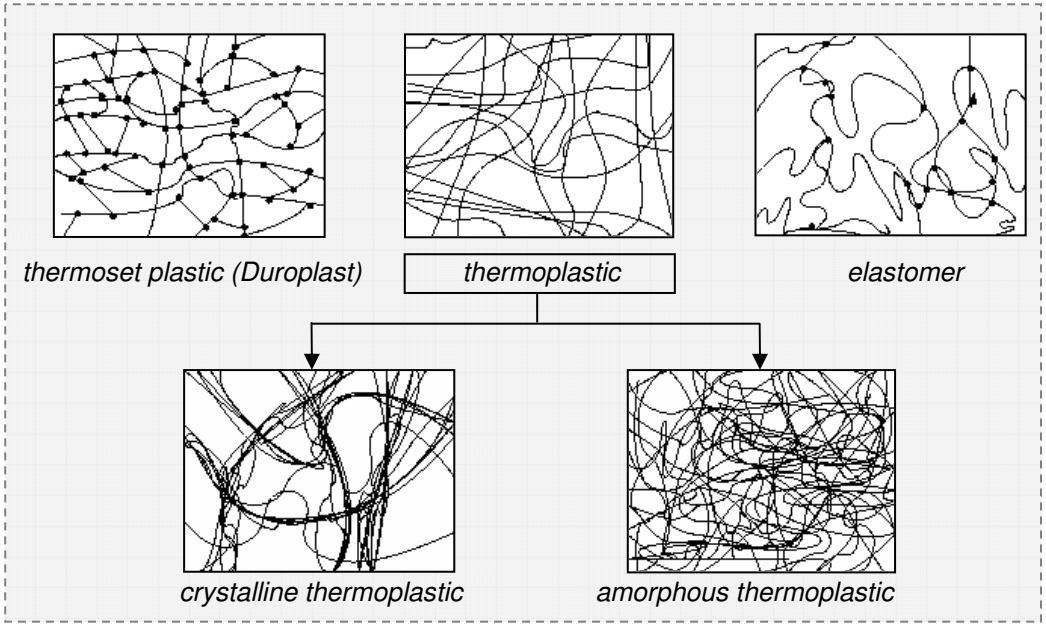
“New” Materials
Polymers
Alloys
High strength steel
Advanced composites

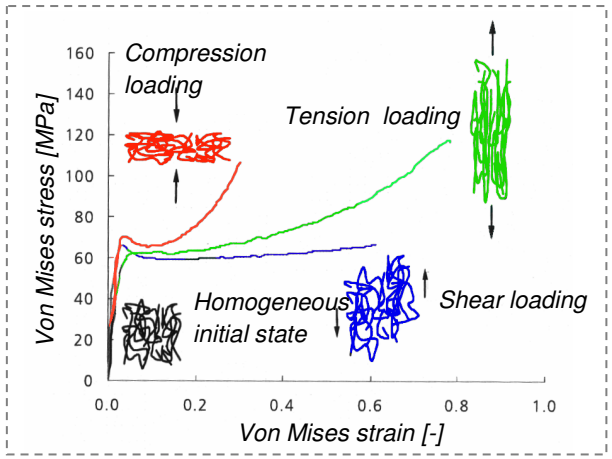
“New” Features
Anisotropy
Damage
Failure
Debonding

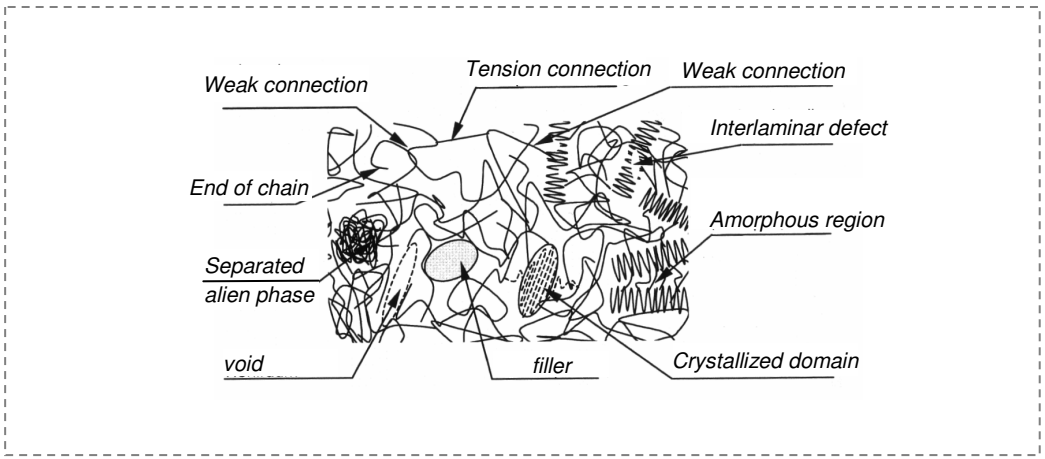
Constitutive Models for Polymers

Characteristic Structure of Plastics









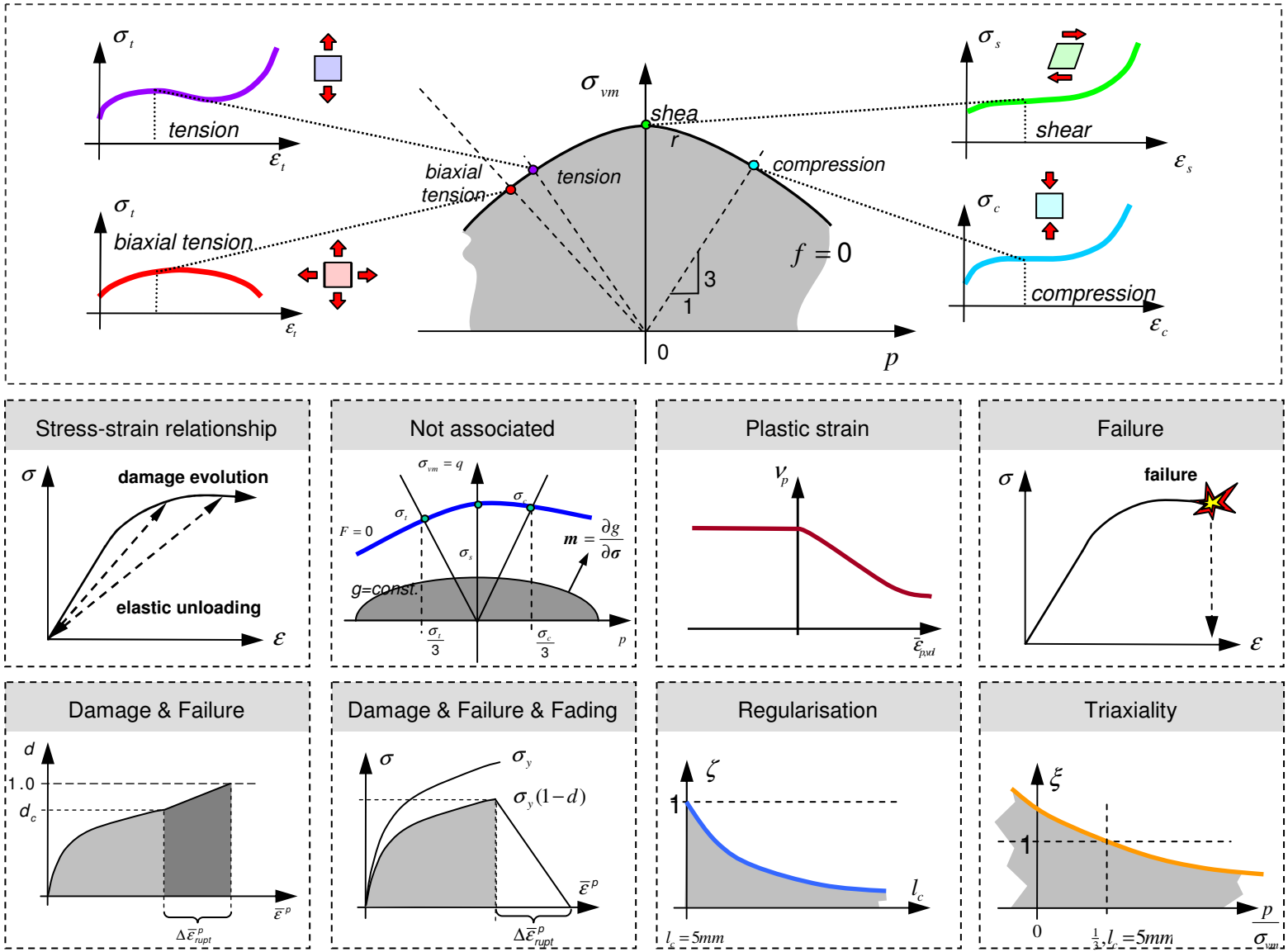
[Junginger 2002]

Some material laws for visco-plasticity in LS-DYNA

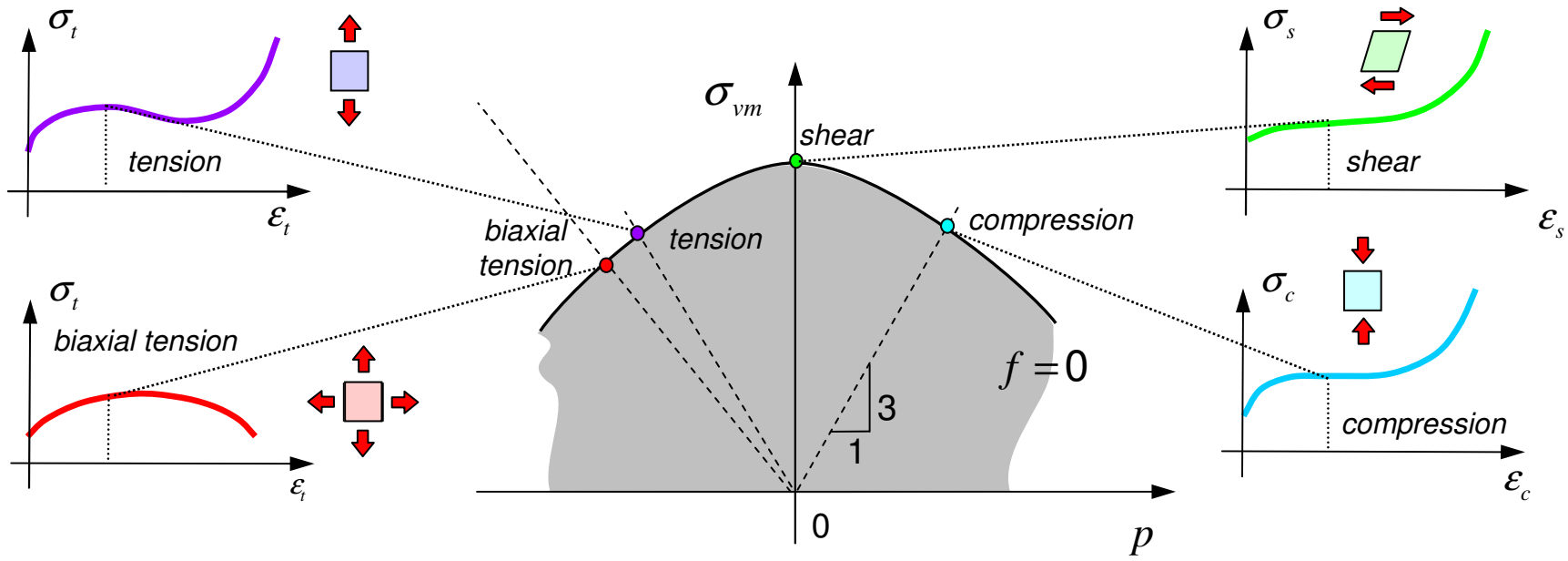
No.	Keyword	Formulation	Input
24,123	MAT_PIECEWISE_LINEAR_PLASTICITY	isotropic, el-pl, von Mises strain rate	LC table
81, 82	MAT_PLASTICITY_WITH_DAMAGE	isotropic, el-pl damage strain rate	LC LC table
89	MAT_PLASTICITY_POLYMER	isotropic, el-pl strain rate	LC parameter
141	MAT_STRAIN_RATE_SENSITIVE_ POLYMER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

MAT_SAMP-1

MAT_SAMP-1: Overview

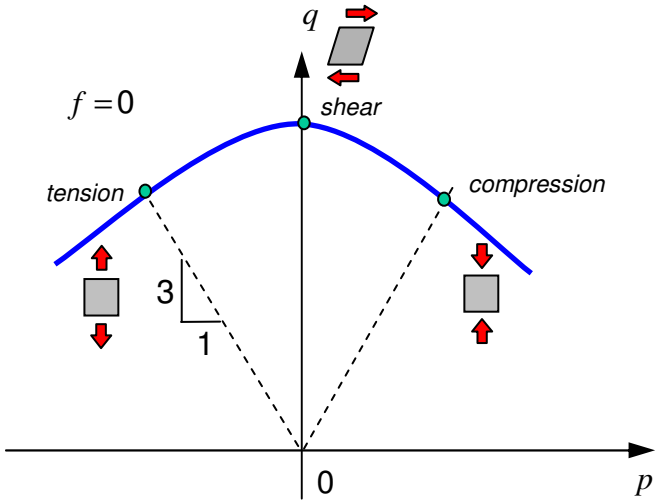


MAT_SAMP-1: Yield surface



It is clear, that polymers exhibit a strong strain rate sensitive behavior, hence this curves need to be determined a different load velocities!

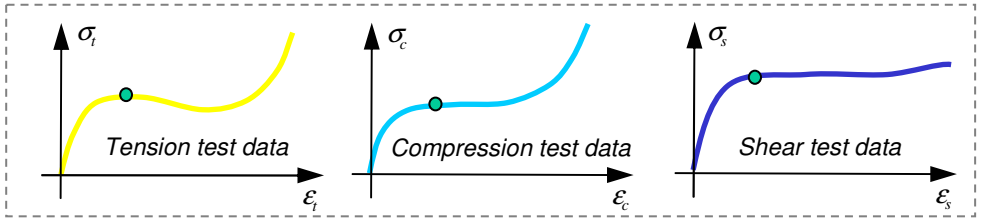
MAT_SAMP-1: Yield surface input



Yield surface:

$$f(p, \sigma_{vm}, \bar{\varepsilon}^{pl}) = \sigma_{vm}^2 - A_0 - A_1 p - A_2 p^2 \leq 0$$

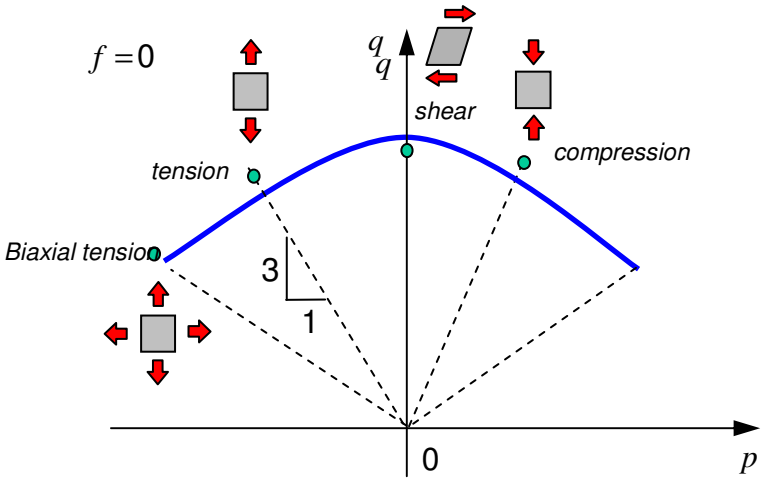
To achieve a fast and easy calibration process, test results from tension, compression and shear tests can be fed directly into SAMP-1 via table definitions:



Therefore the yield surface coefficients $A_{0,1,2}$ are calculated directly from stresses gained from a table lookup.

$$A_0 = 3\sigma_s^2 \qquad A_1 = 9(\sigma_s^2 \frac{\sigma_c - \sigma_t}{\sigma_c \sigma_t}) \qquad A_2 = 9(\frac{\sigma_t \sigma_c - 3\sigma_s^2}{\sigma_t \sigma_c})$$

MAT_SAMP-1: Yield surface input



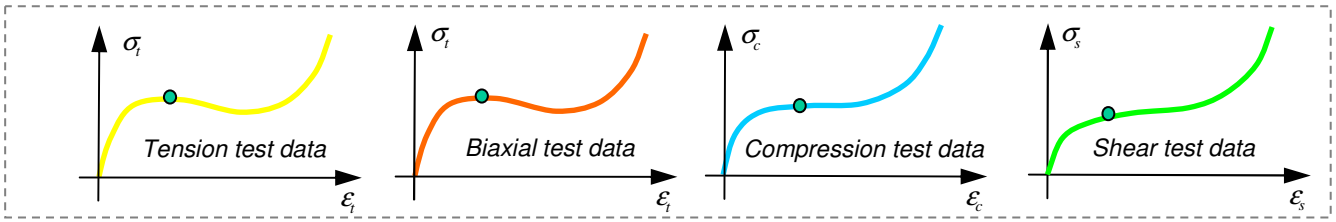
Yield surface:

$$f(p, \sigma_{vm}, \bar{\varepsilon}^{pl}) = \sigma_{vm}^2 - A_0 - A_1 p - A_2 p^2 \leq 0$$

