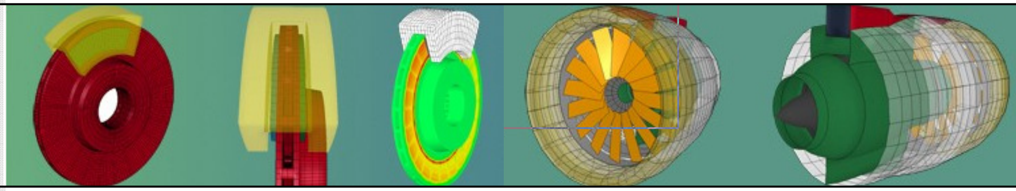

A Comparison of recent Damage and Failure Models for Steel Materials in Crashworthiness Application in LS-DYNA

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Bundesministerium für Bildung und Forschung

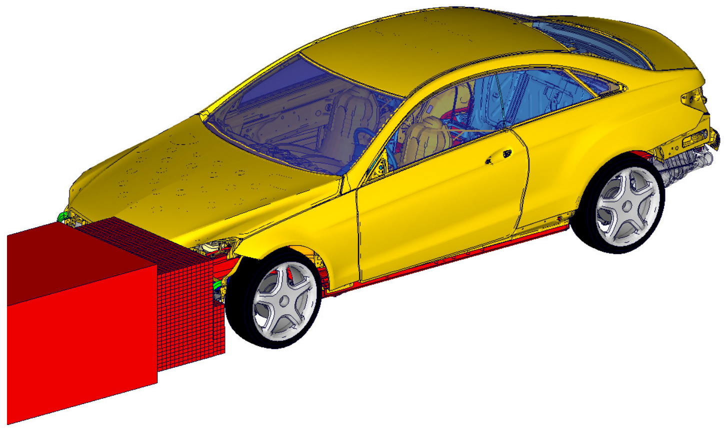
Technological challenges in the automotive industry

Weight

Safety requirements

New materials

- Composites
- High strength steel
- Light alloys
- Polymers

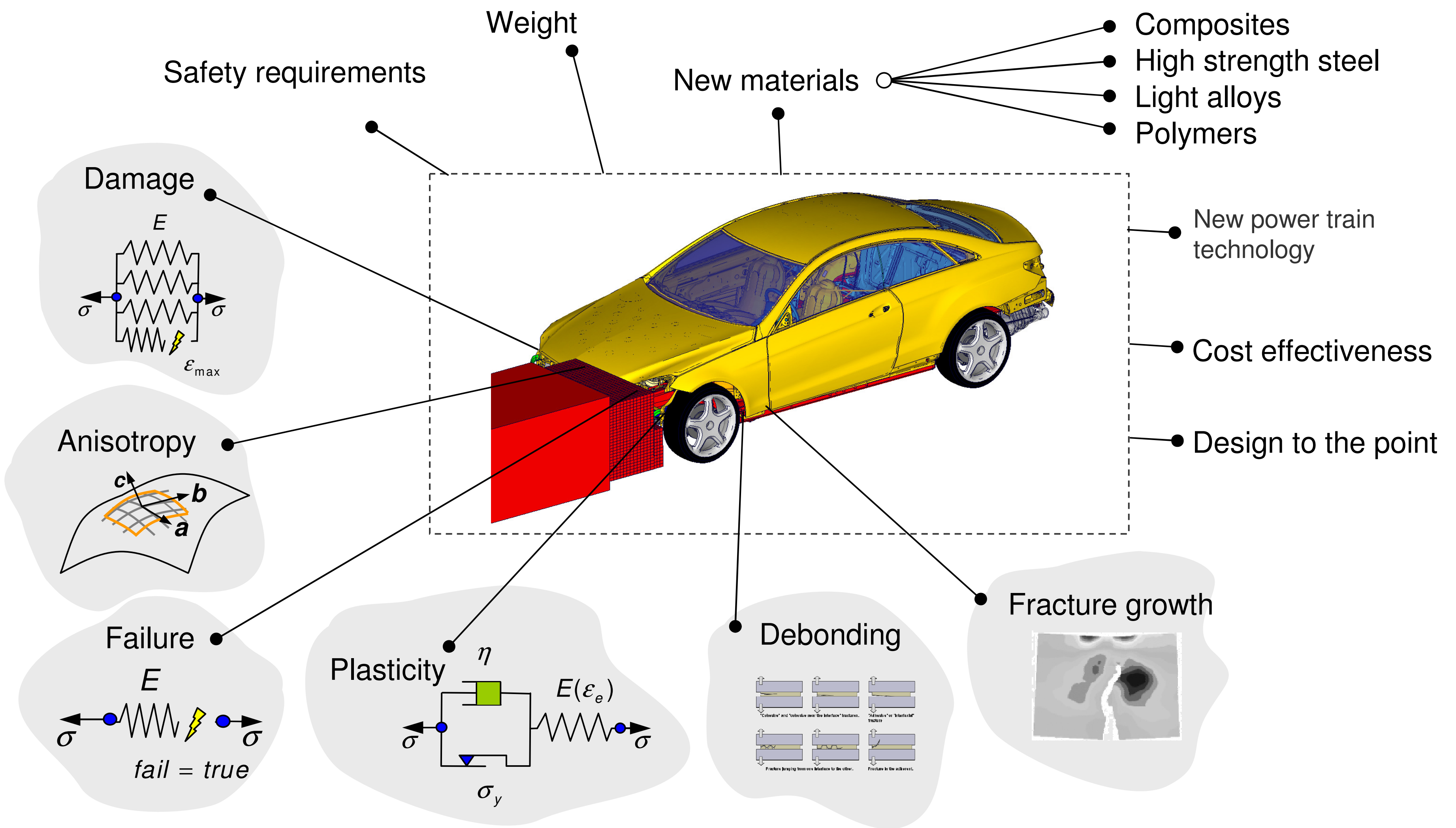


New power train technology

Cost effectiveness

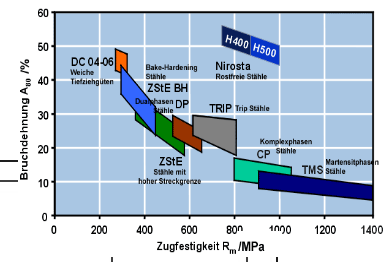
Design to the point

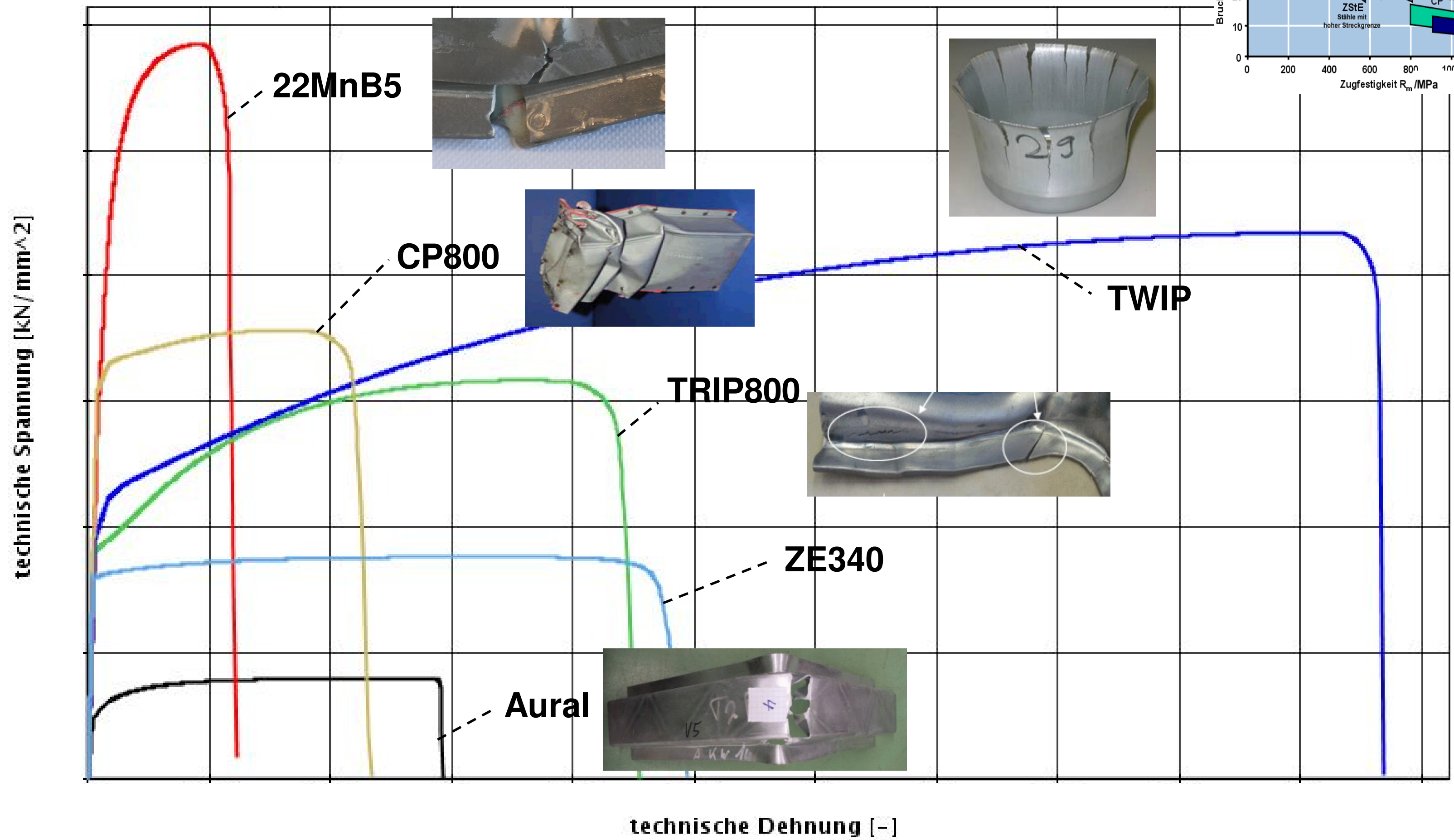
Technological challenges in the automotive industry



Motivation

Lightweight steel/aluminium design!
Can we predict failure modes (brittle, ductile, time delayed)?



