Instability and Failure Prediction for Sheet Metal Forming Applications with LS-DYNA

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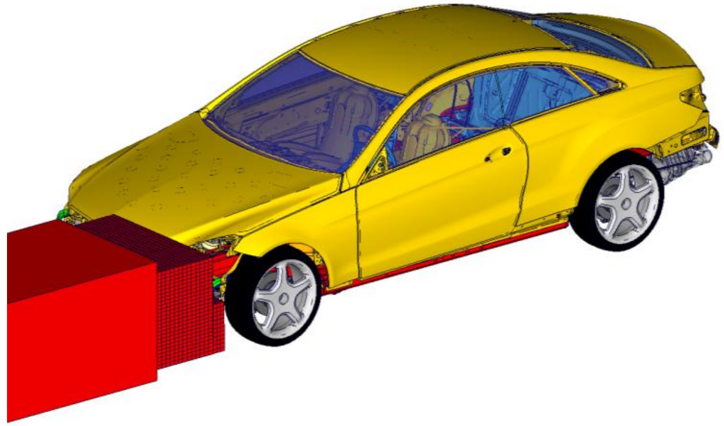
Motivation

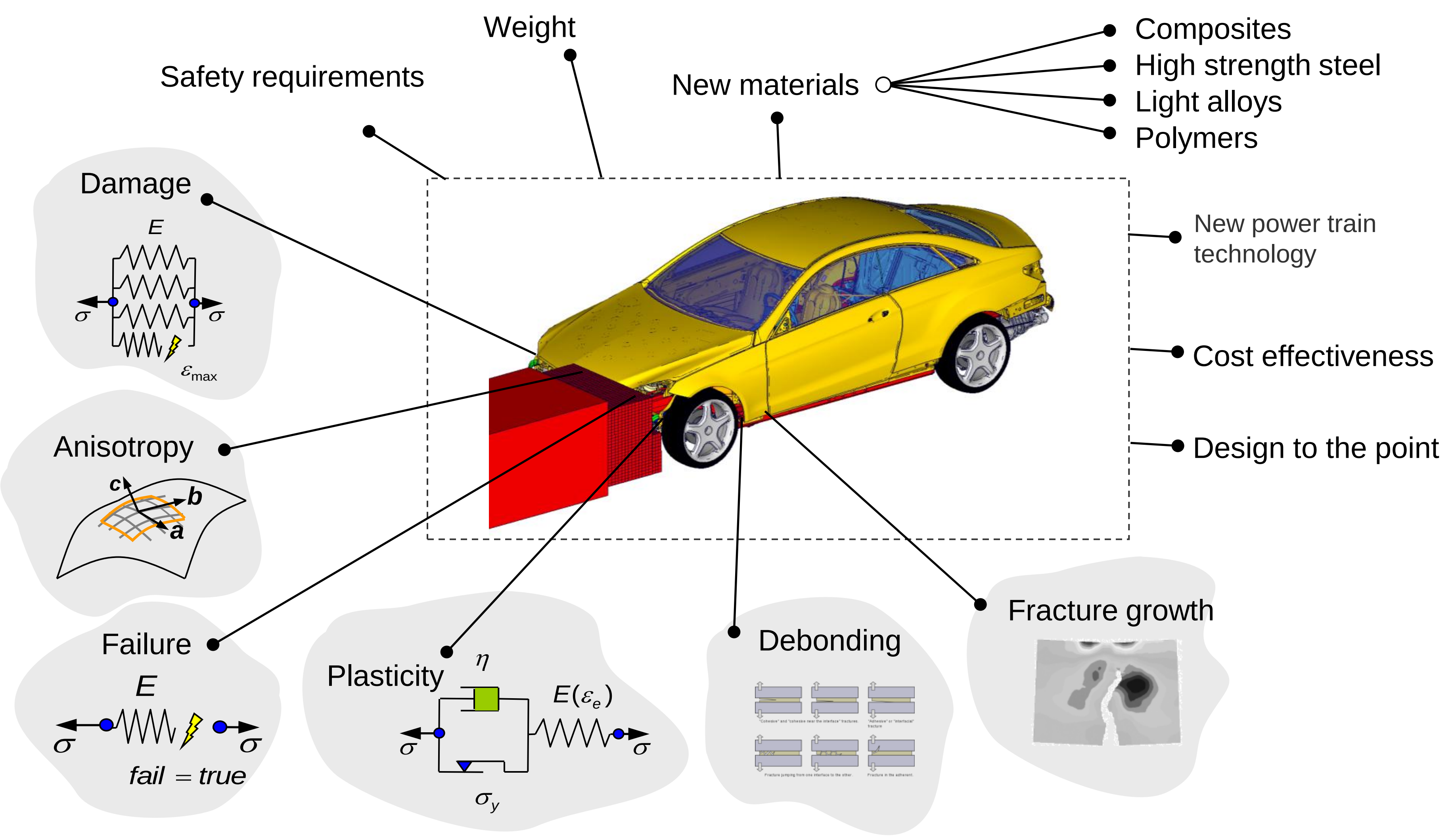
Technological challenges in the automotive industry

- Safety requirements
- Weight
- New materials
  - Composites
  - High strength steel
  - Light alloys
  - Polymers



- New power train technology
- Cost effectiveness
- Design to the point

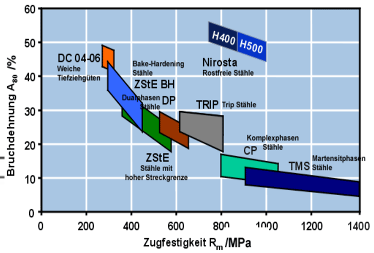
Technological challenges in the automotive industry

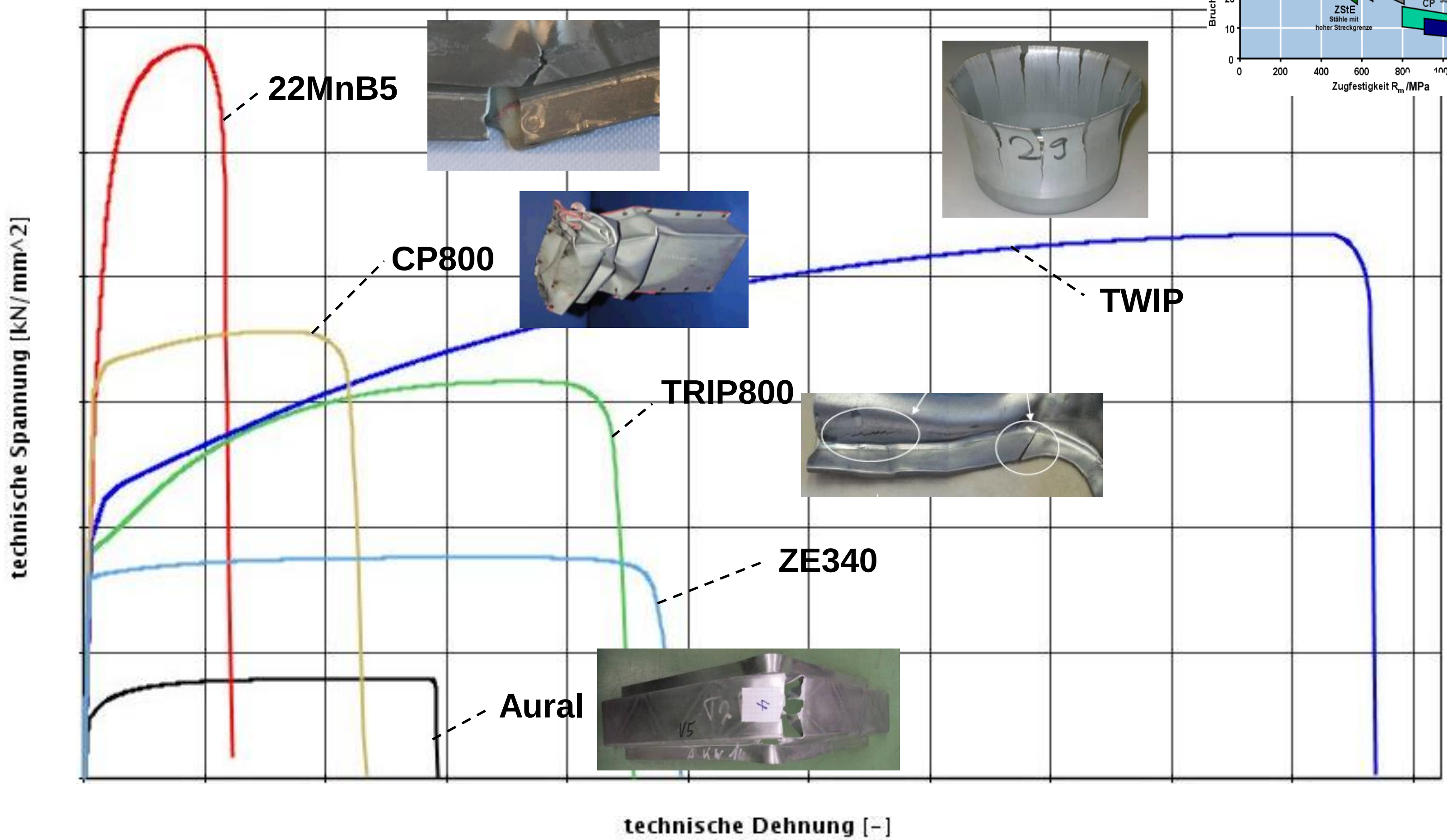


Motivation

Lightweight steel/aluminium design!

Can we predict failure modes (brittle, ductile, time delayed)?



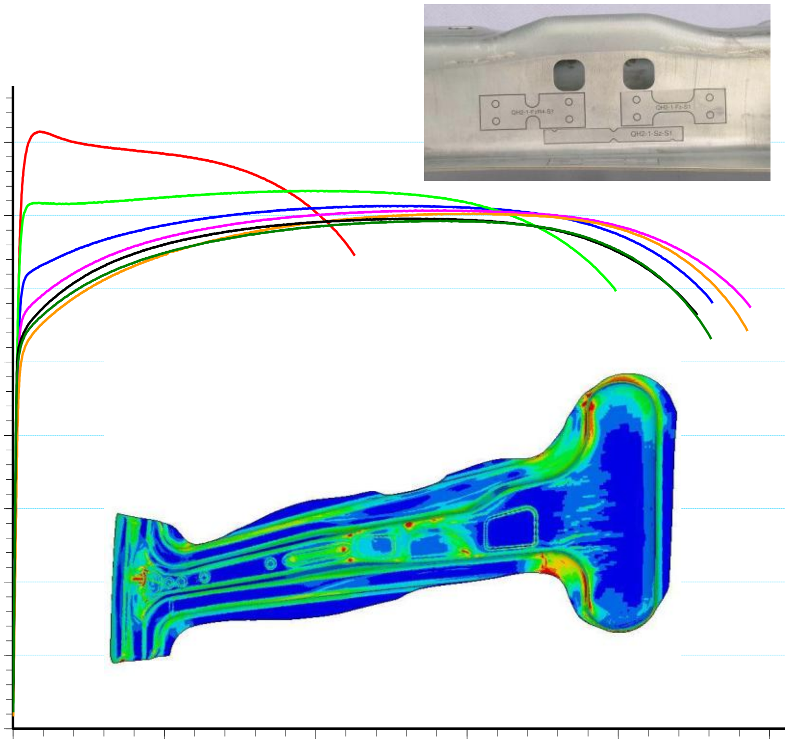


Motivation

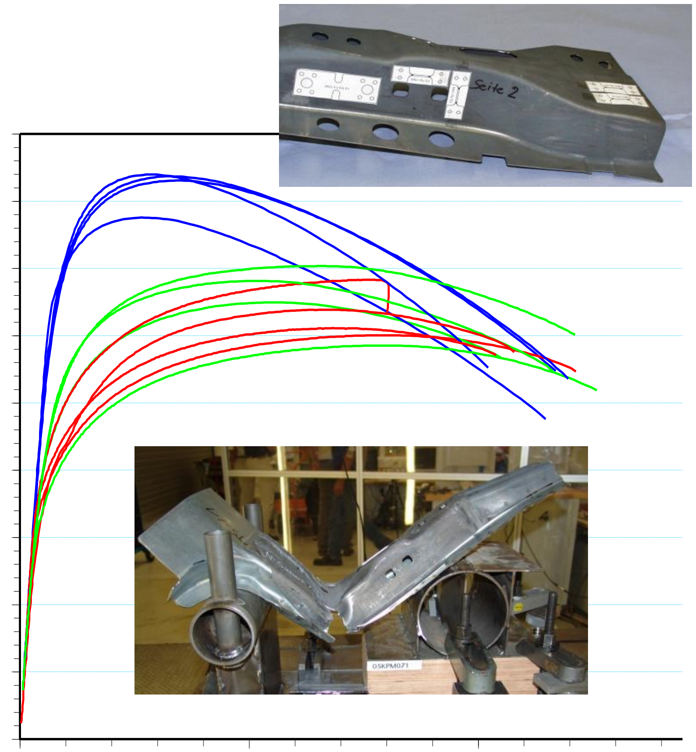
Material behavior dependent on local history of loading

