GISSMO – Material Modeling with a sophisticated Failure Criteria

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Motivation

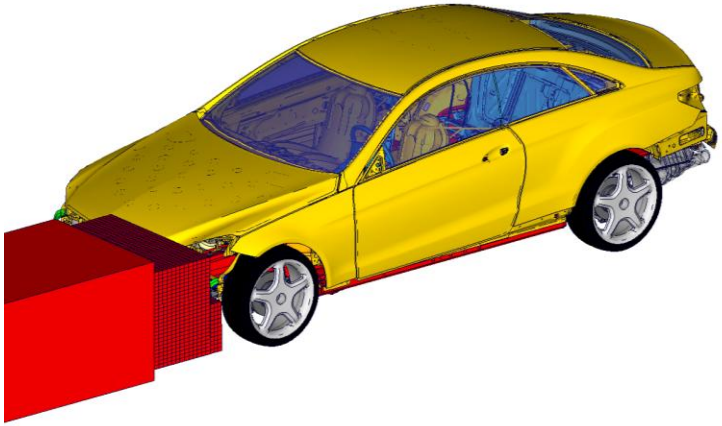
Technological challenges in the automotive industry

Weight

Safety requirements

New materials

- Composites
- High strength steel
- Light alloys
- Polymers

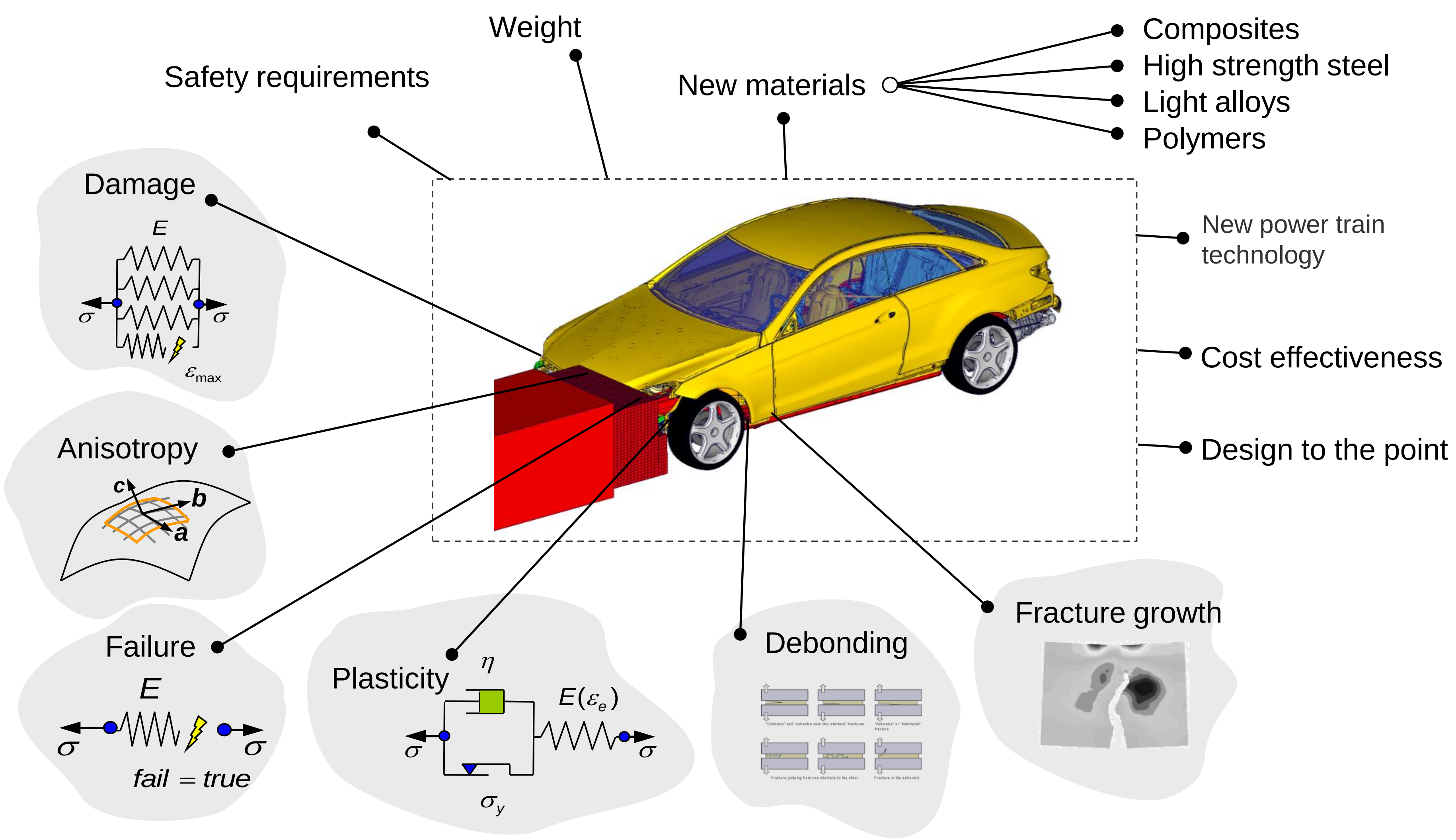


New power train technology

Cost effectiveness

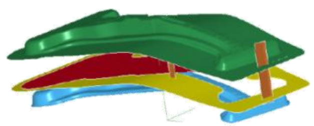
Design to the point

Technological challenges in the automotive industry

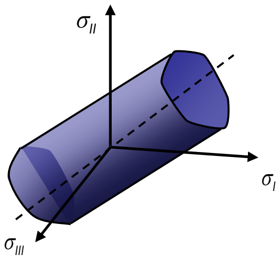


Closing the process chain: Standard materials / state of the art

Forming simulation



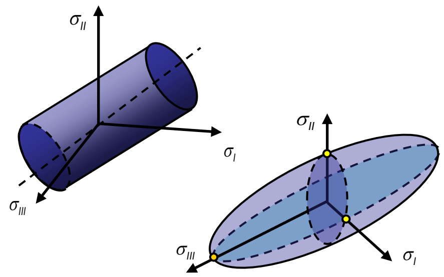
- **Hill based models**
- Anisotropiy of yield surface
- Kinematic/Isotropic hardening
- State of the art: Failure by FLD (post-processing)
- NEW: Computation of damage (GISSMO)



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

Some thoughts on damage formulations

- Is path dependence critical for the target application (crashworthiness)?
- Is a phenomenological model good enough?
- Should we take orthotropic effects into account (i.e. tensorial damage) or is a scalar formulation fine?
- Shall we accumulate the damage value based on the stress state or on the strain state?
- Shall the damage accumulation be isotropic, orthotropic or at least pressure dependent?

Isotropic (scalar) damage

Effective stress concept (similar to MAT_81/120/224 etc.)

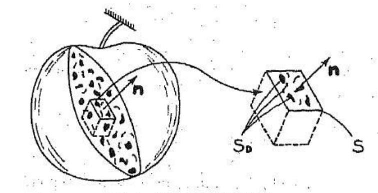
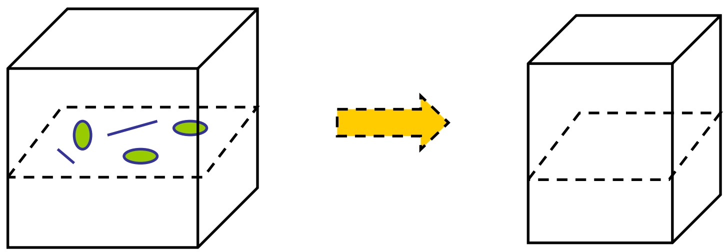


Fig. 1 Damaged element

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

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

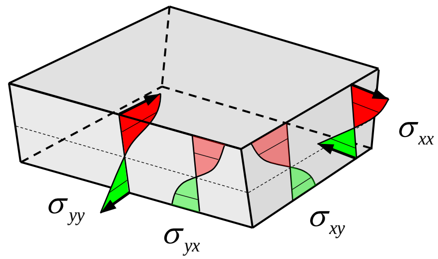
Reduction of effective cross-section leads to reduction of tangential stiffness

→ Phenomenological description

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

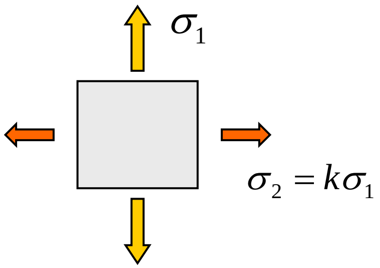
Plane stress condition

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



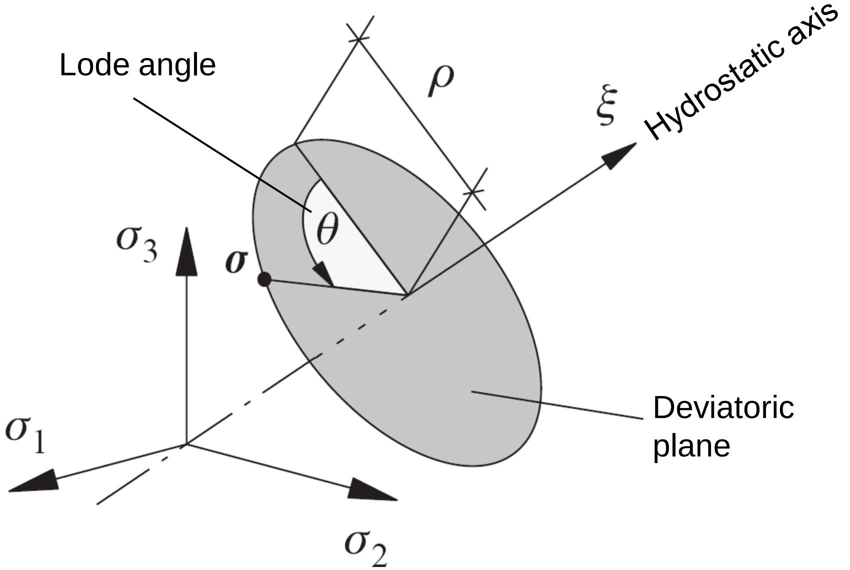
$$\boldsymbol{\sigma} = \begin{bmatrix} \sigma_1 & 0 & 0 \\ 0 & k\sigma_1 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

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

Definition of stress triaxiality:

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

Haigh-Westergaard coordinates in principle stress space



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

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

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

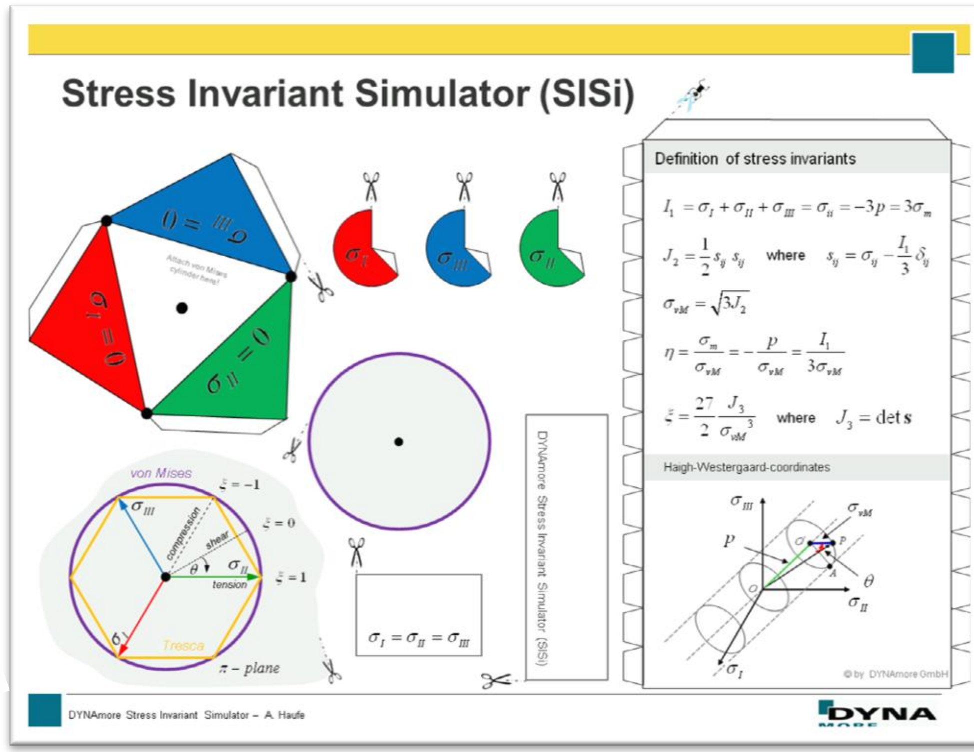
Definition of stress triaxiality: $\eta = \dfrac{p}{\sigma_{vm}}$

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:



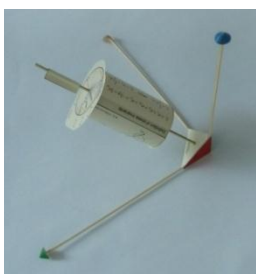
A toy to visualize stress invariants

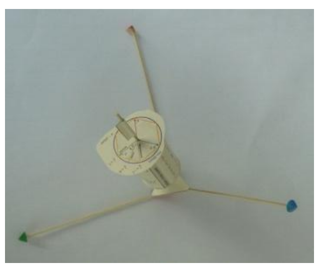
(downloadable from the www.dynamore.se)

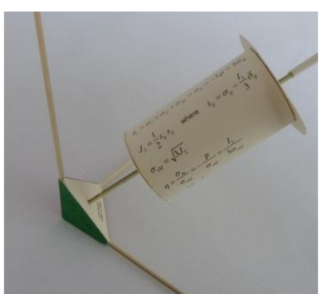
Crafting instructions

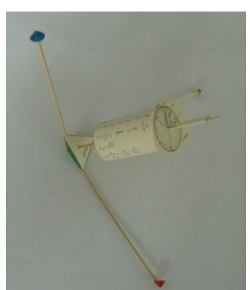
- Page 2 of the set may be added for further clarification of the triaxiality variable.