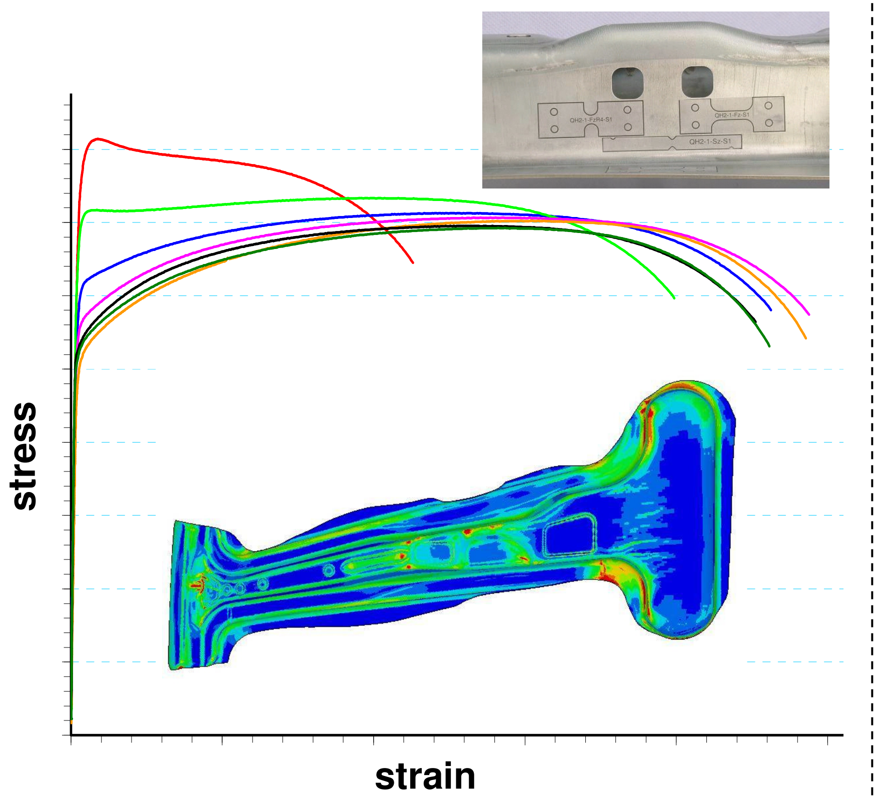


Motivation

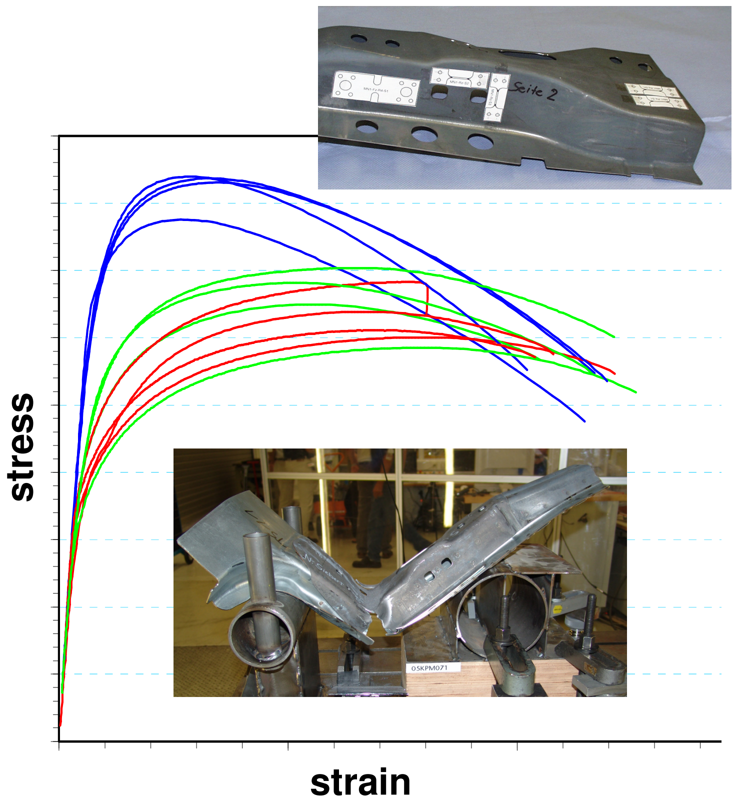
Material behavior dependent on local history of loading

Institut Werkstoffmechanik

Micro-alloyed steel



Hot-formed steel

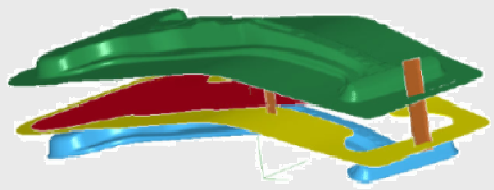


Material models along the process chain

Forming Simulation

- Correct description of yield locus
- Anisotropic yield locus:

Typical models: Barlat89, Barlat2000, Hill48, Yoshida, …



Transfer of Variables

Plastic Strain	✓
Thickness	✓
Damage	✗

Crash Simulation

- Energy absorption
- Prediction of structural folding patterns
- Strain rate dependent models (including damage)

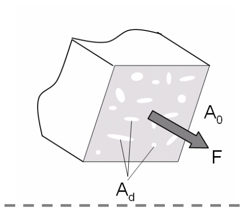
Typical models: von Mises, Gurson, Gurson-JC, …

Von Mises with damage

Von Mises plasticity with damage in LS-DYNA (MAT_81/82)

Enhancement of *MAT_PIECEWISE_LINEAR_PLASTICITY(#024) with damage.
Instead of abrupt failure (#024) continuous softening by damage formulation (#081/082)

➡ Elasto - Visco - Plasticity with isotropic Hardening and Damage:
No regularisation & damage/failure independent of state of stress!!

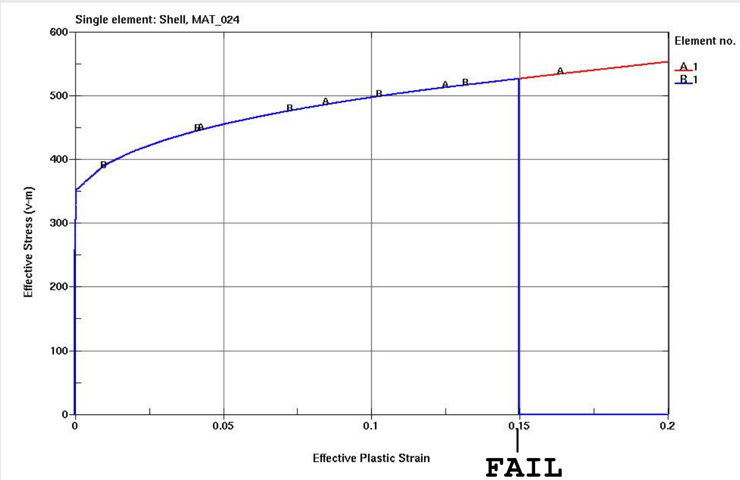


$D = \frac{A_d}{A_0}$ with $0.0 \le D \le 1.0$

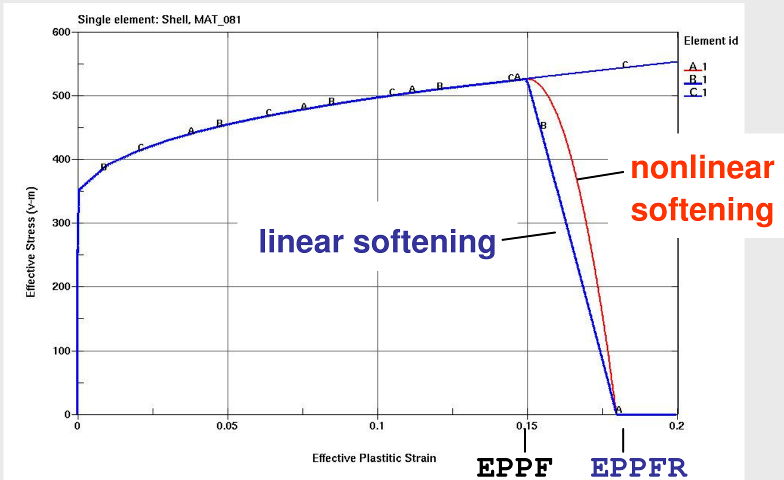
D = scalar (isotropic failure)

$$D = D(\varepsilon^p) = \frac{\varepsilon^p - EPPF}{EPPFR - EPPF} \Rightarrow \boldsymbol{\sigma} = (1 - D)\mathbf{C}^{ep} : \boldsymbol{\varepsilon}$$

MAT_024: only abrupt failure



MAT_081:damage, linear or nonlinear softening



The Gurson model

The Gurson-model in LS-DYNA

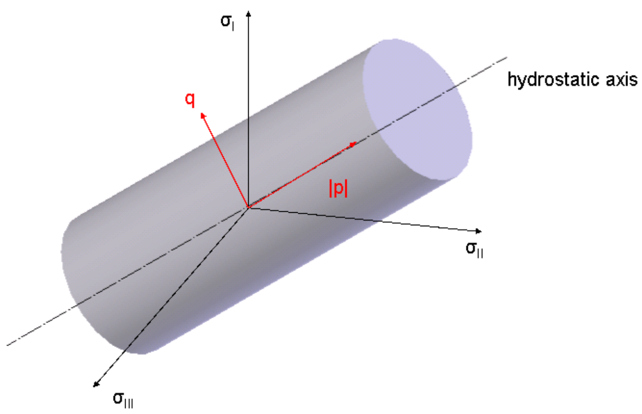
- The yield function is given as

$$\Phi(\boldsymbol{\sigma},\sigma_M,f)=\frac{\sigma_e^2}{\sigma_M^2}+2q_1f^*\cosh\left(\frac{q_2\ tr\boldsymbol{\sigma}}{2\sigma_M}\right)-1-\left(q_1f^*\right)^2=0$$

- The effective void volume fraction is defined according to

$$f^*(f)=\begin{cases} f & f\le f_c \\ f_c+\dfrac{1/q_1-f_c}{f_F-f_c}(f-f_c) & f>f_c \end{cases}$$

- For the matrix material associative von Mises plasticity is assumed for the undamaged state.
- Yield is NOT isochoric though!
- q_1 and q_2 are free parameters of the model to fit the yield surface to experimental data.
- f_c is the critical void volume fraction above which the voids start to combine and grow.
- Failure is being initiated at $f^*(f_F)=\dfrac{1}{q_1}$



Undamaged Gurson yield surface

σ_e = equivalent von Mises stress

σ_M = yield stress (matrix)

$\boldsymbol{\sigma}$ = stress tensor

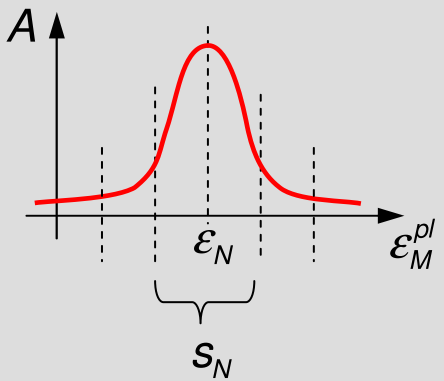
f_c = critical void volume fraction

The Gurson-model in LS-DYNA

The growth of the void volume is $\dot{f} = \dot{f}_N + \dot{f}_G$
and can be considered as damage.