Plastic potential (optional):

$$g = \sqrt{\sigma_{vm}^2 - \alpha p^2}$$

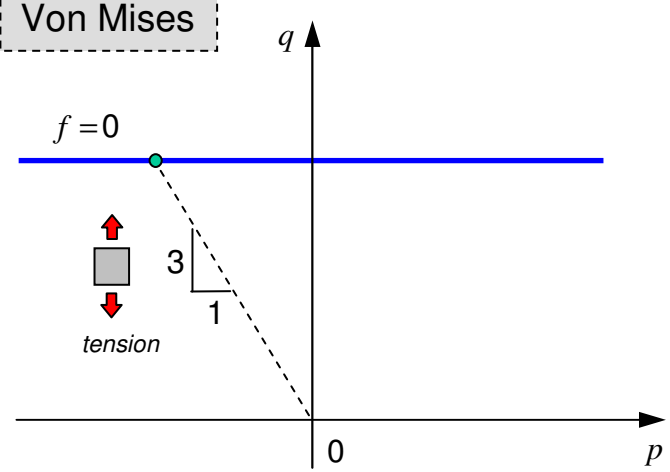
To achieve a fast and easy calibration process, test results from tension, compression, shear and biaxial tests can be fed directly into SAMP-1 via table definitions:

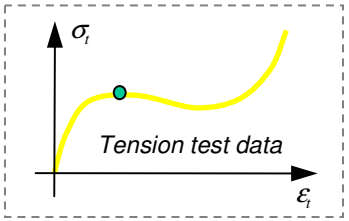


In this case the yield surface coefficients $A_{0,1,2}$ are calculated each time step by a least squares approach fitting the yield stress values obtained by a table-lookup

MAT_SAMP-1: Yield surface input

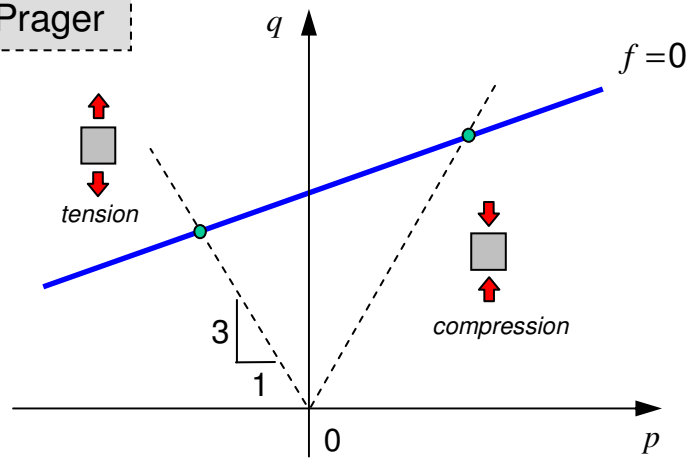
Von Mises

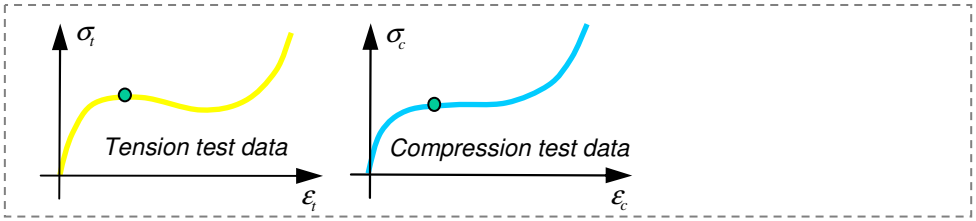




$$\upsilon_p \leq 0.5$$

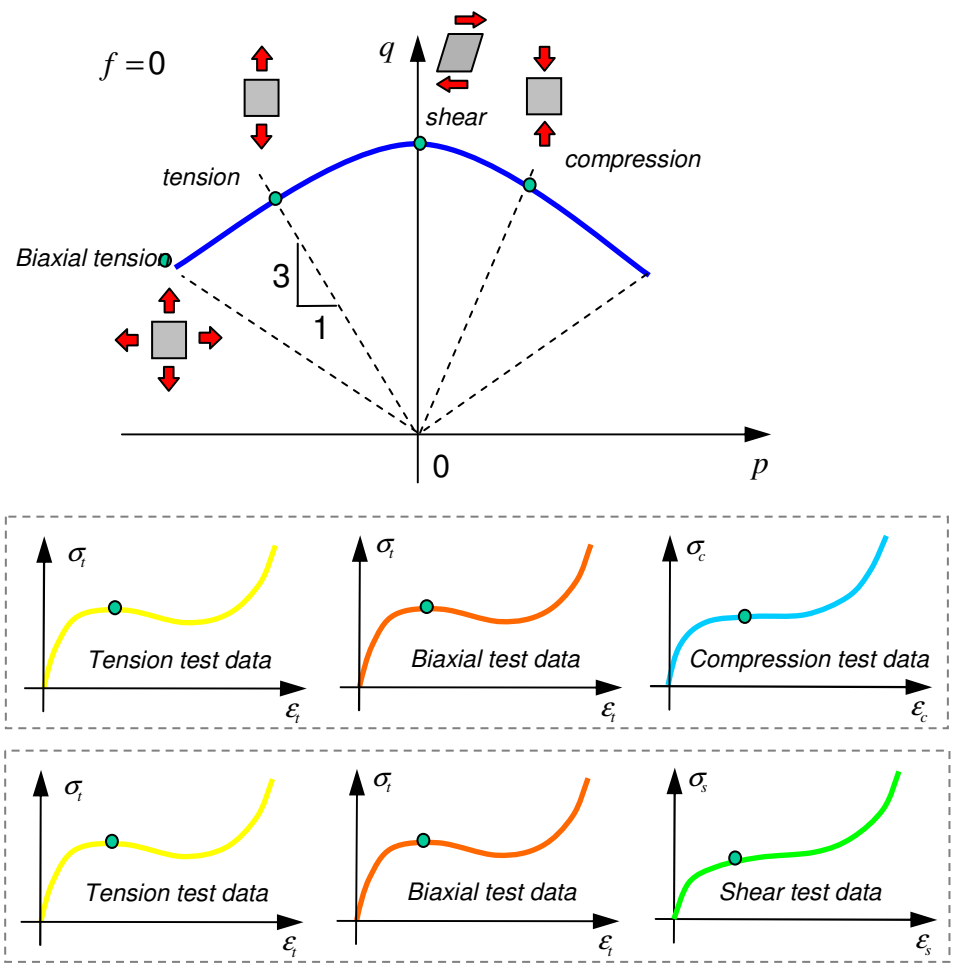
Drucker-Prager

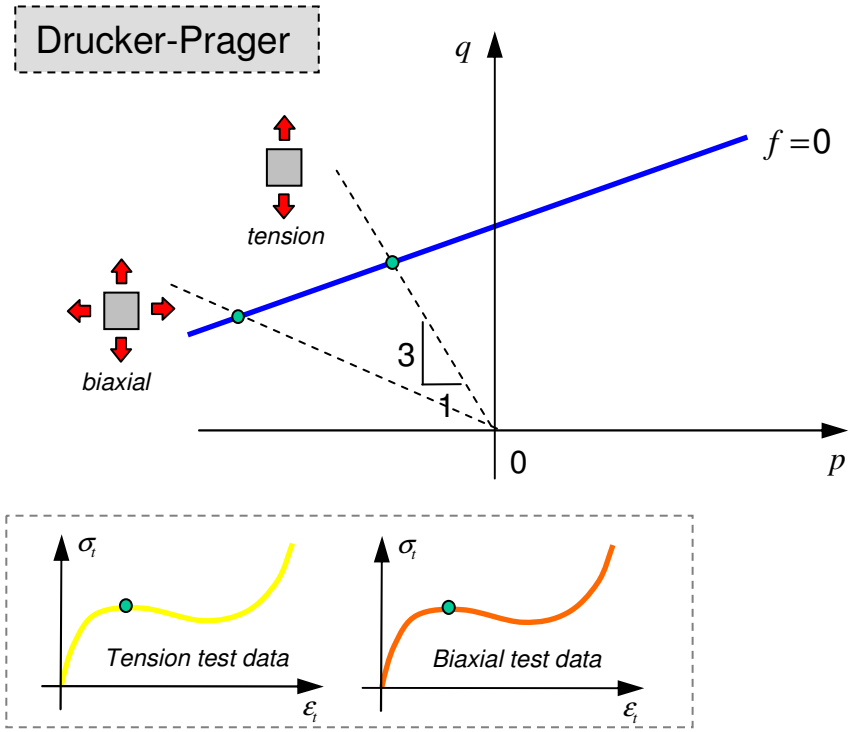




alternatively

MAT_SAMP-1: Yield surface input



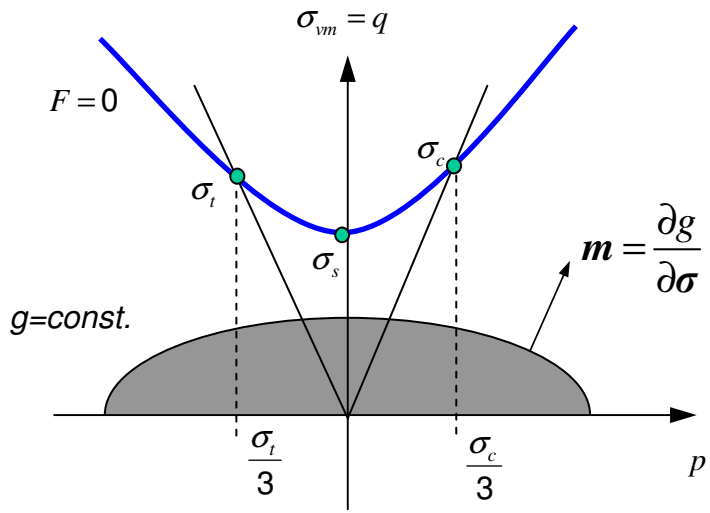


MAT_SAMP-1: Plastic flow definition

$$\dot{\boldsymbol{\varepsilon}}_{\mathbf{p}} = \dot{\lambda}\frac{\partial g}{\partial \boldsymbol{\sigma}}$$

The plastic potential is defined as:

$$g = \sqrt{q^2 + \alpha p^2} \quad \Leftarrow \text{ non-associated}$$

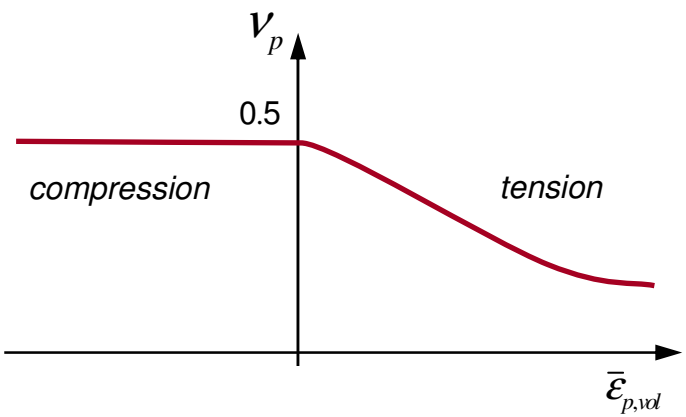


Flow parameter correlates to plastic Poisson's ratio:

$$\alpha \propto \upsilon_p = \frac{9-2\alpha}{18+2\alpha} \leq 0.5$$

Here α is the angle between hydrostatic axis and plastic potential in $p-\sigma_{vM}$ space!

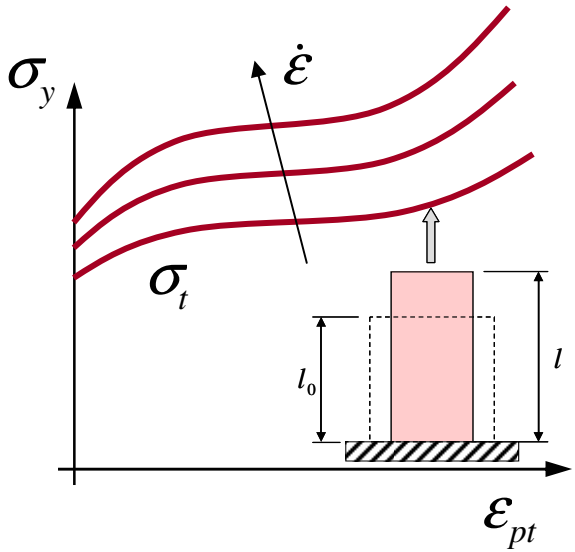
The plastic Poisson's ratio may be given as a curve as function of the equivalent volumetric strain.



MAT_SAMP-1: Tabulated strain rate (Perzyna type)

Elasto-plastic consistency condition

$$f\left(\lambda,\dot{\lambda}=0\right)=\sigma_{vm}^{2}-A_0-A_1p-A_2p^2\leq 0$$



Visco-plastic constitutive law:

$$\dot{\lambda}=\frac{\langle\Phi(f)\rangle}{2\eta}$$

$$f\left(\lambda,\dot{\lambda}\right)-\Phi^{-1}\left(2\eta\dot{\lambda}\right)=0$$

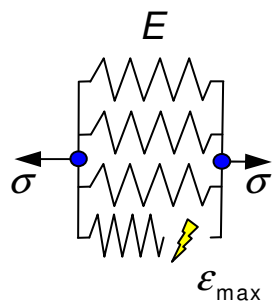
$$\Phi^{-1}\left(2\eta\dot{\lambda}\right)=f\left(\lambda,\dot{\lambda}\right)-f(\lambda,0)$$

$$=A_0\left(\lambda,\dot{\lambda}\right)+A_1\left(\lambda,\dot{\lambda}\right)p+A_2\left(\lambda,\dot{\lambda}\right)p^2-A_0(\lambda,0)-A_1(\lambda,0)p-A_2(\lambda,0)p^2$$

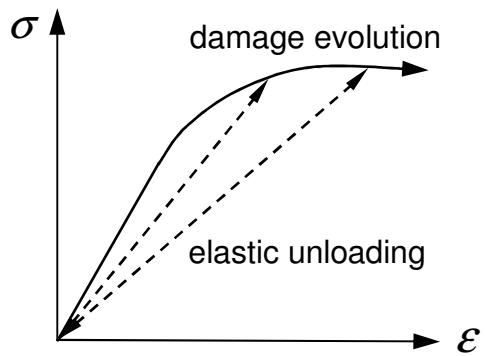
MAT_SAMP-1: Damage formulation

- Damage allows fitting of the unloading path, cyclic loading paths and load paths with strain softening. All of this are major effects for polymers.
- A damage variable (d or f) quantifies the part of the material cross section that no longer transmits forces due to cracks or pores.
- Isotropic damage is the simplest approach to this.
- Elastic damage affects material stiffness: Only deterioration of elastic parameters.
- Ductile damage affects material strength (deterioration of yield stress) or both material strength and material stiffness!

Rheological model



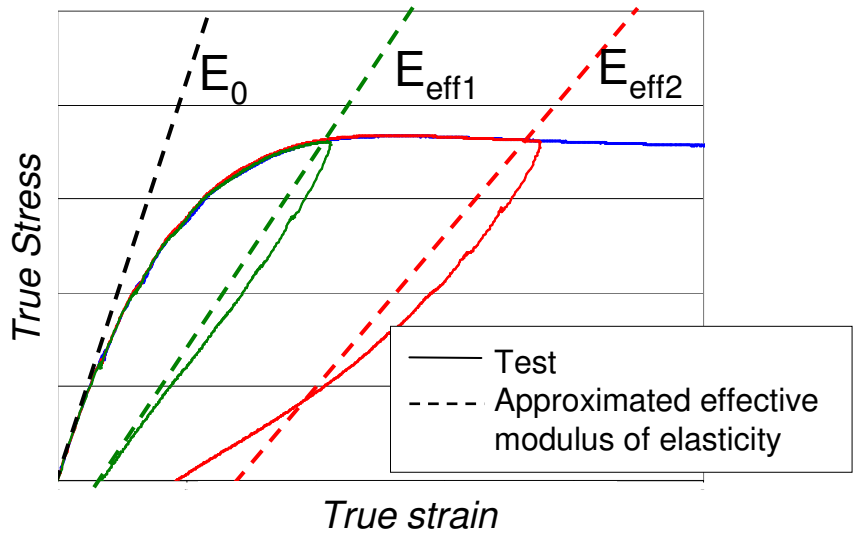
Stress-strain relationship



MAT_SAMP-1: Damage behavior

Damaging of the stresses by scalar curve definition $d(\bar{\varepsilon}^{pl}) = [0,1[$ (plastic damage)

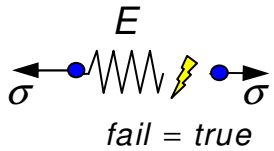
$$\boldsymbol{\sigma}_{eff} = \boldsymbol{\sigma}_{pl} \cdot \left(1 - d(\bar{\varepsilon}^{pl})\right)$$



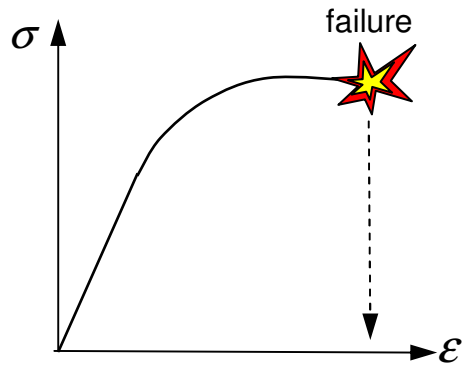
MAT_SAMP-1: Failure

- Mesh: should be fine enough to capture localization arising before failure!
- Consideration of deformation history: stress/strain path during manufacturing may influence failure during crash event.
- Physical material data are needed up to failure, true hardening data beyond necking strain can only be obtained through reverse engineering
- Regularization: each softening problem is inherently mesh dependent, no material and/or failure law is meaningful unless it is regularized!
- Damage and failure law: Verification and validation process is needed to calibrate a damage and/or failure law to physical experiments.