Final shape of toy

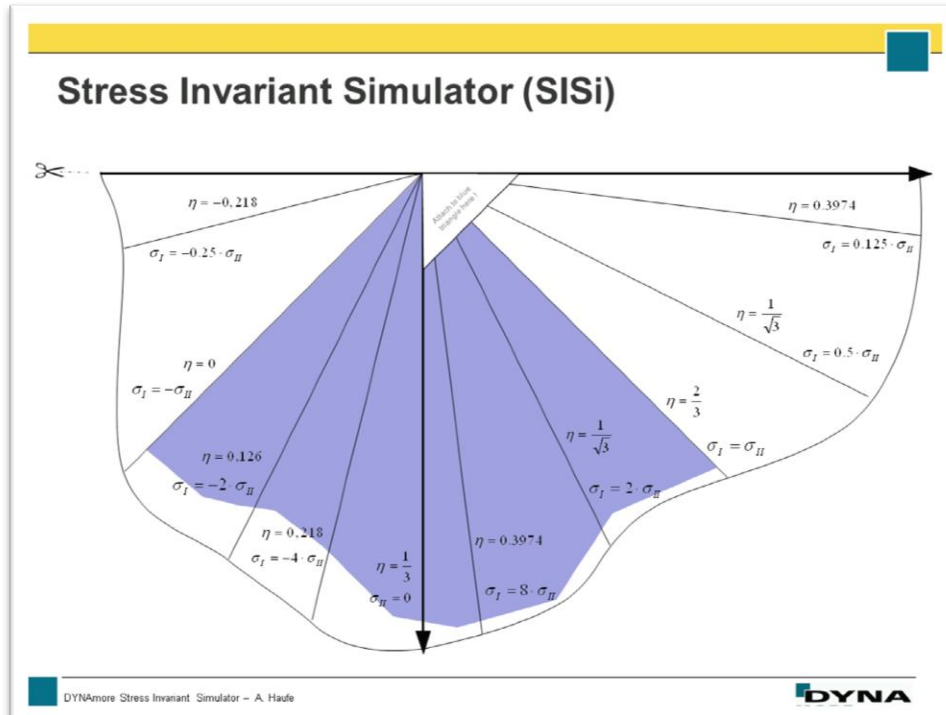








page 2:



Plane stress parameterised for shells

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

Bounds:

Compression

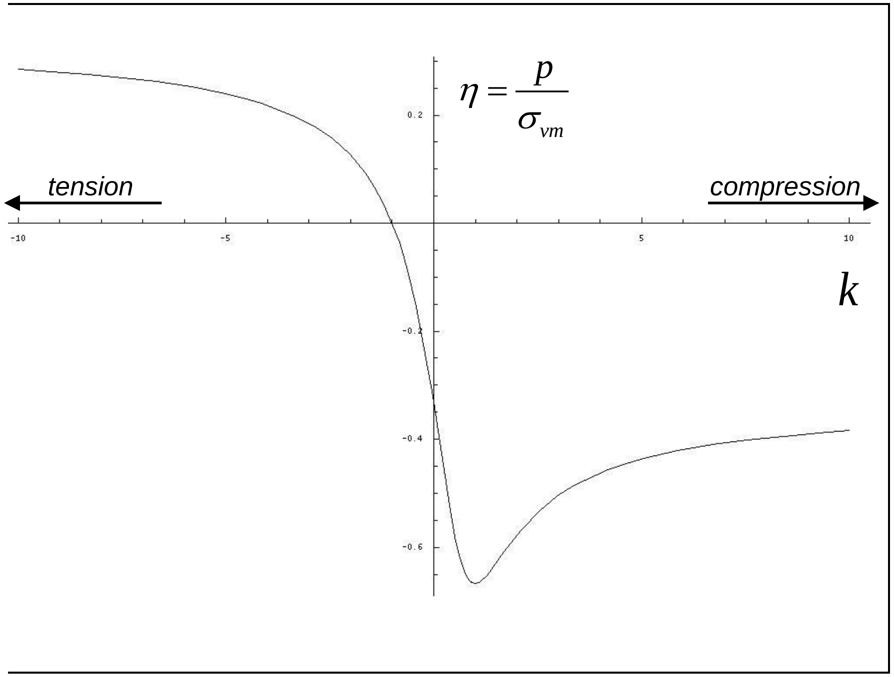
$$\lim_{k\to\infty}\eta = \lim_{k\to\infty} -\frac{(k+1)}{3\sqrt{1+(k-1)k}}\mathrm{sign}(\sigma_1) = -\frac{1}{3}\mathrm{sign}(\sigma_1)$$

Tension

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

Biaxial tension

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



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

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

Four criteria

Principal strain:

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

Equivalent plastic strain:

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

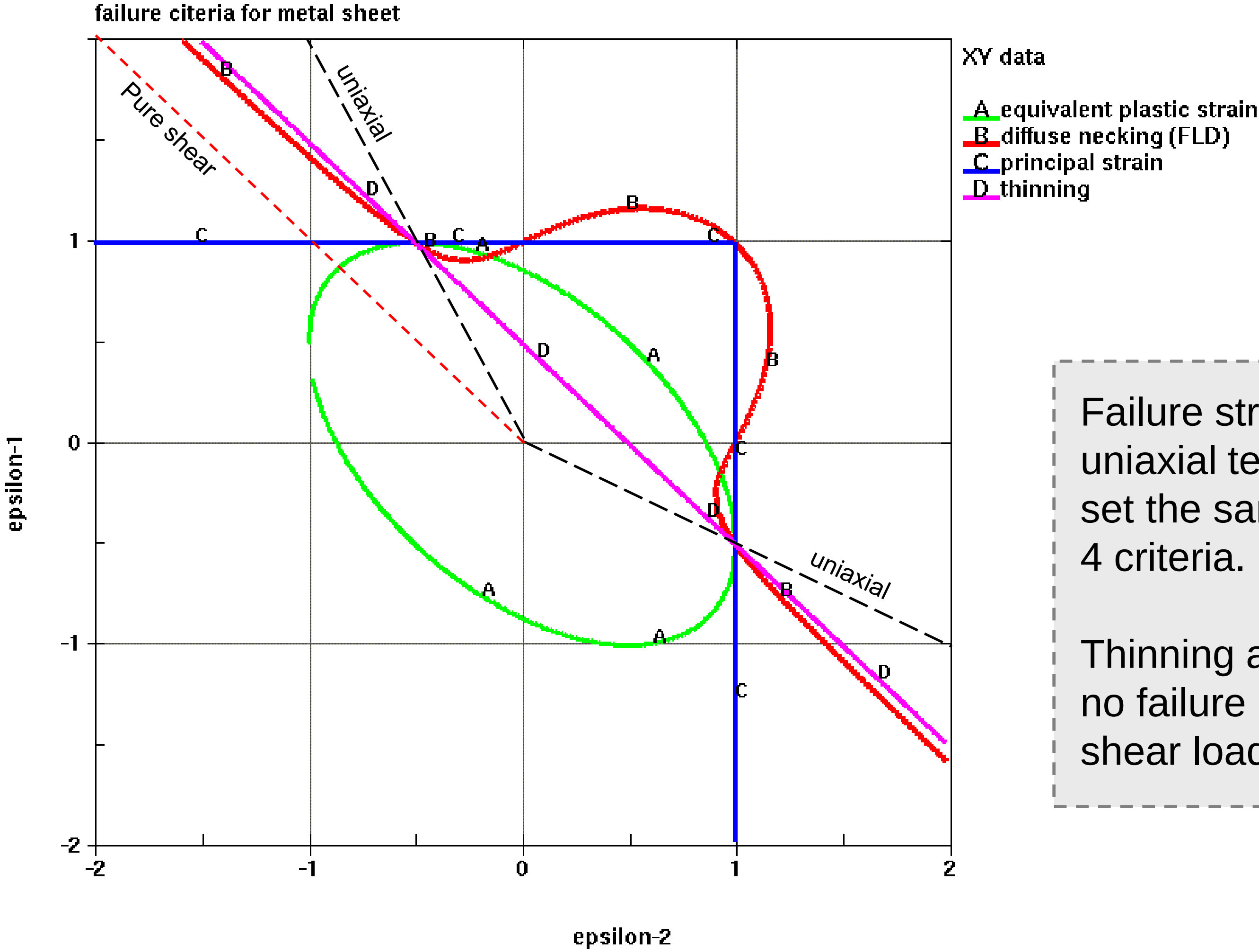
Thinning:

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

Diffuse necking:

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

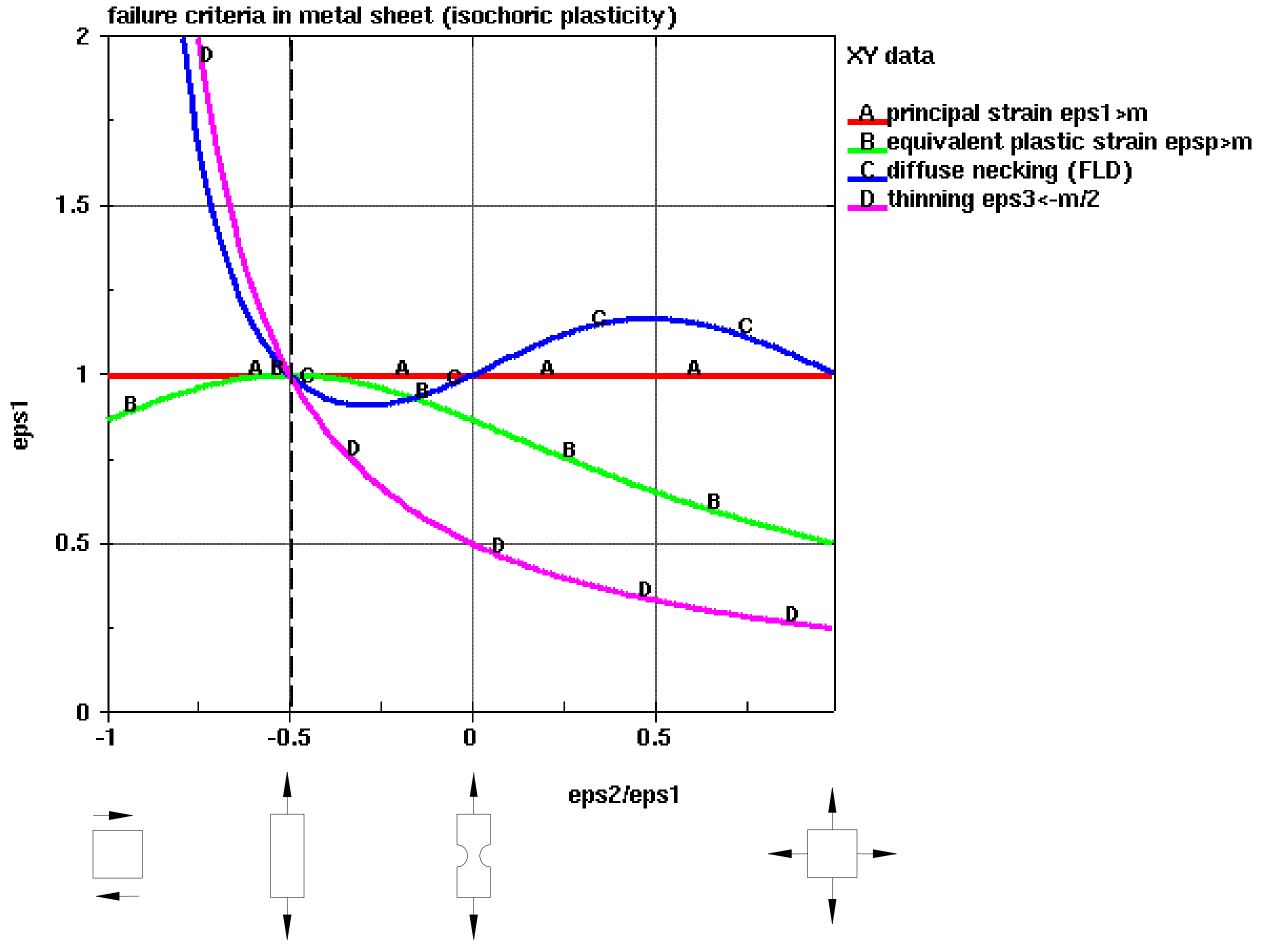
Failure models in the plane of principal strain