Institut Werkstoffmechanik

Micro-alloyed steel

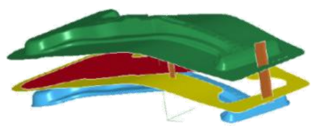


Hot-formed steel

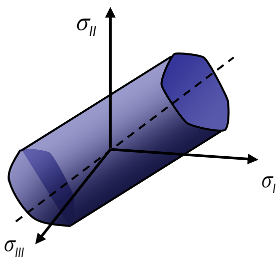


Closing the process chain: Standard materials / state of the art

Forming simulation



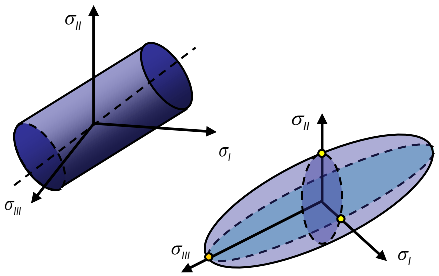
- **Hill based models**
- Anisotropiy of yield surface
- Kinematic/Isotropic hardening
- State of the art: Failure by FLD (post-processing)
- NEW: Computation of damage (GISSMO)



Mapping

Crash simulation

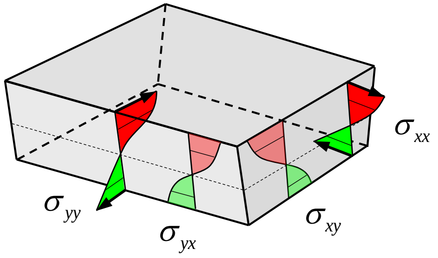
- **v. Mises or Gurson model**
- Strain rate dependency
- Isotropic hardening
- Damage evolution
- Failure models (mapping of damage variable)



Preliminary considerations for plane stress

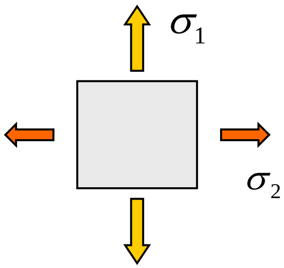
Plane stress condition

Typical discretization with shell elements:



Principle axis	Plane stress
$\boldsymbol{\sigma} = \begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \\ 0 \\ 0 \\ 0 \end{bmatrix}$	$\sigma_1 \in (-\infty, +\infty)$ $\sigma_2 \in (-\infty, +\infty)$ $\sigma_3 = 0$

Parameterised



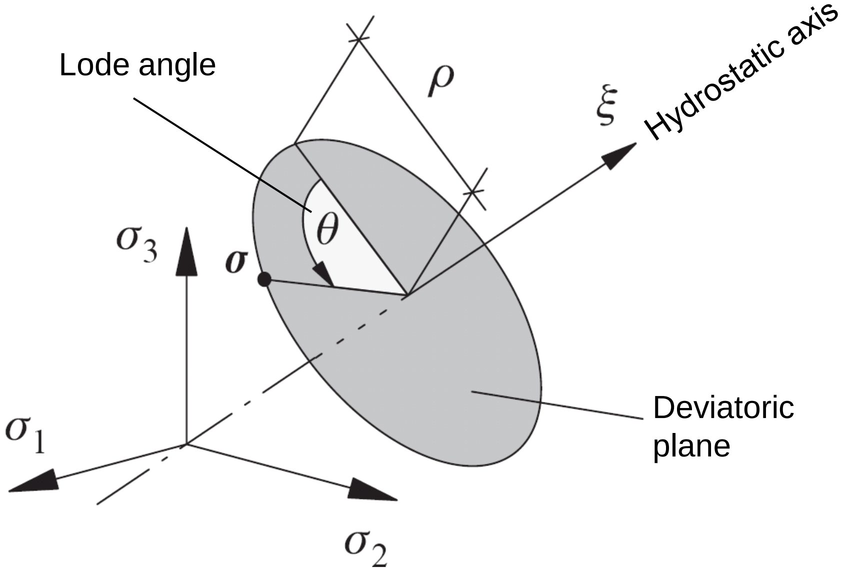
$$\boldsymbol{\sigma} = \begin{bmatrix} \sigma_1 & 0 & 0 \\ 0 & k\sigma_1 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

$$\Rightarrow \sigma_{vm} = \sqrt{\left(1 + (k-1)k\right)\sigma_1^2}$$

Definition of stress triaxiality:

$$\eta = \frac{p}{\sigma_{vm}} = -\frac{\sigma_1(k+1)}{3\sqrt{\left(1+(k-1)k\right)\sigma_1^2}} = -\frac{(k+1)}{3\sqrt{1+(k-1)k}}\,\mathrm{sign}(\sigma_1)$$

Haigh-Westergaard coordinates in principle stress space



$$\xi = \frac{1}{\sqrt{3}}\,\mathrm{tr}(\boldsymbol{\sigma}) = \frac{I_1}{\sqrt{3}}$$

$$\rho = \sqrt{2\,J_2} = \sqrt{\mathbf{s}:\mathbf{s}}$$

$$\theta = \frac{1}{3}\arccos\left(\frac{3\sqrt{3}}{2}\,\frac{J_3}{J_2^{1.5}}\right)$$

Definition of stress triaxiality: $\eta = \dfrac{p}{\sigma_{vm}}$

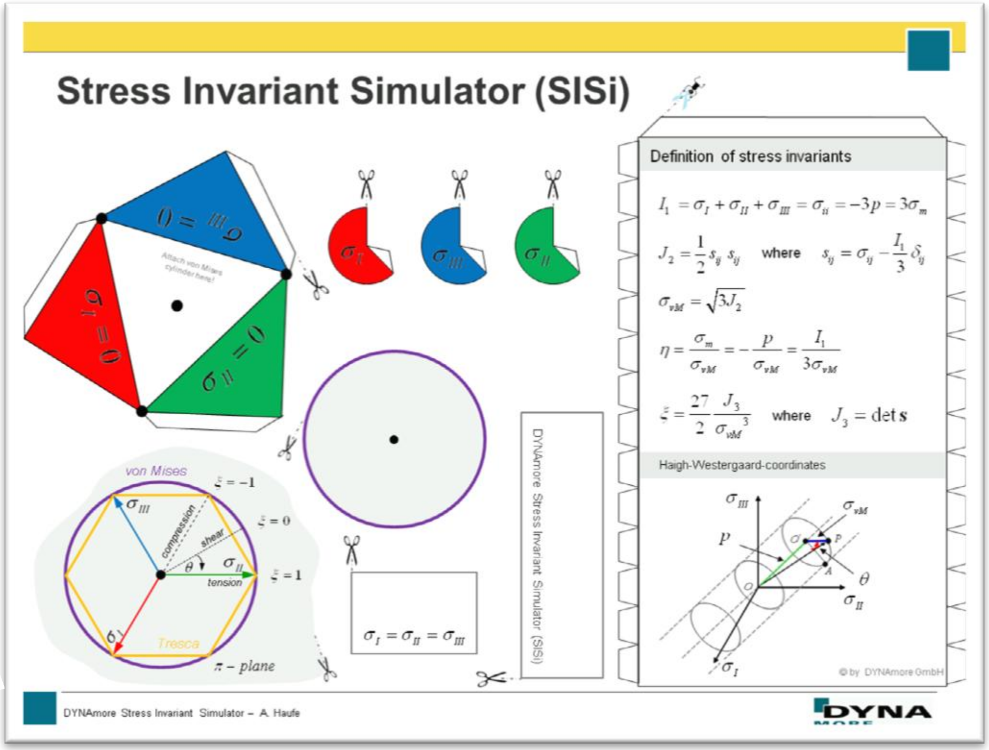
A toy to visualize stress invariants

(downloadable from the www.dynamore.se)

Crafting instructions

- Download the PDF-file
- Print on thick piece of paper
- Cut out where indicated
- Add four wooden sticks (15cm)
- Add some glue where necessary
  (engineers should find out the locations without further instructions – all others contact their local distributor)
- Have fun!

page 1:

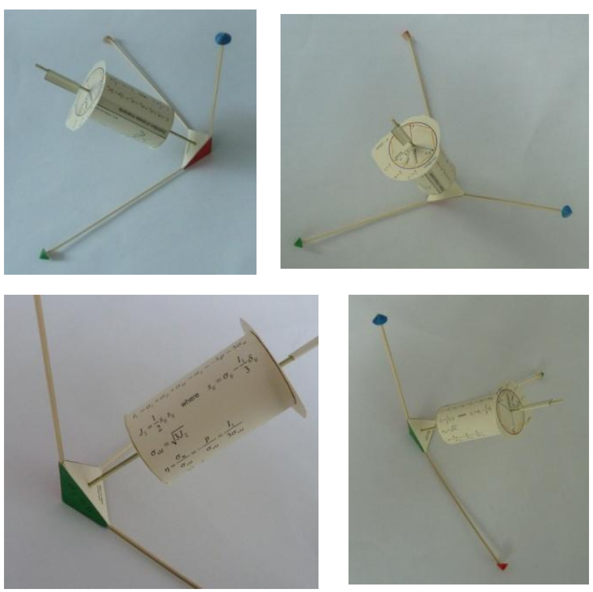


A toy to visualize stress invariants
(downloadable from the www.dynamore.se)

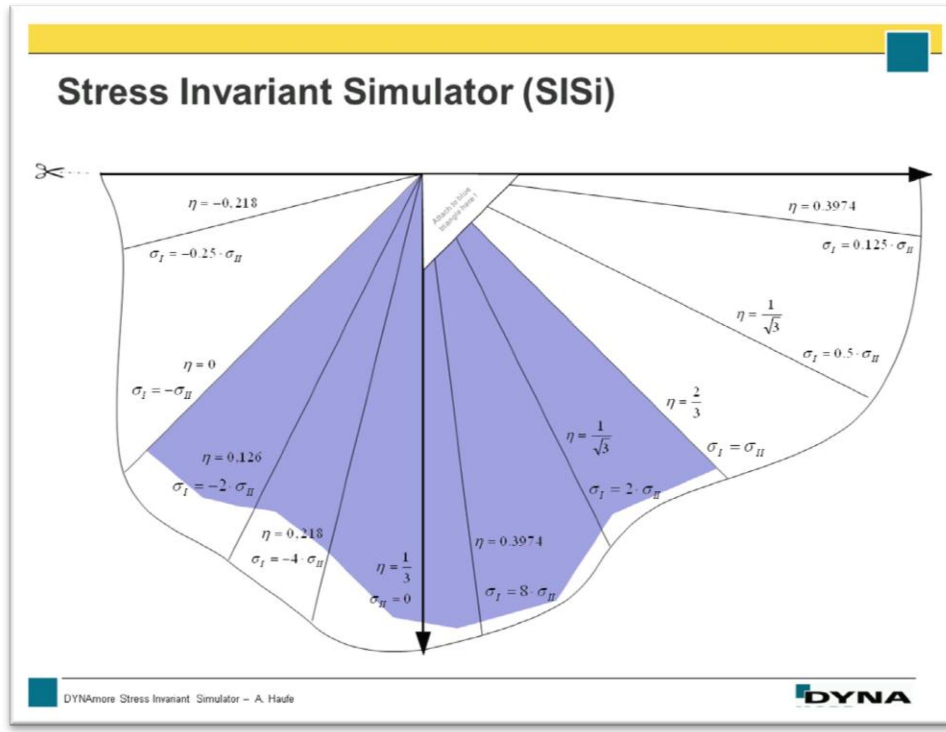
Crafting instructions

- Page 2 of the set may be added for further clarification of the triaxiality variable.

Final shape of toy



page 2:



Plane stress parameterised for shells

Triaxiality $\eta = \frac{p}{\sigma_{vm}} = -\frac{\sigma_1(k+1)}{3\sqrt{\left(1+(k-1)k\right)\sigma_1^2}} = -\frac{(k+1)}{3\sqrt{1+(k-1)k}}\operatorname{sign}(\sigma_1)$

Bounds:

Compression

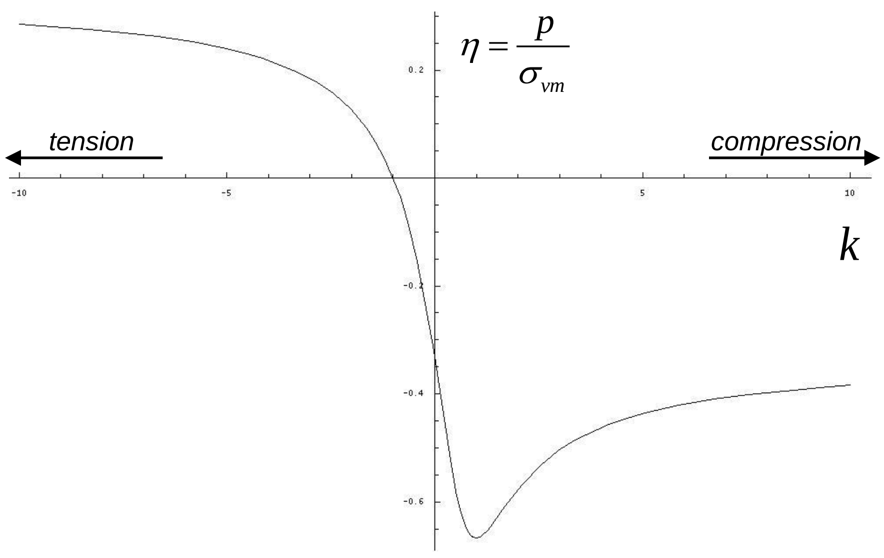
$$\lim_{k\to\infty}\eta = \lim_{k\to\infty} -\frac{(k+1)}{3\sqrt{1+(k-1)k}}\operatorname{sign}(\sigma_1) = -\frac{1}{3}\operatorname{sign}(\sigma_1)$$

Tension

$$\lim_{k\to-\infty}\eta = \lim_{k\to-\infty} -\frac{(k+1)}{3\sqrt{1+(k-1)k}}\operatorname{sign}(\sigma_1) = \frac{1}{3}\operatorname{sign}(\sigma_1)$$

Biaxial tension

$$\lim_{k\to 1}\eta = \lim_{k\to 1} -\frac{(k+1)}{3\sqrt{1+(k-1)k}}\operatorname{sign}(\sigma_1) = -\frac{2}{3}\operatorname{sign}(\sigma_1)$$



How to define the accumulation of damage ?