Nucleation of new voids intension: $\dot{f}_N = A\dot{\varepsilon}_M^{pl}$

where $A = \frac{f_N}{s_N\sqrt{2\pi}} \exp\left(-\frac{1}{2}\left(\frac{\varepsilon_M^{pl} - \varepsilon_N}{s_N}\right)^2\right)$



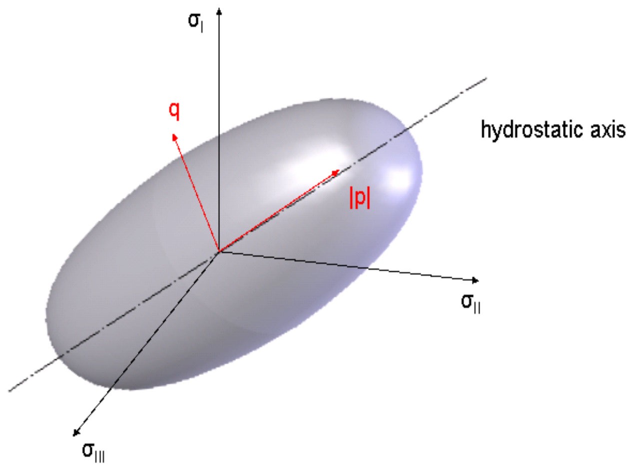
ε_N = mean nucleation strain

ε_M^{pl} = eff. pl. strain (matrix)

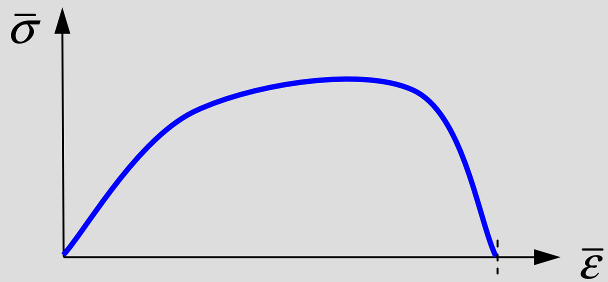
s_N = std. deviation

Growth of existing voids: $\dot{f}_G = (1 - f)\dot{\varepsilon}_{kk}^{pl}$

where $f = \frac{V_{voids}}{V_{voids} + V_{matix}}$



Damaged Gurson yield surface
(needs in hydrostatic loading)



Typical Gurson stress-strain curve

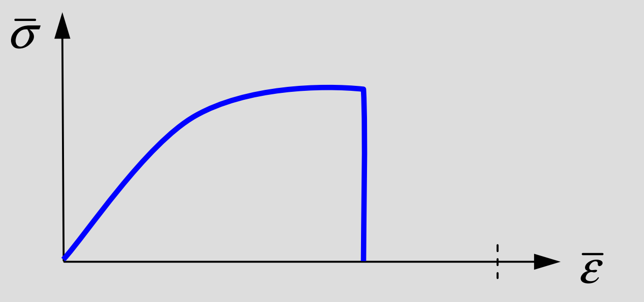
Gurson enhanced by JC-failure model

- Void growth in the standard Gurson model is triggered by **volumetric straining** (see also VGTYP for differences between tension and compression for nucleation of new voids).
- Hence for **pure shear** loading softening and subsequent failure is not taking place. The Johnson-Cook enhancement adds a failure criterion that is invoked between two defined triaxiality values and triggers **sudden** failure via element erosion.
- The definition of triaxiality play a major role: $\lambda_{tri} = \dfrac{\sigma_{ii}}{3\sigma_{vM}}$
- Definition of failure strain $\varepsilon_f = \left[D_1 + D_2 \exp\left(D_3 \lambda_{tri}\right)\right]\left(1 + D_4 \ln \dot{\varepsilon}\right)\Lambda$

  where $L_1 < \lambda_{tri} < L_2$ with L_1 and L_2 being user defined lower and upper triaxiality bounds

  and D_1 – D_4 are user defined Johnson-Cook failure parameters.

  Λ is the user defined curve LCDAM that defines a scalar value vs. element length and hence acts a regularisation means.



Typical GJC stress-strain curve

- Failure (i. e. element erosion) is initiated iff:

$$D_f = \sum \frac{\Delta\varepsilon_p}{\varepsilon_f} \begin{cases} < 1 & \textit{no failure} \\ \geq 1 & \textit{failure (element erosion)} \end{cases}$$

The Gurson_JC-model

Interaction between submodels by definition of L1 and L2

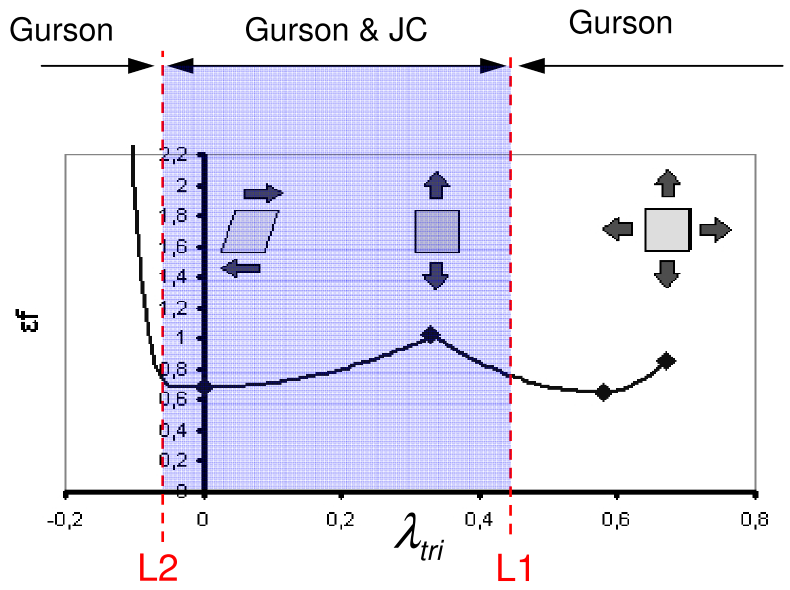
Remember: L1 and L2 are triaxiality values.
Triaxilality is defined as

$$\lambda_{tri} = \frac{\sigma_{ii}}{3\sigma_{vM}}$$

Hence positive values define tension,
negative define compression.

The following holds for the JC-corridor:

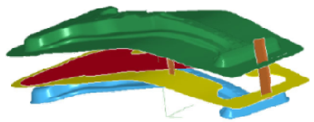
$\lambda_{tri} < L2$	Only Gurson is active
$L2 \leq \lambda_{tri} \leq L1$	Gurson and JC-criteria is active
$L1 < \lambda_{tri}$	Only Gurson is active



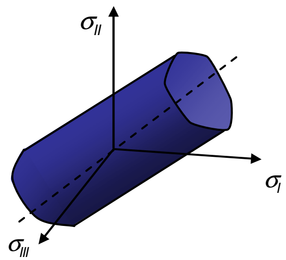
Produceability to Serviceability

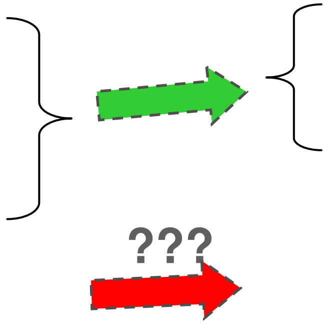
Closing the process chain

Forming simulation

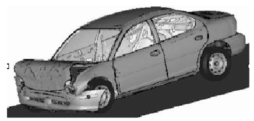


- **Hill based models**
- Anisotropiy of yield surface
- Kinematic/Isotropic hardening
- Failure by FLD
  (post-processing)
- No computation of damage

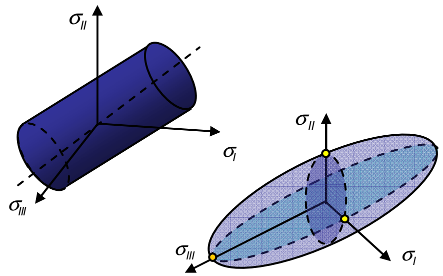




Crash simulation



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



Different ways to realize a consistent modeling

One Material Model for Forming and Crash Simulation

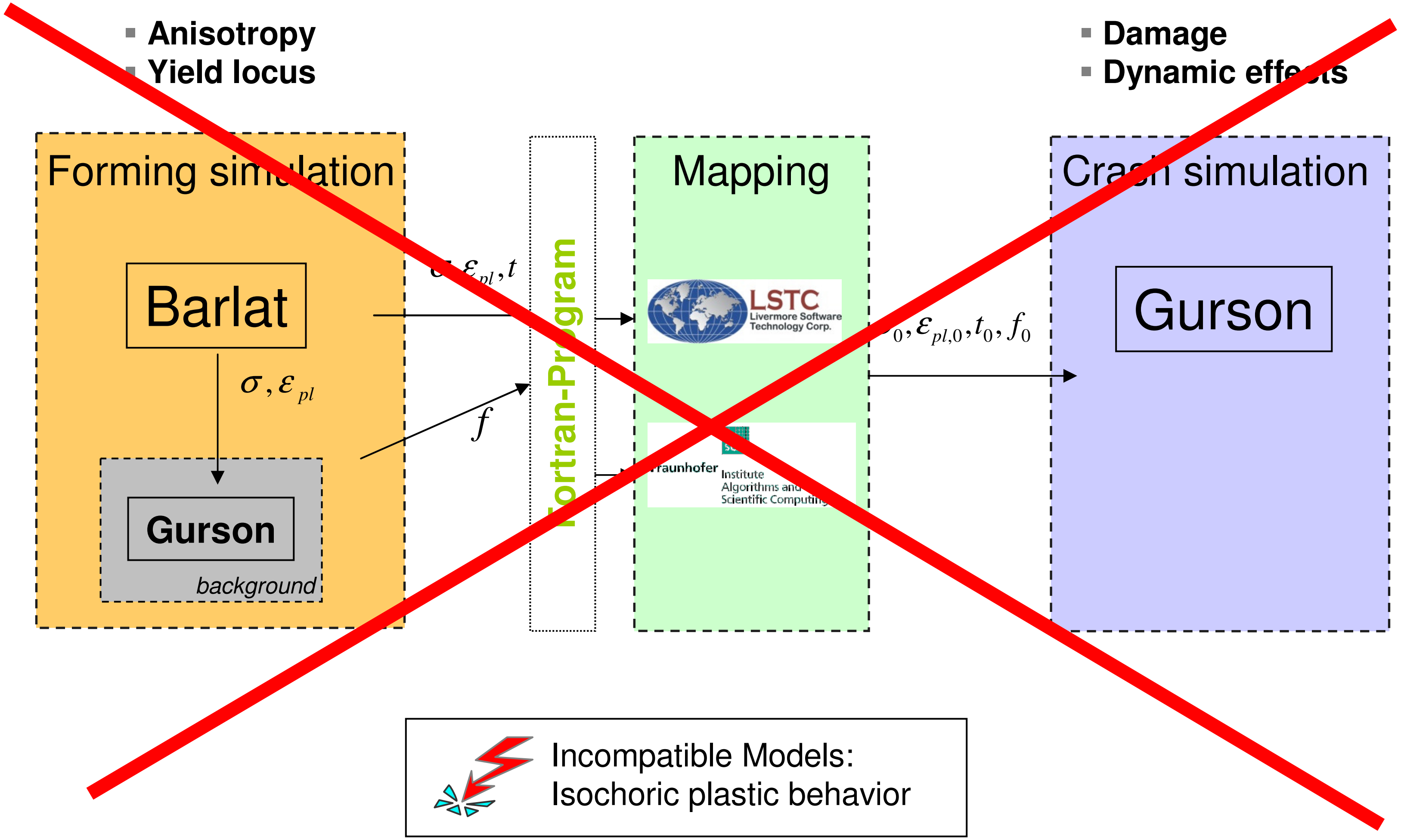
- Requirements for Forming Simulations: Anisotropy, Exact Description of Yield Locus, Kinematic Hardening, etc.
- Requirements for Crash Simulation: Dynamic Material Behavior, Failure Prediction, Energy Absorption, Robust Formulation
- Leads to very complex model

Modular Concept for the Description of Plasticity and 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