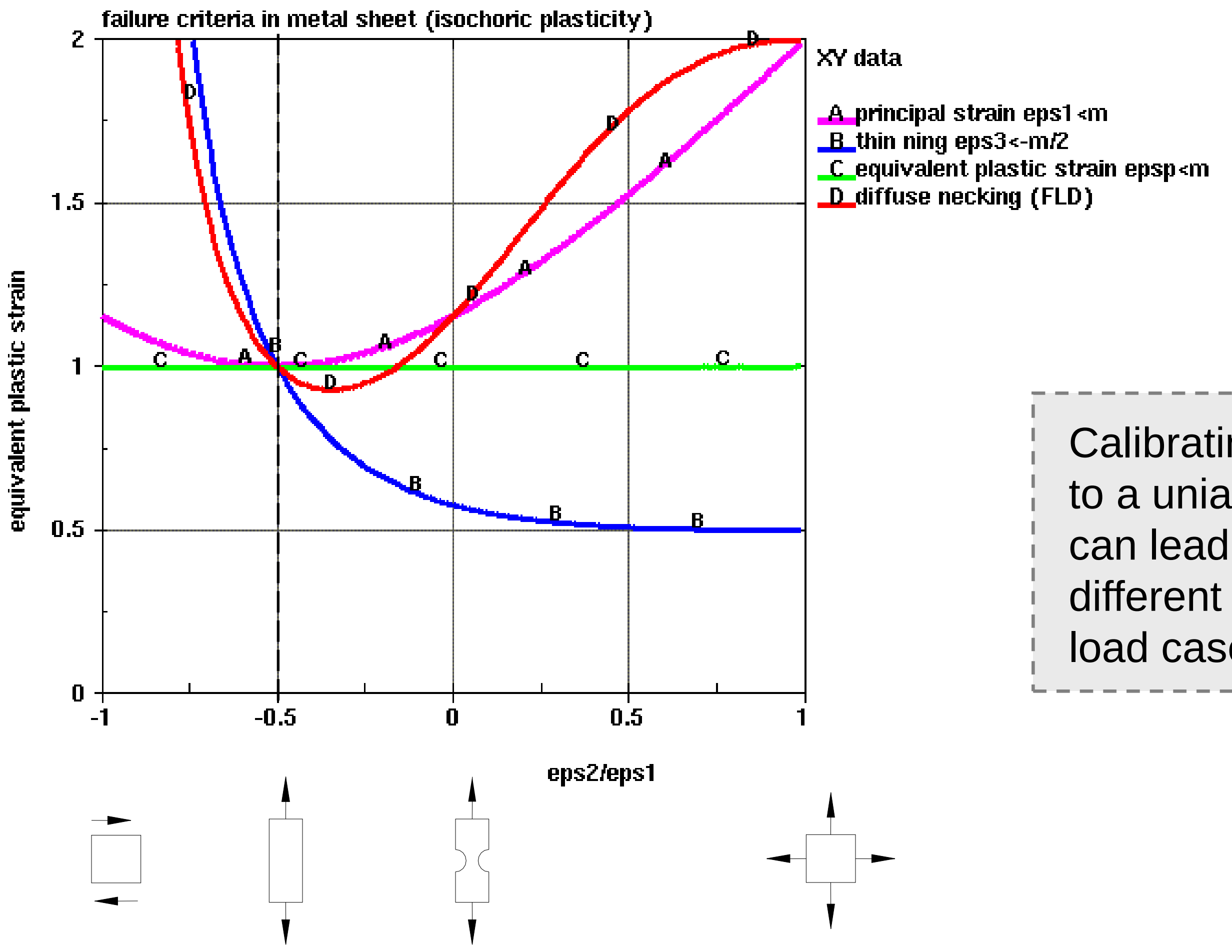
Failure strain under uniaxial tension is set the same in all 4 criteria.

Thinning and FLD predict no failure under pure shear loading.

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

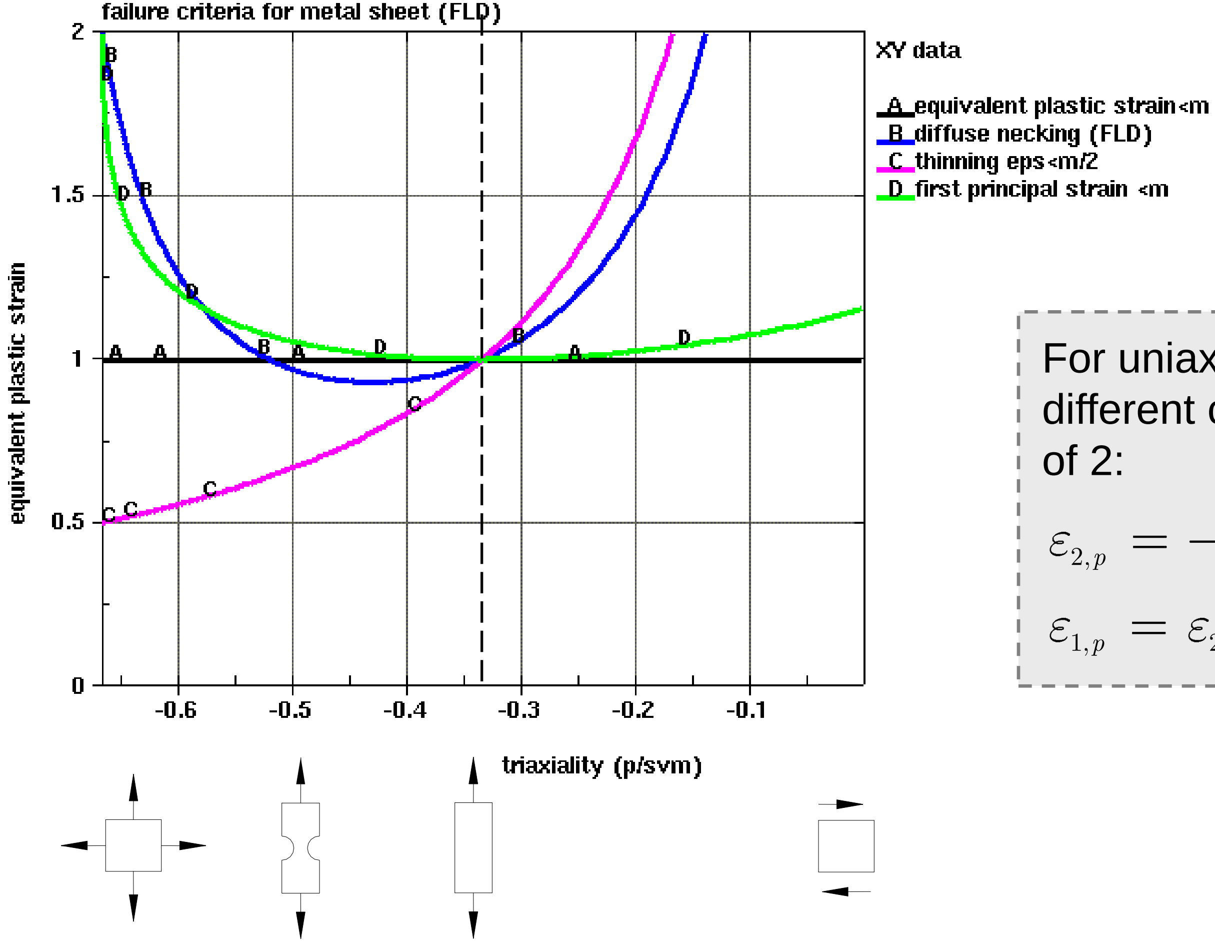


Failure models in the plane equivalent plastic strain vs. *b*



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

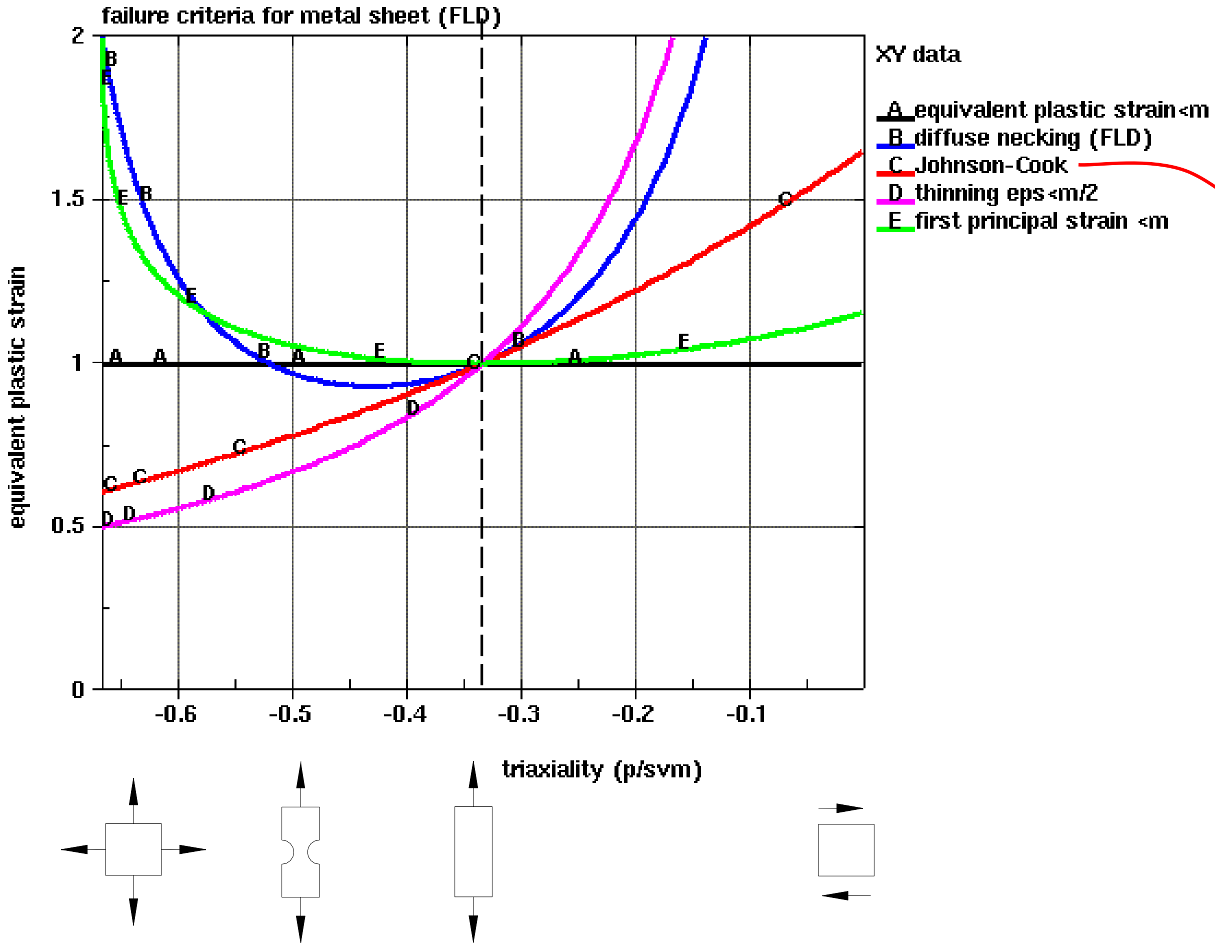


For uniaxial and biaxial tension different criteria lead to a factor of 2:

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

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

Johnson-Cook criterion (Hancock-McKenzie)



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

$$d_1 = 0$$

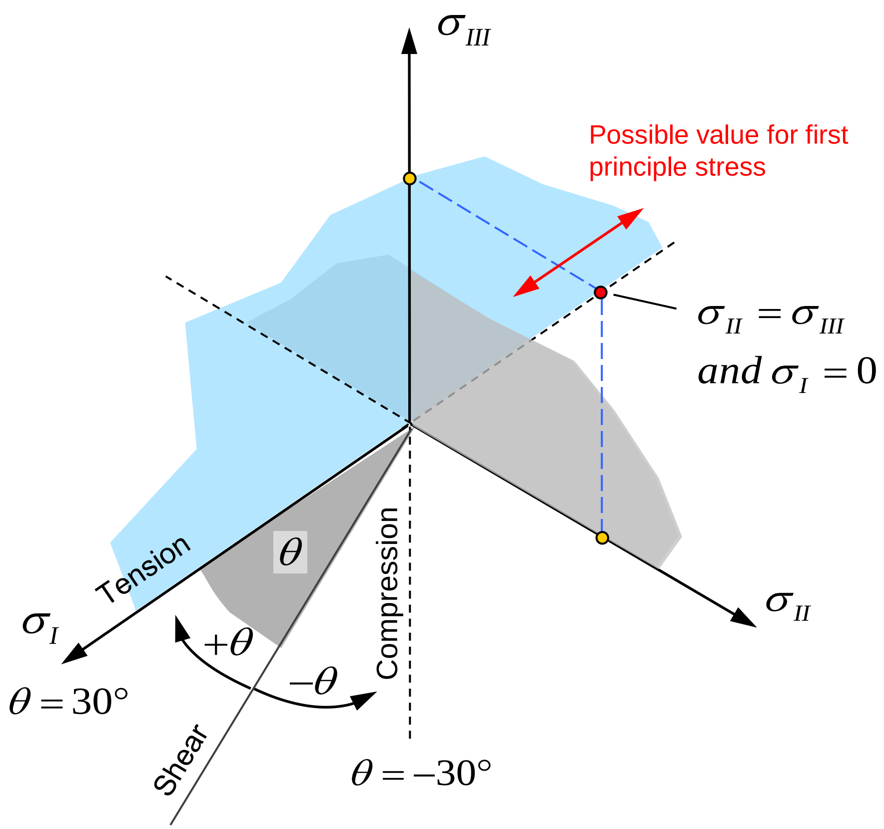
$$d_3 = \frac{3}{2}$$

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

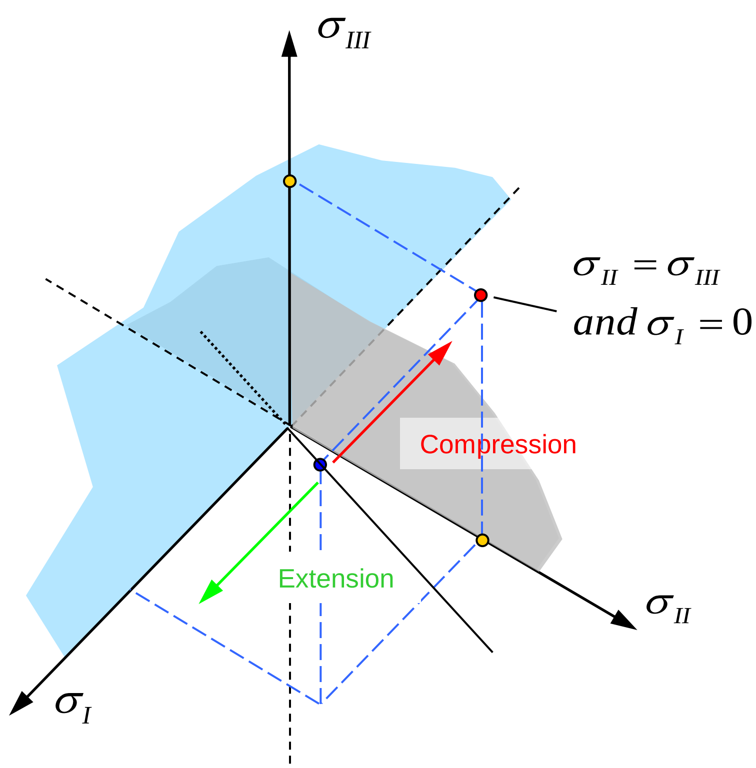
Johnson-Cook and FLC are very close in the neighborhood of uniaxial tension.