A comparison of model approaches

Investigation of failure criteria for the following case:

- Plane stress: $\sigma_3 = 0$
- Small elastic deformations: $\varepsilon_1 \approx \varepsilon_{p1} \;\; and \;\; \varepsilon_2 \approx \varepsilon_{p2}$
- Isochoric plasticity: $\varepsilon_3 \approx \varepsilon_{p3} = -\varepsilon_{p1} - \varepsilon_{p2}$
- Proportional loading: $\sigma_2 = a\sigma_1$

$$\varepsilon_{p2} = b\varepsilon_{p1}$$

$$a = \frac{1+2b}{2+b}$$

Damage or failure criteria

$$\varepsilon_p = \sqrt{\frac{4}{3}\varepsilon_{p1}^2 \;\; 1 + b^2 + b}$$

$$\sigma_{vm} = \sqrt{\sigma_1^2 \;\; 1 + a^2 - a}$$

$$\frac{p}{\sigma_{vm}} = -\frac{1+a}{3\sqrt{1+a^2-a}}$$

How to define the accumulation of damage ?

A comparison of classical model approaches

Some typical loading paths

	$a = \frac{\sigma_2}{\sigma_1}$	$b = \frac{\varepsilon_{p2}}{\varepsilon_{p1}}$	$\eta = \frac{p}{\sigma_{vm}}$
Uniaxial stress (tension)	0	-0.5	-0.3333
Biaxial stress	1	1	-0.6666
Uniaxial tension laterally confined	0.5	0	-0.57735 $= -\frac{1}{\sqrt{3}}$
Pure shear	-1	-1	0
Uniaxial stress (compression)	∞	-2	0.3333

How to define the accumulation of damage ?

A comparison of classical model approaches

Some typical loading paths

	$a = \frac{\sigma_2}{\sigma_1}$	$b = \frac{\varepsilon_{p2}}{\varepsilon_{p1}}$	$\eta = \frac{p}{\sigma_{vm}}$
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Biaxial stress	1	1	
Uniaxial tension laterally confined	0.5	0	
Pure shear	-1	-1	
Uniaxial stress (compression)	∞	-2	

Four criteria

Principal strain:

$$\varepsilon_1 \leq \varepsilon_{\max} \Rightarrow \varepsilon_{p1} \approx \varepsilon_1 \leq \varepsilon_{\max}$$

Equivalent plastic strain:

$$\varepsilon_p = \sqrt{\frac{4}{3}\varepsilon_{p1}^2 \; 1 + b^2 + b} \leq \varepsilon_{\max} \Rightarrow \varepsilon_{p1} \leq \sqrt{\frac{3}{4}\frac{\varepsilon_{\max}^2}{1 + b^2 + b}}$$

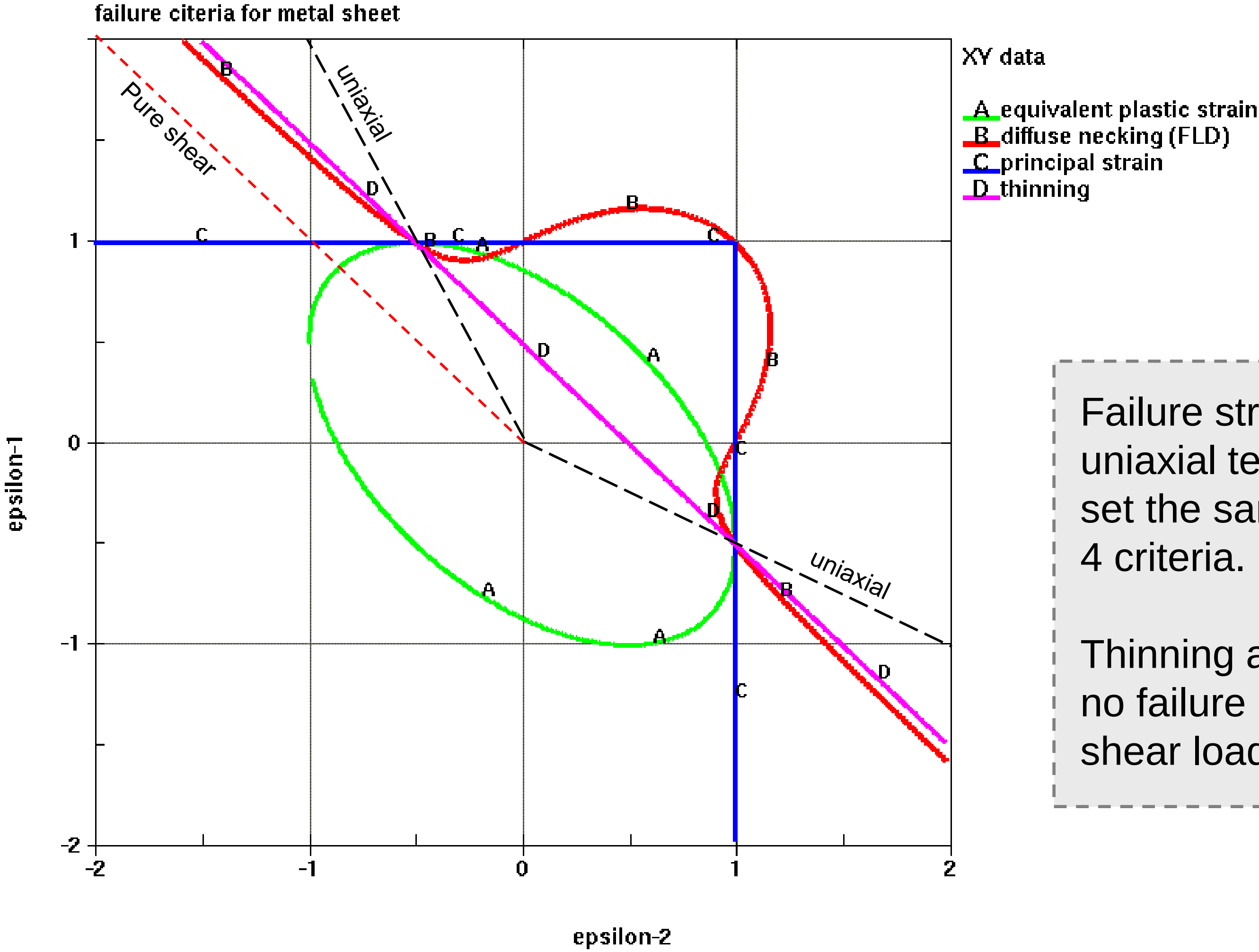
Thinning:

$$\varepsilon_{p3} \leq -\frac{\varepsilon_{\max}}{2} \Rightarrow \varepsilon_{p1} = \frac{-\varepsilon_{p3}}{1+b} \leq \frac{\varepsilon_{\max}}{2 \;\; 1+b}$$

Diffuse necking:

$$\varepsilon_{p1} \leq \varepsilon_{\max} \frac{2 \;\; 1 + b^2 + b}{1 + b \;\;\; 2 - b + 2b^2}$$

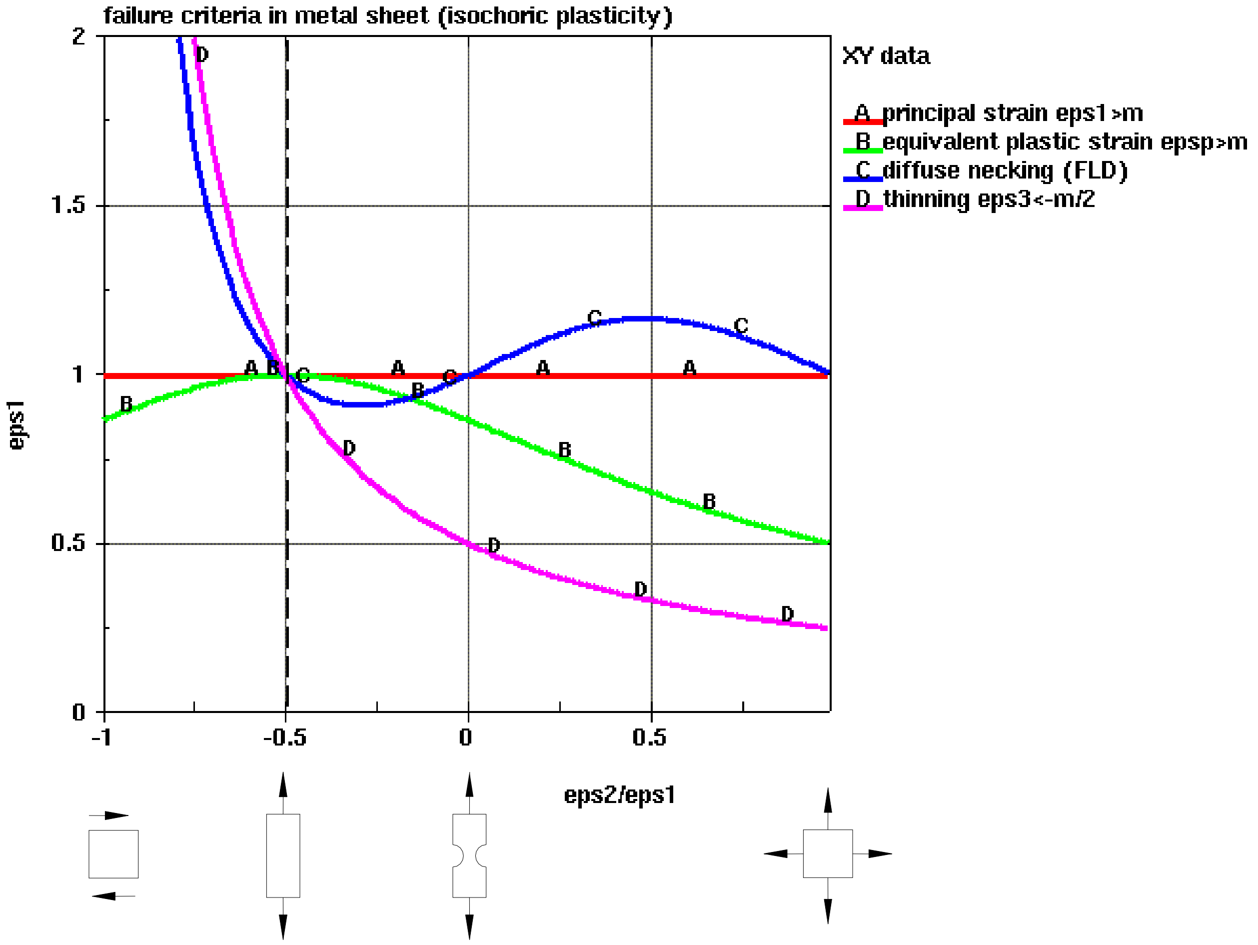
Failure models in the plane of principal strain