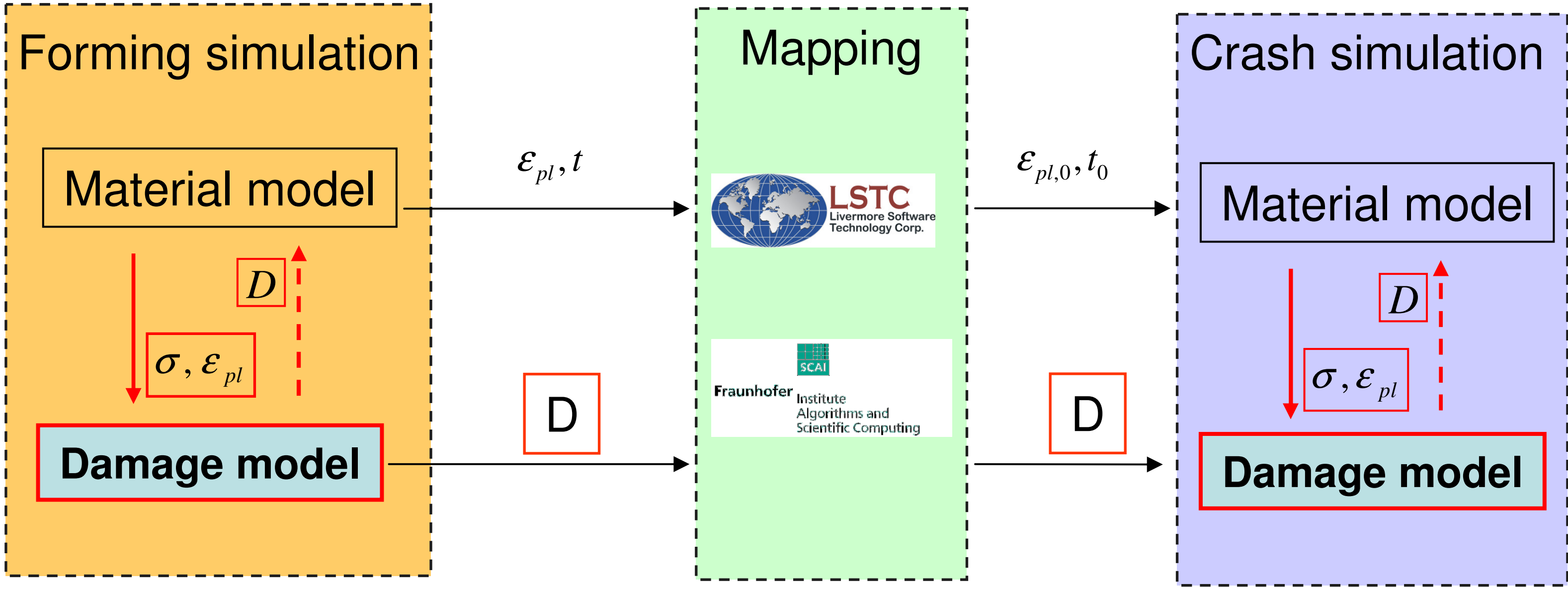
*MAT_ADD….(damage)

Produceability to Serviceability



Schmeing, Haufe & Feucht [2007]
Neukamm, Feucht & Haufe [2007]

Produceability to Serviceability: Modular Concept

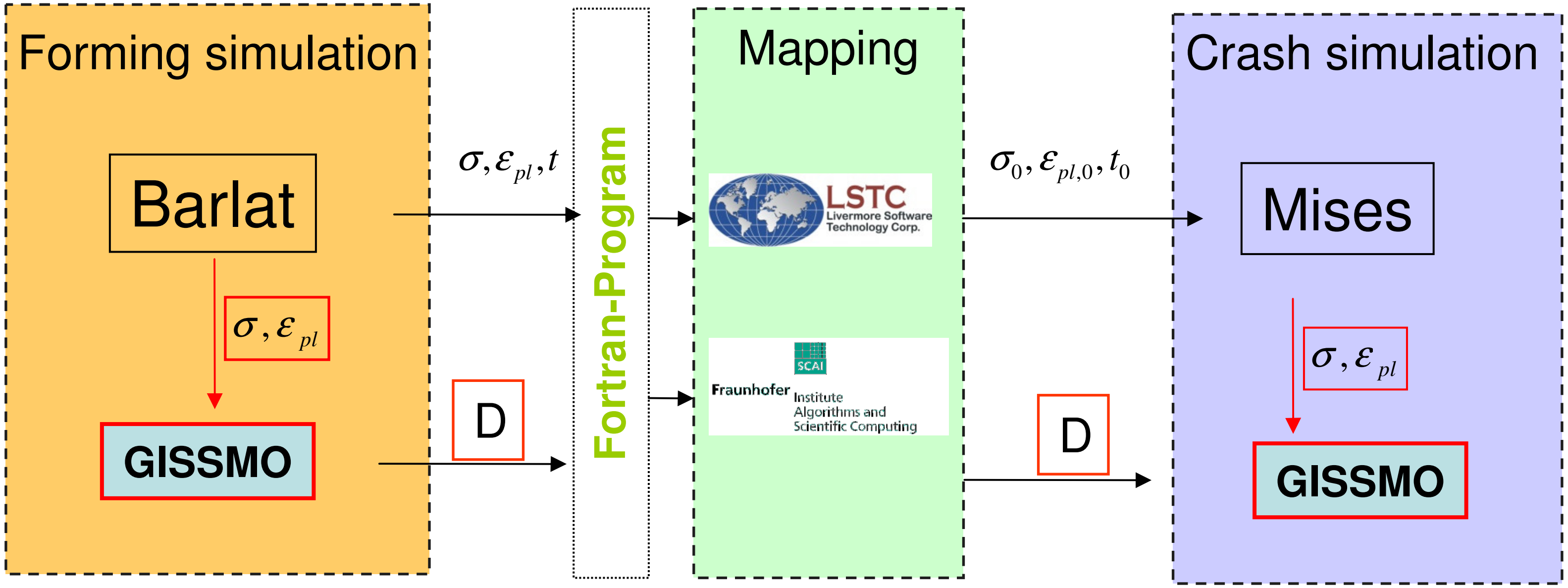


Modular Concept:

•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.)

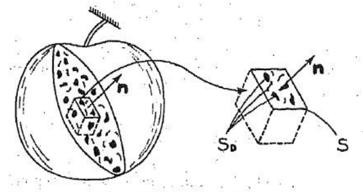
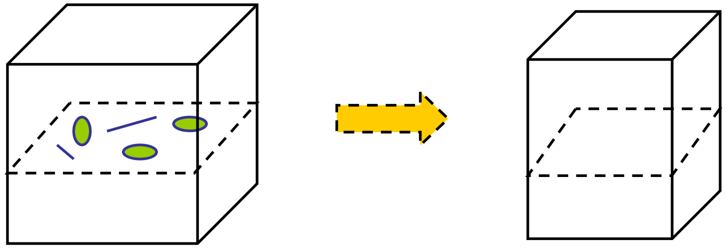


Fig. 1 Damaged element

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

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

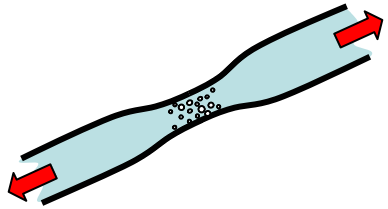
Reduction of effective cross-section leads to reduction of tangential stiffness

→ Phenomenological description

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

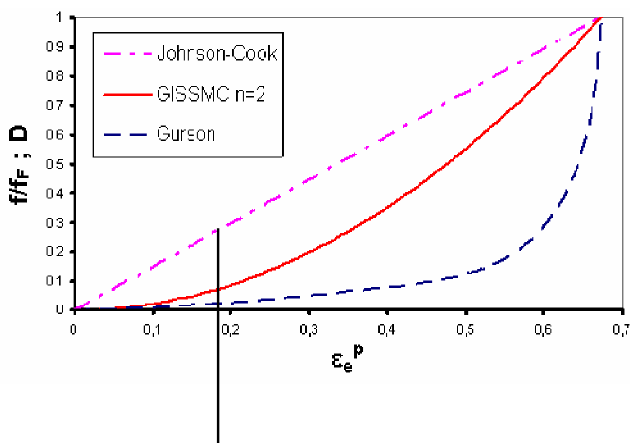
GISSMO - a short description

Ductile damage and failure



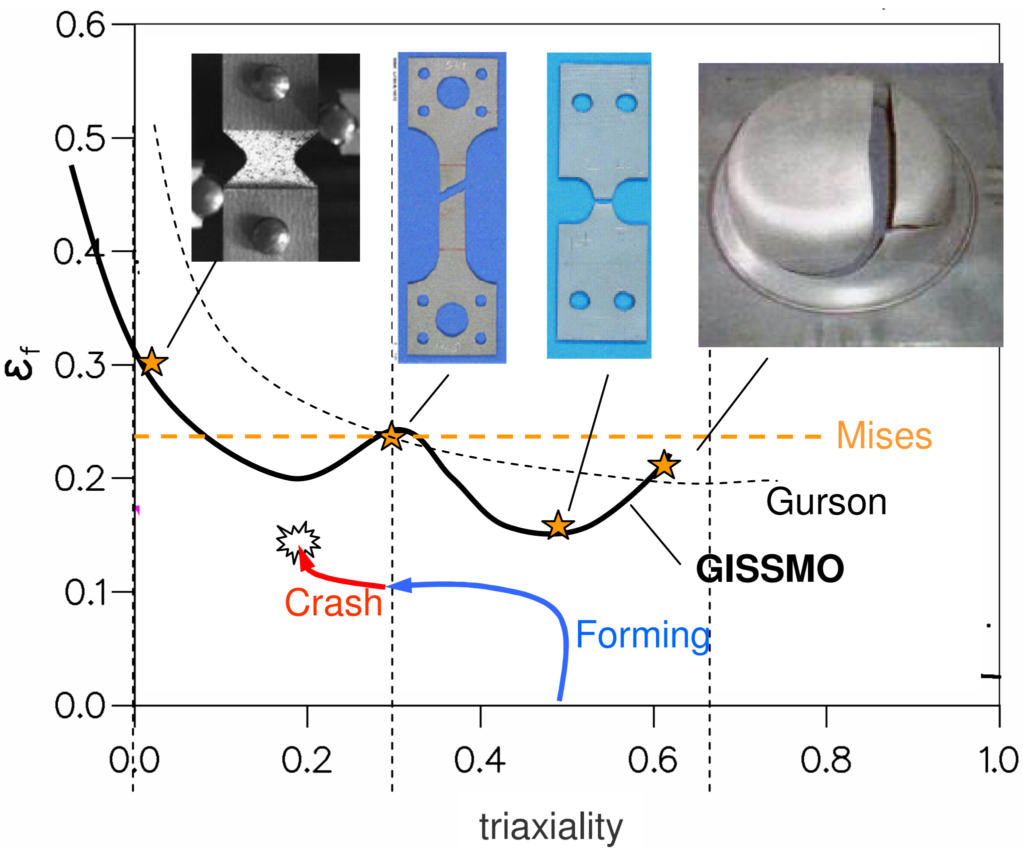
Damage Evolution

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



Damage overestimated for linear damage accumulation

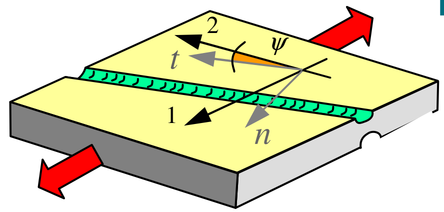
Failure Curve



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

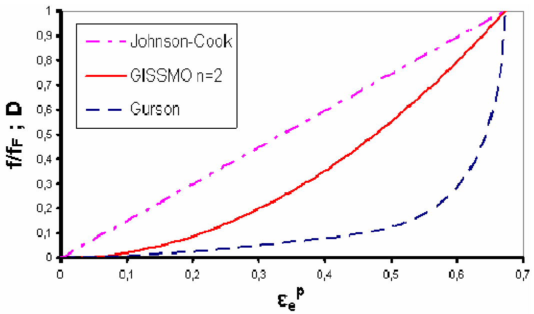
GISSMO – a short description

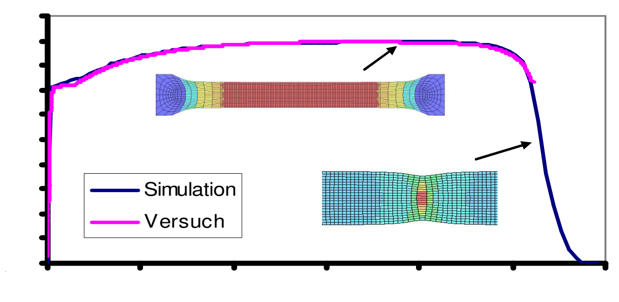
Engineering approach for instability failure