Parametrized for 3D stress space

Lode-angle: Extension- and Compression test

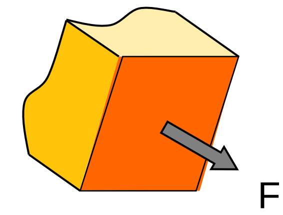


View parallel and on hydrostatic axis
(perpendicular to deviator plane)

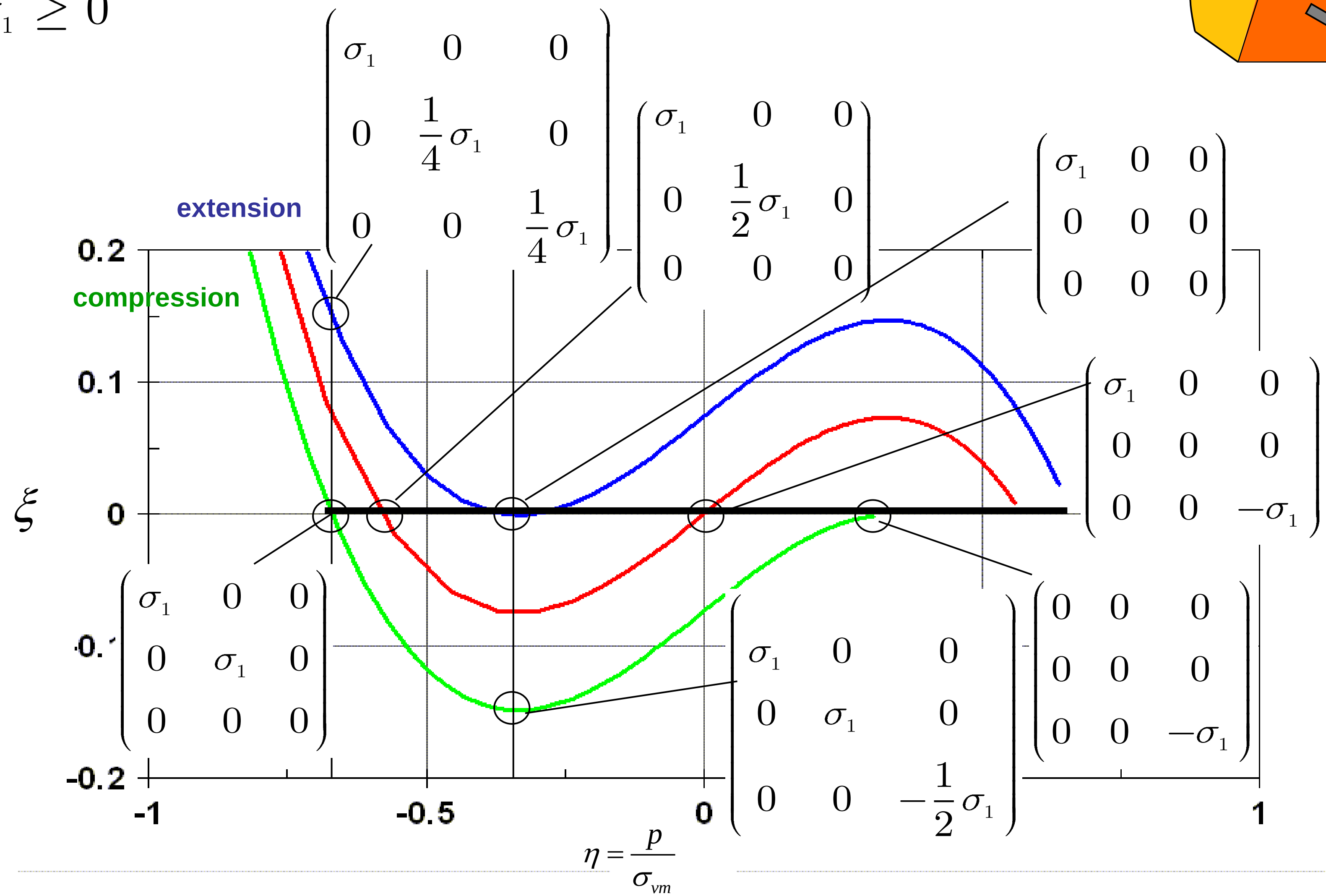


View **not** parallel to hydrostatic axis

3D-Stress state parameterised for volume elements

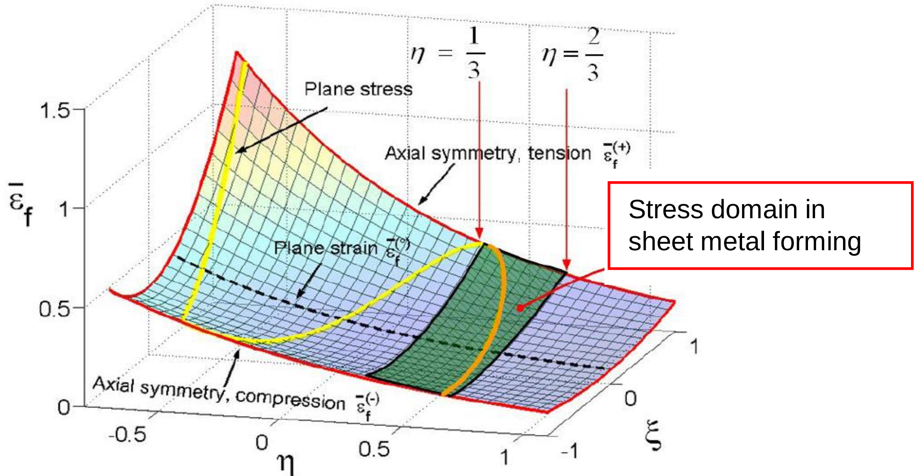


$$\sigma_1 \geq 0$$



Invariants in 3D stress space

Failure criterion extd. for 3D solids

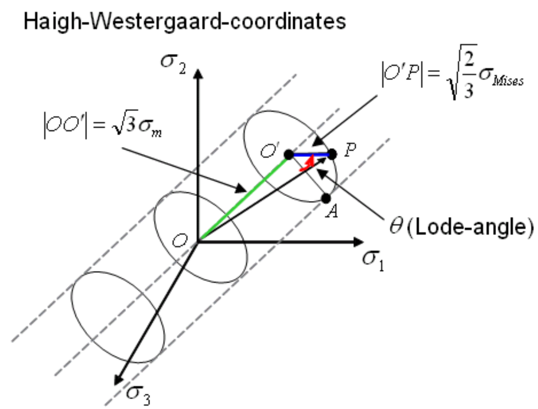


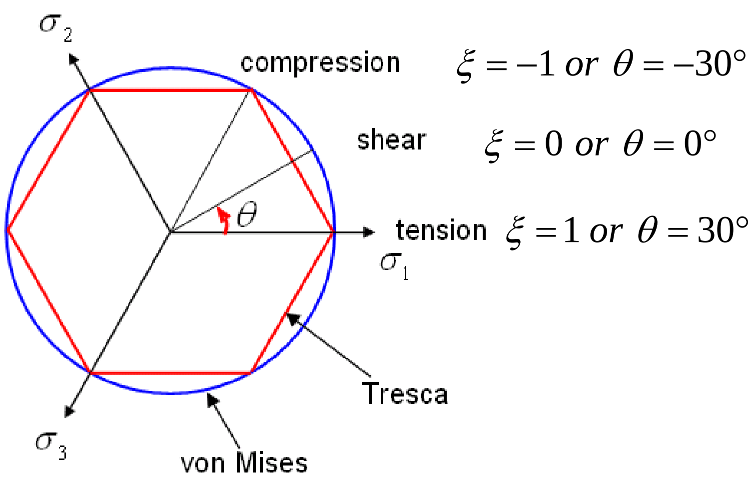
[Source: Wierzbicki et al.]

Parameter definition

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

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

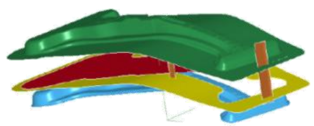




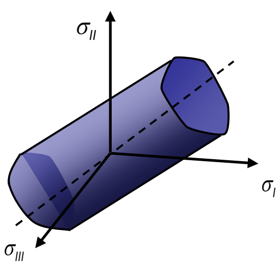
Deriving GISSMO from that…

Closing the process chain: UHS materials for press hardening

Forming simulation



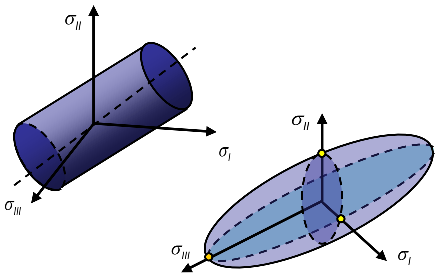
- **Hill based models**
- Ortho- or isotropic yield surface
- Isotropic hardening
- Feasibility by thinning or damage (calibration?!)
- Dependency on temperature
- Microstructural evolution (#244)



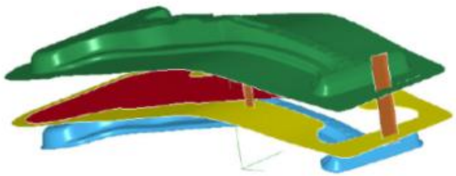
Mapping

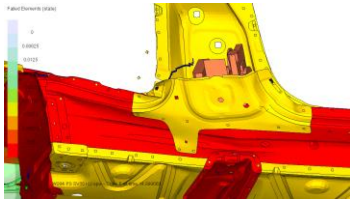
Crash simulation

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



Different ways to realize a consistent modeling





One Material Model for Forming and Crash Simulation

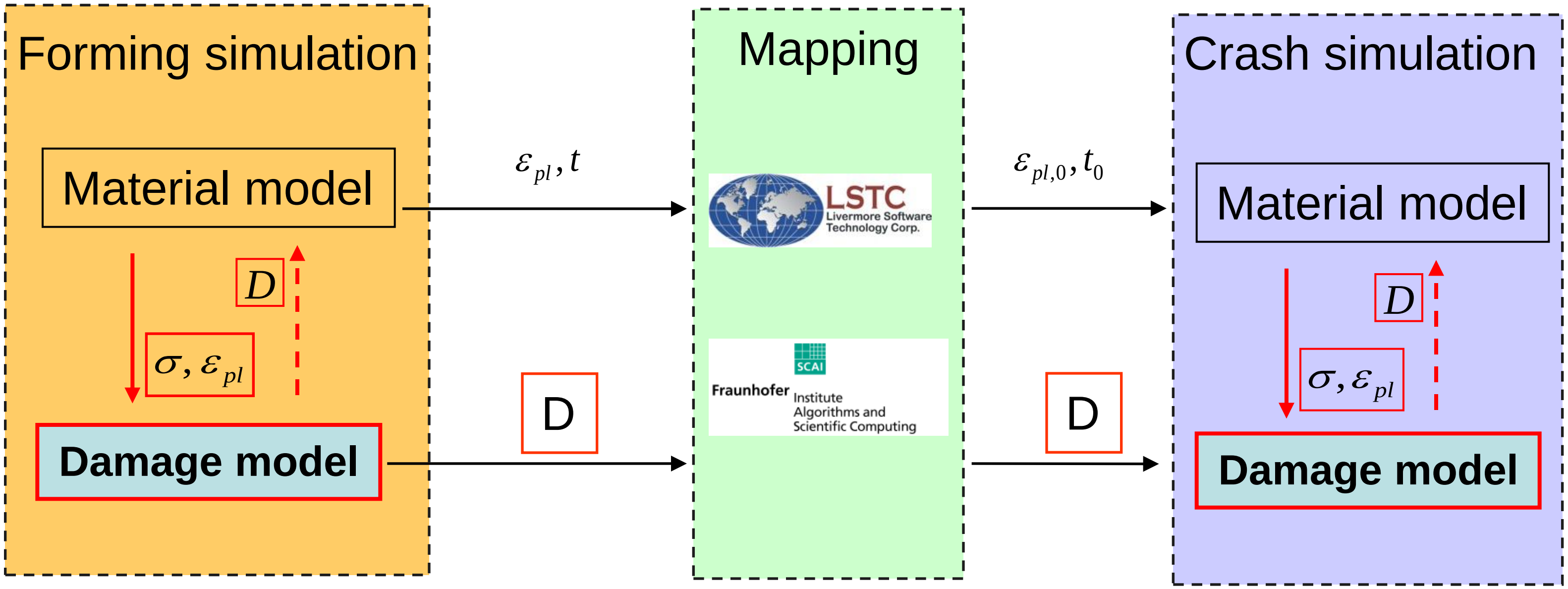
- Requirements for Forming Simulations: Anisotropy, Exact Description of Yield Locus, Kinematic Hardening, etc.
- Requirements for Crash Simulation: Dynamic Material Behavior, Failure Prediction, Energy Absorption, Robust Formulation
- Leads to very complex model

Modular Concept for the Description of Plasticity & Failure

- Plasticity and Failure Model are treated separately
- Existing Material Models are kept unaltered
- Consistent modeling through the use of one damage model for forming and crash simulation