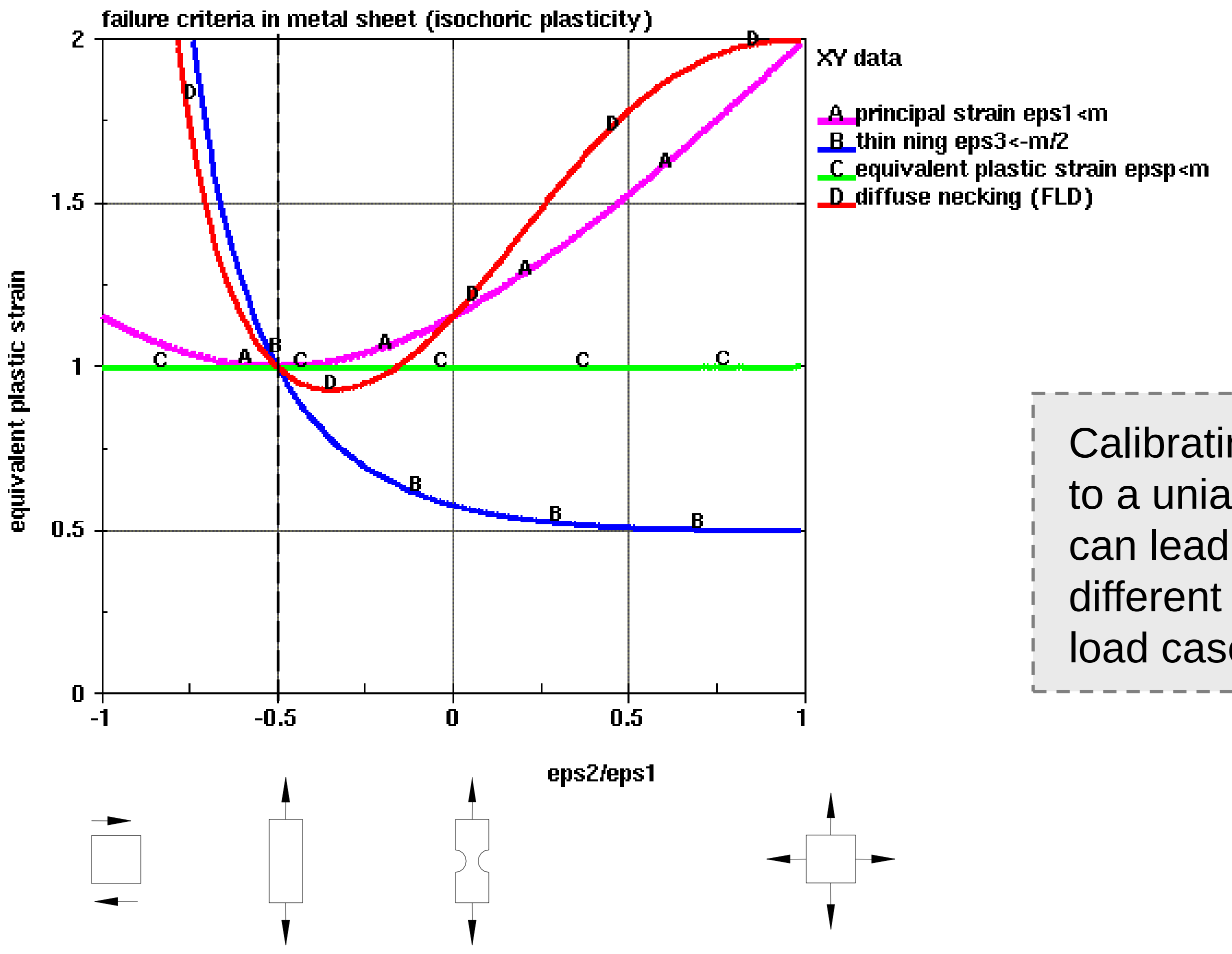
Failure strain under uniaxial tension is set the same in all 4 criteria.

Thinning and FLD predict no failure under pure shear loading.

Failure models in the plane of major strain vs. *b*

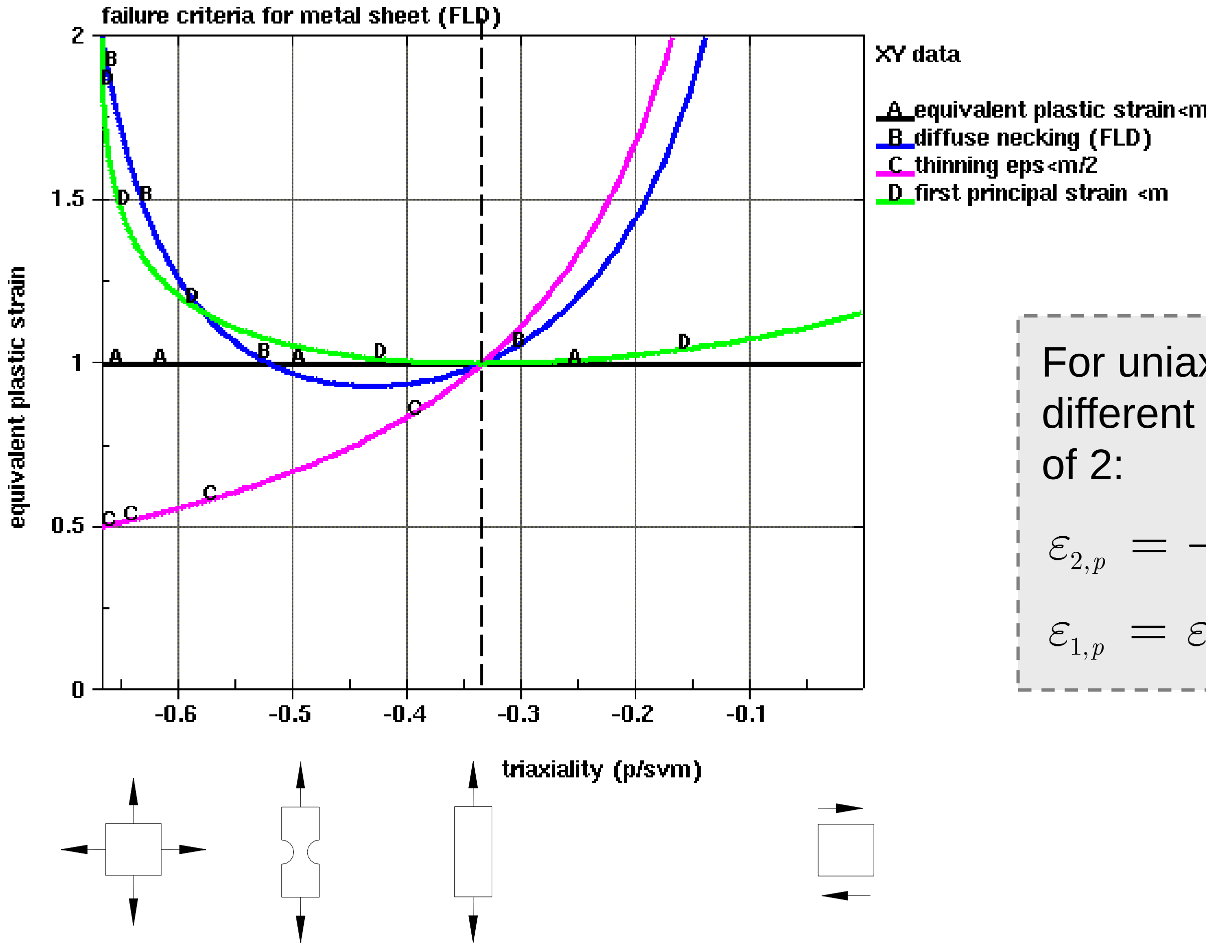


Failure models in the plane equivalent plastic strain vs. *b*



Calibrating different criteria to a uniaxial tension test can lead to considerably different response in other load cases.

Failure models: equivalent plastic strain vs. triaxiality

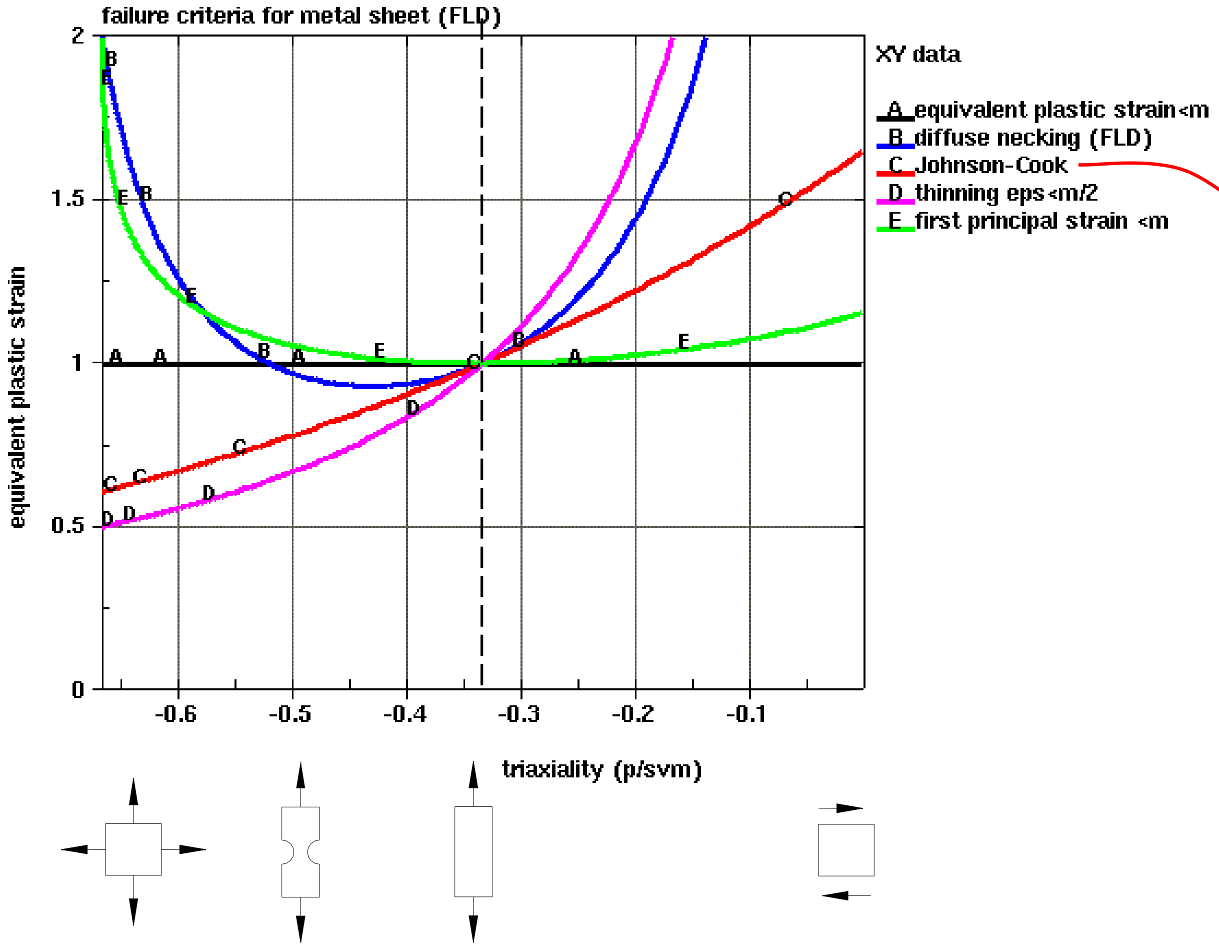


For uniaxial and biaxial tension different criteria lead to a factor of 2:

$$\varepsilon_{2,p} = -0.5\varepsilon_{1,p} \Rightarrow \varepsilon_p = \varepsilon_{1,p}$$

$$\varepsilon_{1,p} = \varepsilon_{2,p} \Rightarrow \varepsilon_p = 2\varepsilon_{1,p}$$

Johnson-Cook criterion (Hancock-McKenzie)



$$\varepsilon_{pf} = d_1 + d_2 e^{d_3 \frac{p}{\sigma_{vm}}}$$

$$d_1 = 0$$

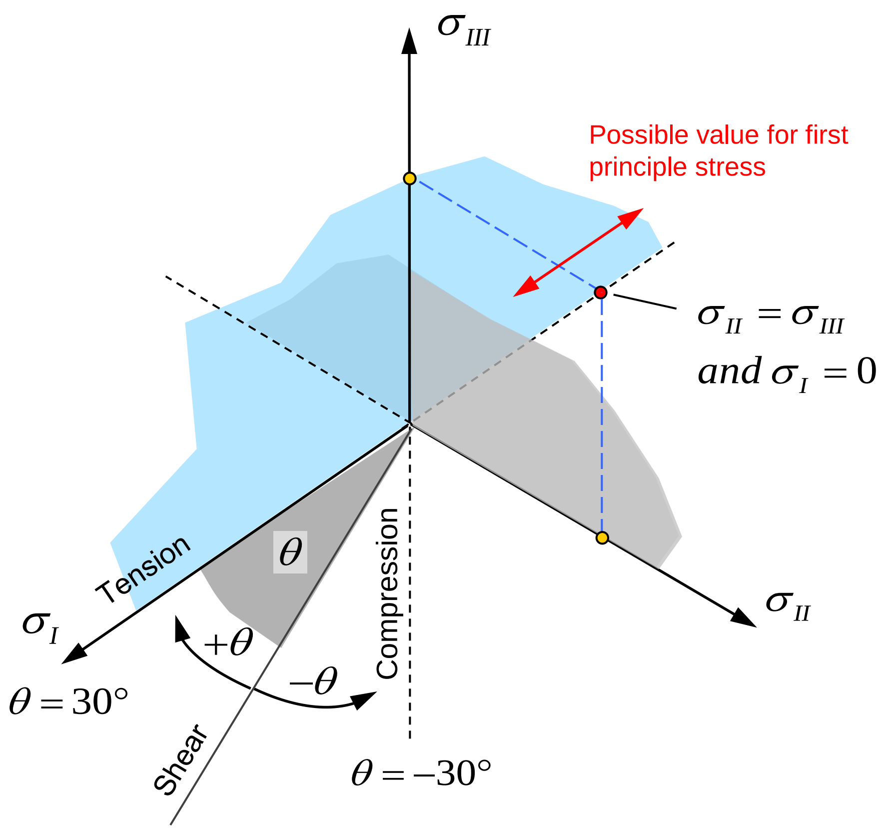
$$d_3 = \frac{3}{2}$$

$$d_2 = \varepsilon_{1f} e^{-\frac{1}{2}}$$

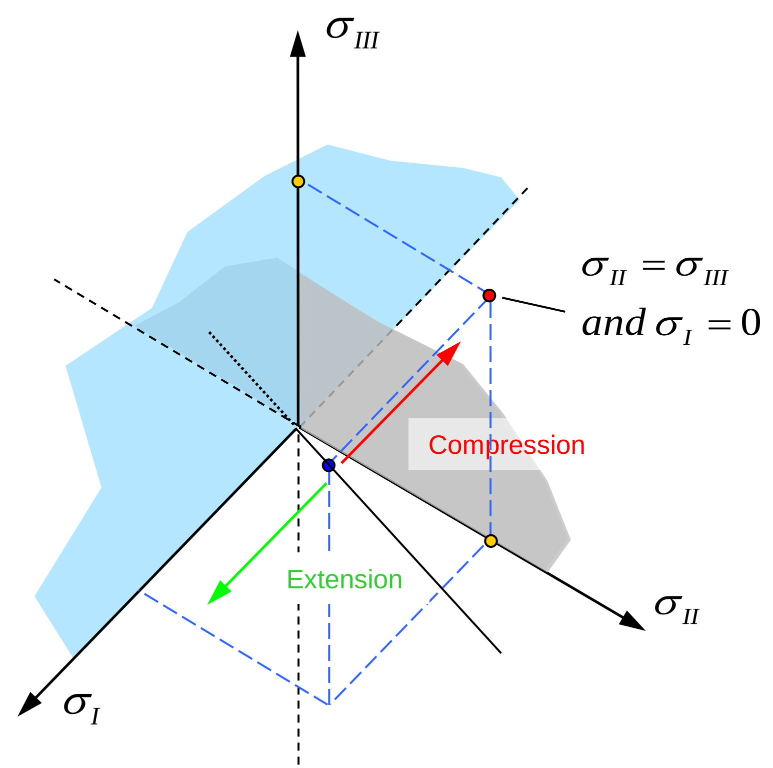
Johnson-Cook and FLC are very close in the neighborhood of uniaxial tension.