Rheological model

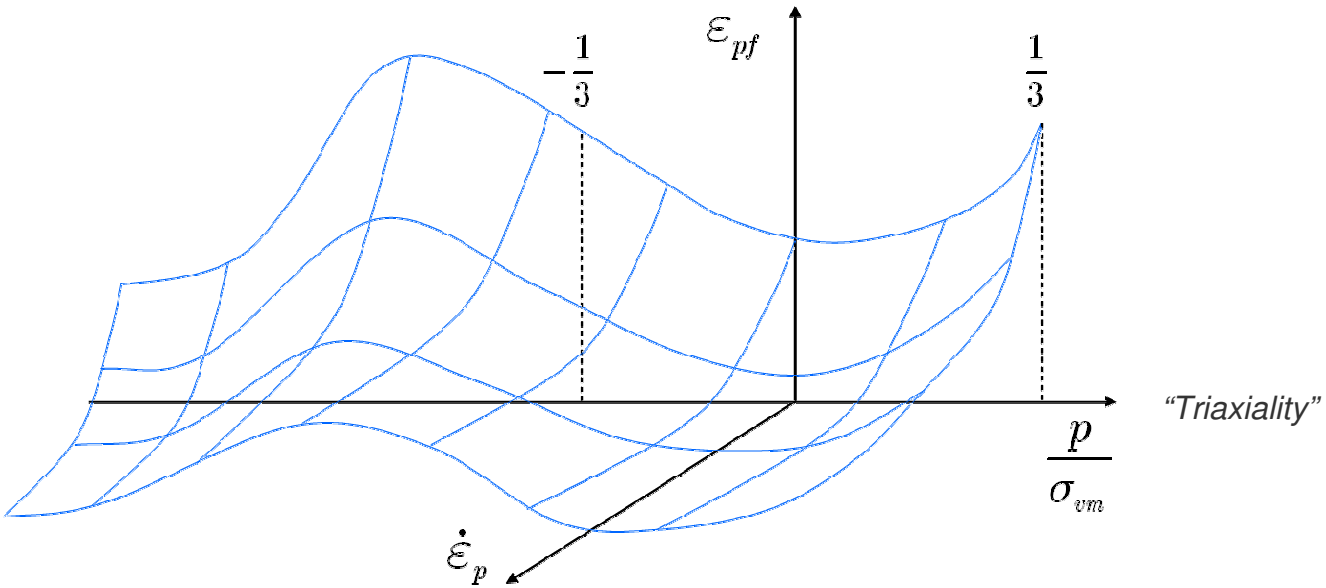


Stress-strain relationship



MAT_SAMP-1: Failure definition

- All dependencies (strain rate and state of stress) are tabulated
- In a mathematical sense, a tabulated curve is the most general form of a continuous function in the Euclidian manifold – so why settle for less?
- The SAMP failure criterion can be considered a tabulated generalization of the Johnson-Cook criterion



MAT_SAMP-1: Damage and fading definition

- Failure onset defined by the parameter $\Delta\bar{\varepsilon}^{p}_{rupt}$
- Further fading of the element defined by d_c
- Strain rate dependent failure by an optional input curve

$$d_c = d_c(\dot{\varepsilon}^p)$$

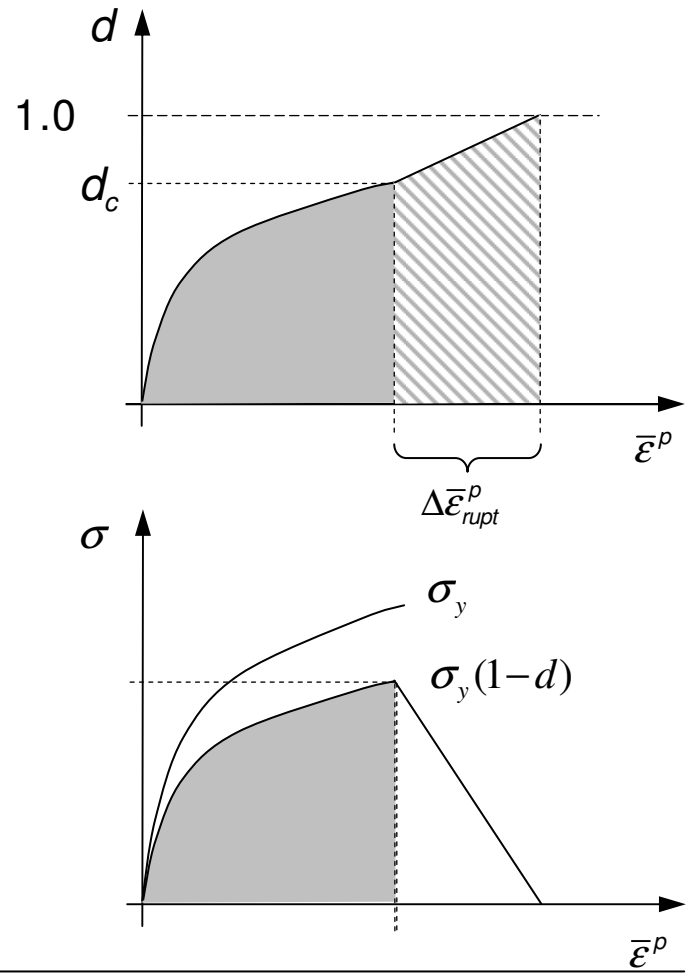
- Regularization by an input optional curve

$$\zeta = \zeta(l_c)$$

- Triaxiality dependent failure by an optional input curve

$$\xi = \xi\left(\frac{p}{\sigma_{vm}}\right)$$

- Finally: $d_c = d_c(\dot{\varepsilon}_p)\cdot\xi\left(\frac{p}{\sigma_{vm}}\right)\cdot\zeta(l_c)$



MAT_SAMP-1: Regularization

- Failure onset defined by the parameter $d_c \quad \Delta\bar{\varepsilon}^p_{rupt}$
- Further fading of the element defined by
- Strain rate dependent failure by an optional input curve

$$d_c = d_c(\dot{\varepsilon}^p)$$

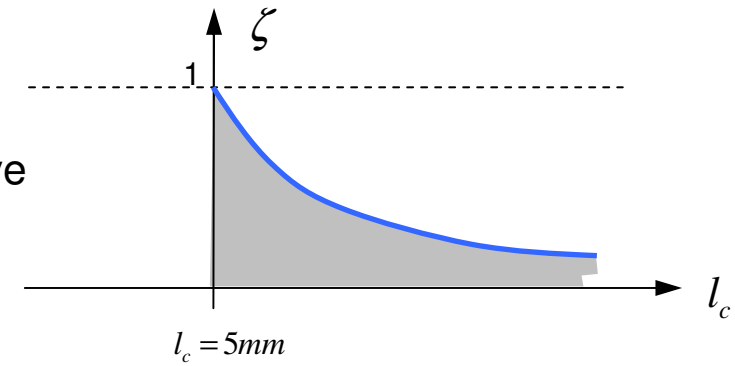
- Regularization by an input optional curve

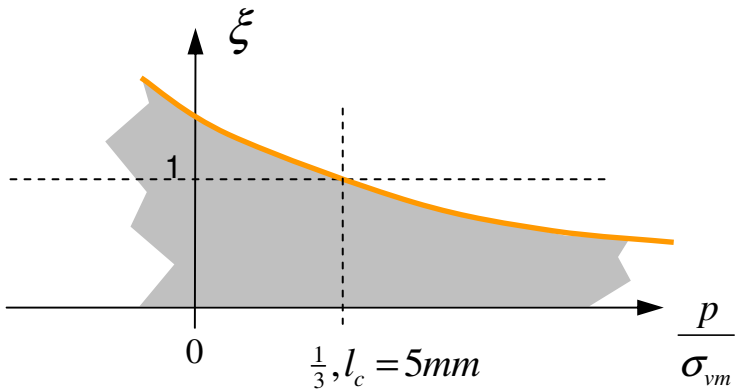
$$\zeta = \zeta(l_c)$$

- Triaxiality dependent failure by an optional input curve

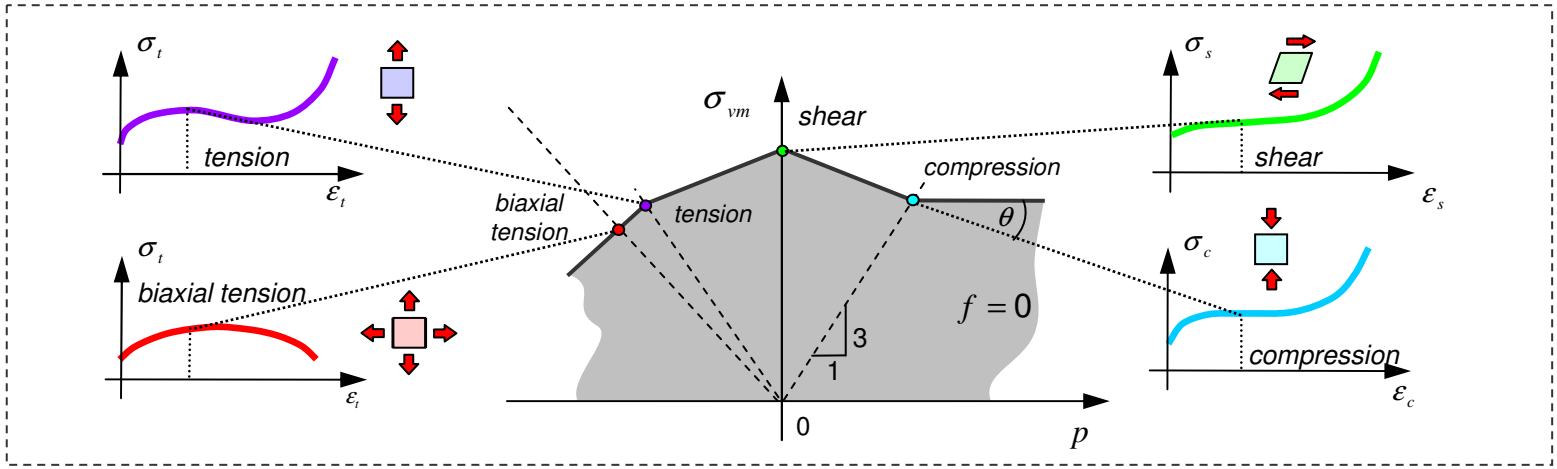
$$\xi = \xi\left(\frac{p}{\sigma_{vm}}\right)$$

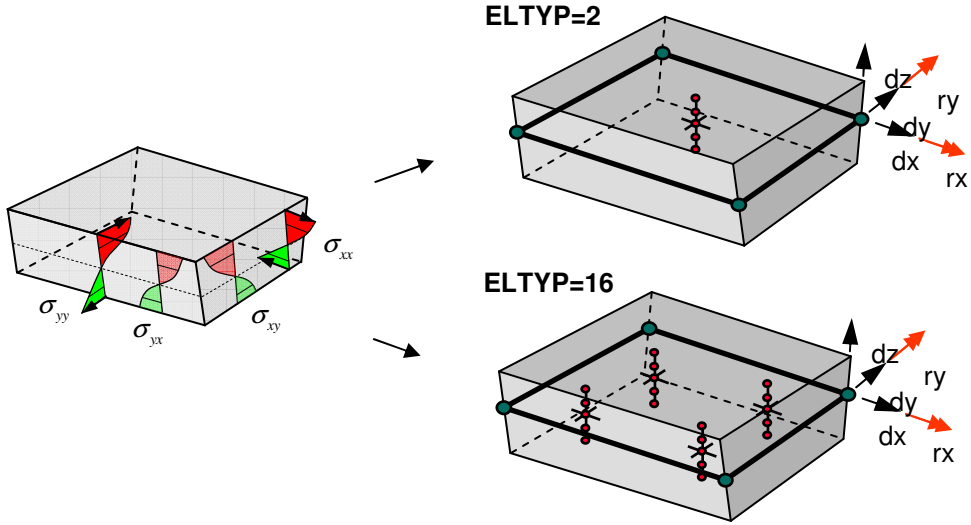
- Finally: $d_c = d_c(\dot{\varepsilon}_p) \cdot \underbrace{\xi\left(\frac{p}{\sigma_{vm}}\right)}_{\frac{p}{\sigma_{vm}} = \frac{1}{3},\ l_c = 5mm} \cdot \zeta(l_c)$

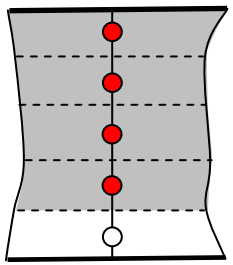




MAT_SAMP-1: New features in R5!







20% Failure

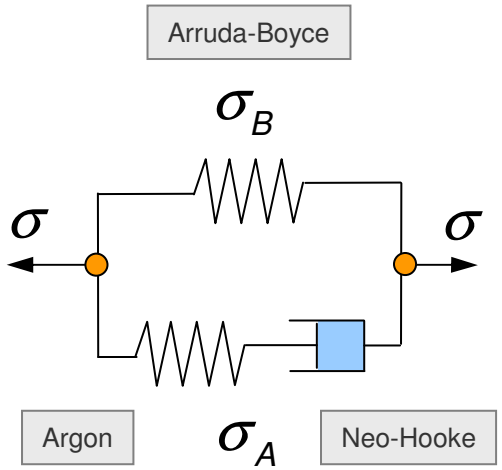
Element deletion is defined via a section percentage value of integration points that is flagged as failed

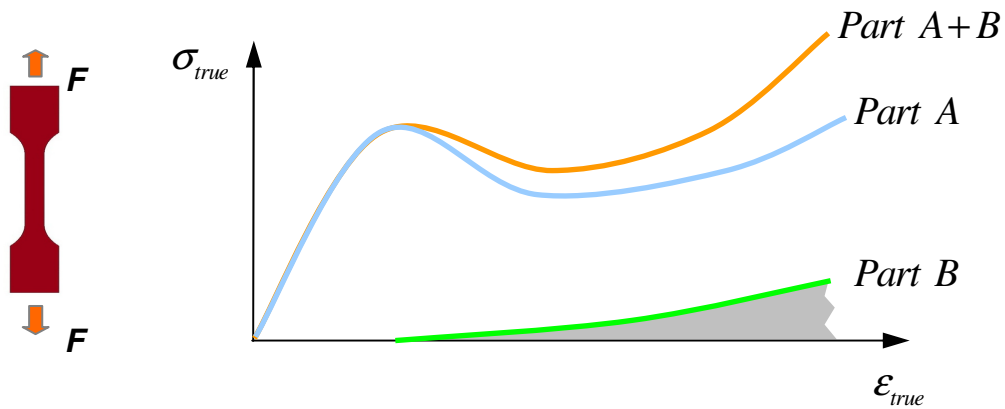
MAT_POLYMER

Polymer material model 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

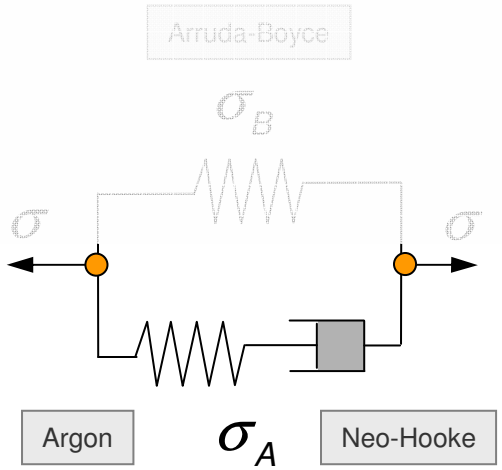




Deformation tensor: $\mathbf{F} = \mathbf{F}_A = \mathbf{F}_B$ corresponding final stresses $\boldsymbol{\sigma} = \boldsymbol{\sigma}_A + \boldsymbol{\sigma}_B$