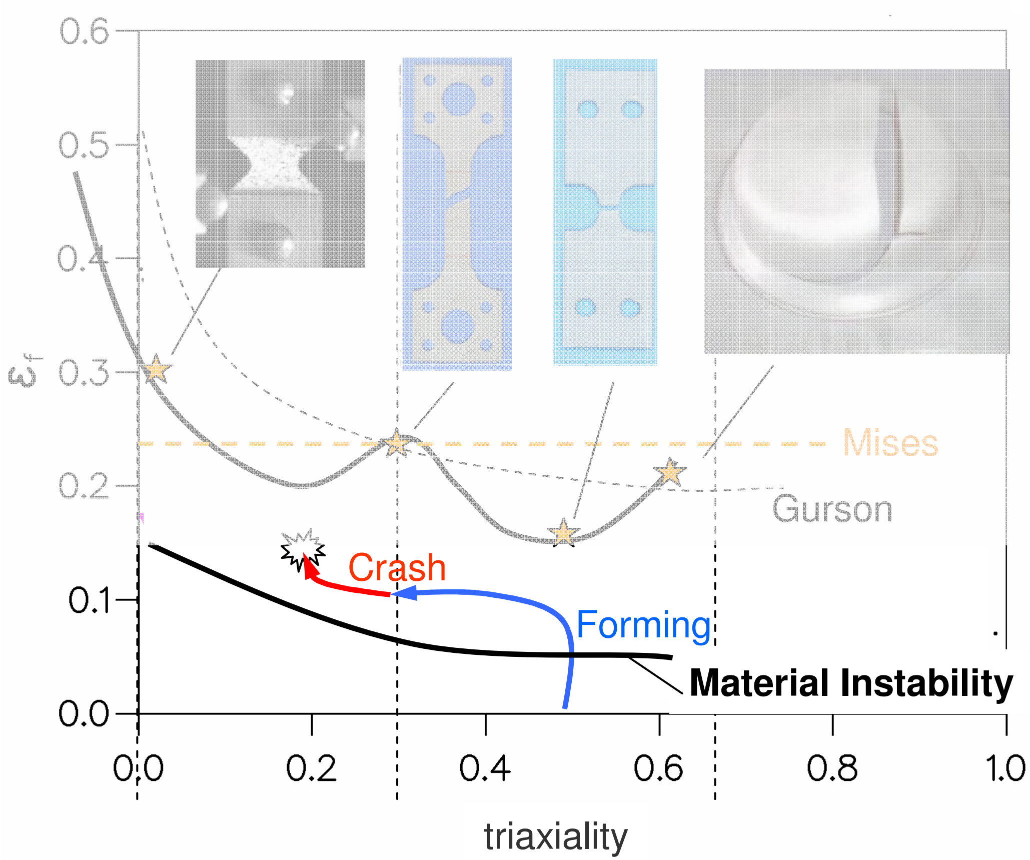
Evolution of Instability

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





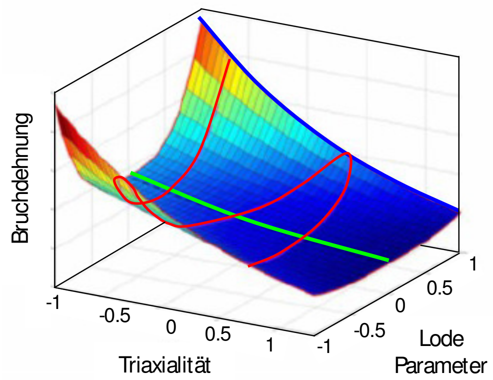
Material Instability

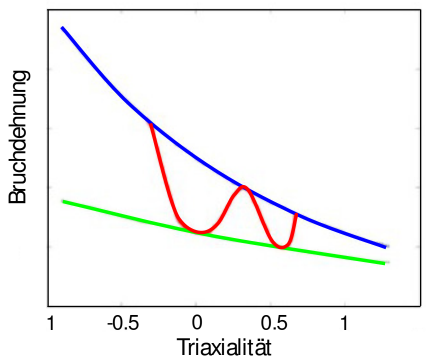


Neukamm, Feucht, DuBois & Haufe [2008-2010]

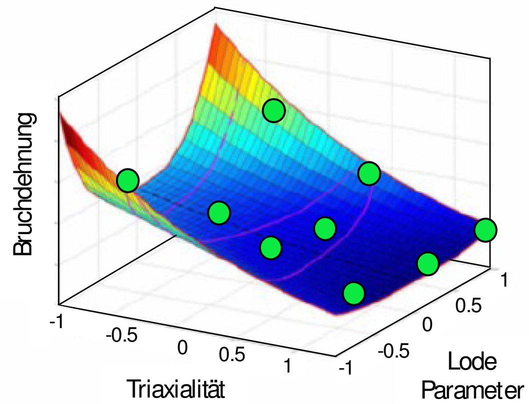
REMARK: Failure criterion for plane stress and 3D solids

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

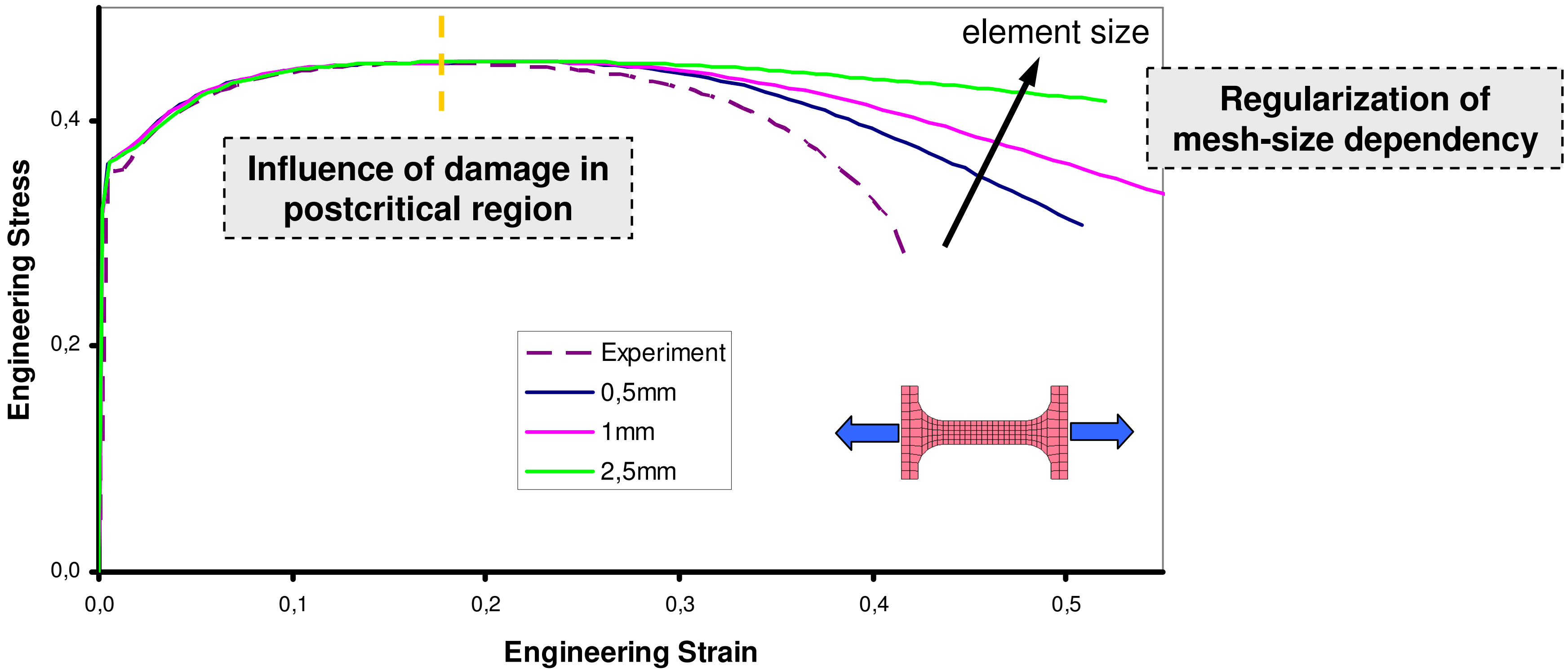
- For Solids (3D) both the Lode angle and triaxiality are independent