Parametrized for 3D stress space

Lode-angle: Extension- and Compression test

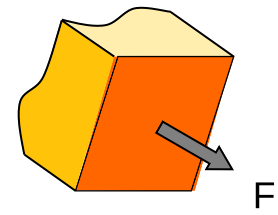


View parallel and on hydrostatic axis (perpendicular to deviator plane)

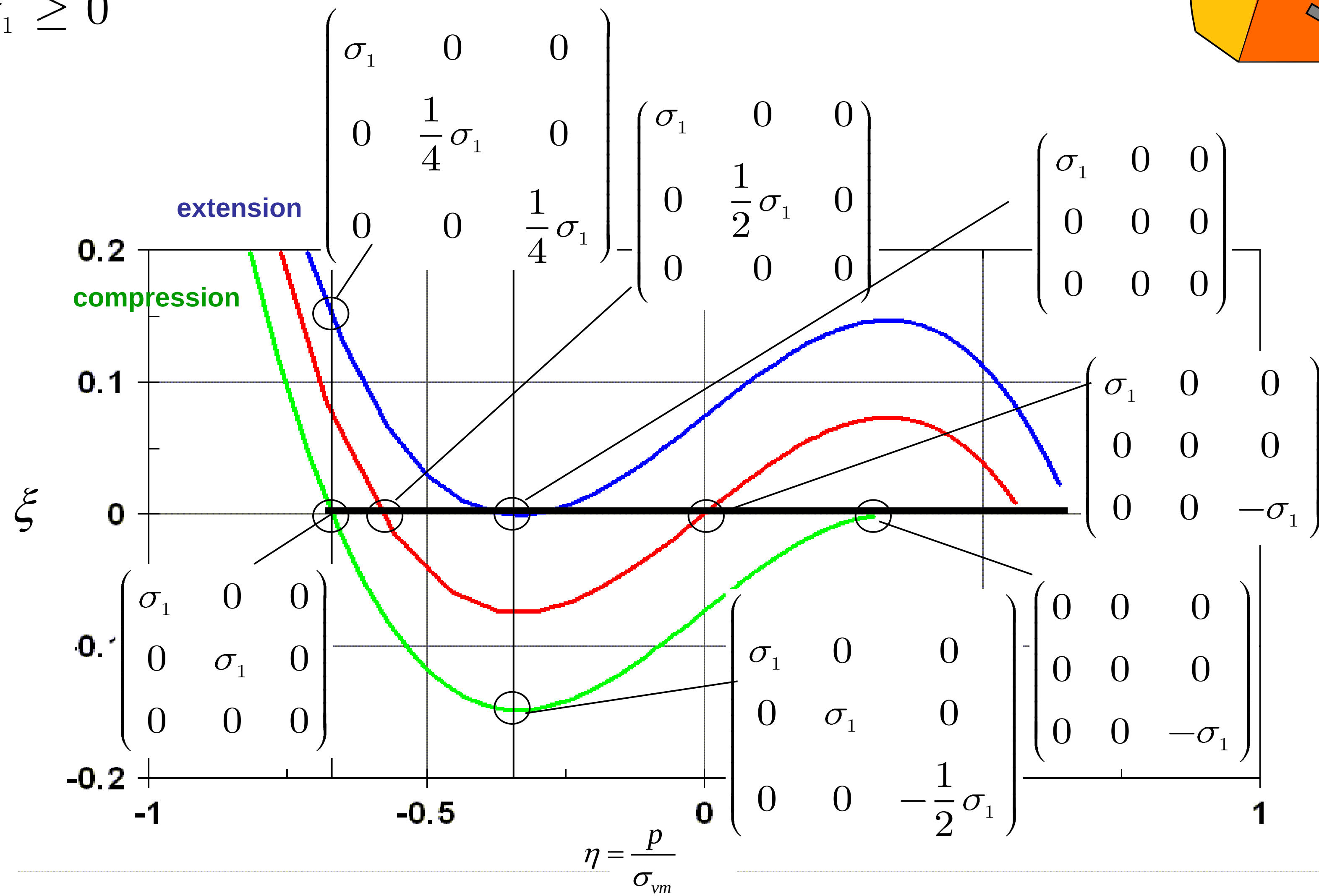


View **not** parallel to hydrostatic axis

3D-Stress state parameterised for volume elements

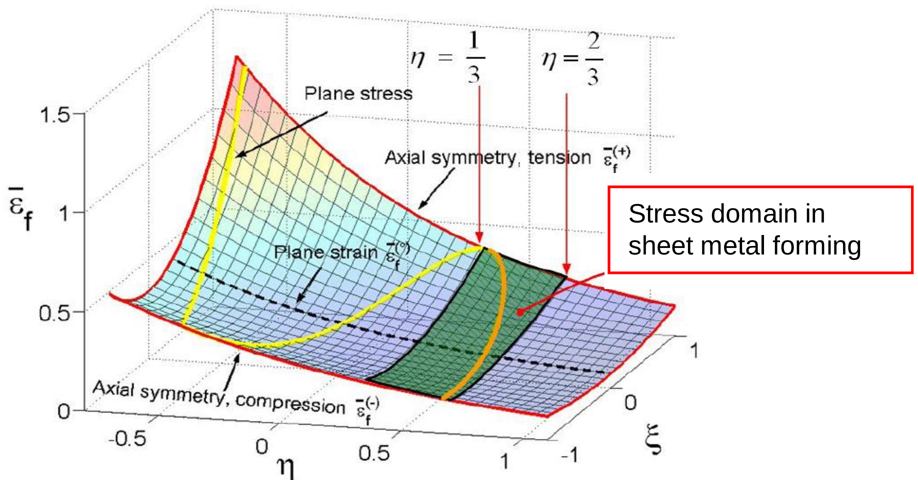


$$\sigma_1 \geq 0$$



Invariants in 3D stress space

Failure criterion extd. for 3D solids



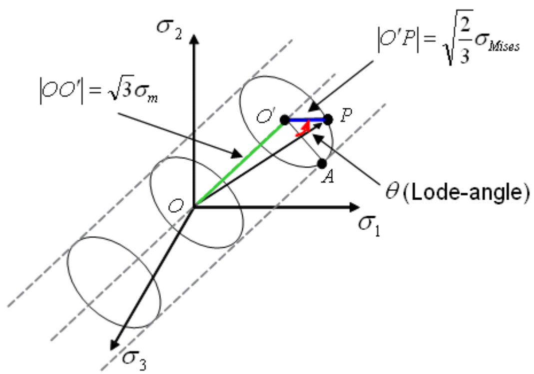
[Source: Wierzbicki et al.]

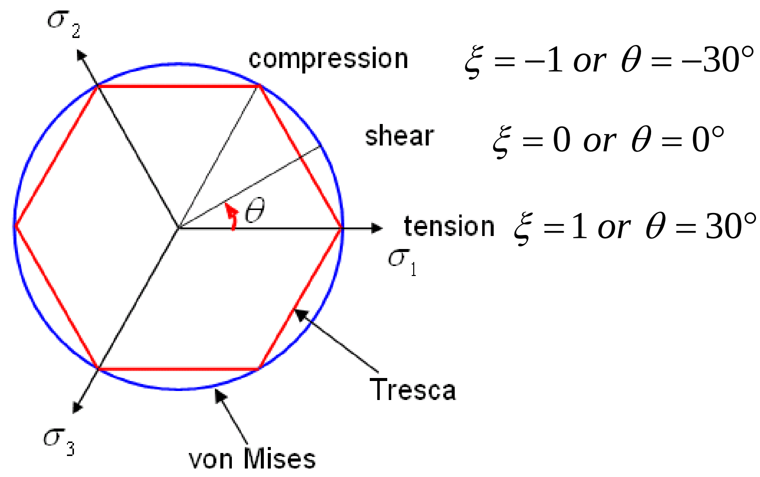
Parameter definition

$$\eta = \frac{\sigma_m}{\sigma_{vM}} = \frac{I_1}{3\sigma_{vM}}$$

$$\xi = \frac{27}{2}\frac{J_3}{\sigma_{vM}^3} \quad \text{mit} \quad J_3 = s_1 s_2 s_3$$

Haigh-Westergaard-coordinates

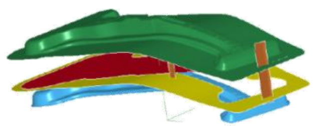




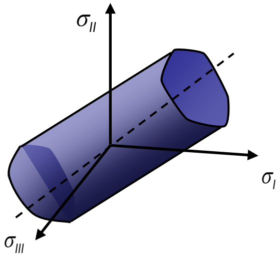
Failure Prediction for UHSS:
Adding some damage

Closing the process chain: Standard materials / state of the art

Forming simulation



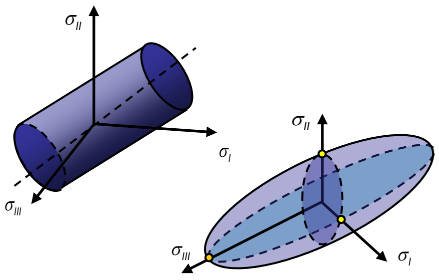
- **Hill based models**
- Anisotropiy of yield surface
- Kinematic/Isotropic hardening
- State of the art: Failure by FLD (post-processing)
- NEW: Computation of damage (GISSMO)



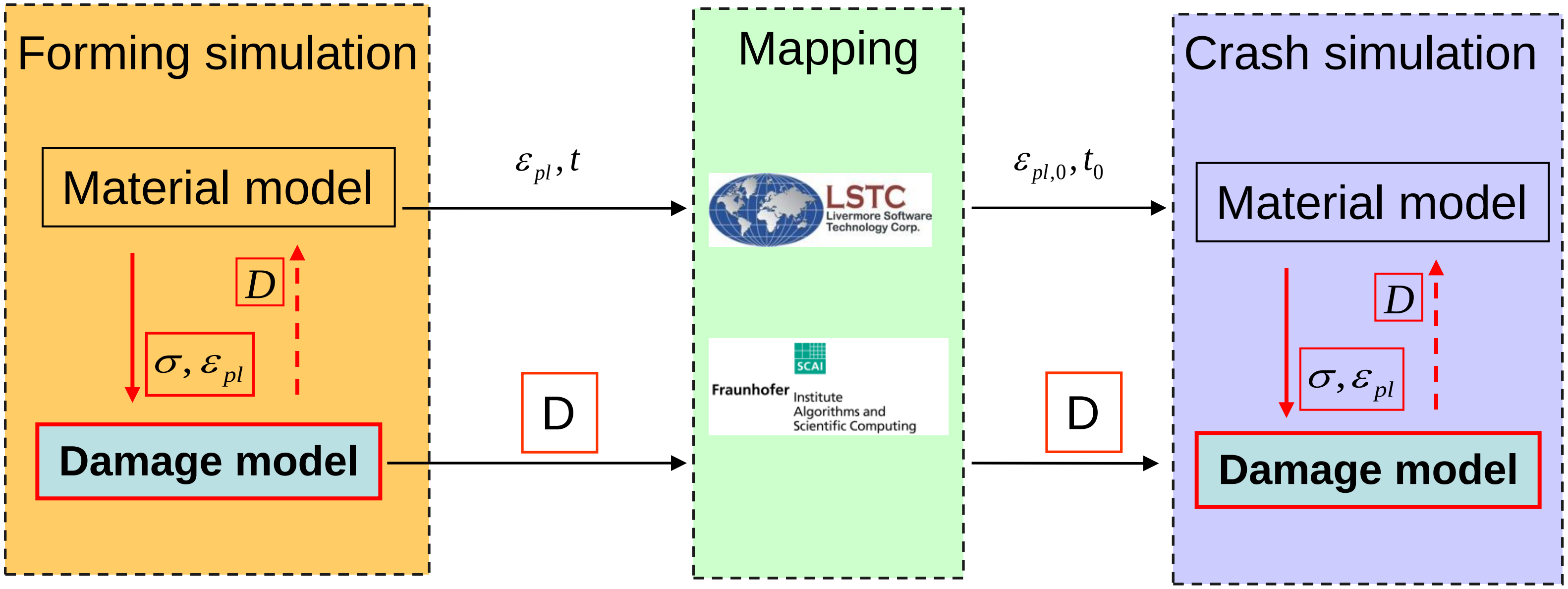
Mapping

Crash simulation

- **v. Mises or Gurson model**
- Strain rate dependency
- Isotropic hardening
- Damage evolution
- Failure models (mapping of damage variable)