Polymer material model 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.): $\mathbf{L}_A^e = \mathbf{D}_A^e + \mathbf{W}_A^e = \dot{\mathbf{F}}_A^e \cdot (\mathbf{F}_A^e)^{-1}$

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

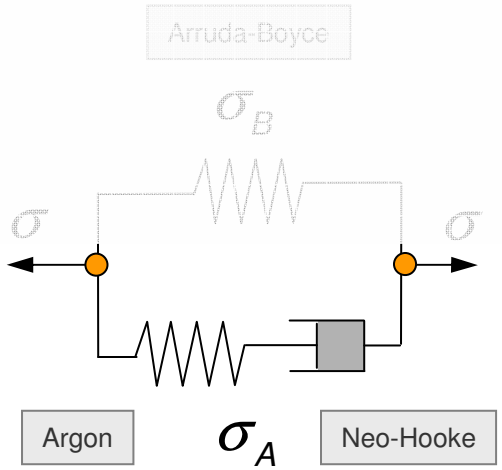
elastic

Heo-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)

Polymer material model 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.): $\mathbf{L}_A^e = \mathbf{D}_A^e + \mathbf{W}_A^e = \dot{\mathbf{F}}_A^e \cdot (\mathbf{F}_A^e)^{-1}$

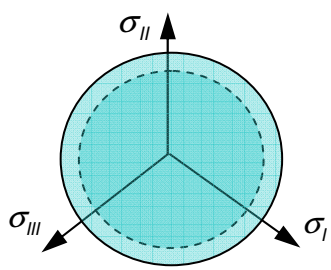
$$\mathbf{L}_A^p = \mathbf{D}_A^p + \mathbf{W}_A^p = \mathbf{F}_A^e \cdot \dot{\mathbf{F}}_A^p \cdot (\mathbf{F}_A^p)^{-1} \cdot (\mathbf{F}_A^e)^{-1} = \mathbf{F}_A^e \cdot \bar{\mathbf{L}}_A^p \cdot (\mathbf{F}_A^e)^{-1}$$

plastic

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

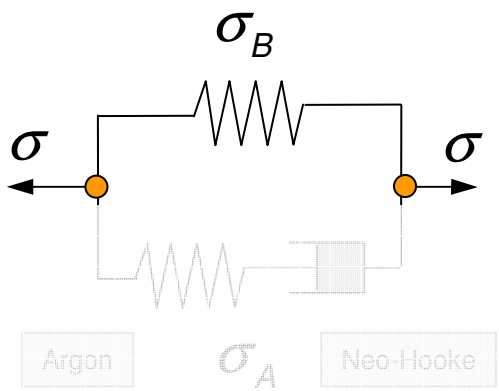
Plastic multiplier, thermal activated where shear resistance ***s*** is dependent on stress triaxiality.



Polymer material model by Boyce et al.

Arruda-Boyce

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



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

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

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

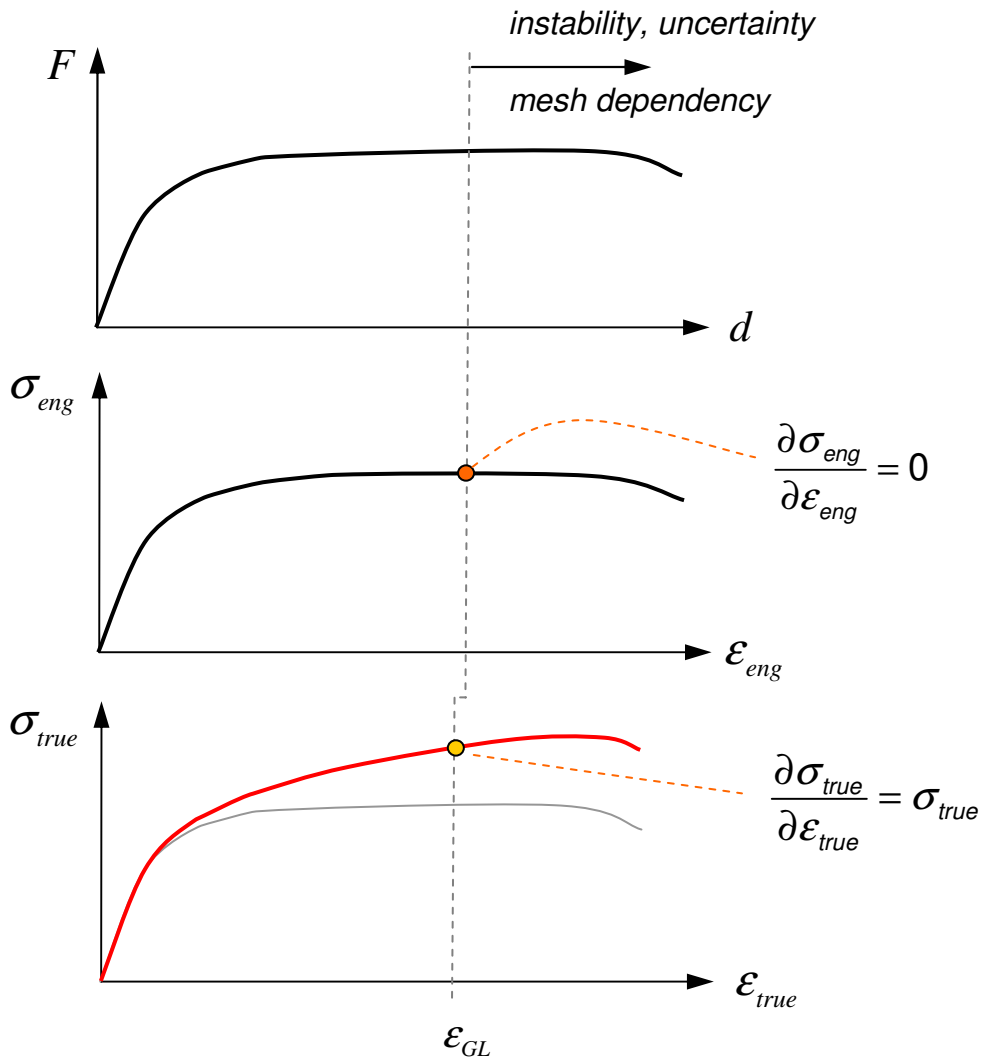
with $$\bar{\lambda}_F = \left[\frac{1}{3}\operatorname{tr}\left(\mathbf{F}_B^F\left\{\mathbf{F}_B^F\right\}^T\right)\right]^{\frac{1}{2}}$$

State of the art in flow curve generation

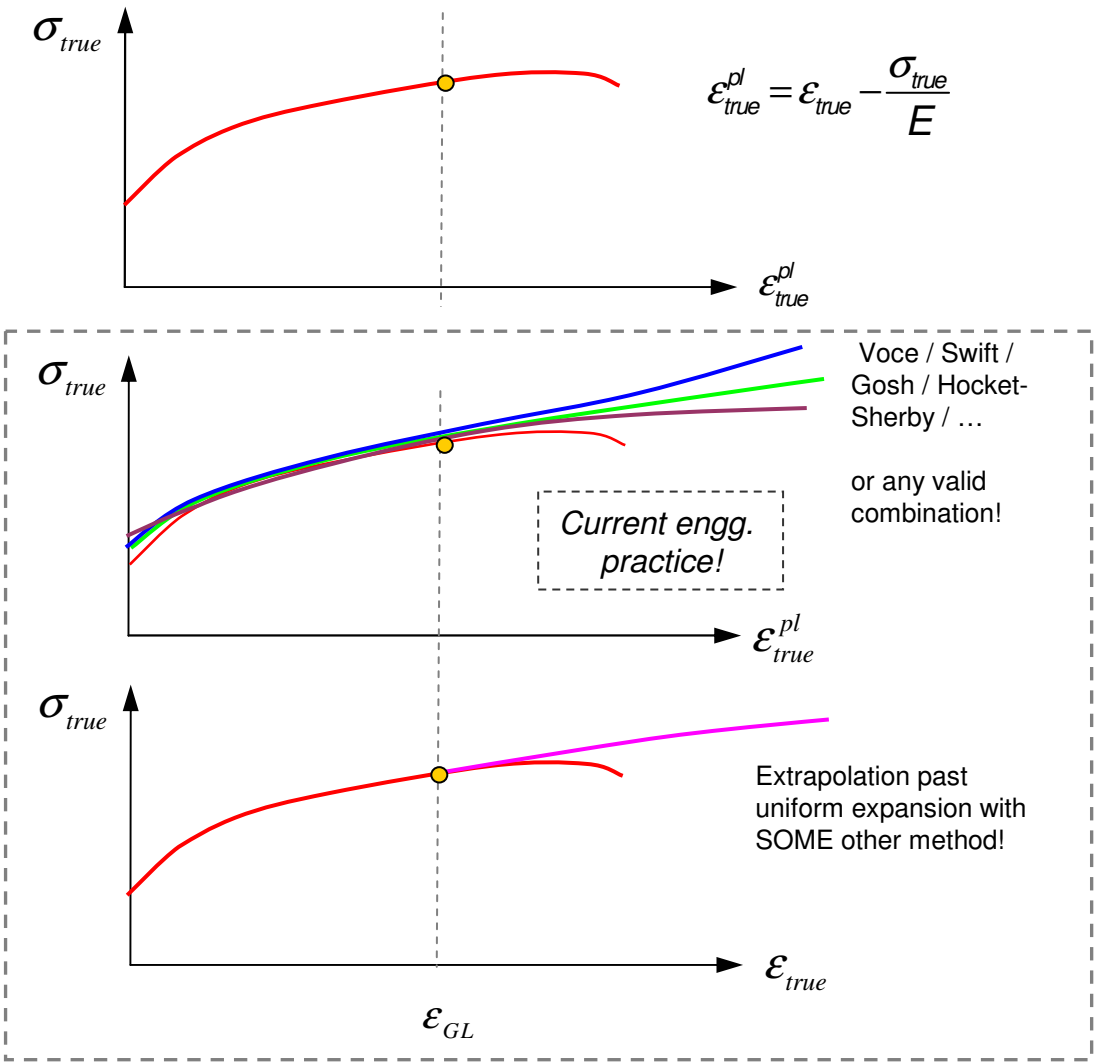
Flow curve generation

$$\sigma_{true} = \frac{F}{A} = \frac{F}{A_0}\frac{A_0}{A} = \frac{F}{A_0}\frac{L}{L_0} = \sigma_{eng}\left(1-\varepsilon_{eng}\right)$$

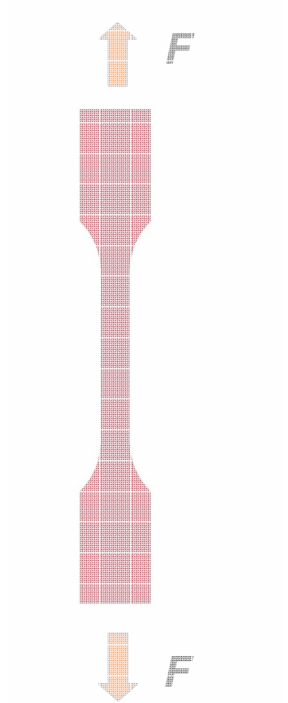
$$\varepsilon_{true} = \ln\frac{L}{L_0} = -\ln\left(1-\varepsilon_{eng}\right)$$



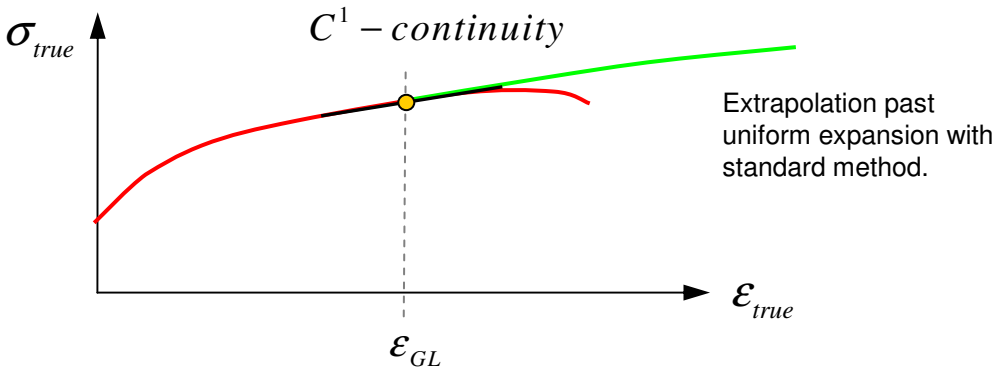
Flow curve extrapolation: Std. equations



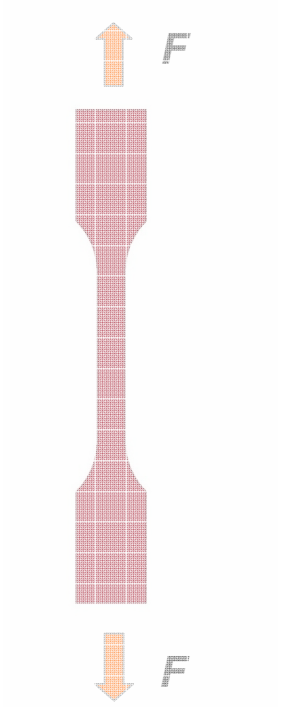
Flow curve extrapolation: Modified approach for std. equations

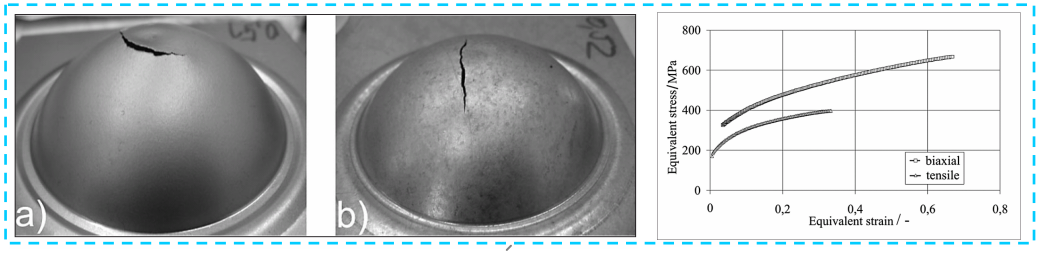


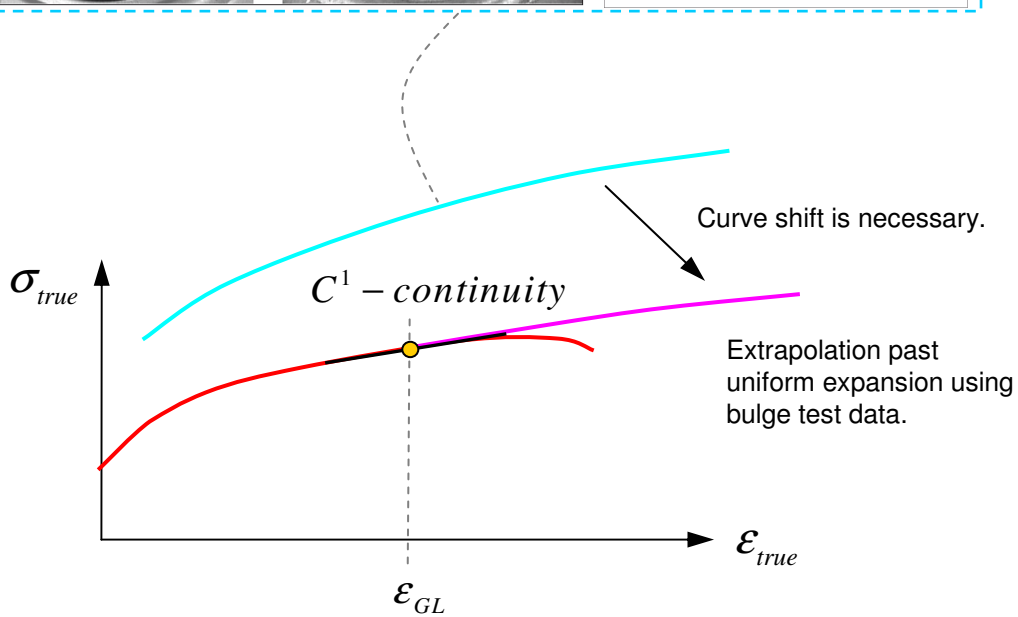
	extrapolation	derivative
Voce	$\sigma_y(\varepsilon_p) = a - b \cdot e^{-c \cdot \varepsilon_p}$	$\sigma_y'(\varepsilon_p) = b \cdot c \cdot \ln \varepsilon_p \cdot e^{-c \cdot \varepsilon_p}$
Hocket-Sherby	$\sigma_y(\varepsilon_p) = a - b \cdot e^{-c \cdot \varepsilon_p^N}$	$\sigma_y'(\varepsilon_p) = b \cdot c \cdot N \cdot e^{-c \cdot \varepsilon_p} \cdot \varepsilon_p^{N-1}$
Gosh	$\sigma_y(\varepsilon_p) = k \cdot (\varepsilon_0 + \varepsilon_p)^N - p$	$\sigma_y'(\varepsilon_p) = k \cdot N \cdot (\varepsilon_0 + \varepsilon_p)^{N-1}$
Swift	$\sigma_y(\varepsilon_p) = k \cdot (\varepsilon_0 + \varepsilon_p)^N$	$\sigma_y'(\varepsilon_p) = k \cdot N \cdot (\varepsilon_0 + \varepsilon_p)^{N-1}$ *No free parameters for Swift!*



Flow curve extrapolation: Bulge test!