***MAT_ADD….(damage)**

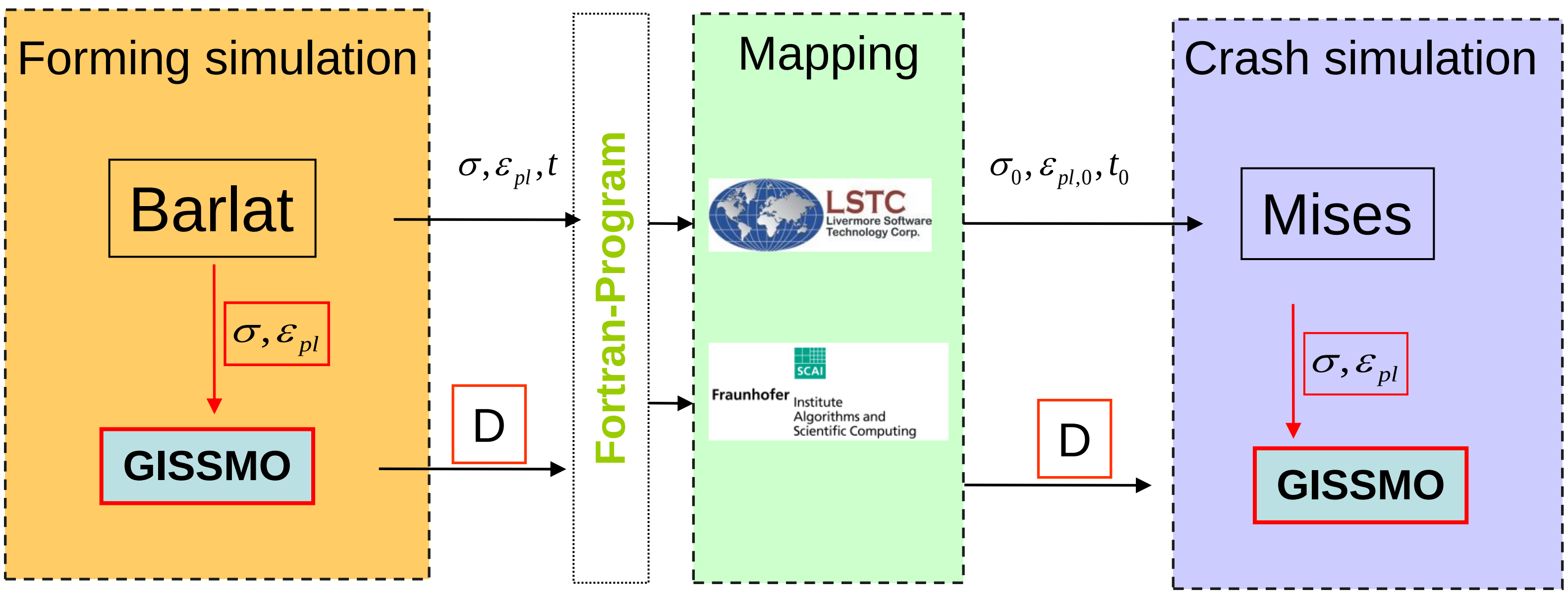
Produceability to Serviceability: Modular Concept



Modular Concept:

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

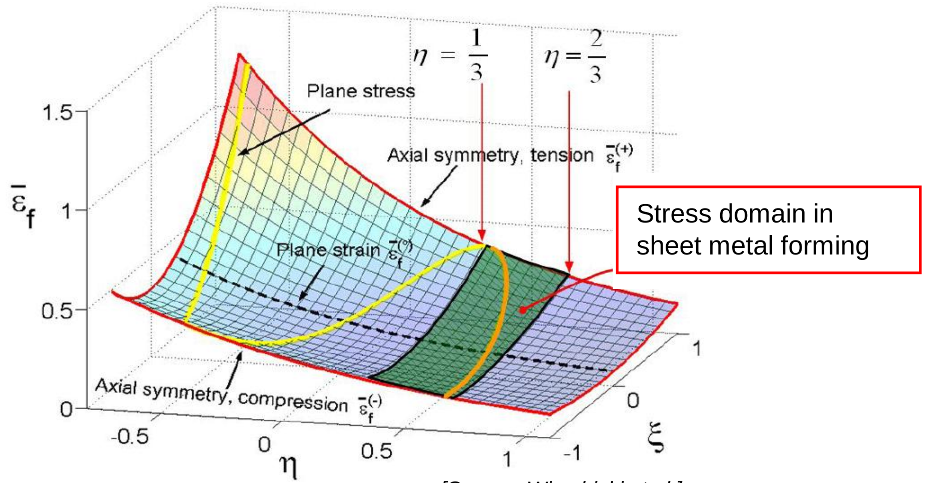
Produceability to Serviceability: Modular Concept
Current status in 971R5



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

GISSMO

Failure criterion extd. for 3D solids



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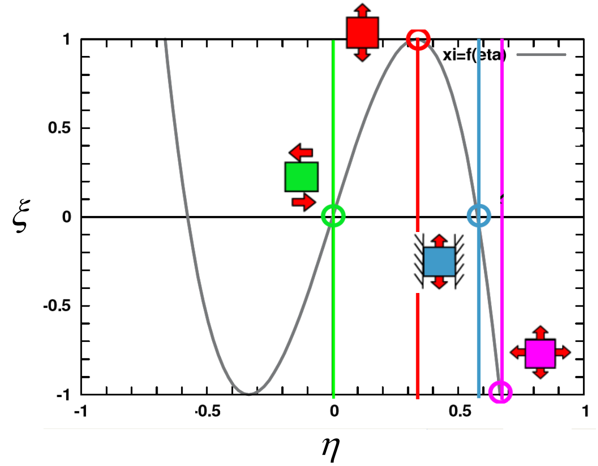
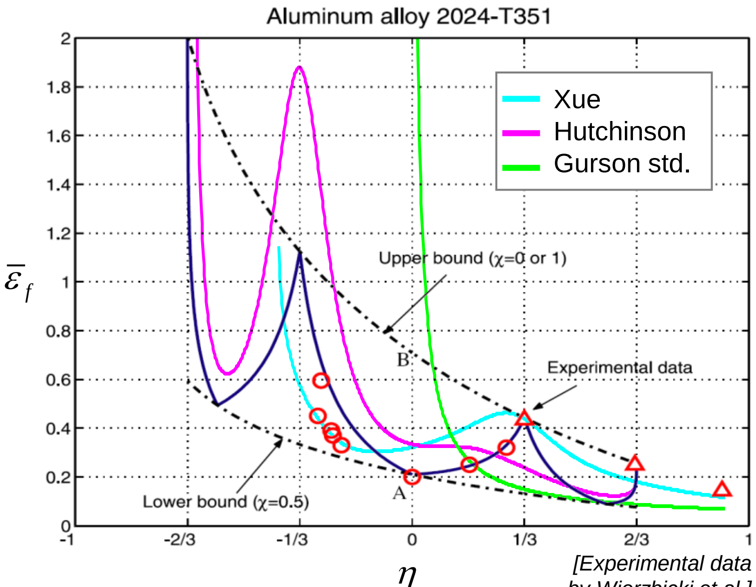
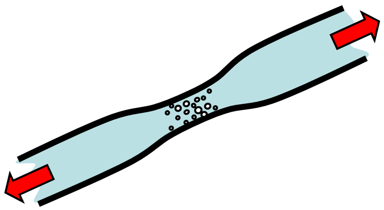




[Experimental data by Wierzbicki et al.]

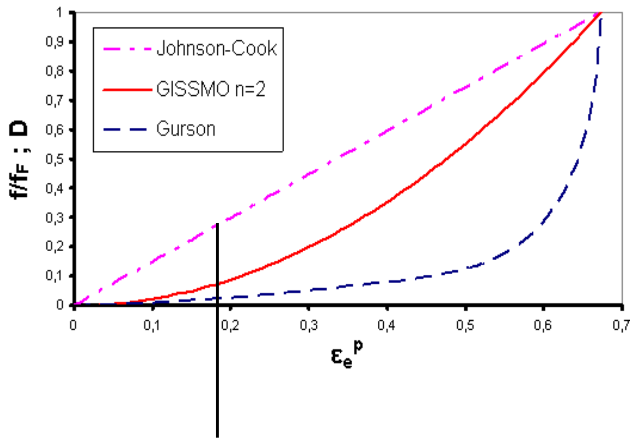
GISSMO - a short description

Ductile damage and failure



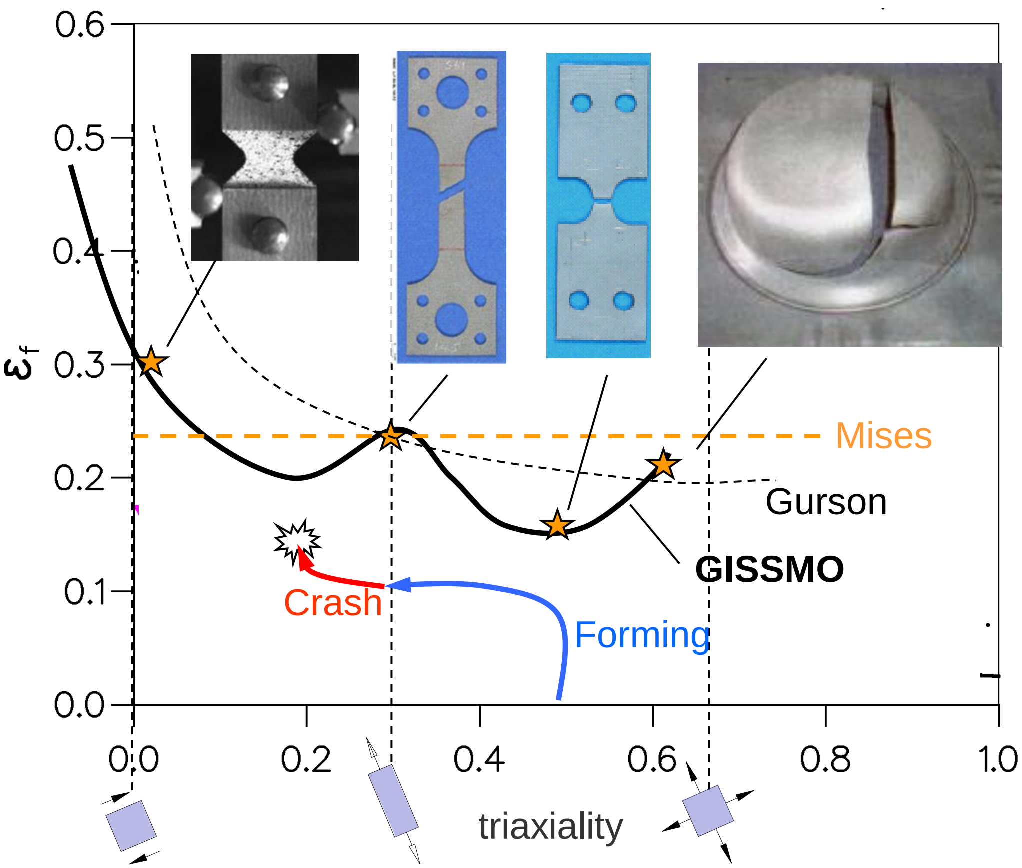
Damage evolution

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

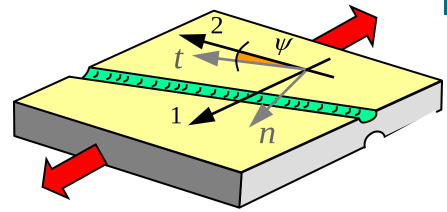


Damage regularly overestimated for linear damage accumulation!!

Failure curve



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

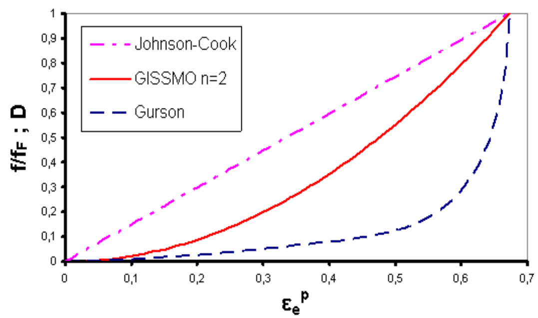


GISSMO – a short description

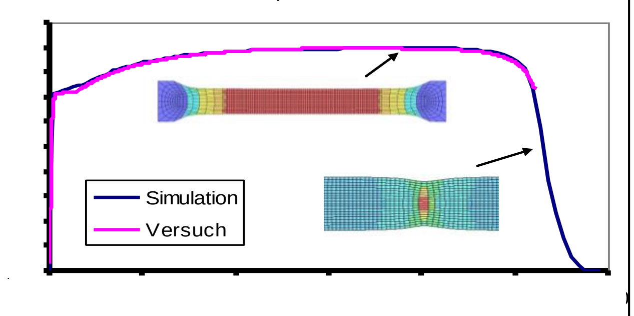
Engineering approach for instability failure