  → fracture strain is a function of triaxiality and Lode angle

GISSMO – a short description

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

Simulations of tensile test specimen with different mesh sizes

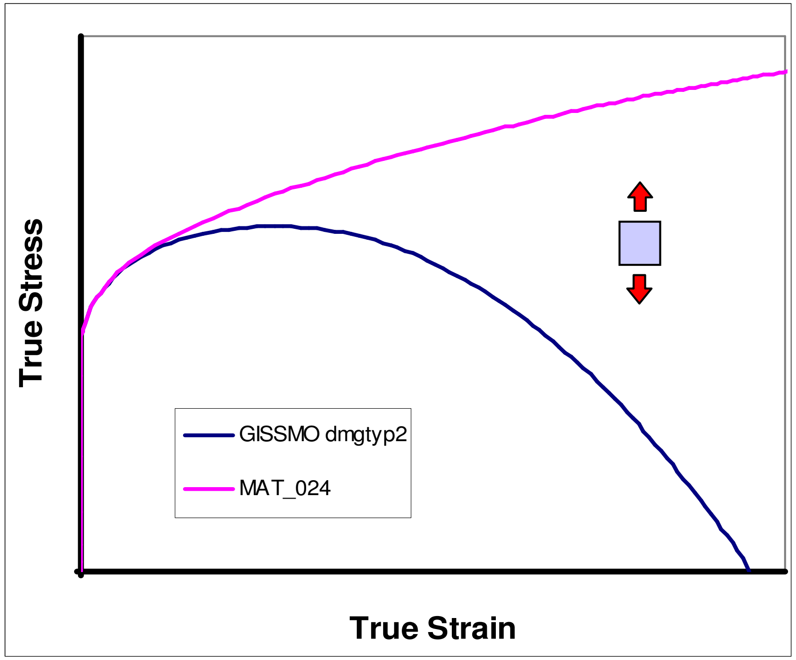


GISSMO – a short description

Generalized Incremental Stress State dependent damage MOdel

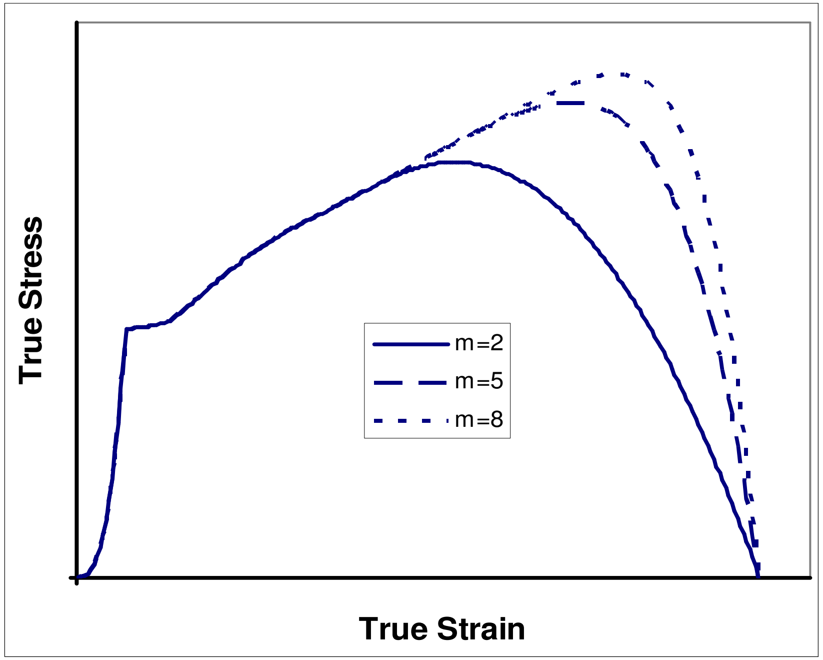
DMGTYP: Flag for coupling (Lemaitre)

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



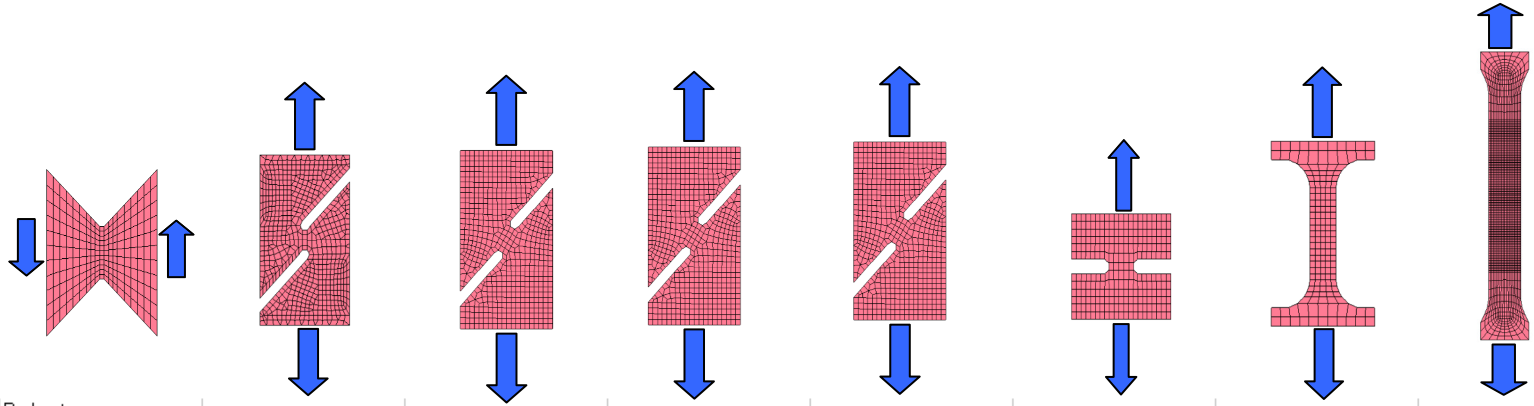
DCRIT, FADEXP: Post-critical behavior

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



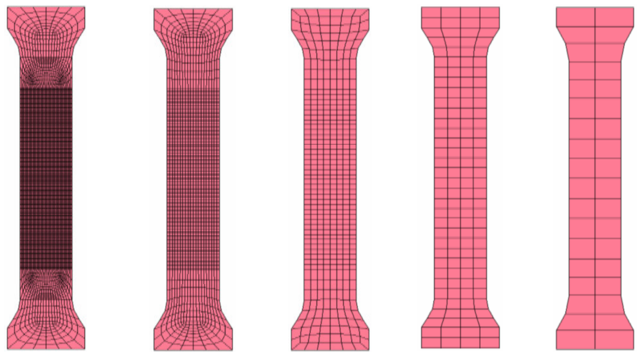
GISSMO

Identification of damage parameters: Range of experiments and simulations



	Probentyp							
Netzfeinheit	Arcan	Scherzug 0°	Scherzug 15°	Scherzug 30°	Scherzug 45°	Kerbzug R1	Mini-Flachzug	DIN-Flachzug
0,5mm								
1mm								
2,5mm								
5mm								
10mm								

To be considered:
8 Specimen geometries
5 Discretisations



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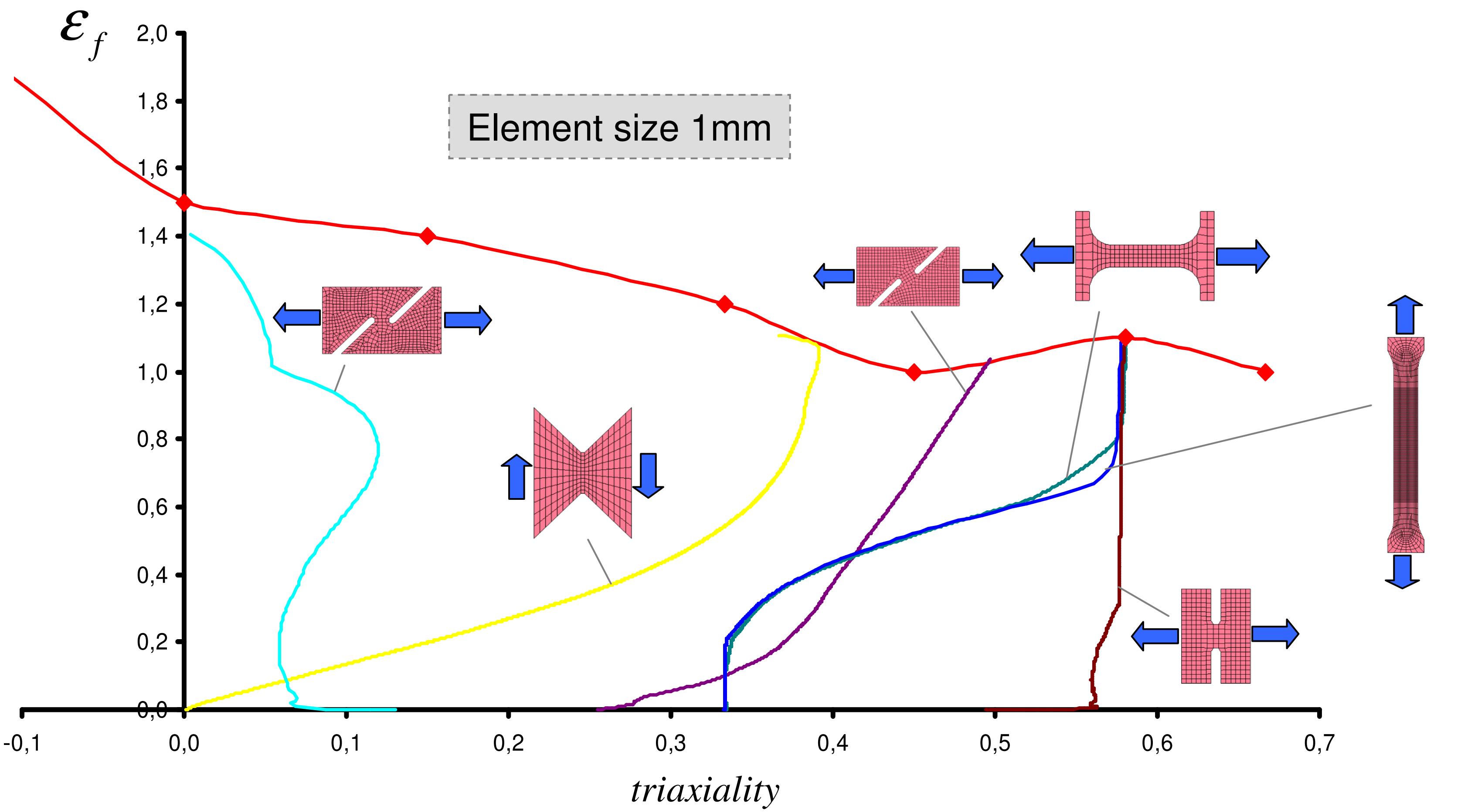
GISSMO