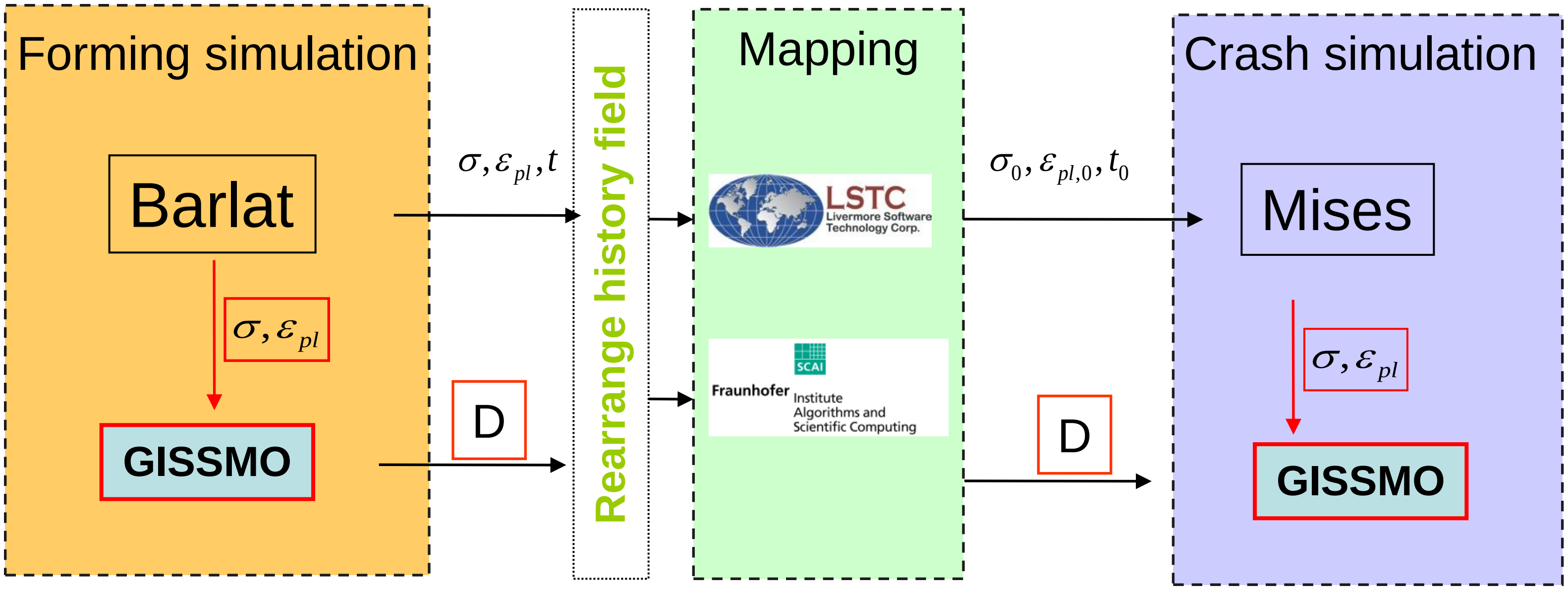
Produceability to Serviceability: Modular Concept



Modular Concept:

- Proven material models for both disciplines are retained
- Use of one continuous damage model for both

Produceability to Serviceability: Modular Concept
Current status in 971R5



Ebelsheiser, Feucht & Neukamm [2008]
Neukamm, Feucht, DuBois & Haufe [2008-2010]

GISSMO – a short description

Effective stress concept (similiar to MAT_81/224 etc.)

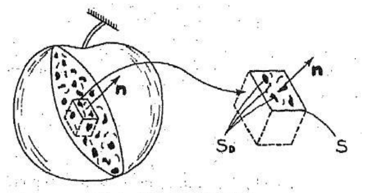
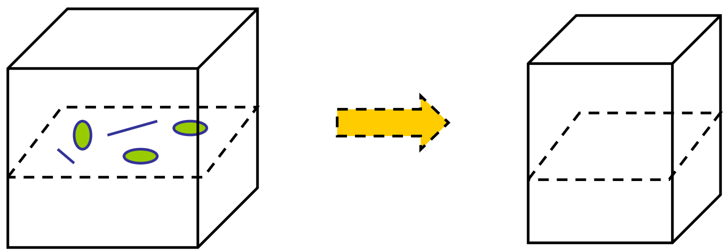


Fig. 1 Damaged element

J. Lemaitre, A Continuous Damage Mechanics Model for Ductile Fracture



Overall Section Area containing micro-defects

$$S$$

Reduced (“effective“) Section Area

$$\hat{S} < S$$

Measure of Damage

$$D = \frac{S - \hat{S}}{S}$$

Reduction of effective cross-section leads to reduction of tangential stiffness

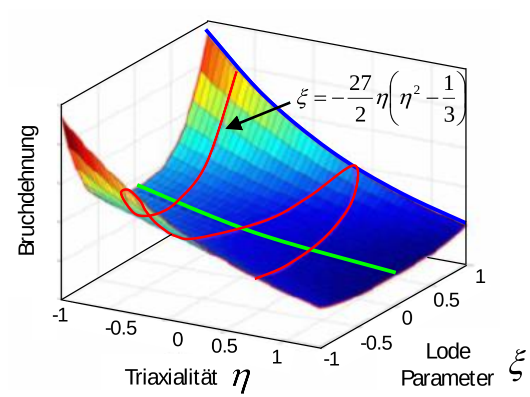
→ Phenomenological description

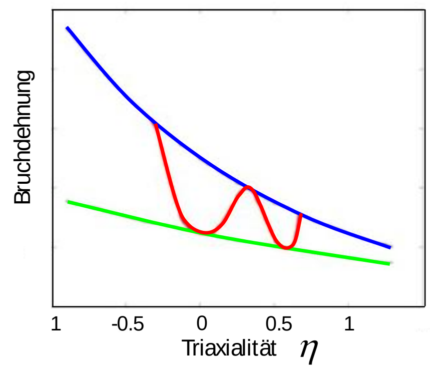
$$\boldsymbol{\sigma}^* = \boldsymbol{\sigma}(1 - D)$$

GISSMO

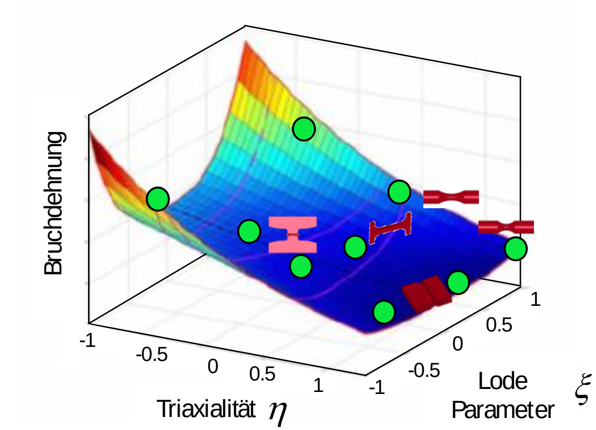
Failure criterion for plane stress and extd. for 3D solids

Shells (2D)





Solids (3D)



- For shells (2D with the assumption of plane stress) triaxility and Lode angle depend on each other.

  → fracture strain is a function of the triaxiality

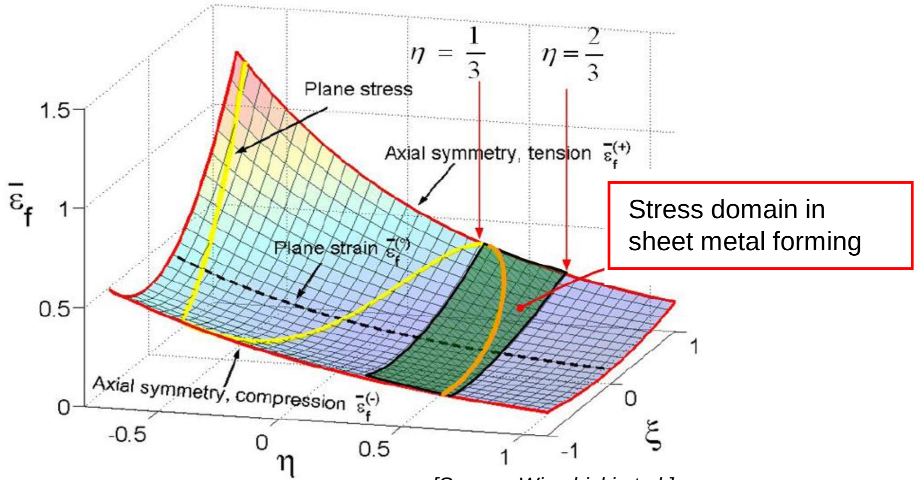
- For Solids (3D) both the Lode angle and triaxiality are independent

  → fracture strain is a function of triaxiality and Lode angle

Baseran [2010]

GISSMO

Failure criterion extd. for 3D solids



[Source: Wierzbicki et al.]

Parameter definition

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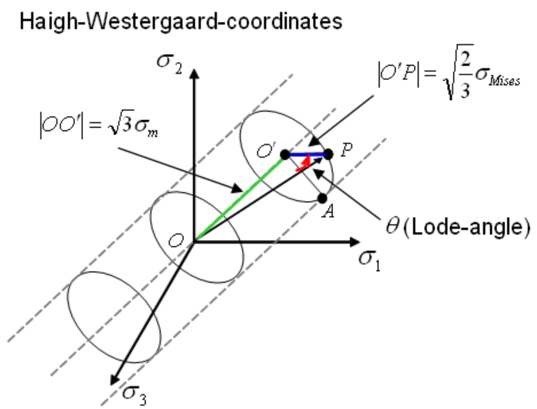
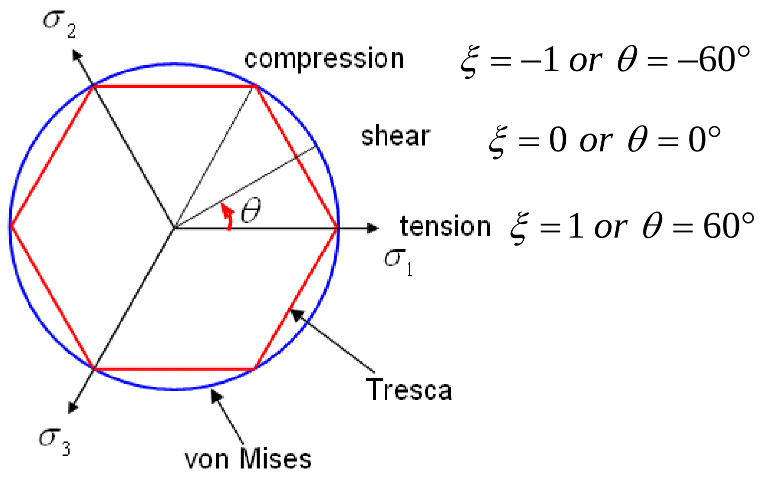
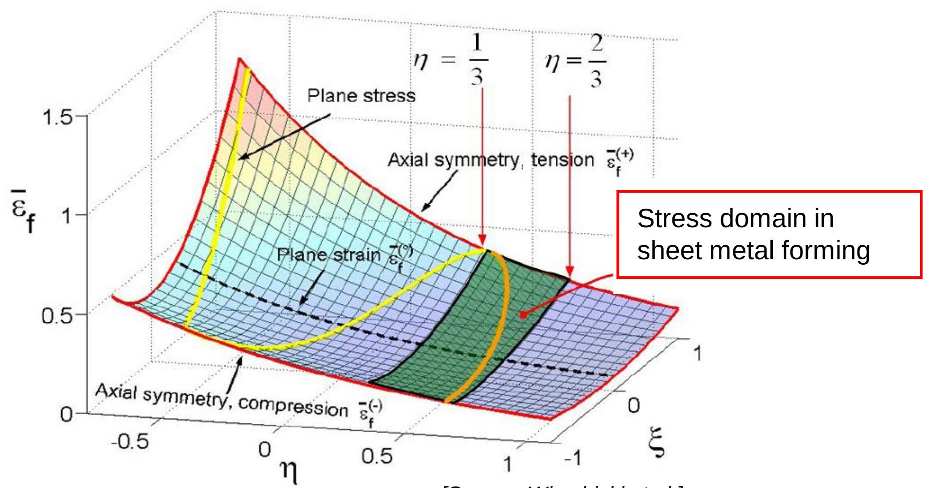