Instability evolution

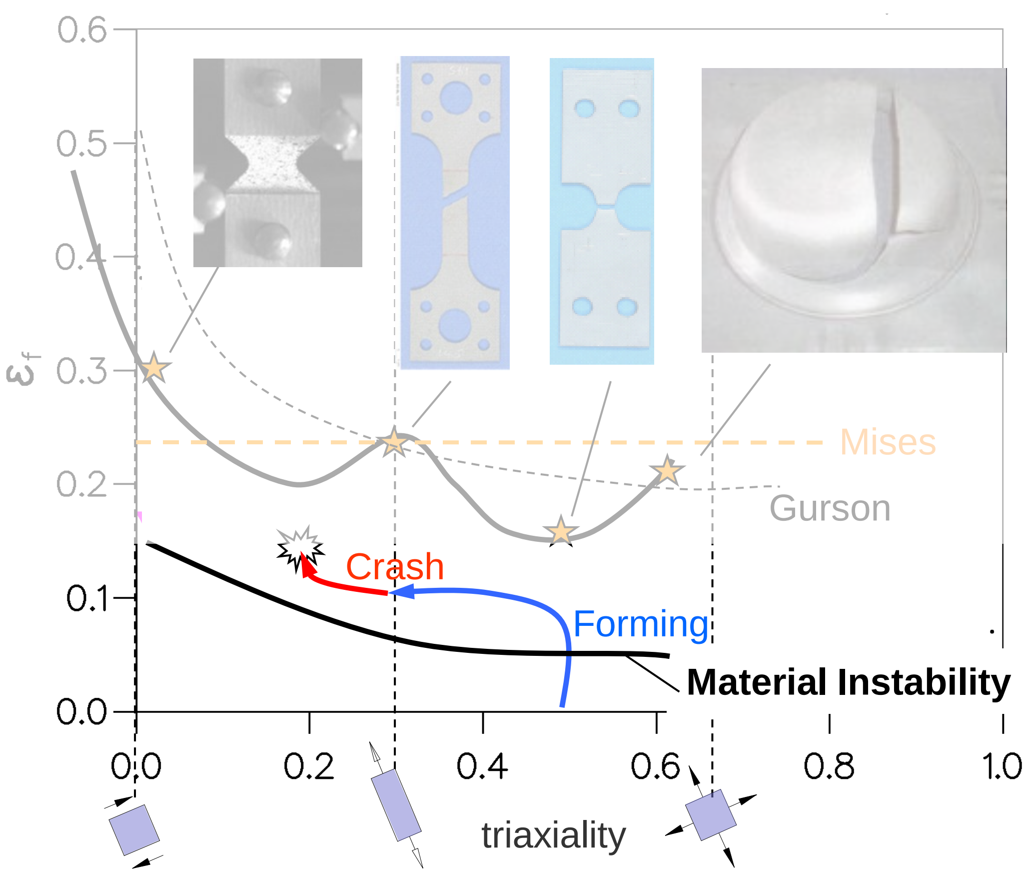
$$\dot{F} = \frac{n}{\varepsilon_{v,loc}} F^{\left(1-\frac{1}{n}\right)} \dot{\varepsilon}_v$$



Tensile test specimen DIN EN 12001



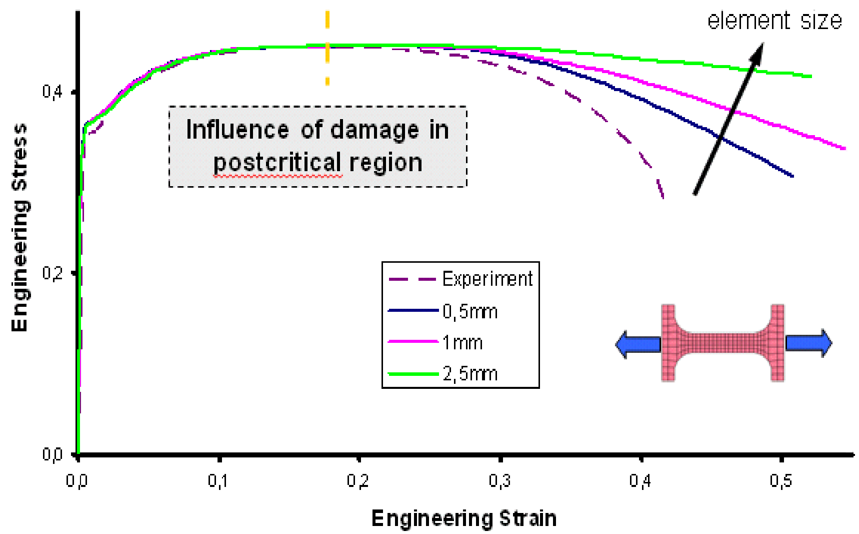
Instability curve definition



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

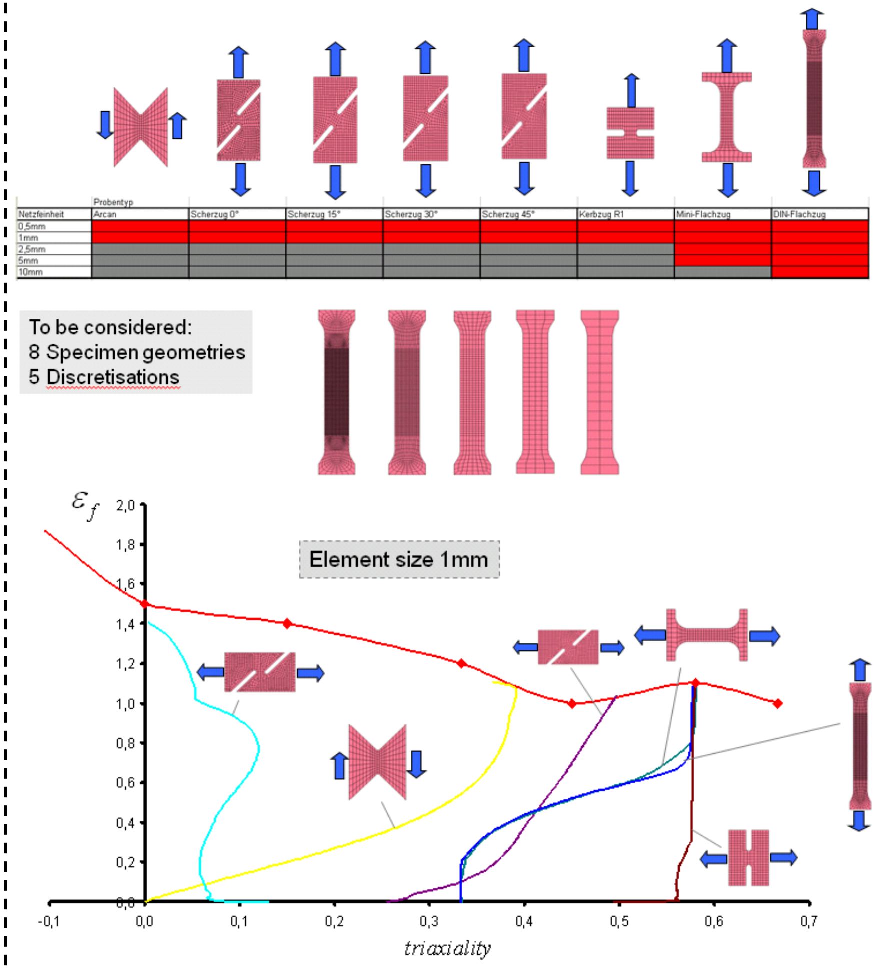
GISSMO – a short description

Mesh size dependency: Simple regularisation



- Inherent mesh-size dependency of results in the post-critical region
- Simulation (and calibration) of tensile test specimen with different mesh sizes

Test program and calibration

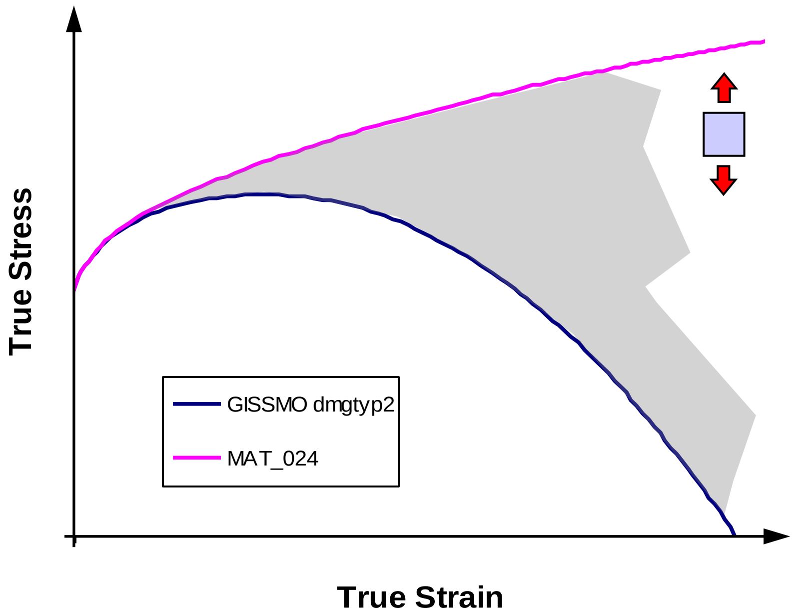


GISSMO – a short description for the uniaxial case

Generalized Incremental Stress State dependent damage MOdel

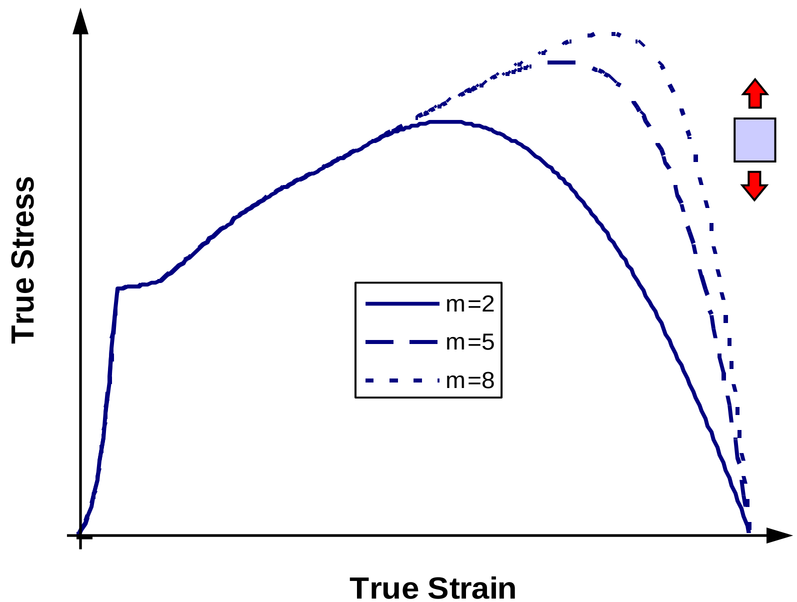
DMGTYP: Flag for coupling (Lemaitre)

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



DCRIT, FADEXP: Post-critical behavior

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

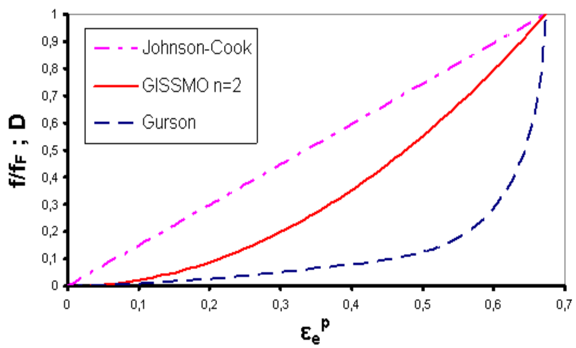


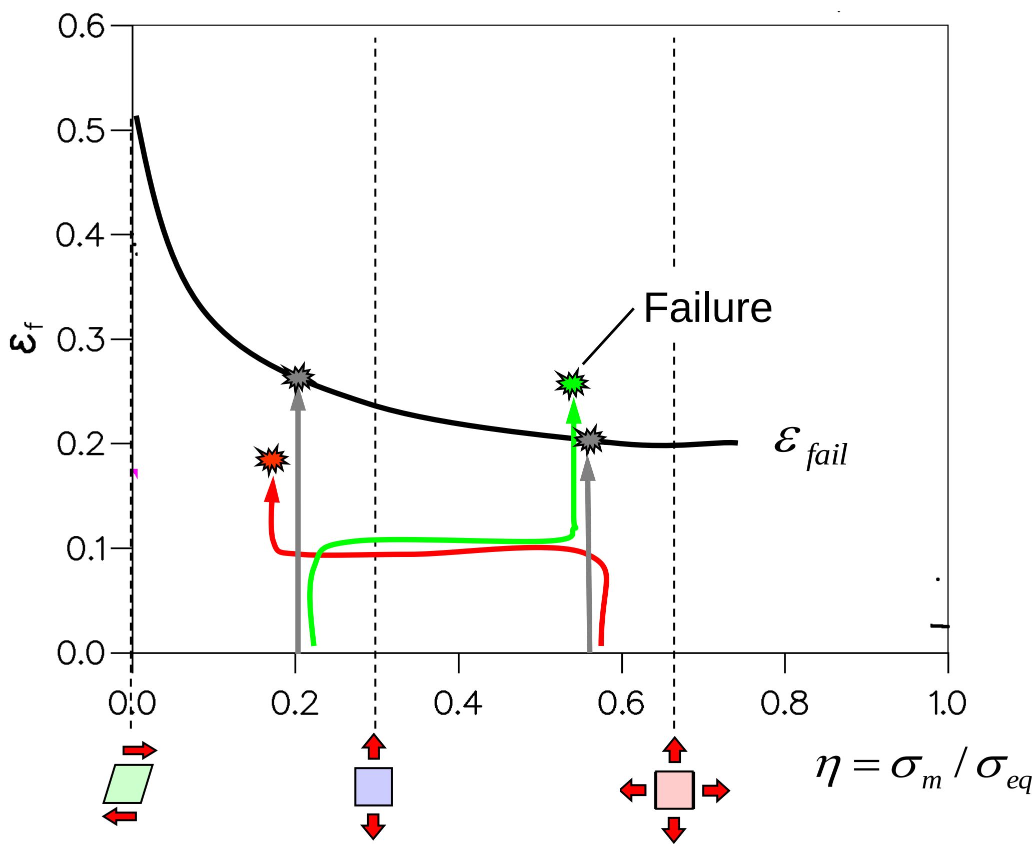
GISSMO

Non-proportional loading influence on failure behavior

Failure strain depending on

- Loading state $\varepsilon_{fail}(\eta)$
- Load path and pre-damage
- Accumulation of damage