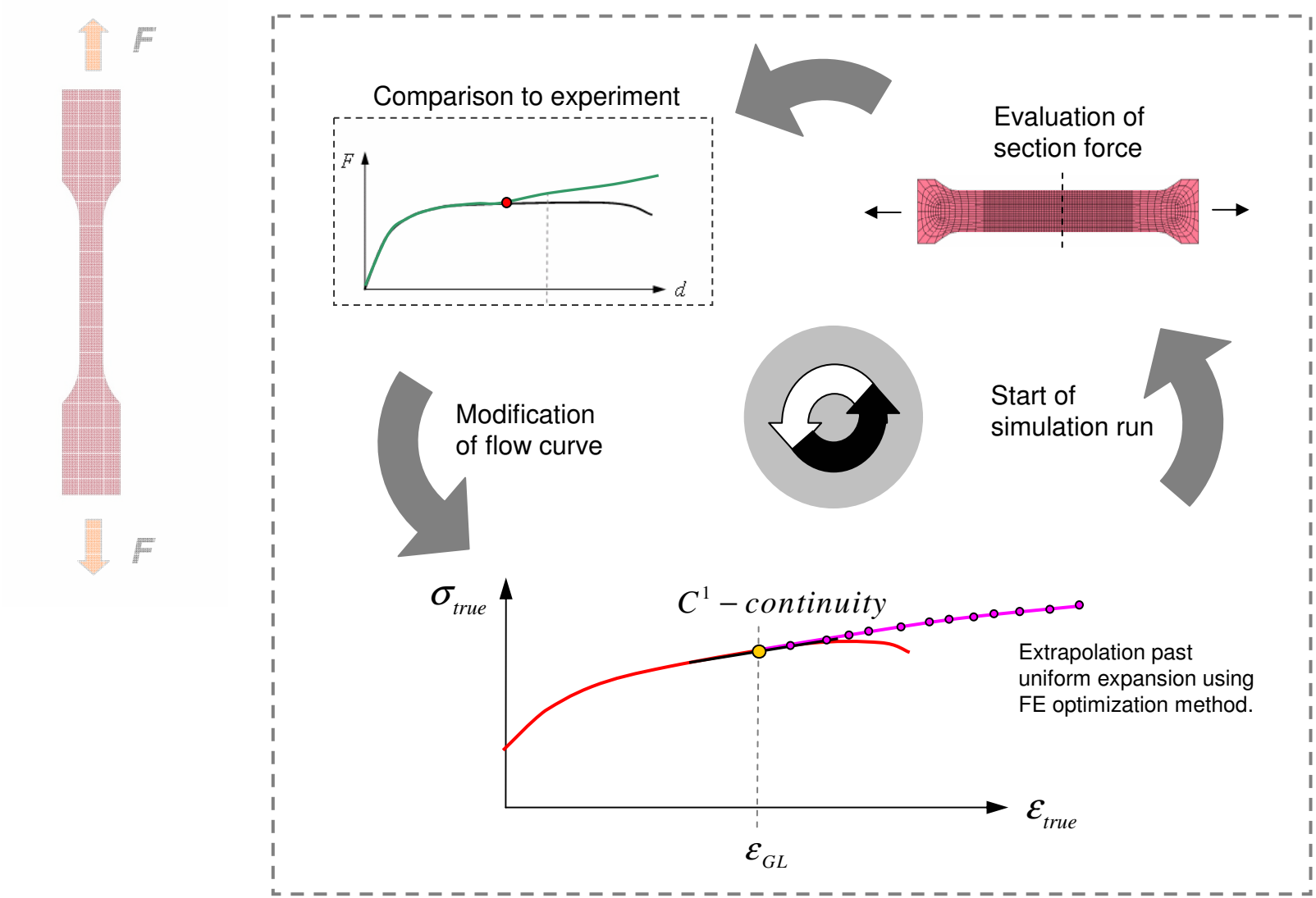


Result from bulge test is to be converted based on energy equivalence to uni-axial stress-strain data by:

$$\sigma_b = \frac{p \cdot \rho}{2 * t}$$

Keep in mind, that non-isotropic flow will influence the deformation and introduces uncertainties.

Flow curve extrapolation: FE piecewise optimization



Flow curve extrapolation: Still an open point ?!

If we assume, that one of the previous methods was successful indeed, we must recognize that the solution is always strongly mesh size dependent if the part is deformed past the point of uniform expansion!

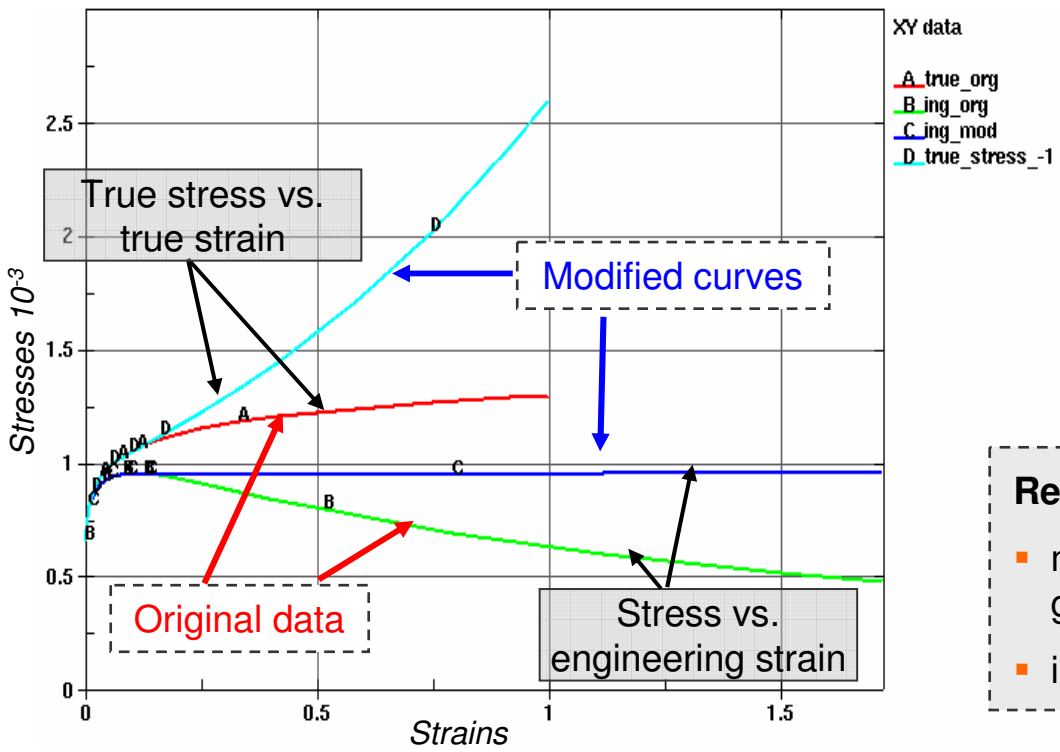
Why is that?

Some thoughts about localization

Localization phenomena

Starting point: Load curve (or table) definition exhibits softening behavior.

Engineering stresses vs. engineering strains show non-positive gradient (green data).
But: True stress vs. true strain gradient is always positive (red data)!



$$\varepsilon_{eng} = \frac{l - l_0}{l_0}$$

$$\varepsilon_{true} = \ln\frac{l}{l_0} = \ln\left(1 + \varepsilon_{eng}\right)$$

$$\sigma_{true} = \frac{F}{A} = \frac{F}{A_0}\frac{A_0}{A} = \frac{F}{A_0}\frac{L}{L_0}$$

$$= \sigma_{eng}\frac{L}{L_0} = \sigma_{eng}\left(1 + \varepsilon_{eng}\right)$$

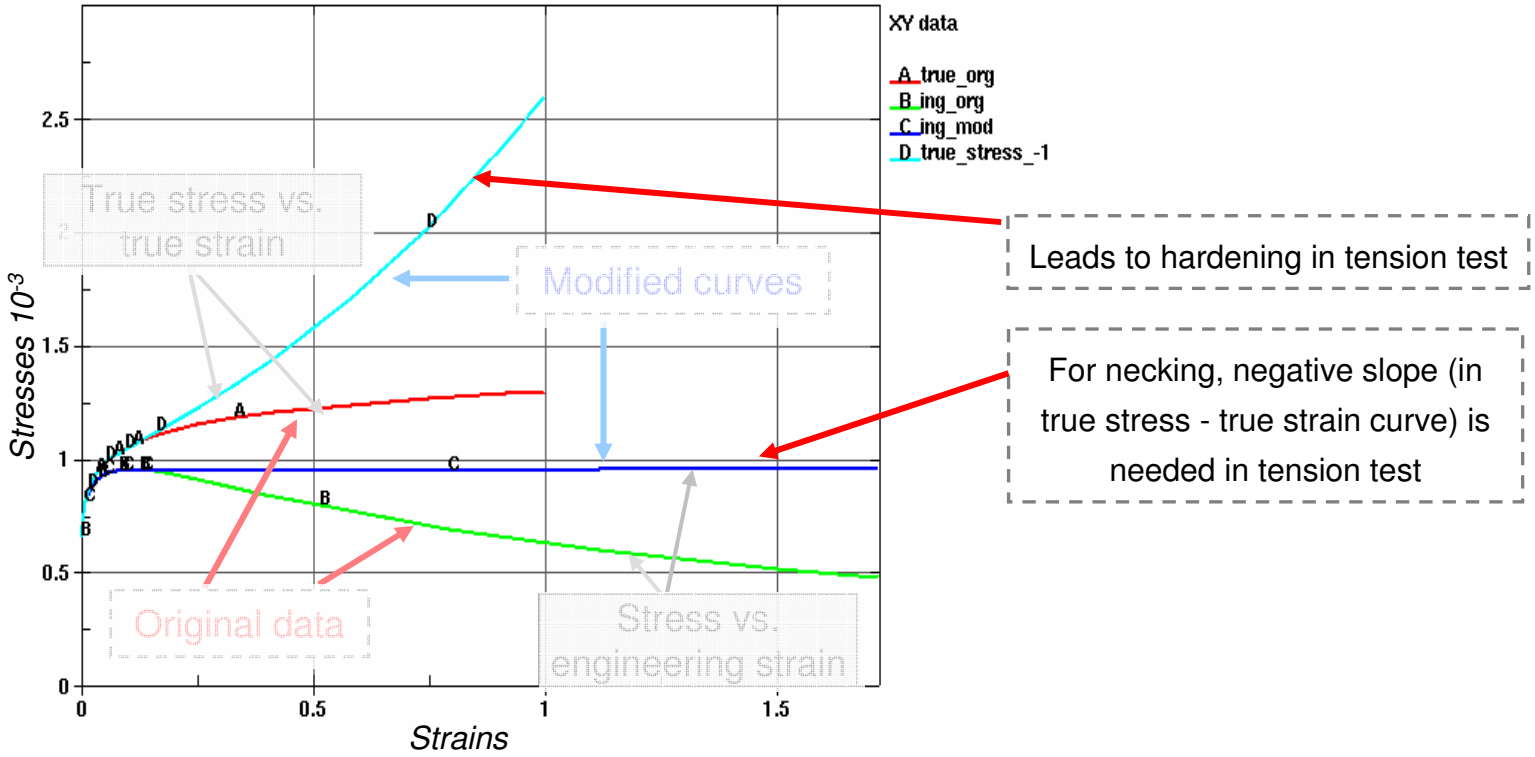
Remedies:

- modify evolution curve (positive gradient) but leads to hardening
- introduce artificial visco-plasticity

Localization phenomena

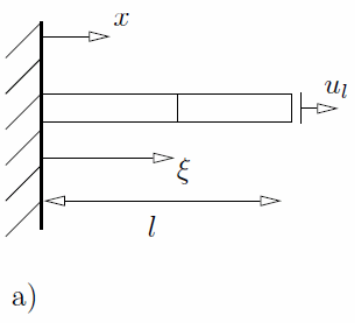
Starting point: Load curve (or table) definition exhibits softening behavior.

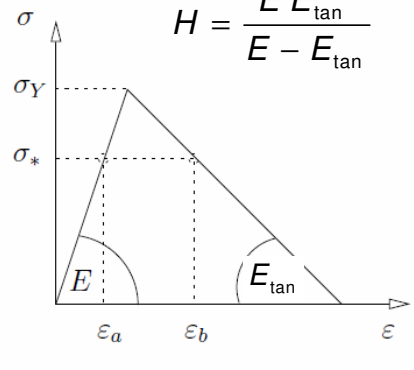
Engineering stresses vs. engineering strains show non-positive gradient (green data).
But: True stress vs. true strain gradient is always positive (red data)!



Why does strain-softening lead to localization?

Example: tension rod





$$H = \frac{E\,E_{tan}}{E - E_{tan}}$$

$$u_l = \int_0^l \varepsilon\,dx = \int_0^l \varepsilon^{el}\,dx + \int_{l-\xi}^l \varepsilon^{pl}\,dx,$$

$$\varepsilon^{el} = \frac{\sigma_*}{E}$$

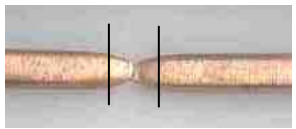
$$\varepsilon^{pl} = \frac{\sigma_Y - \sigma_*}{H}$$

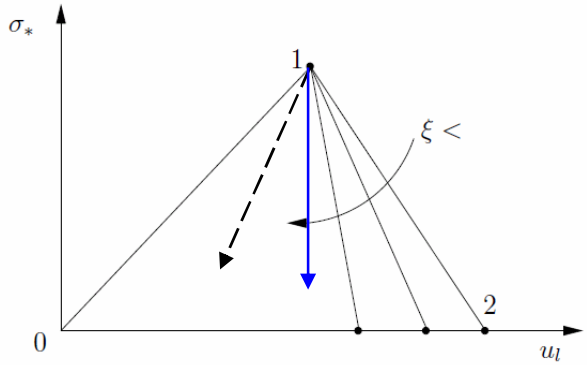
- Non-unique stress state when softening occurs
- Failure displacement/strain depends on width of localization zone
- Vanishing plastic work for $\xi \to 0$
- Stability of deformation process 1-2:

$$\sigma_*(u_l) = \frac{u_l - \xi\frac{\sigma_Y}{H}}{\frac{l}{E} - \frac{\xi}{H}}.$$

$$u_l^{Versagen} = \frac{\sigma_Y \xi}{H}$$

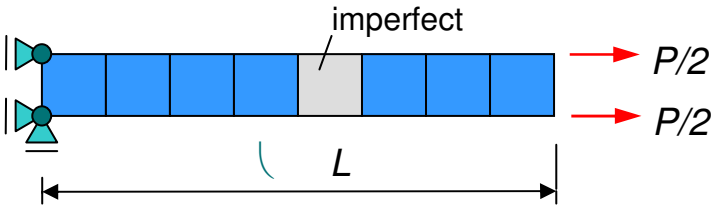
$$W_{ges}^{1-2} = -\frac{\sigma_Y^2 l}{2E} + \frac{\sigma_Y^2 \xi}{2H} \geq 0 \quad \Rightarrow \quad l < \frac{\xi E}{H}$$

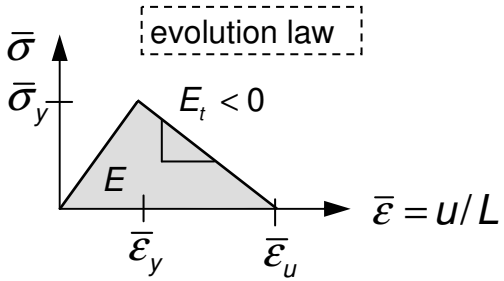




FEM: Mesh dependency and softening material

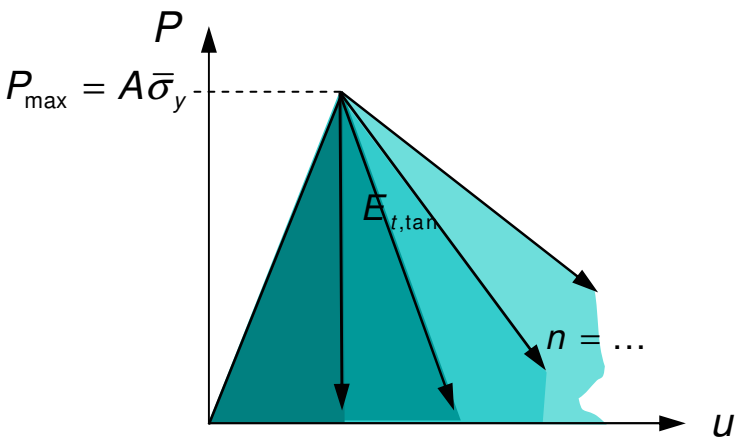
Example: tension rod with *A=1xL/n* discretized with *n* finite elements:





$$H = \frac{E\,E_{\tan}}{E - E_{\tan}}$$

Result of experiment:



- Mean strain in one element:

$$\bar{\varepsilon} = \bar{\varepsilon}^e + \bar{\varepsilon}^{pl} = \frac{\sigma}{E} + \frac{1}{n}\left(\frac{\sigma - \bar{\sigma}_y}{H}\right)$$

- Tangent operator:

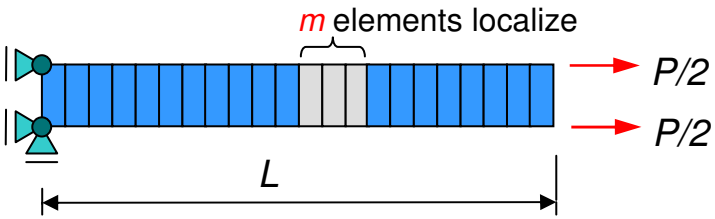
$$E_{t,\tan} = \left[\frac{d\bar{\varepsilon}}{d\sigma}\right]^{-1} = \left[\frac{1}{E} + \frac{1}{n\,H}\right]^{-1} = \frac{E\,H\,n}{n\,H + E}$$

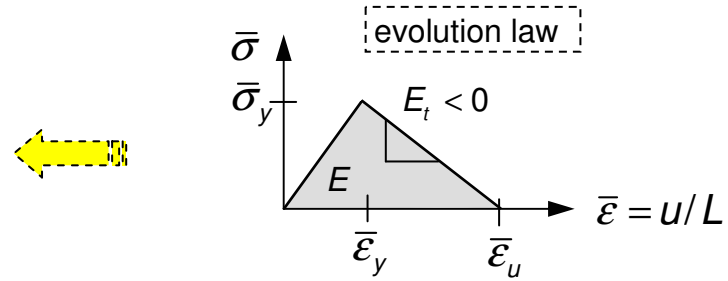
- Fracture energy:

$$G_t = \int \sigma\, du = \frac{1}{2n}\, E\bar{\varepsilon}_y \bar{\varepsilon}_u w_c \qquad w_c = \text{crack width}$$

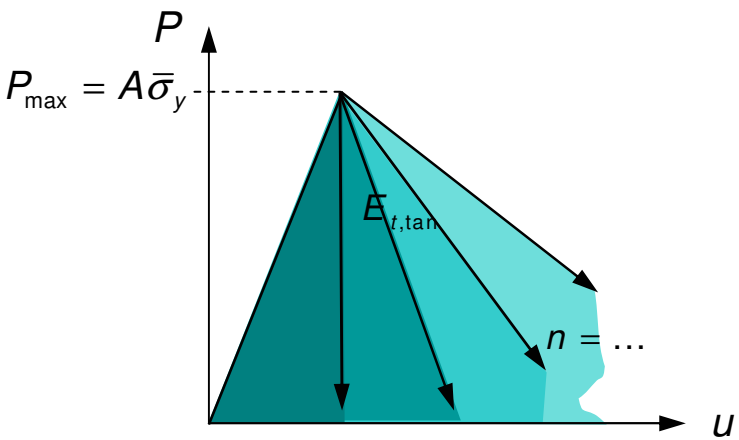
FEM: Mesh dependency and softening material

Example: tension rod with *A=1xL/n* discretized with *n* finite elements and localization in *m* elements:





Result of experiment:



- Mean strain in one element:

$$\bar{\varepsilon} = \bar{\varepsilon}^e + \bar{\varepsilon}^{pl} = \frac{\sigma}{E} + \frac{m}{n}\left(\frac{\sigma - \bar{\sigma}_y}{H}\right)$$

- Tangent operator:

$$E_{t,\tan} = \left[\frac{d\bar{\varepsilon}}{d\sigma}\right]^{-1} = \left[\frac{1}{E} + \frac{m}{nH}\right]^{-1} = \frac{EHn}{nH + mE} = \frac{EH\frac{n}{m}}{\frac{n}{m}H + E}$$

If n/m can be held constant for different discretizations, we gain non-mesh dependent solutions!!

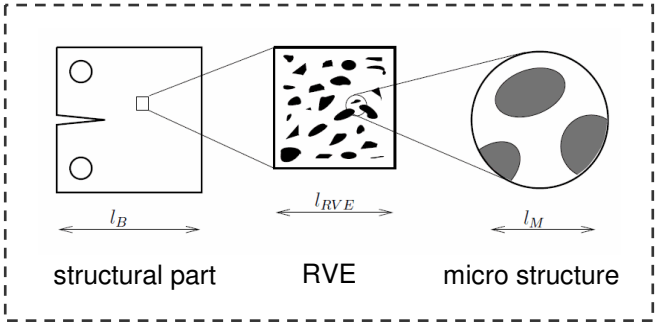
- Fracture energy:

$$G_t = \int \sigma\, du = \frac{m}{2n}\left(E\bar{\varepsilon}\right)_y \bar{\varepsilon}_u w_c$$

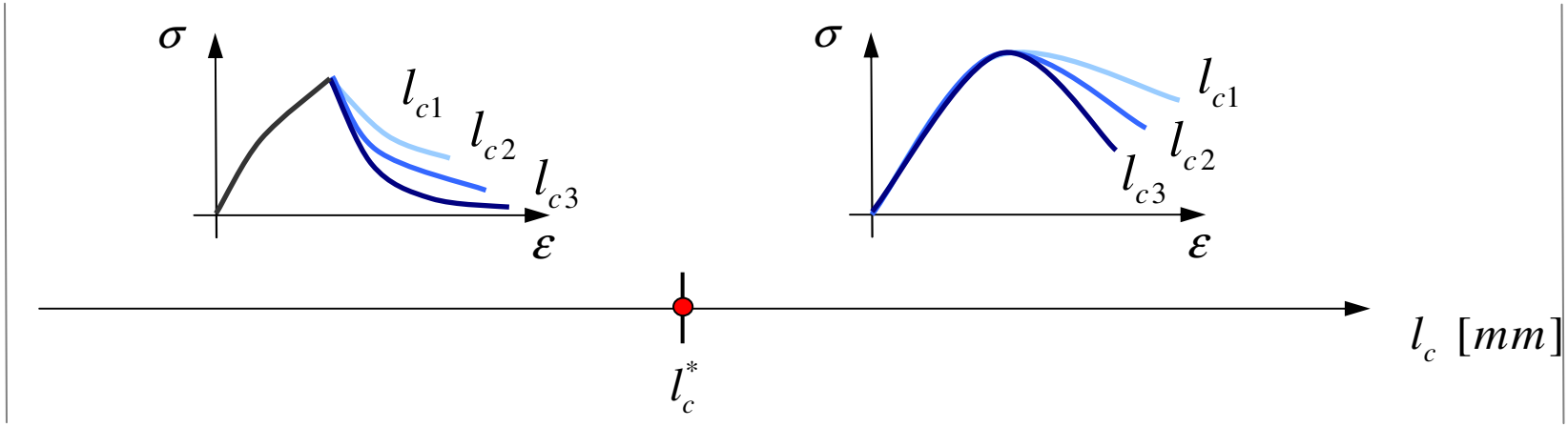
Poor man's regularisation

l_c = Characteristic element length

l_c^* = Characteristic element length when real world strains and deformations match simulation data.



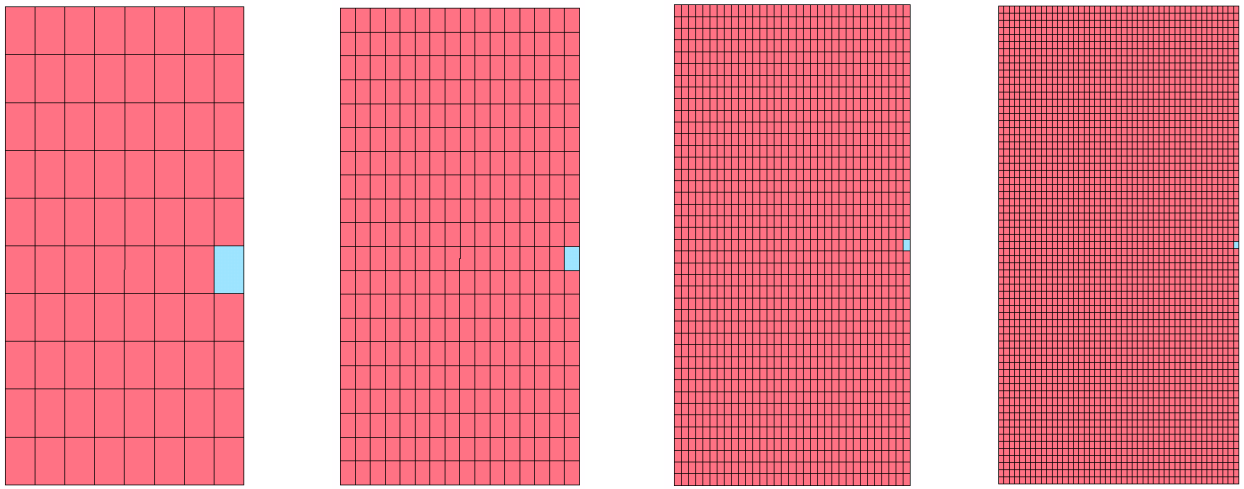
Localization limiter		Fading of stresses dependent on element length



Regularisation usually done by fracture energy or nonlocal theory.	No regularisation necessary!	Regularisation usually done by element size dependent input parameters.

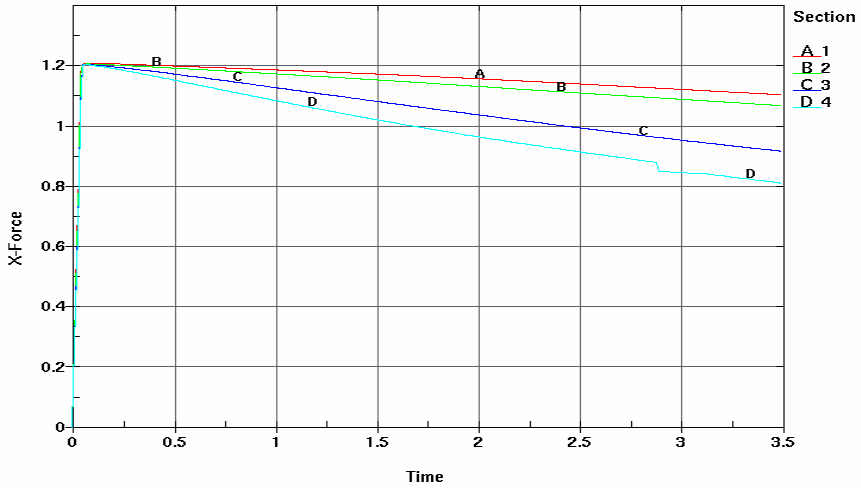
Example: Localization of tension rod

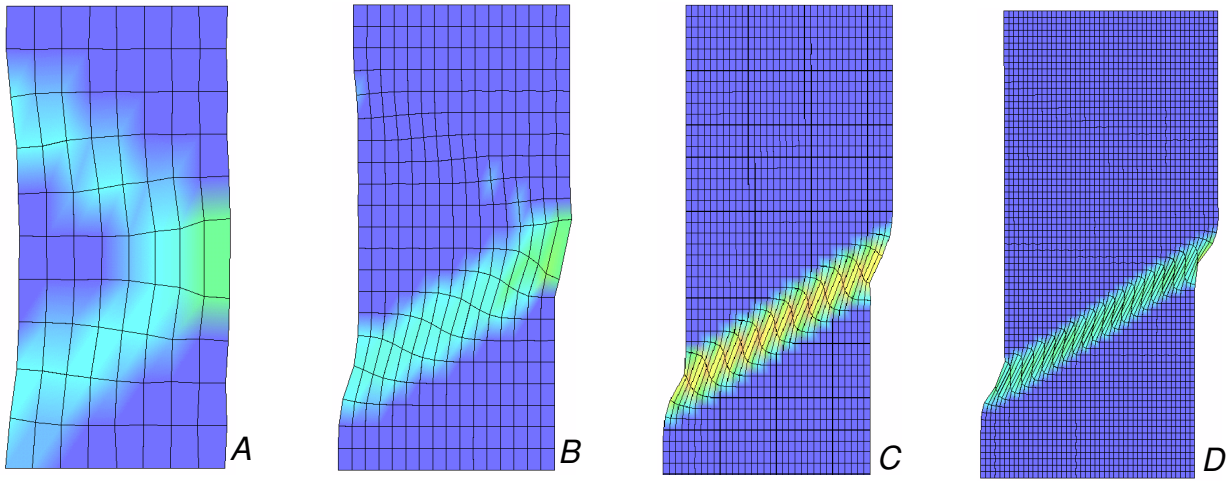
- *A tension rod will be discretized with an increasing number of elements*
- *Softening plastic material is employed*
- *One element is imperfect (weakened)*
- *The load is applied via prescribed displacements*
- *The experiment will show the effects (pros/cons) of different possibilities for regularization*



80 elements *320 elements* *1280 elements* *1920 elements*

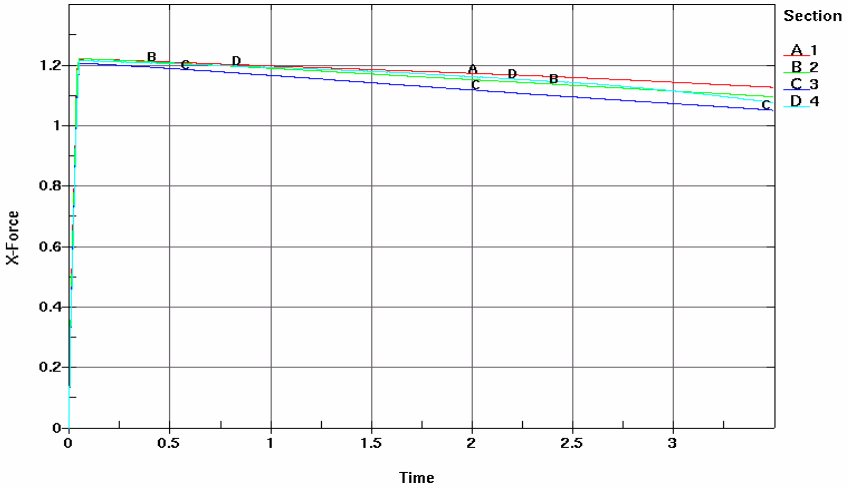
Example: Tension rod non-regularized

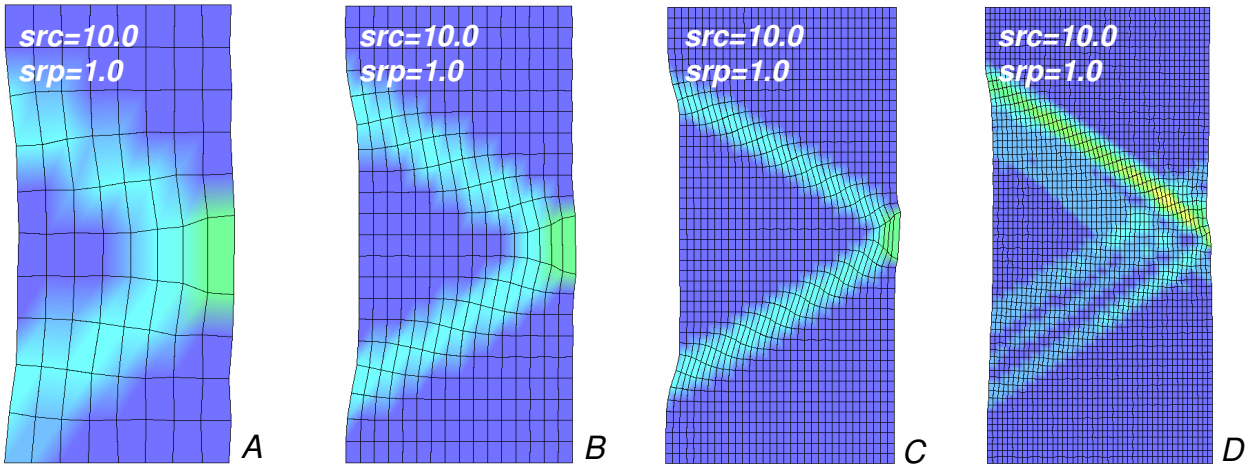




[plastic strains at t=3ms and ETAN=-50 N/mm^2]