GISSMO

Failure criterion extd. for 3D solids



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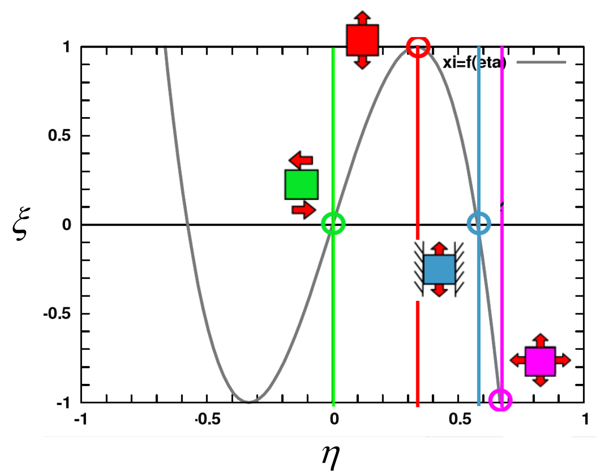
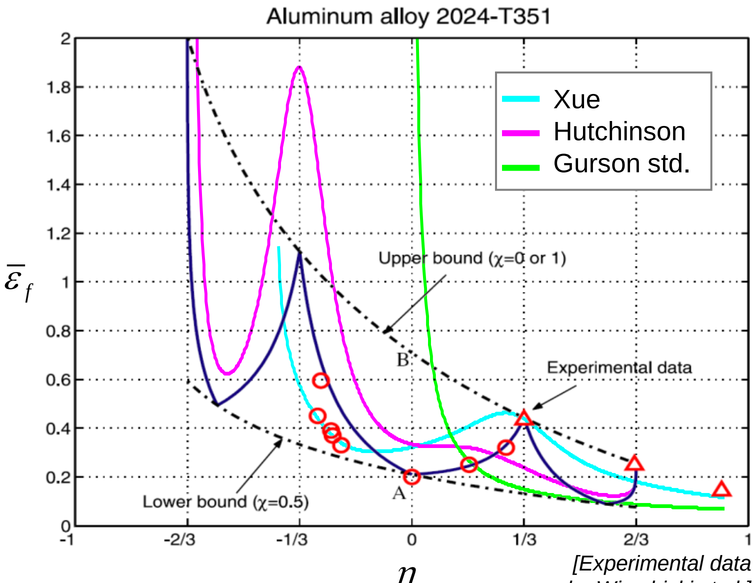
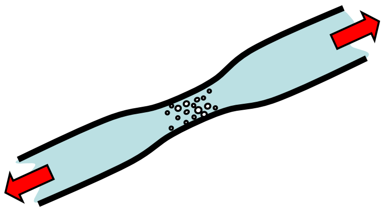




[Experimental data by Wierzbicki et al.]

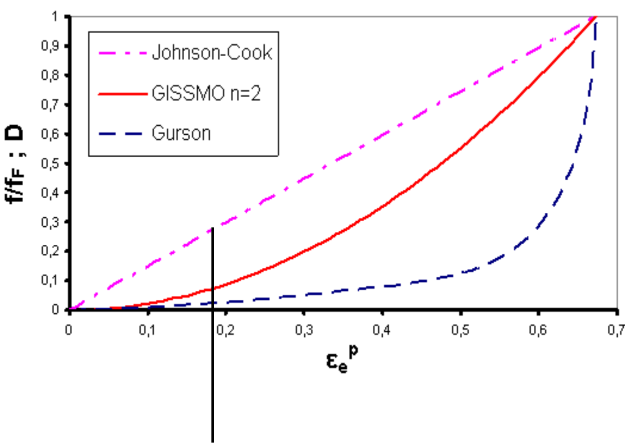
GISSMO - a short description

Ductile damage and failure



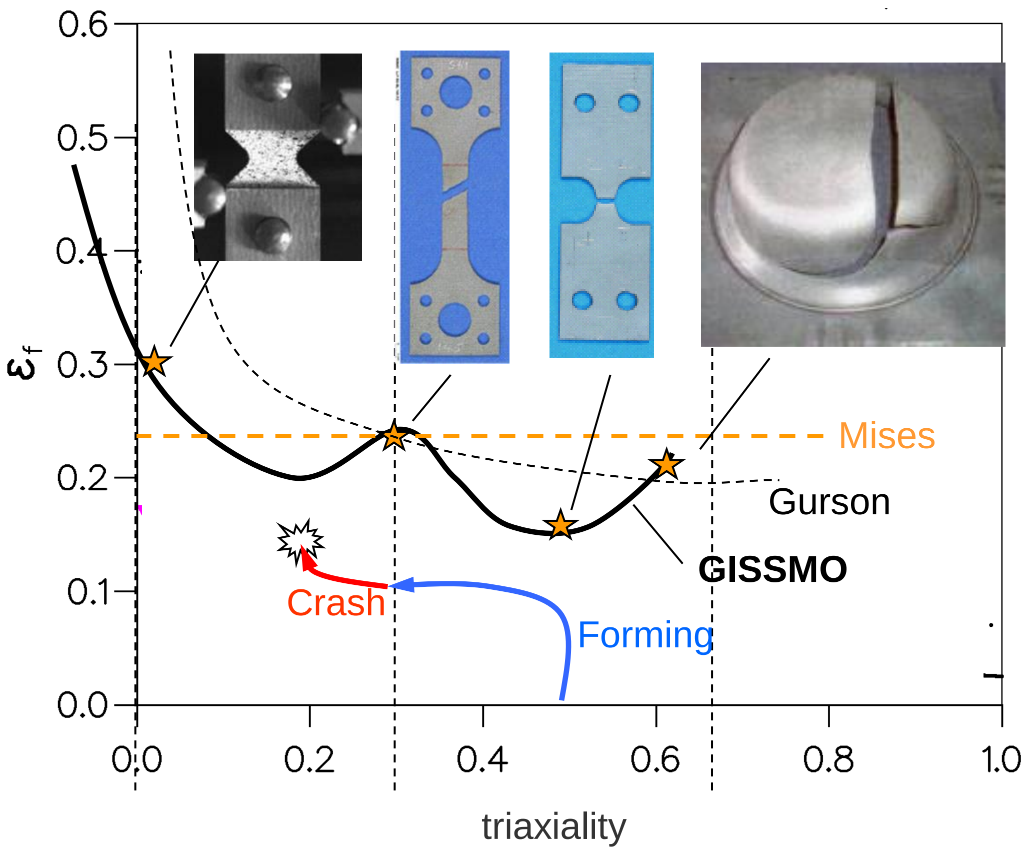
Damage Evolution

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



Damage overestimated for linear damage accumulation

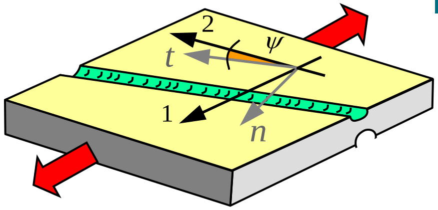
Failure Curve



Wierzbicki et al. (and many more…) / Neukamm, Feucht, DuBois & Haufe [2008-2011]

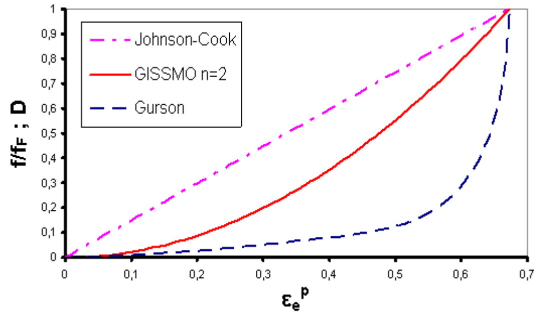
GISSMO – a short description

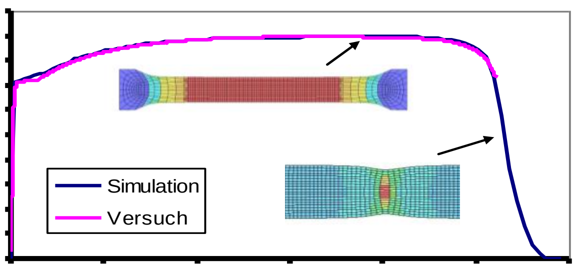
Engineering approach for instability failure



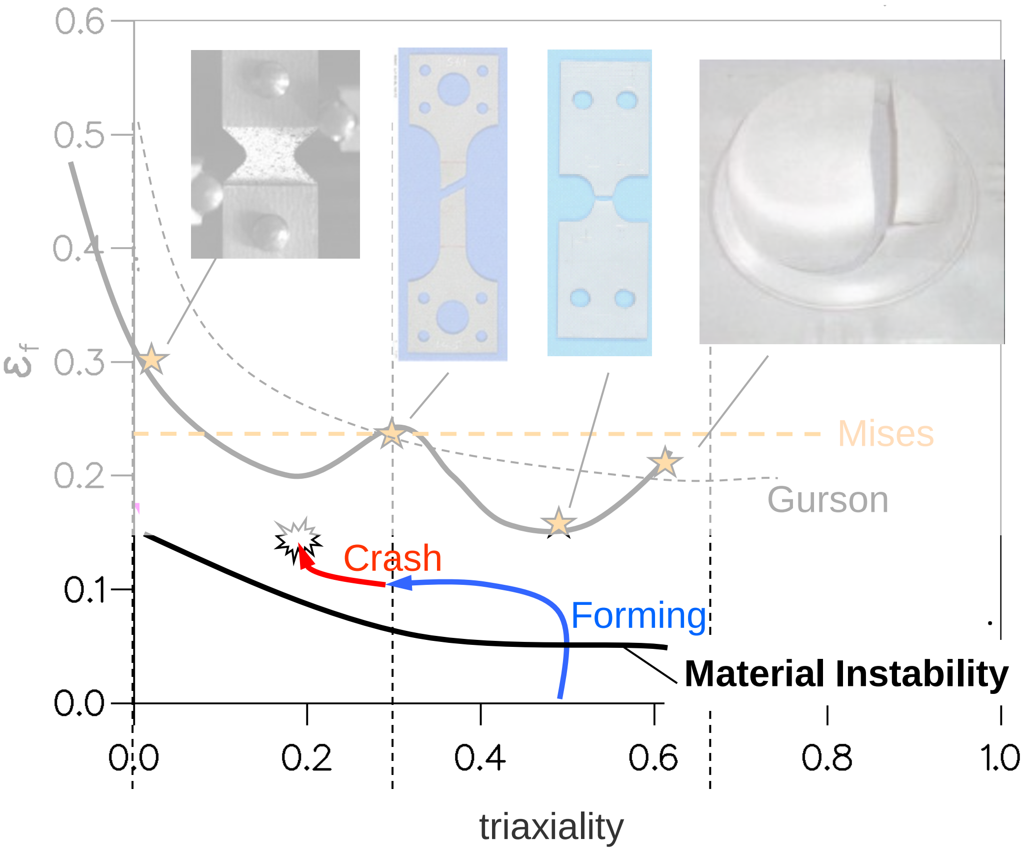
Evolution of Instability

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





Material Instability

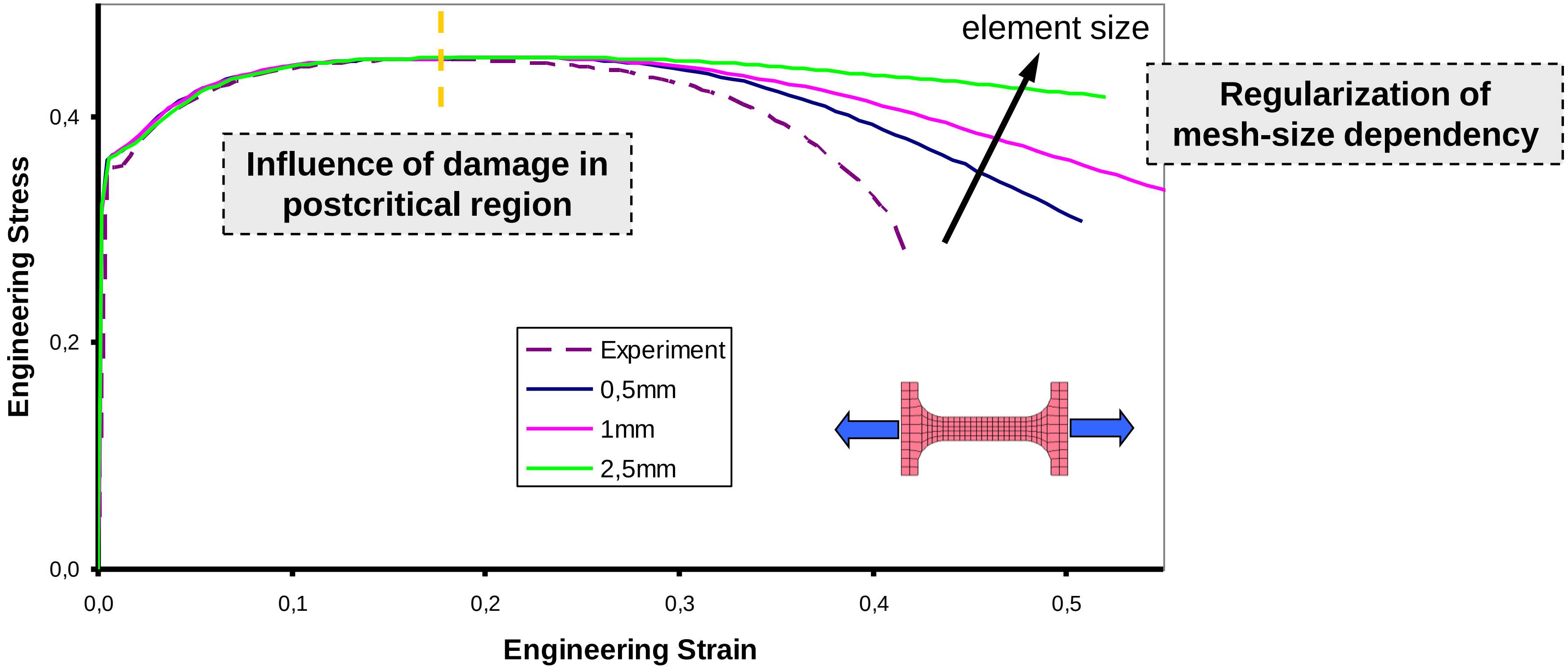


Neukamm, Feucht, DuBois & Haufe [2008-2011]