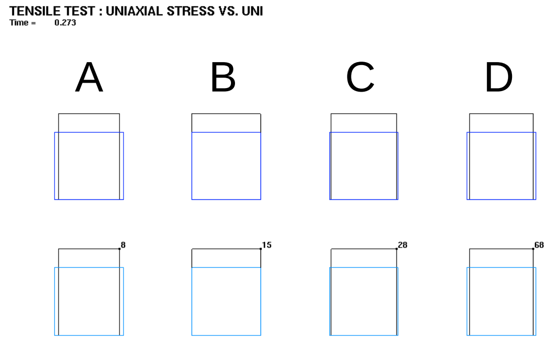


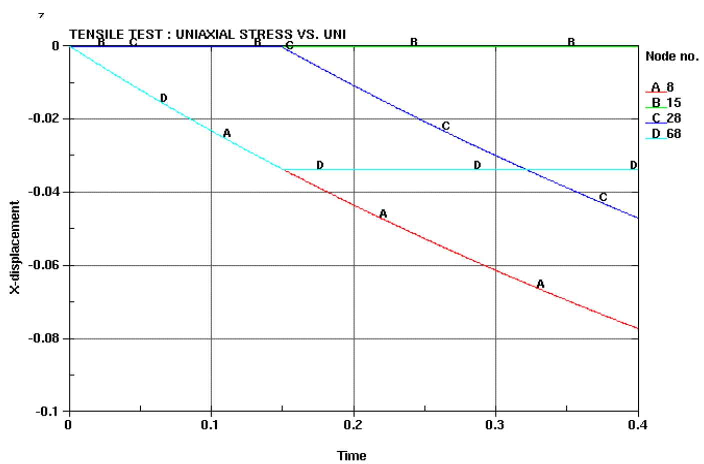


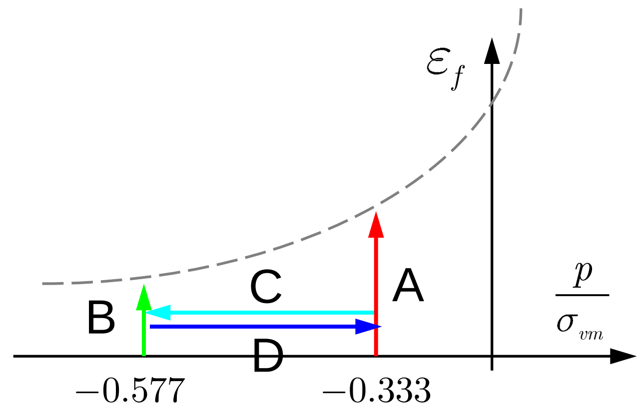
Non-Proportional Loading

Compare 4 load paths:

- A uniaxial tension
- B uniaxial tension with lateral confinement
- C uniaxial tension with/without confinement
- D uniaxial tension without/with confinement

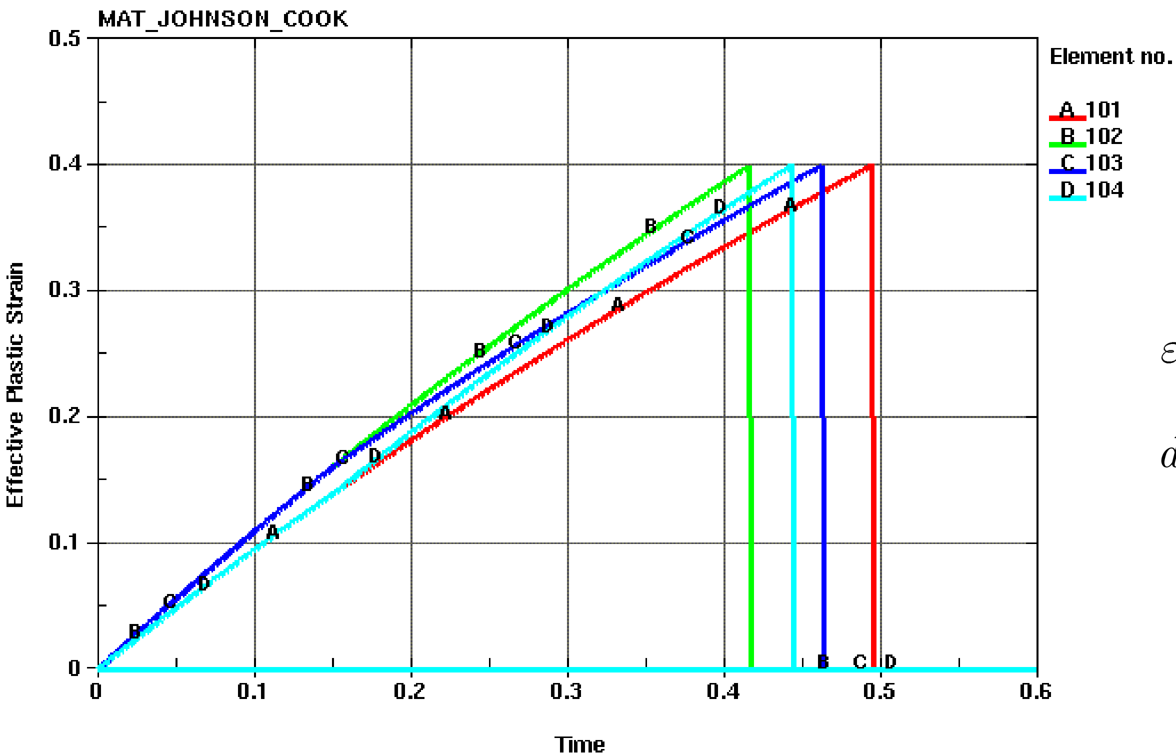






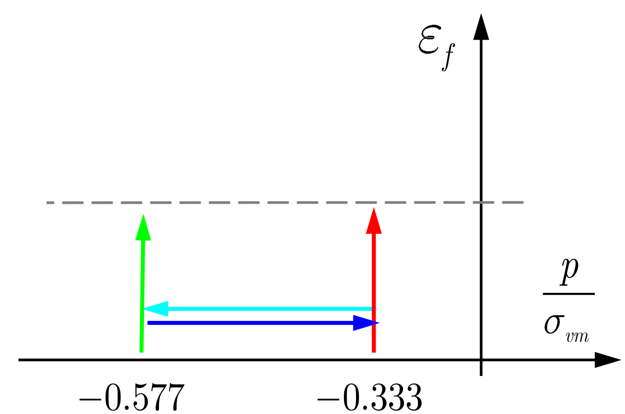
Triaxiality is no longer constant over the stress-strain path if lateral constraint is imposed or lifted.

Non-proportional loading criterion without triaxiality

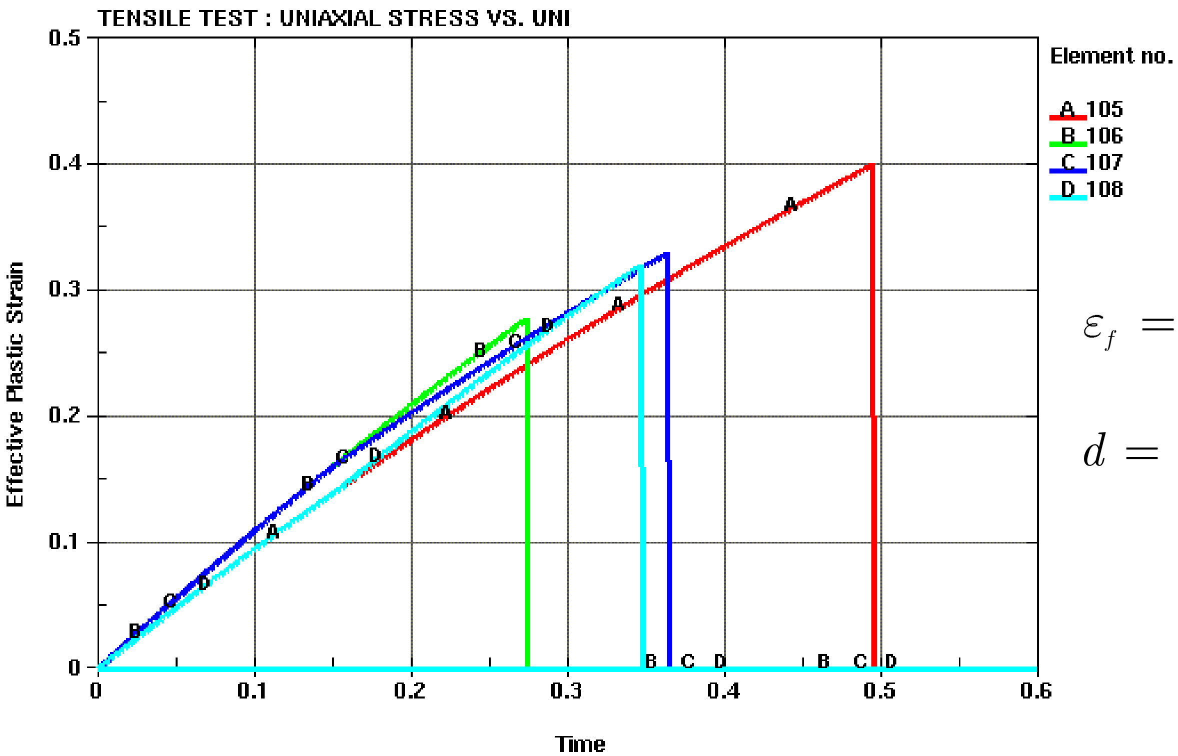


$$\varepsilon_f = d_1 = 0.4$$

$$d = \int \frac{\dot{\varepsilon}_p}{\varepsilon_f} dt \le 1 \Rightarrow \varepsilon_p \le \varepsilon_f$$

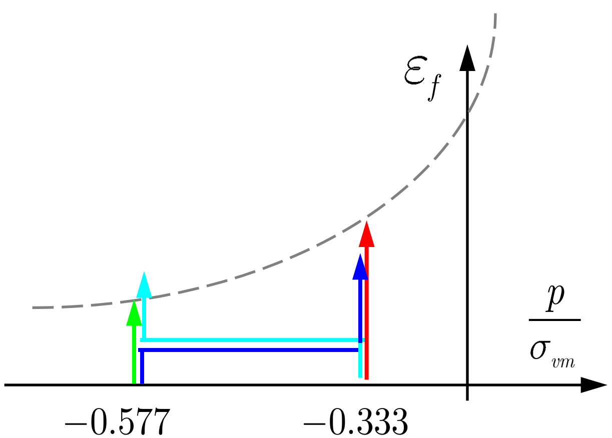


Non-proportional loading criterion with triaxiality

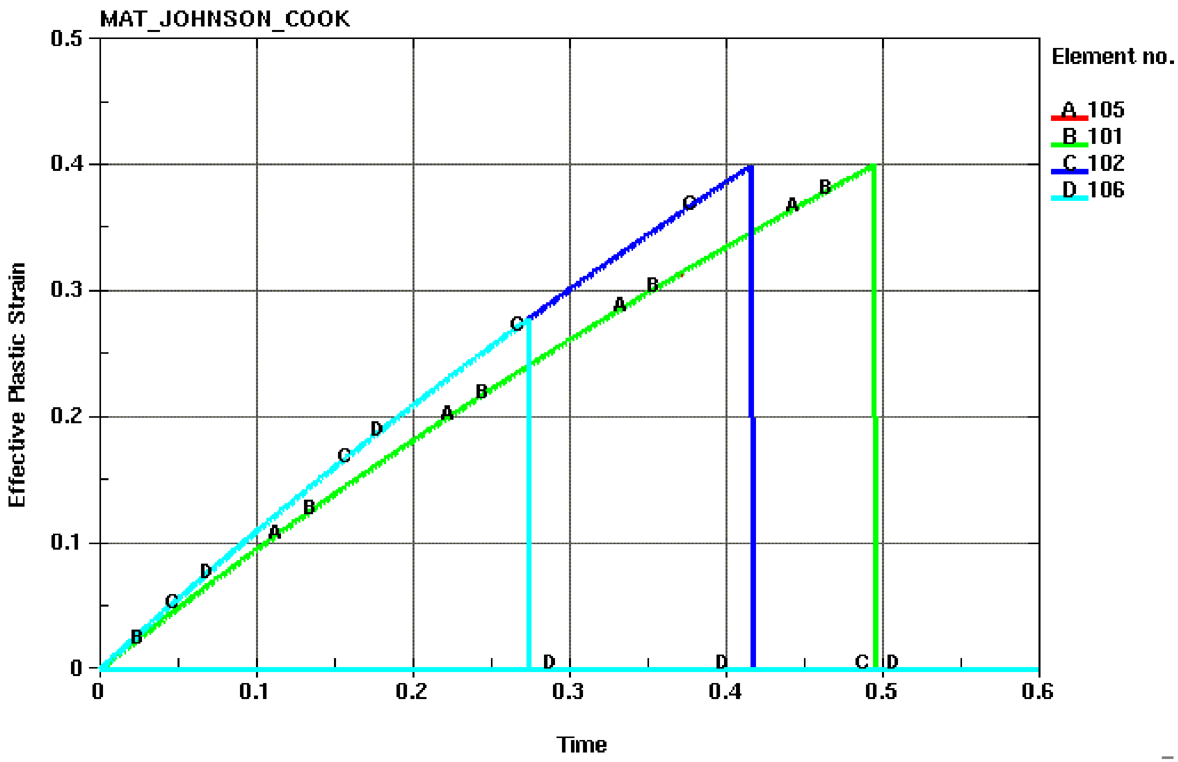


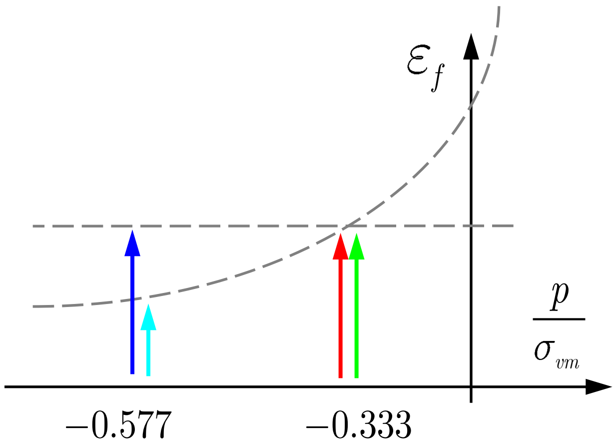
$$\varepsilon_f = d_1 + d_2 e^{d_3 \frac{p}{\sigma_{vm}}} = 0.66 e^{1.5 \frac{p}{\sigma_{vm}}}$$

$$d = \int \frac{\dot{\varepsilon}_p}{\varepsilon_f} dt \leq 1 \overset{\frac{p}{\sigma_{vm}} = cte}{\Rightarrow} \varepsilon_p \leq \varepsilon_f$$