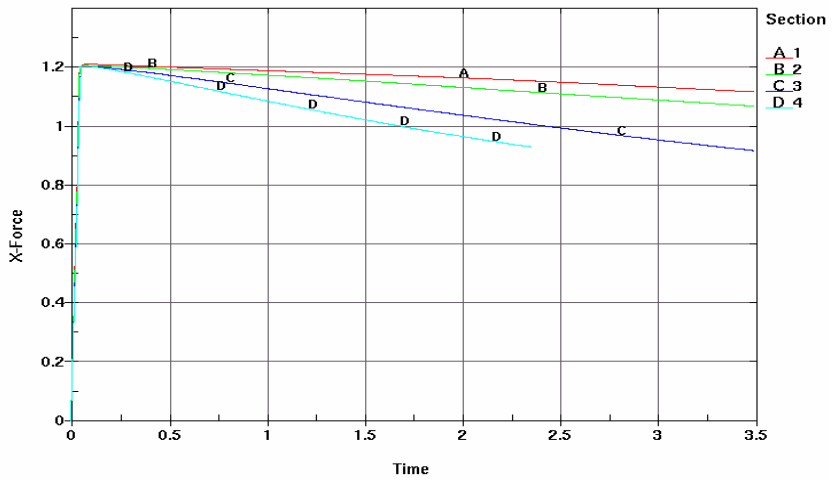
Example: Tension rod visco-plastic formulation

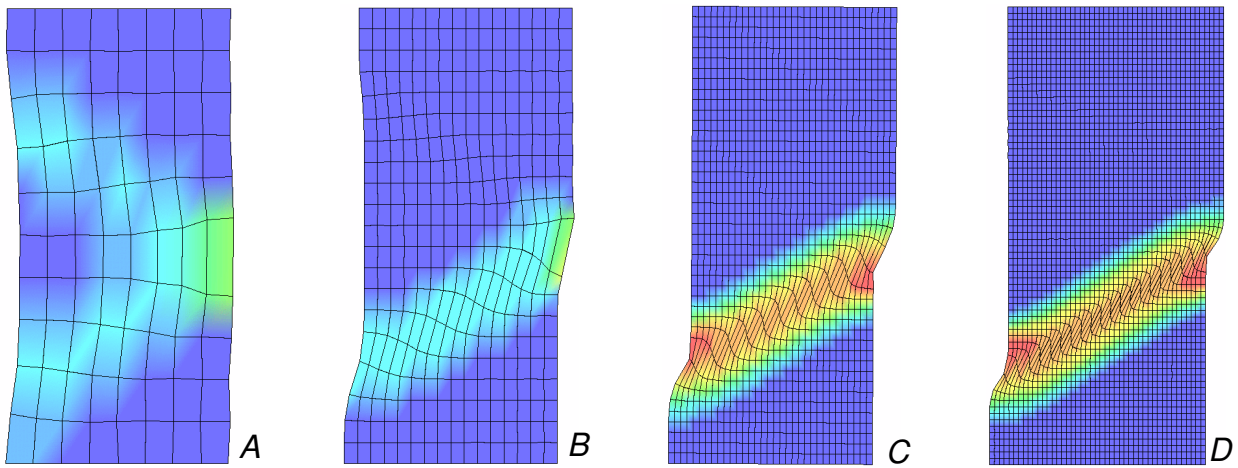




[plastic strains at t=3ms and ETAN=-50 N/mm^2]

Example: Tension rod non-local formulation

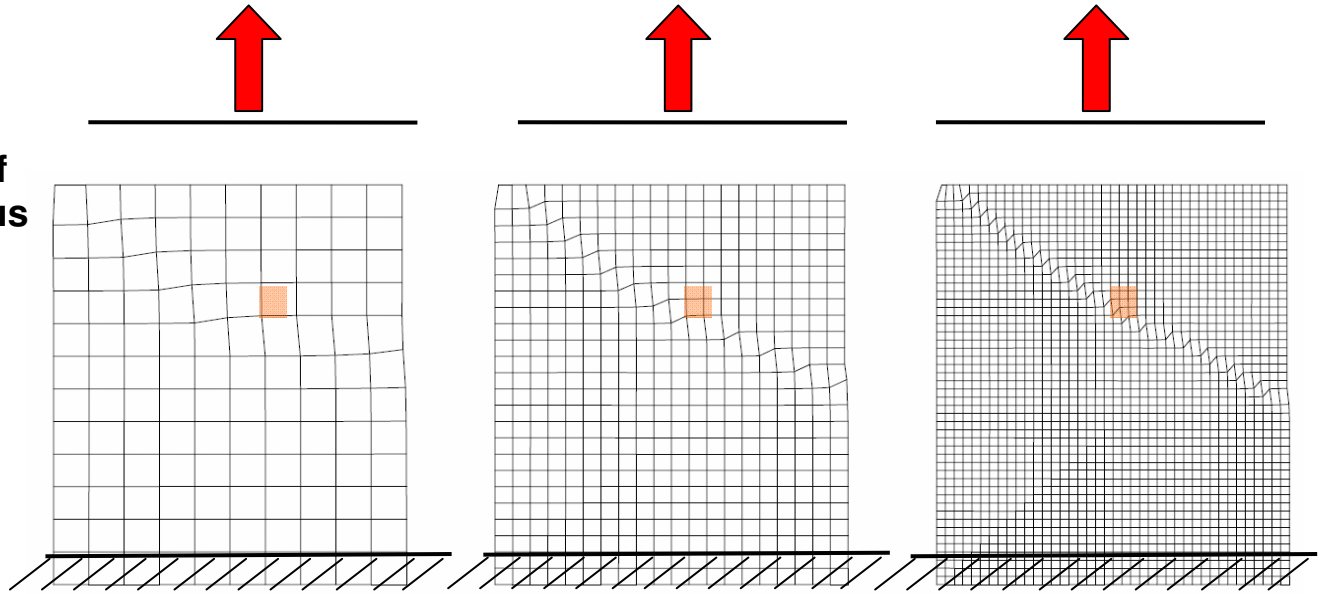




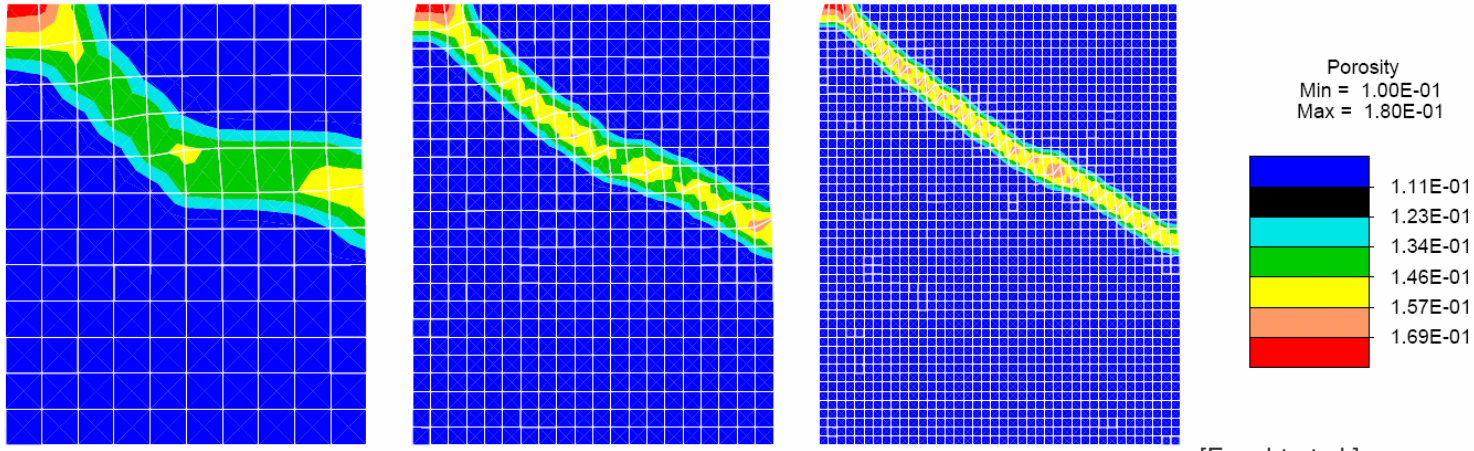
[plastic strains at t=3ms and ETAN=-50 N/mm^2]

Gurson model with local formulation

Deformation of mesh of various element sizes



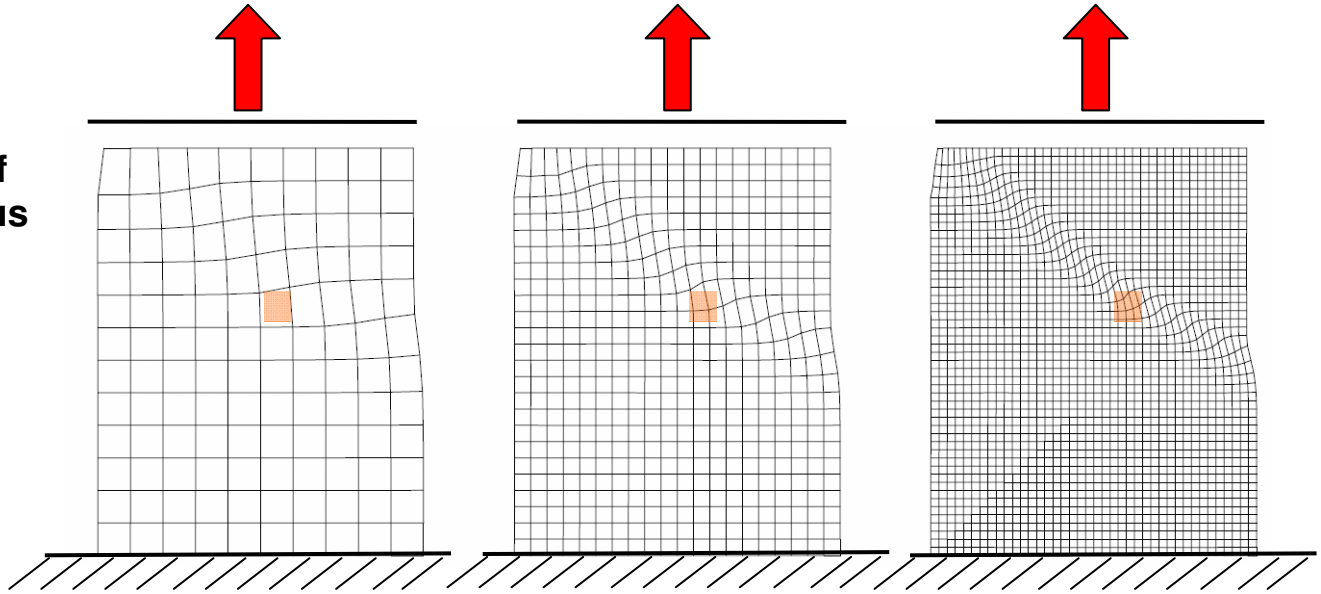
Fringe of porosity values



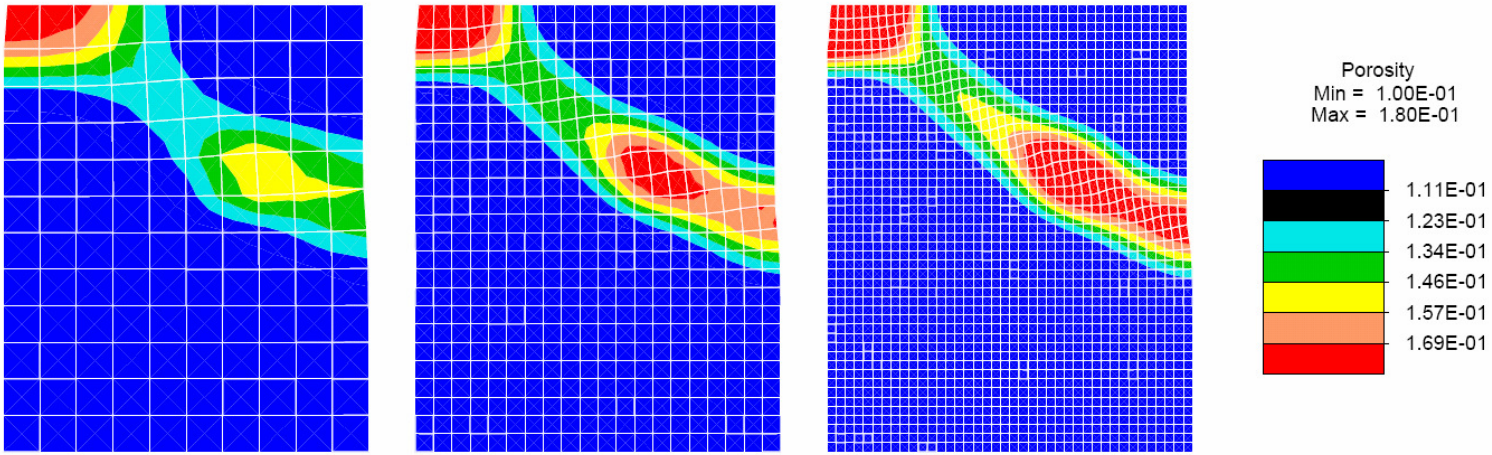
[Feucht et al.]

Gurson model with non-local (gradient) formulation

Deformation of mesh of various element sizes



Fringe of porosity values



[Feucht et al.]

Softening and mesh dependency

In general: Enhance the continuum or material formulation by further information about size of failure zone (internal length parameter). Currently the following approaches are known:

- Use of Cosserat continuum (includes rotation degrees of freedom on material point level) instead of Bolzmann continuum.
- ☆ Making use of “time dependent” constitutive formulations, e. g. use of viscous material formulations in dynamic simulation. But still a certain tendency to localize within a small band may develop depending on the mesh-size, material properties and loading velocity.
- ☆ Formulations that take the size of the element into account to adjust the softening branch of the evolution law (fracture energy approach).
  Here m/n is a factor that takes the dimension of the problem (internal length parameter) into account!!!
- ☆ Non-local material formulations that take strain gradients of neighboring elements into account to determine the constitutive evolution within the actual element.
  Here n/m is a held constant by defining a radius of influence – again a internal length parameter!

☆ *available in LS-DYNA*

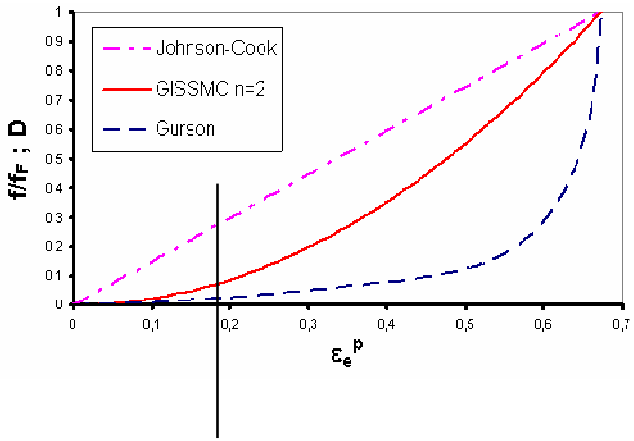
Additive failure model
with scalar (isotropic) damage

GISSMO

Generalized Incremental Stress State dependent damage MOdel

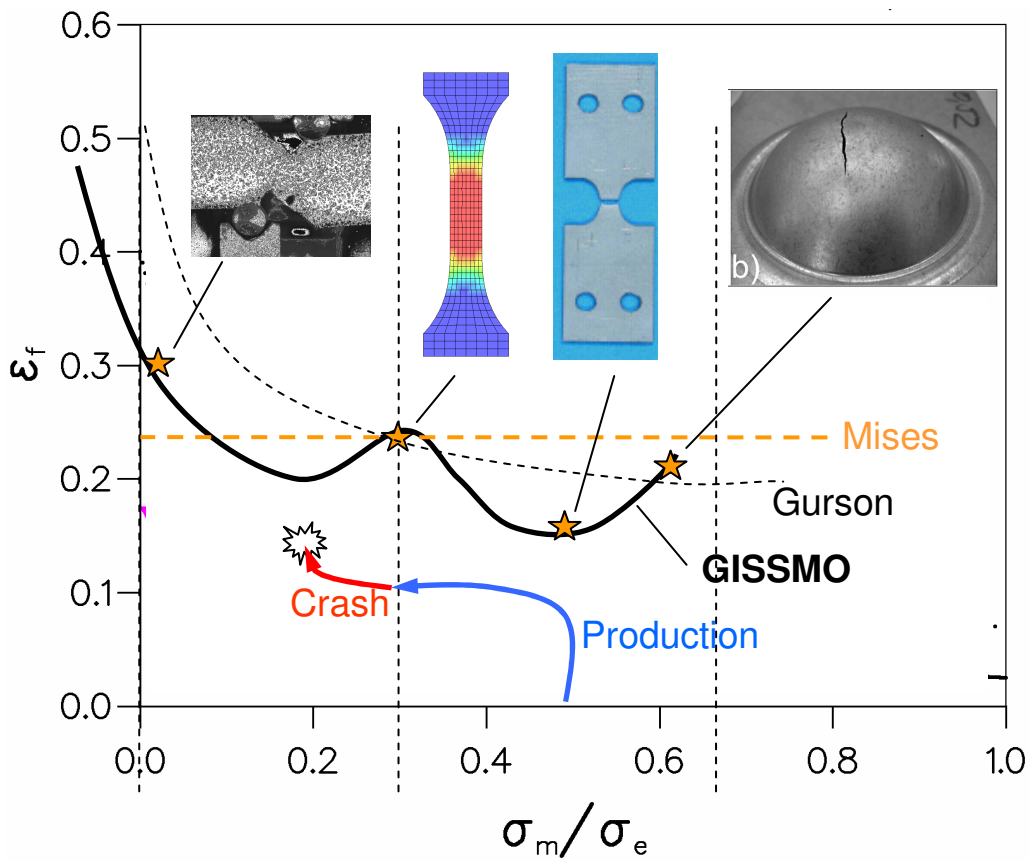
Damage Evolution

$$\dot{D}_f = \frac{n}{\varepsilon_f} D_f^{(1-\frac{1}{n})} \dot{\varepsilon}_p$$