GISSMO – a short description

Inherent mesh-size dependency of results in the post-critical region

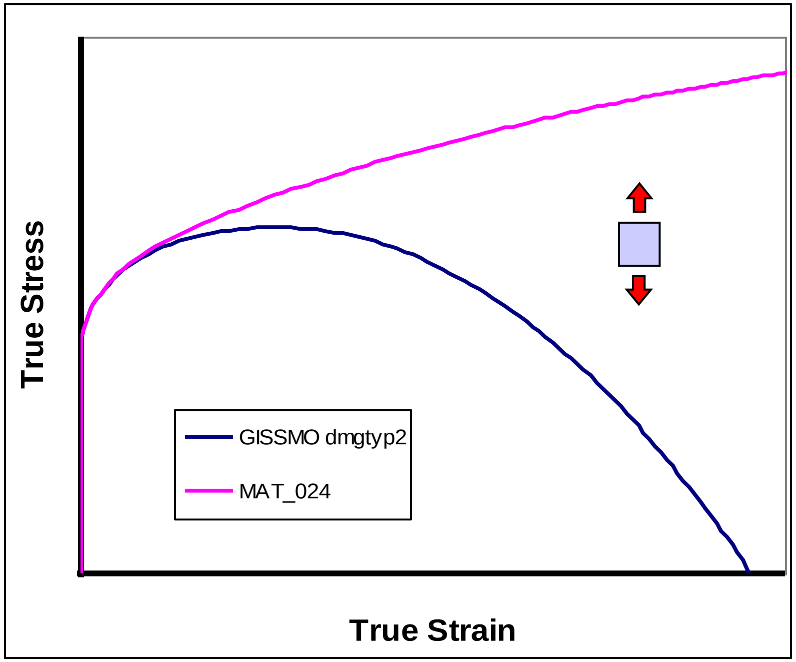
Simulations of tensile test specimen with different mesh sizes



GISSMO – a short description
Generalized Incremental Stress State dependent damage MOdel

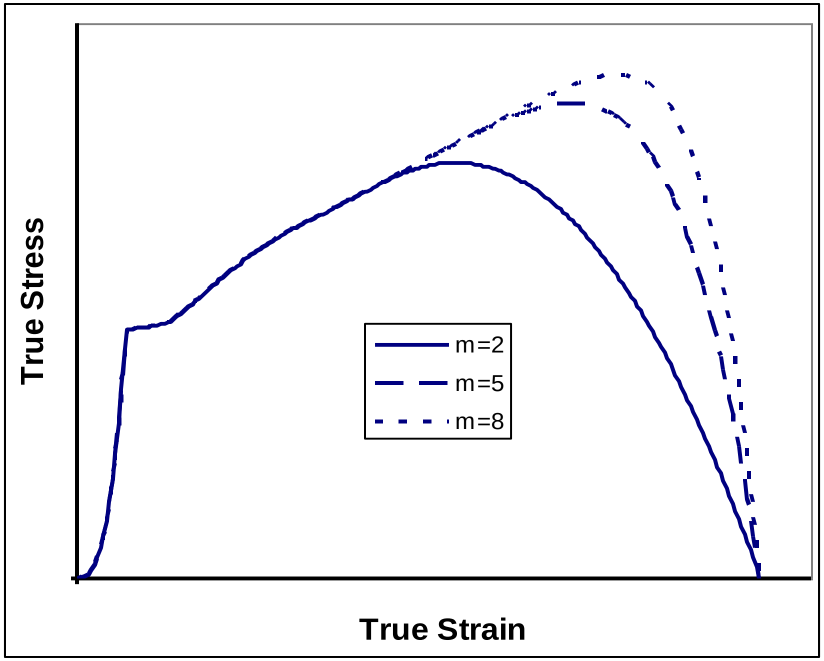
DMGTYP: Flag for coupling (Lemaitre)

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



DCRIT, FADEXP: Post-critical behavior

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

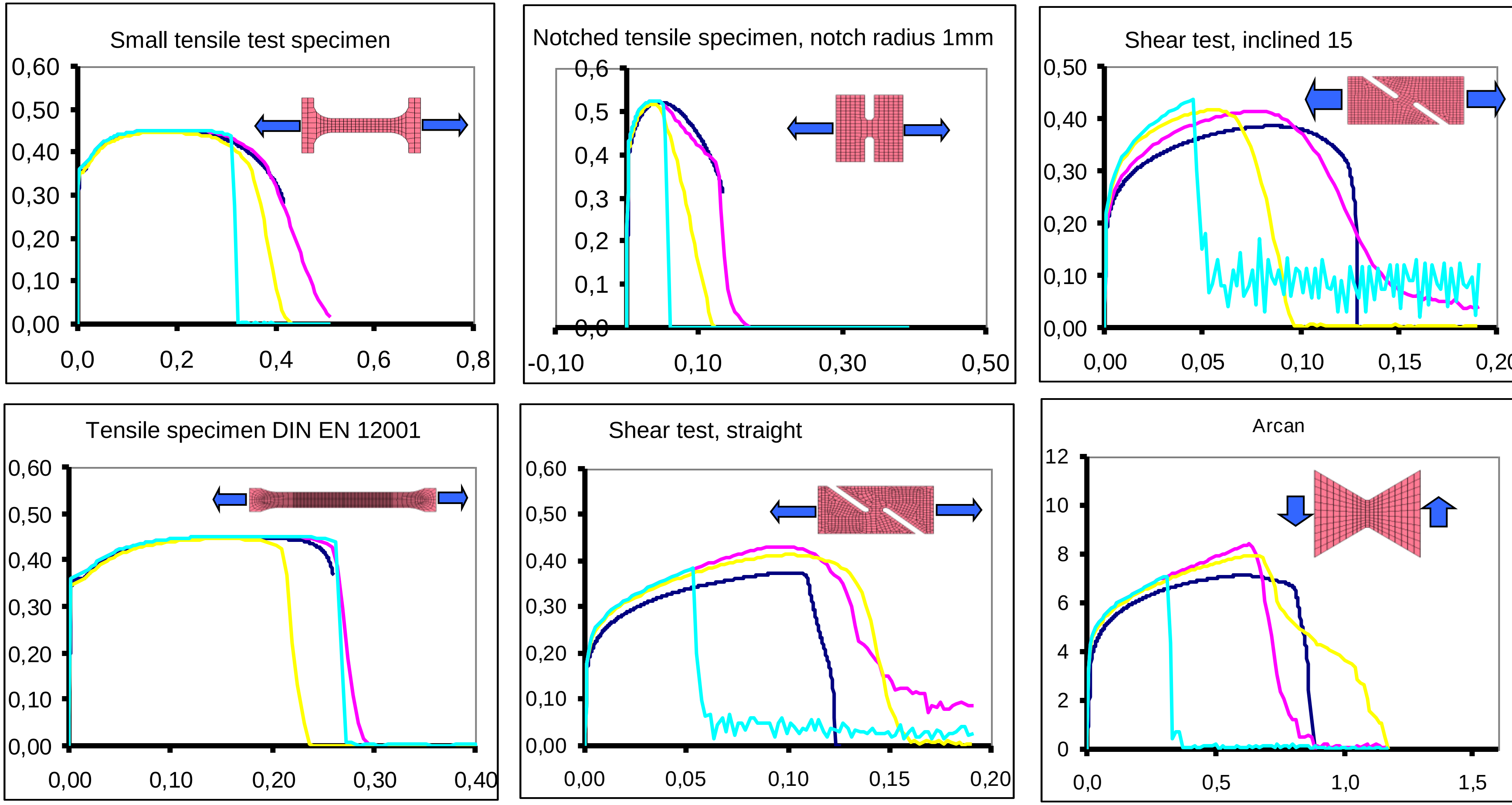


GISSMO vs. Gurson vs. MAT_24/81

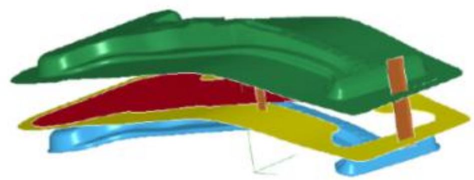
Comparison of experiments and simulations

IWM
Institut Werkstoffmechanik

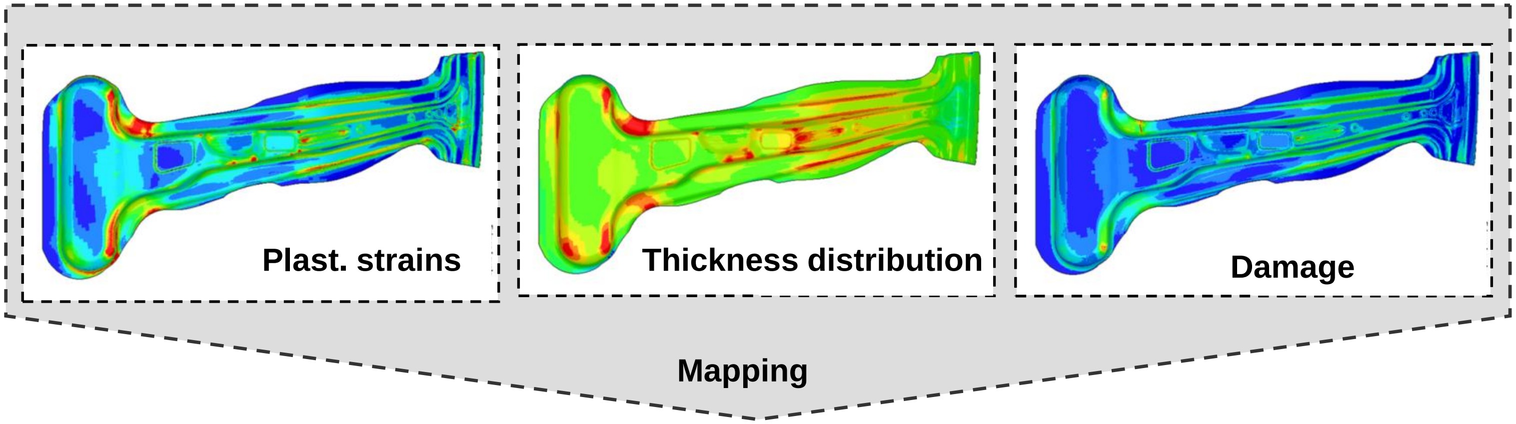
Versuch
GISSMO
Gurson
constant (v. Mises)

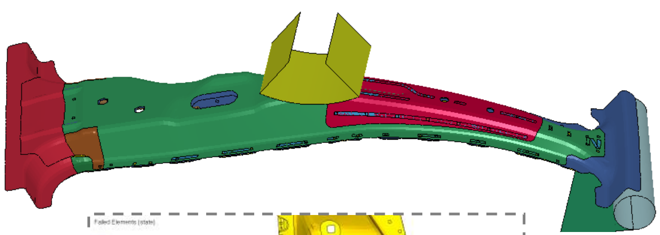


Process chain with GISSMO

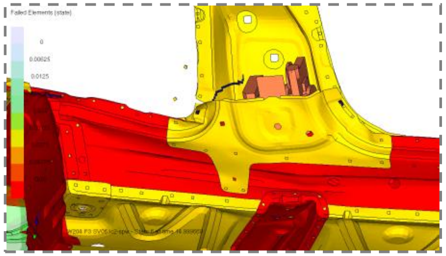


Forming simulation:
***MAT_36 (Barlat 89)**
***MAT_ADD_EROSION**
(GISSMO)





Crash Simulation:
***MAT_24 (Mises)**
***MAT_ADD_EROSION**
(GISSMO)



Summary

Features of GISSMO:

- Use of existing material models and respective parameters
- Constitutive model and damage formulation are treated separately
- Allows for the calculation of pre-damage for forming and crashworthiness simulations
- Characterization of materials requires a variety of tests
- Offers features for a comprehensive treatment of damage in forming simulations and allows simply carrying aver to crash analysis

Thank you for your attention!