Equivalent plastic strain vs. triaxiality



GISSMO vs. Gurson vs. 24/81

Comparison of experiments and simulations

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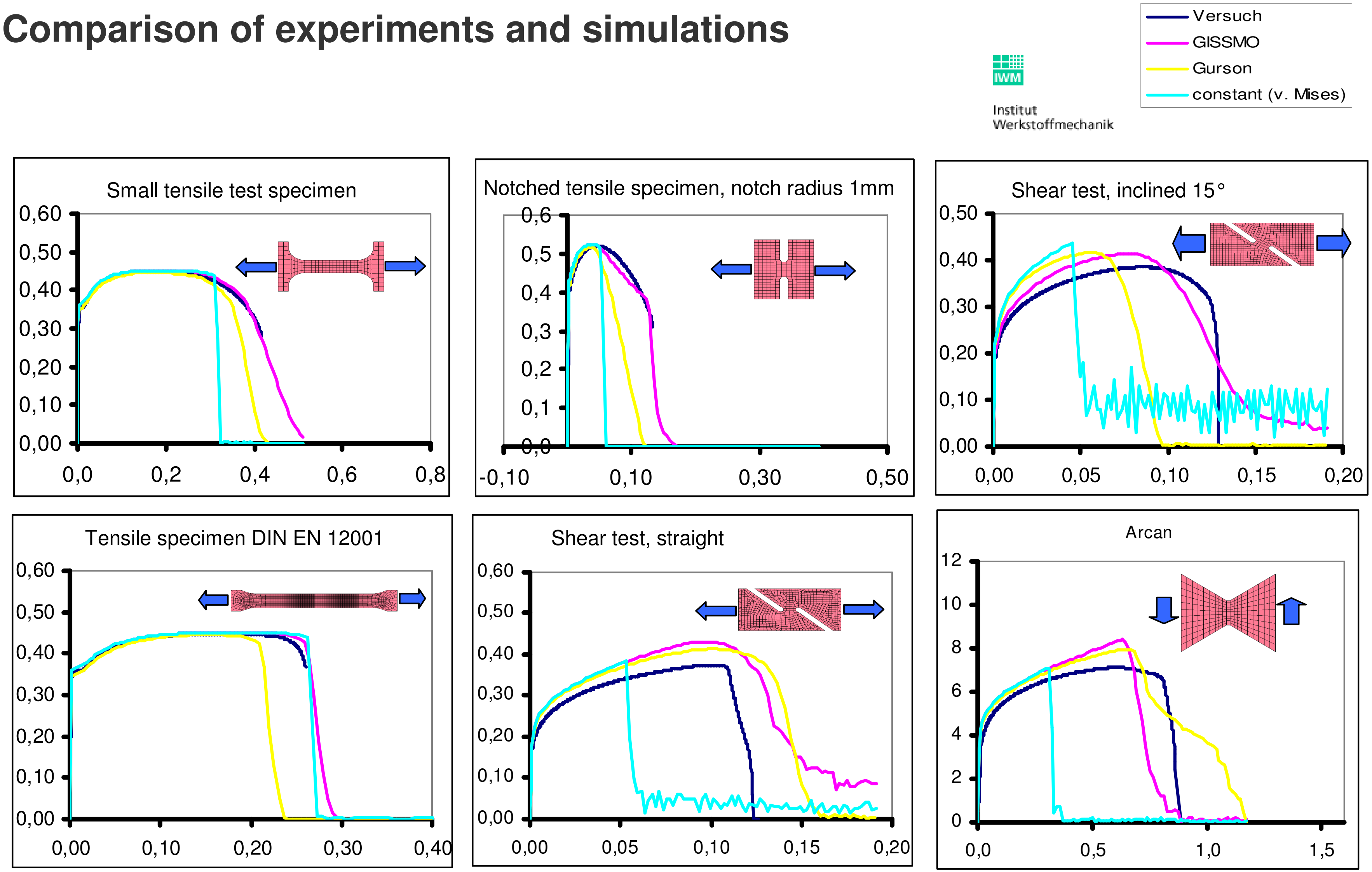
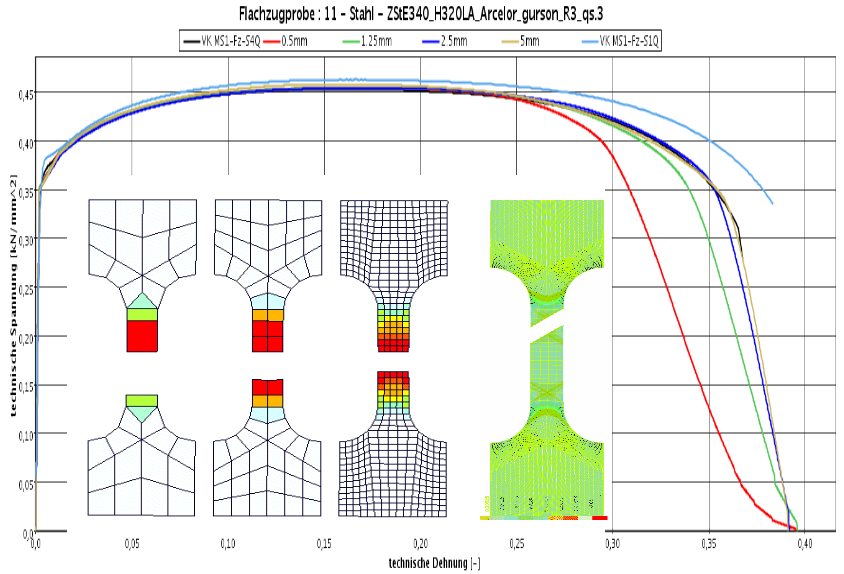
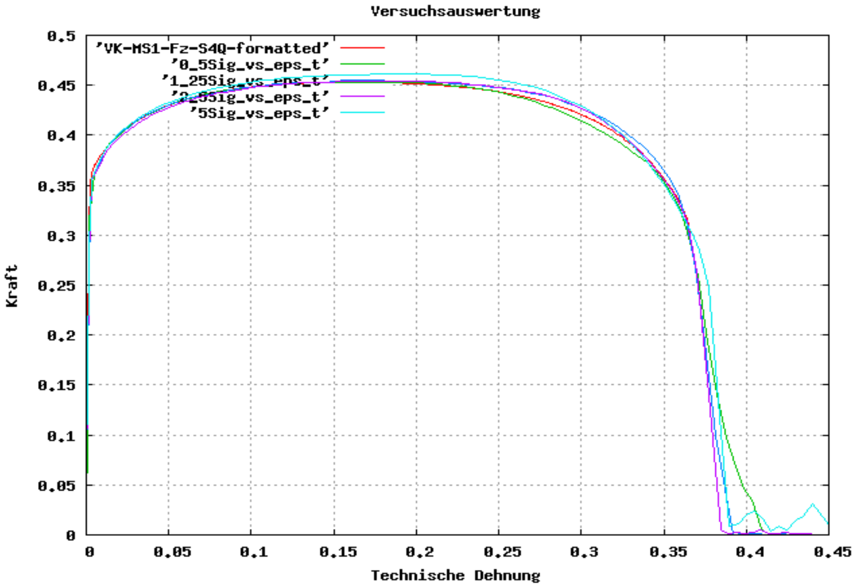


Gurson vs. GISSMO – "regularized"

Regularization of element size dependency

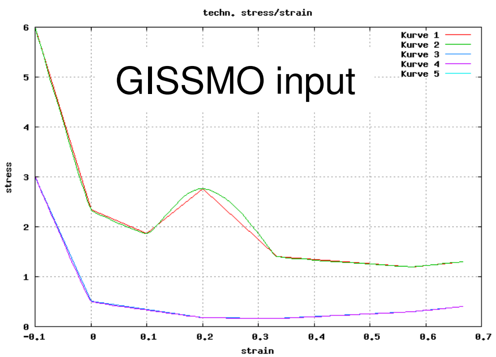


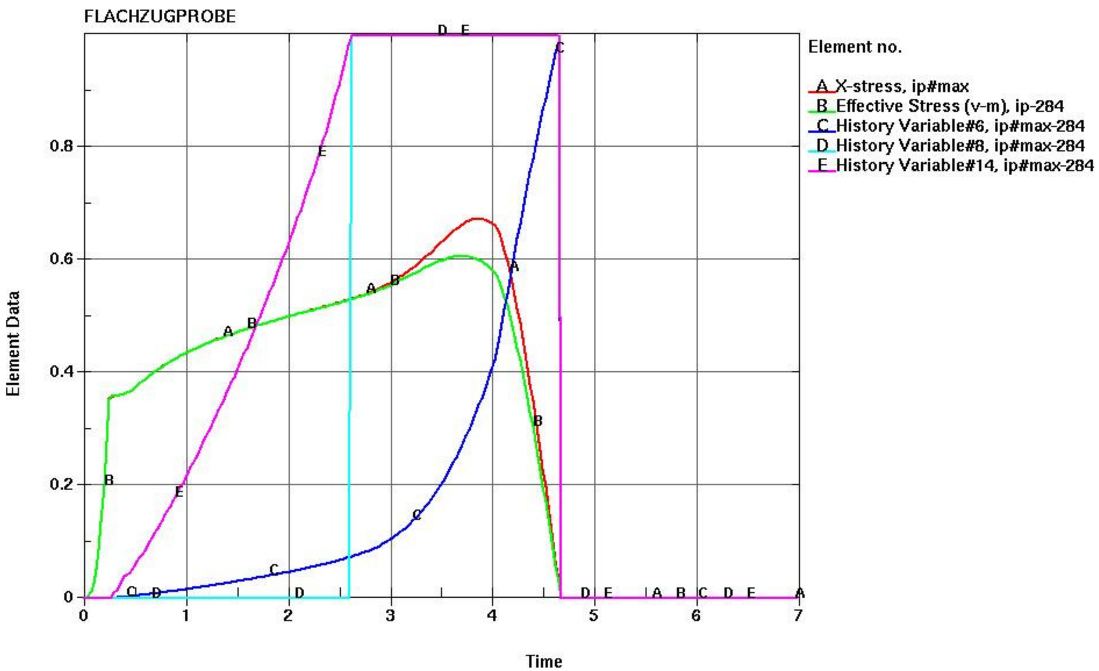


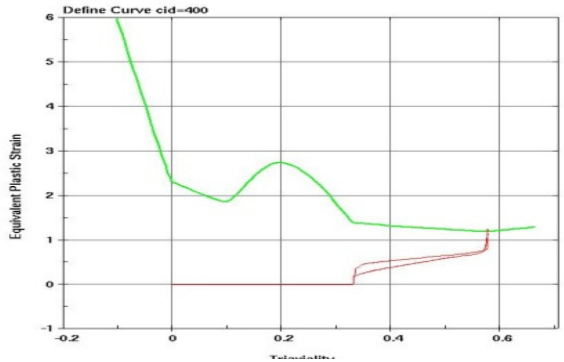
Gurson
- Resultant Failure Strain constant
- Failure energy depending on el. size
- Identification of damage parameters is difficult

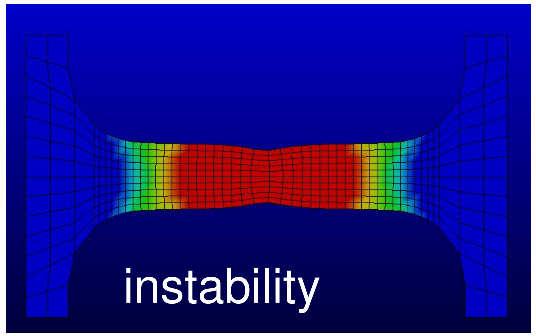
GISSMO
- Failure Strain constant
- Fracture energy constant
- Identification of Damage Parameters is more straight-forward