Damage overestimated for linear damage accumulation

Failure Curve



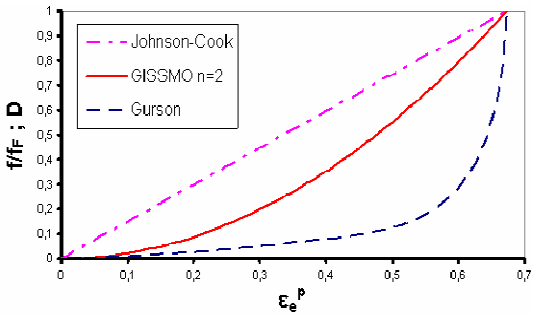
Neukamm, Feucht & Haufe [2008]

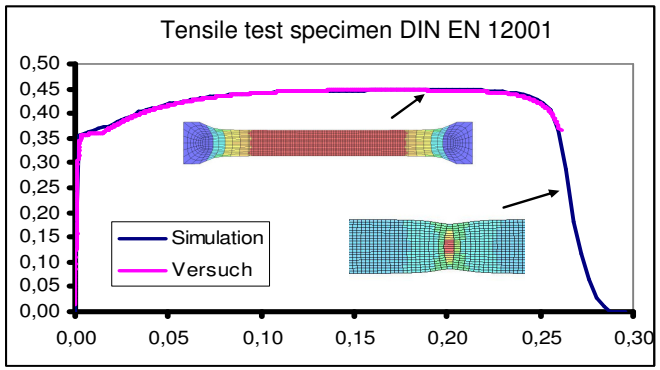
GISSMO

Generalized Incremental Stress State dependent damage MOdel

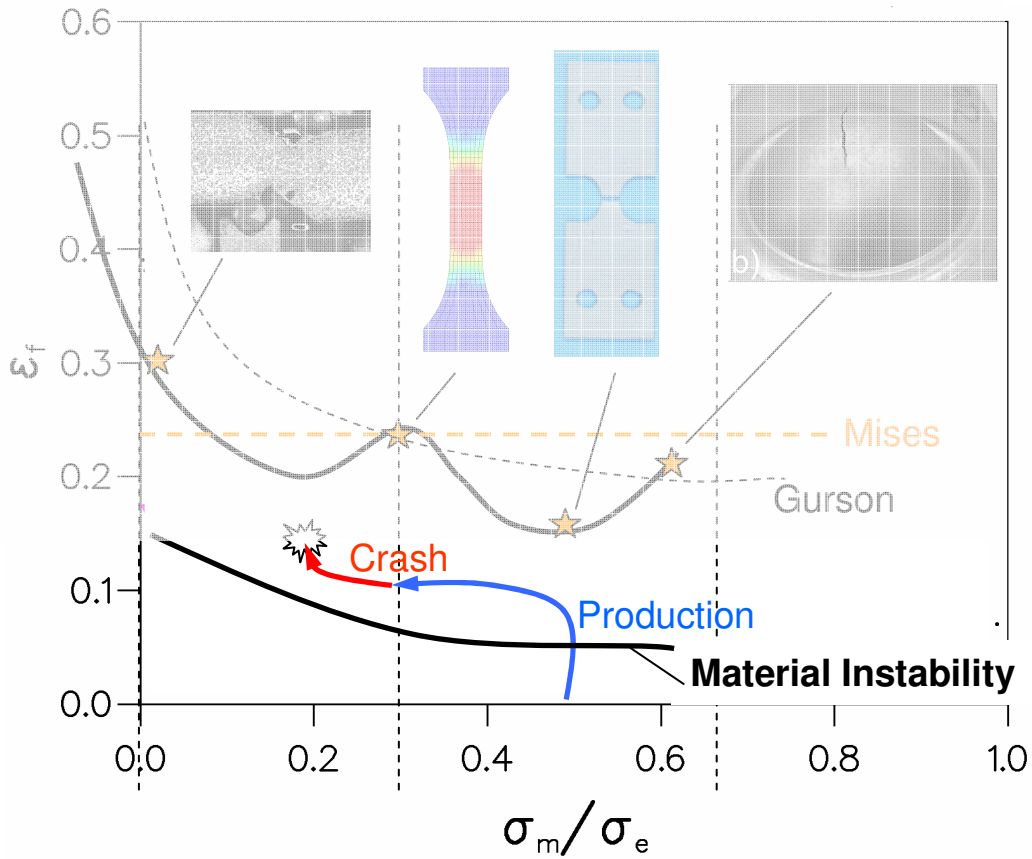
Evolution of Instability

$$\Delta F = \frac{n}{\varepsilon_{v,loc}} F^{\left(1-\frac{1}{n}\right)} \Delta\varepsilon_v$$





Material Instability

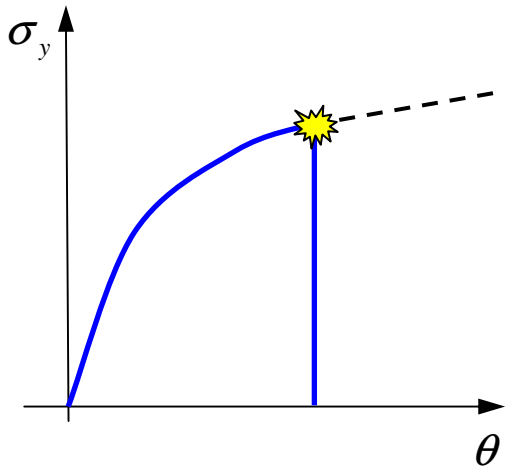


Neukamm, Feucht & Haufe [2008]

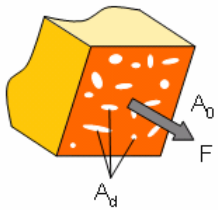
GISSMO: Schädigungsevolution

Sprödes Versagen ohne Schädigung

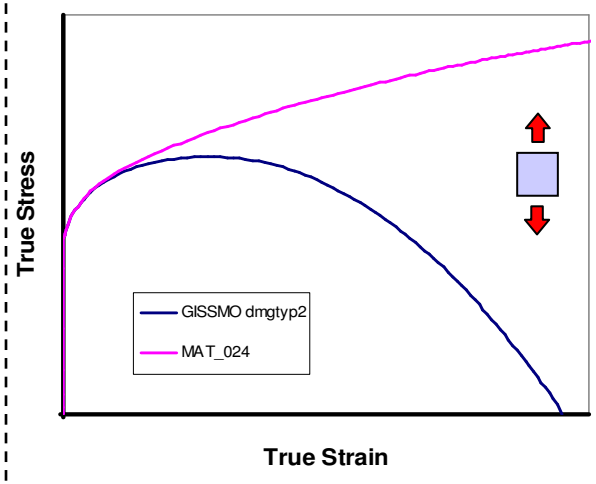
$$\sigma^* = \sigma$$



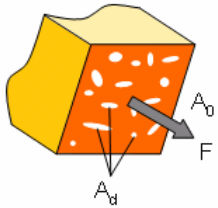
DMGTYP: Initial gekoppelt (Lemaitre)



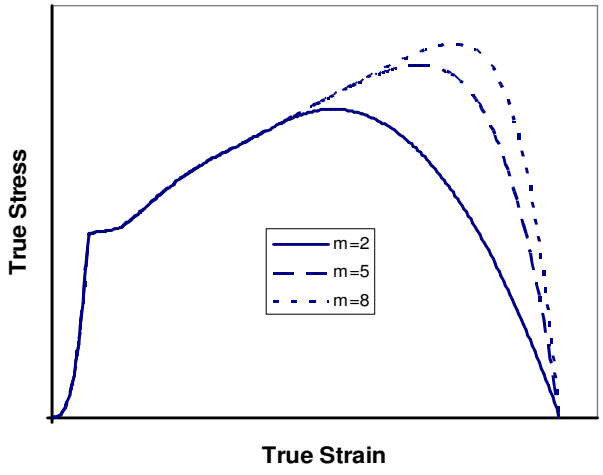
$$\sigma^* = \sigma\,(1 - D)$$



DCRIT, FADEXP: Nachkritisch gekoppelt



$$\sigma^* = \sigma\left(1 - \left(\frac{D - D_{CRIT}}{1 - D_{CRIT}}\right)^{FADEXP}\right)$$



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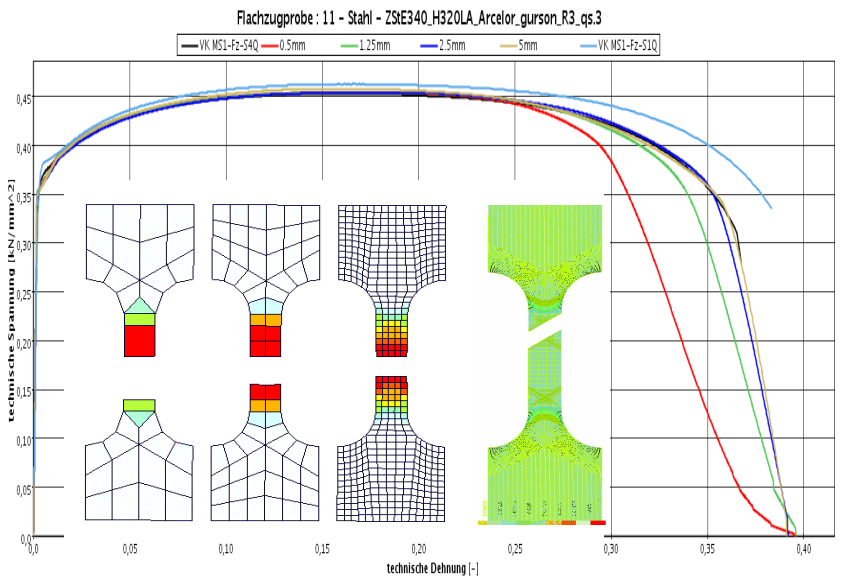
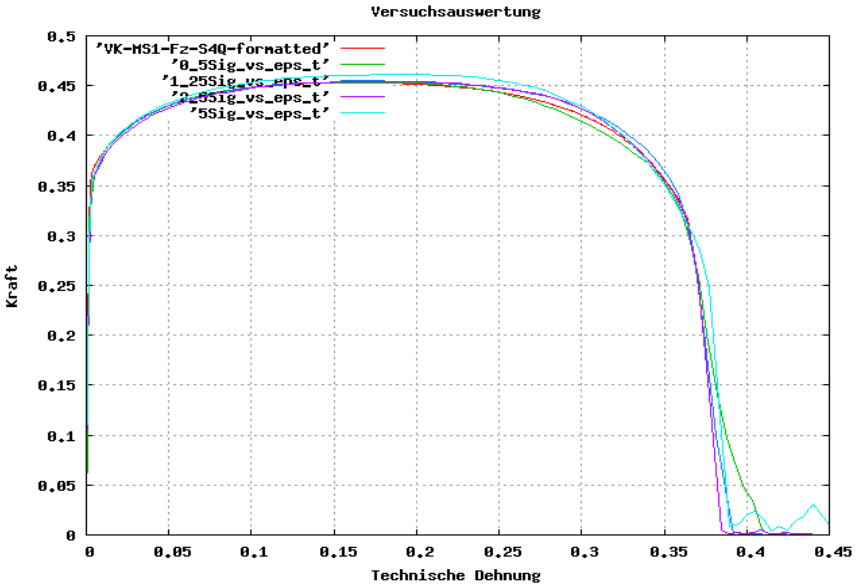
Gurson vs. GISSMO

Regularization of element size dependency





Gurson

- Resultant Failure Strain constant
- Failure energy depending on el. size
- Identification of damage parameters is difficult

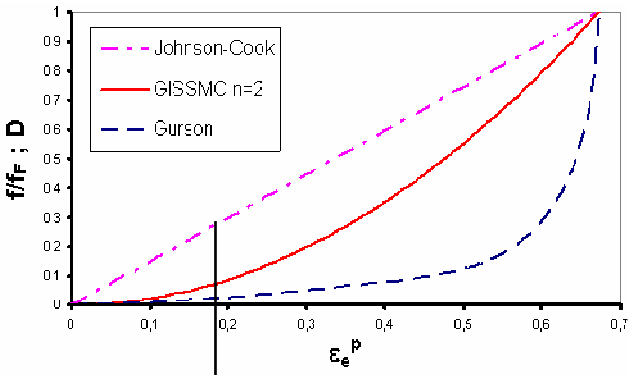
GISSMO

- Failure Strain constant
- Fracture energy constant
- Identification of Damage Parameters is more straight-forward

GISSMO: Einfluss der Belastungsgeschichte

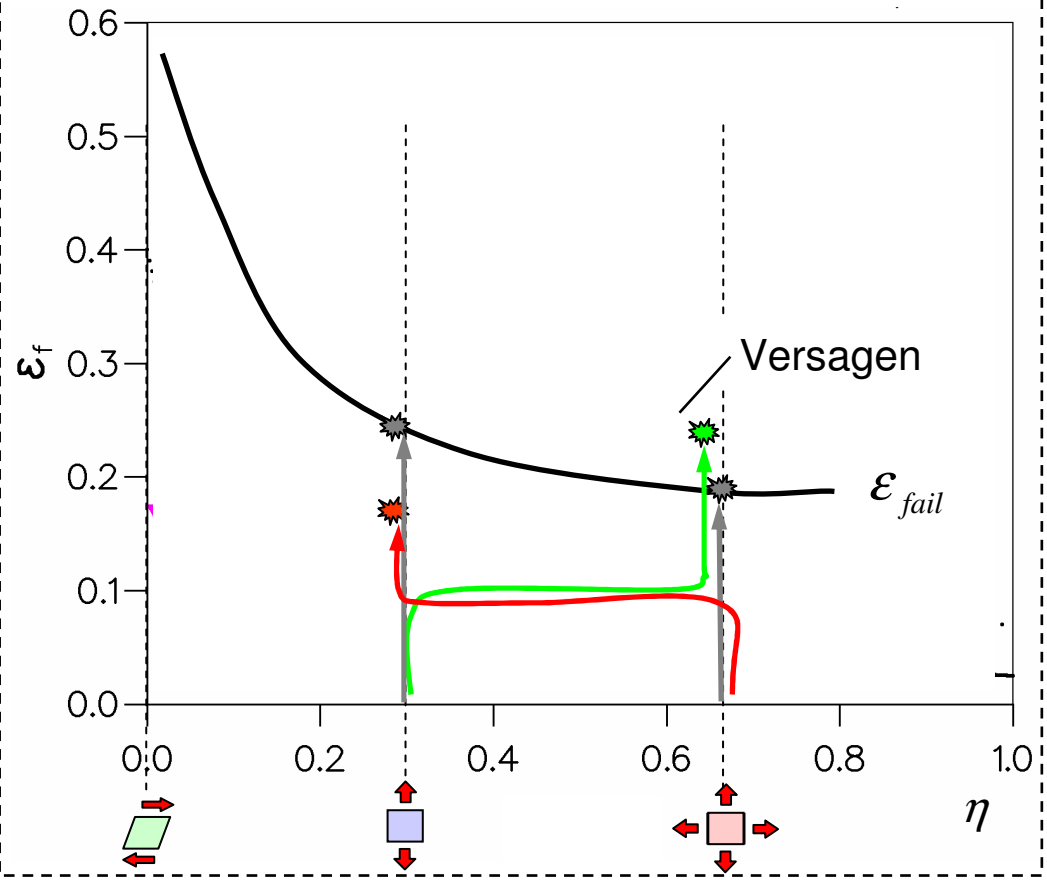
Schädigungsevolution

$$\dot{D}_f = \frac{n}{\varepsilon_f} D_f^{(1-\frac{1}{n})} \dot{\varepsilon}_p$$



Schädigung wird anfangs bei linearer Schädigungsakkumulation überschätzt!

Versagenskurve



Neukamm, Feucht & Haufe [2008]

Thank you for your attention.

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