Comparison: Uniaxial tension with/without confinement





Input of GISSMO
Input definition in LS-DYNA (1/4)

```
*MAT_PIECEWISE_LINEAR_PLASTICITY
$      mid        ro         e        pr      sigy      etan      fail      tdel
       100 7.8000E-9 2.1000E+5  0.300000
$        c         p      lcss      lcsr        vp
     0.000     0.000        99         0     1.000
...

*MAT_ADD_EROSION
$      MID      EXCL    MXPRES     MNEPS    EFFEPS    VOLEPS    NUMFIP       NCS
       100
$   MNPRES     SIGP1     SIGVM     MXEPS     EPSSH     SIGTH   IMPULSE    FAILTM

$     IDAM    DMGTYP     LCSDG     ECRIT    DMGEXP     DCRIT    FADEXP    LCREGD
         1         0        11       0.3         2       0.2         2        12
$   SIZFLG     REFSZ     NAHSV
         0         5         4
```

Standard material Input (i.e. MAT_24)

Standard failure parameters (optional)

GISSMO failure parameters

If IDAMG=1 GISSMO is invoked.
Further parameters are expected.

DMGTYP=0: Damage is accumulated
But not coupled to stresses, no failure.

DMGTYP=1: Damage is accumulated
and coupled to flow stress if $D>D_{crit}$.
Failure occurs if D=1.

Input of GISSMO
Input definition in LS-DYNA (2/4)

```
*MAT_PIECEWISE_LINEAR_PLASTICITY
$      mid        ro         e        pr      sigy      etan      fail      tdel
       100 7.8000E-9 2.1000E+5  0.300000
$        c         p      lcss      lcsr        vp
     0.000     0.000        99         0     1.000
...
```

Standard material Input (i.e. MAT_24)

```
*MAT_ADD_EROSION
$      MID      EXCL    MXPRES     MNEPS    EFFEPS    VOLEPS    NUMFIP       NCS
       100
$   MNPRES     SIGP1     SIGVM     MXEPS     EPSSH     SIGTH   IMPULSE    FAILTM

$     IDAM    DMGTYP     LCSDG     ECRIT    DMGEXP     DCRIT    FADEXP    LCREGD
         1         0        11       0.3         2       0.2         2        12
$   SIZFLG     REFSZ     NAHSV
         0         5         4
```

Standard failure parameters (optional)

GISSMO failure parameters

ID of curve defining equivalent plastic strain at failure vs. triaxiality.
Damage will have values from 0 up to 1.0.

Exponent for nonlinear damage accumulation:

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

ECRIT: Equiv. plastic strain at instability onset.
If negative a curve is expected that defines ECRIT vs. traiaxiality.
If ECRIT=0 the ordinate value Dcrit is used.

Input of GISSMO

Input definition in LS-DYNA (3/4)

```
*MAT_PIECEWISE_LINEAR_PLASTICITY
$      mid        ro         e        pr      sigy      etan      fail      tdel
       100 7.8000E-9 2.1000E+5  0.300000
$        c         p      lcss      lcsr        vp
     0.000     0.000        99         0     1.000
...

*MAT_ADD_EROSION
$      MID      EXCL    MXPRES     MNEPS    EFFEPS    VOLEPS    NUMFIP       NCS
       100
$   MNPRES     SIGP1     SIGVM     MXEPS     EPSSH     SIGTH   IMPULSE    FAILTM

$     IDAM    DMGTYP     LCSDG     ECRIT    DMGEXP     DCRIT    FADEXP    LCREGD
         1         0        11       0.3         2       0.2         2        12
$   SIZFLG     REFSZ    NAHSV
         0         5        4
```

Standard material Input (i.e. MAT_24)

Standard failure parameters (optional)

GISSMO failure parameters

Fading exponent as defined in:

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

Load curve defining element size dependent regularization factors vs. equiv. plastic strain to failure.

SIZFLG=0 (default) Characteristic element is computed with respect to initial configuration.

SIZFLG=1 Characteristic element updated in each increment (actual configuration, not recommended)

Input of GISSMO
Input definition in LS-DYNA (4/4)

```
*MAT_PIECEWISE_LINEAR_PLASTICITY
$       mid        ro         e        pr      sigy      etan      fail      tdel
        100 7.8000E-9 2.1000E+5  0.300000
$         c         p      lcss      lcsr        vp
      0.000     0.000        99         0     1.000
...

*MAT_ADD_EROSION
$       MID      EXCL    MXPRES     MNEPS    EFFEPS    VOLEPS    NUMFIP       NCS
        100
$    MNPRES     SIGP1     SIGVM     MXEPS     EPSSH     SIGTH   IMPULSE    FAILTM

$      IDAM    DMGTYP     LCSDG     ECRIT    DMGEXP     DCRIT    FADEXP    LCREGD
          1         0        11       0.3         2       0.2         2        12
$    SIZFLG     REFSZ    NAHSV
          0         5        4
```

Standard material Input (i.e. MAT_24)

Standard failure parameters (optional)

GISSMO failure parameters

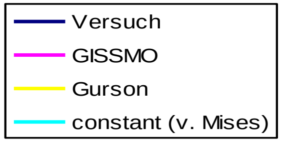
Reference element size for which the failure parameters were calibrated. This may be used when mapping of failure parameters from finer to coarser meshes is necessary.

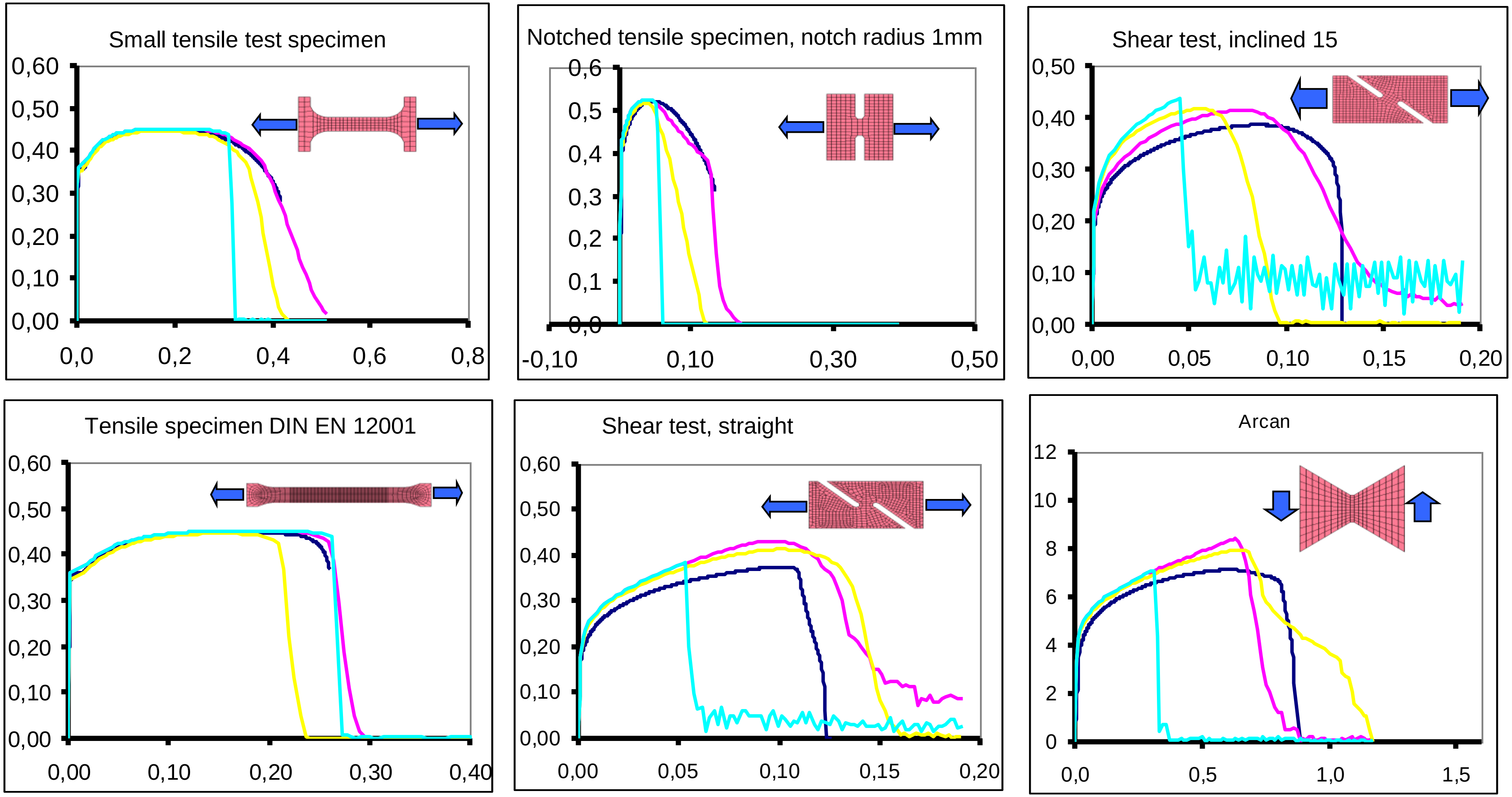
Number of additional history variables written to d3plot-database. Please keep in mind, that this additional. history variable are added to the standard variables of the corresponding material model. I.e. the sum of both history variable sets needs to be defined in *DATABASE_EXTEND_BINARY. The number of the history variables used in the material model (i.e. MAT_24 in this example) is written to d3hsp-file.

GISSMO vs. Gurson vs. MAT_24/81

Comparison of experiments and simulations

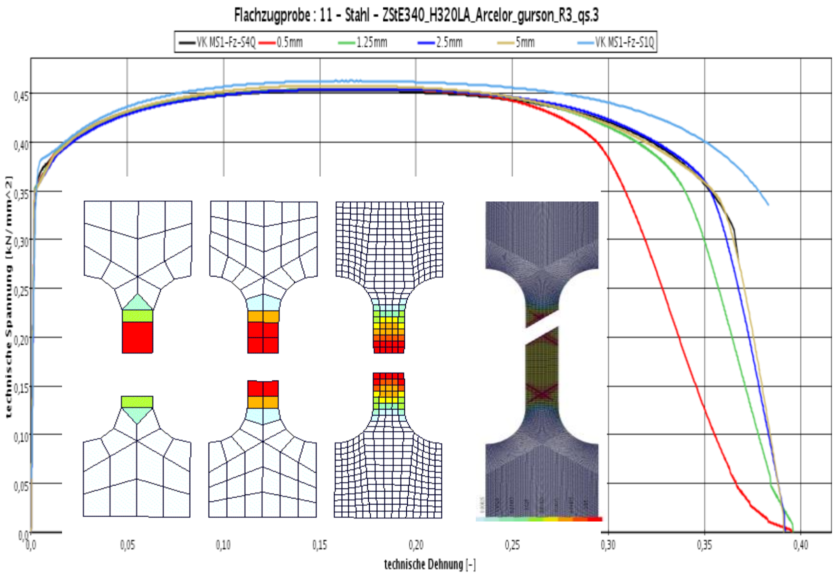
Institut Werkstoffmechanik

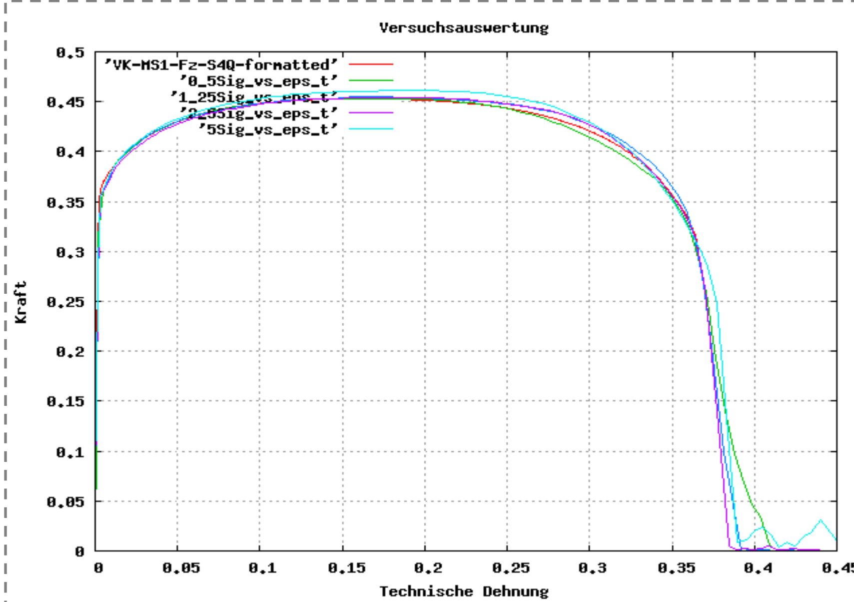




Gurson vs. GISSMO – “regularized”

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

Summary

- 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!