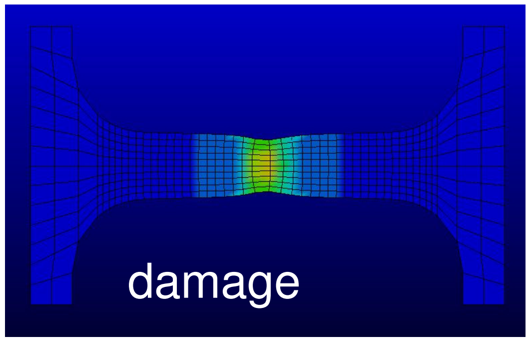
Example: tension rod



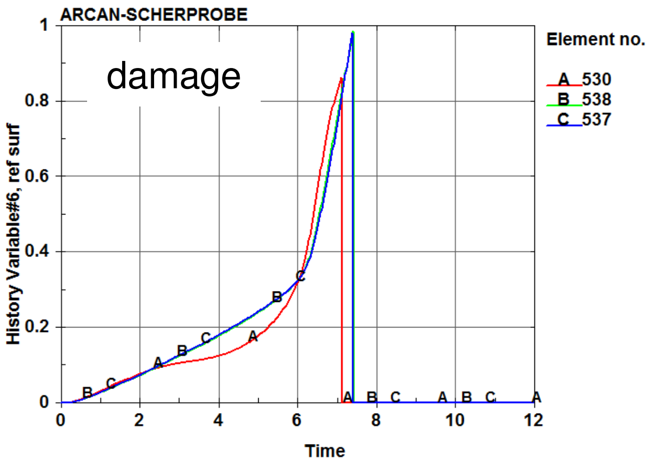


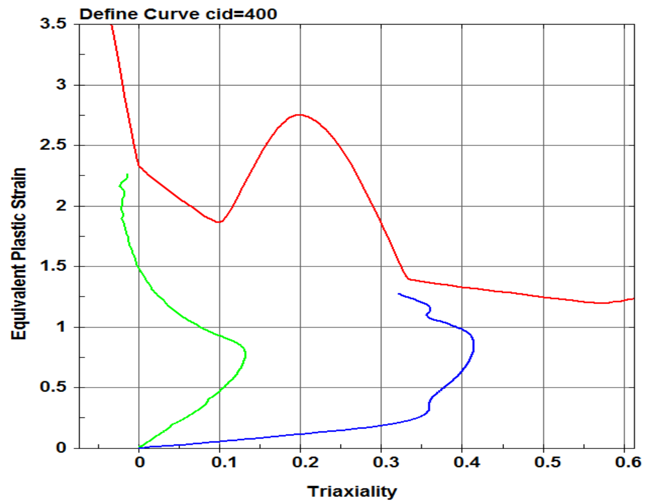


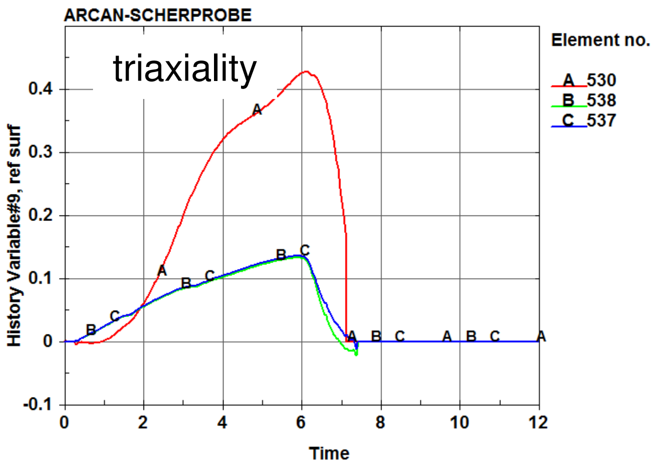


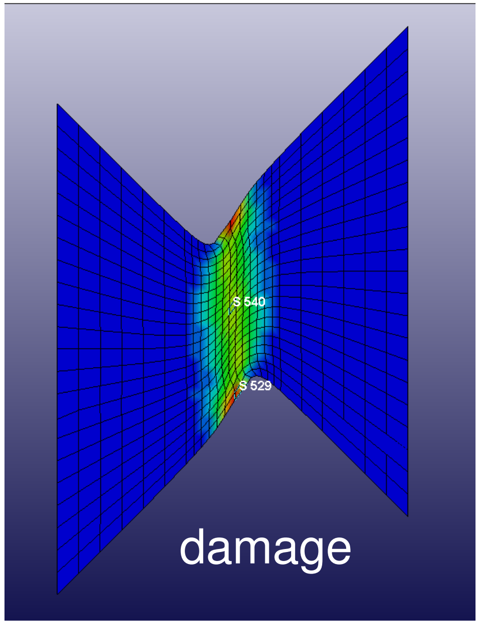


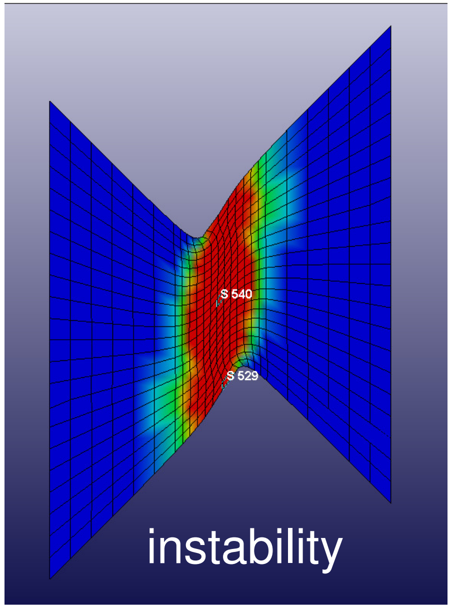
Example: Arcan shear test





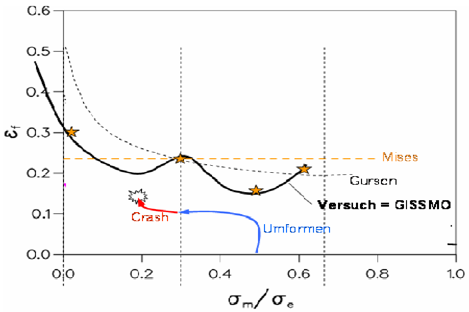


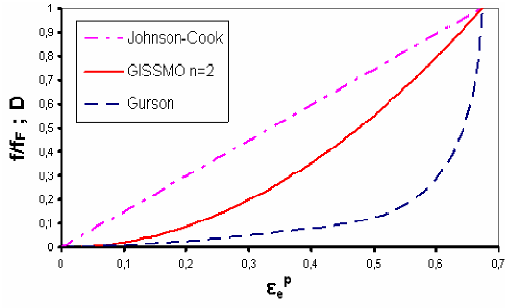




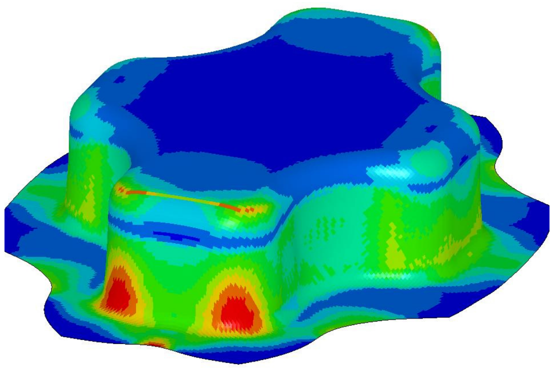
GISSMO

Deep-draw simulation of cross-die using GISSMO

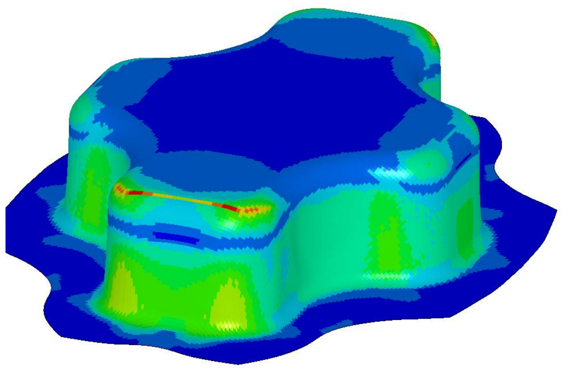




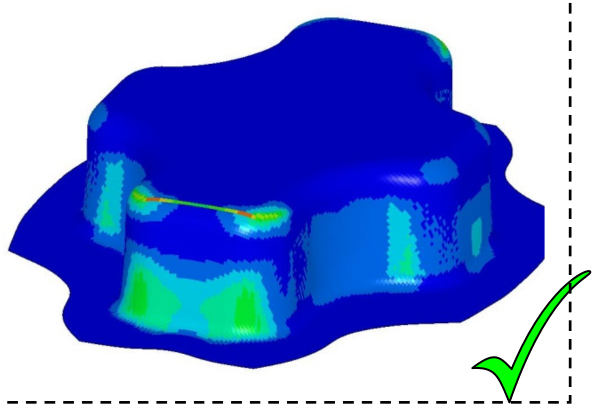
- Constant failure criterion
- Linear damage accumulation
- Failure not predicted correctly



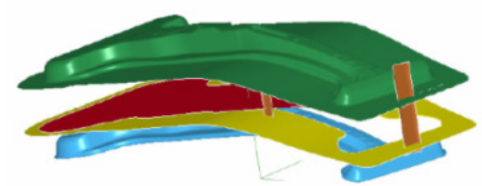
- GISSMO-Criterion
- Linear accumulation of damage
- Possibly overestimated damage



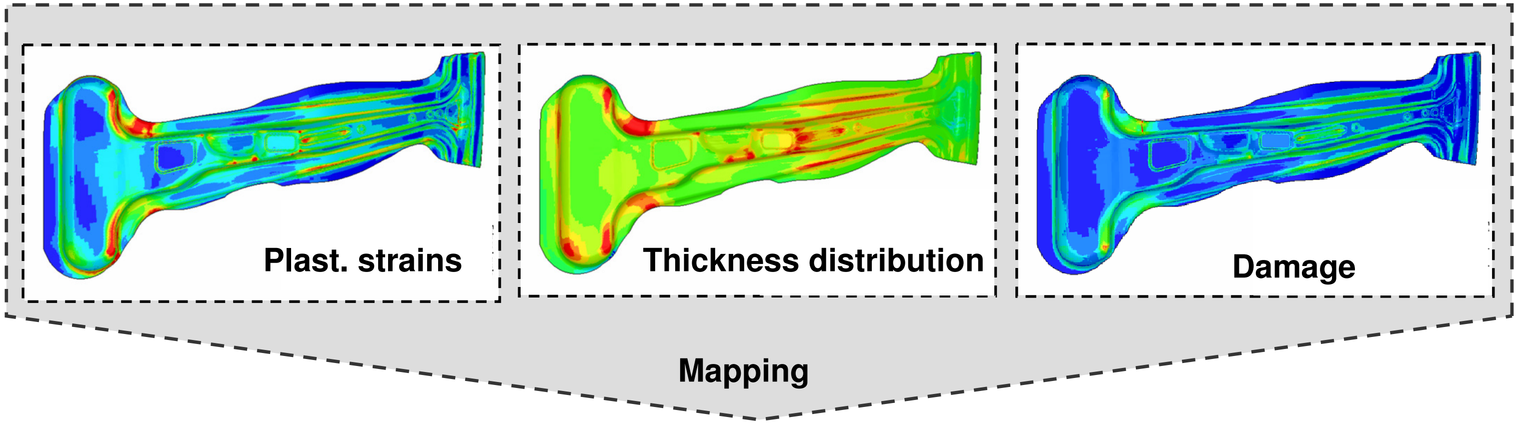
- GISSMO-Criterion
- Nonlinear damage accumulation
- Rupture predicted correctly

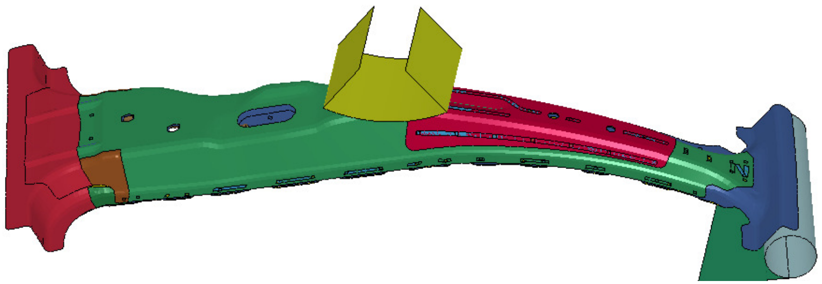


Process chain with GISSMO



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





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

Summary

- Features of GISSMO:
  - The use of existing material models and respective parameters
  - The 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
- Automatic method for identification of parameters is to be developed
- Offers features for a comprehensive treatment of damage in forming simulations
- Available in LS-DYNA V9.71 R5
- Verification und validation of concept are under way

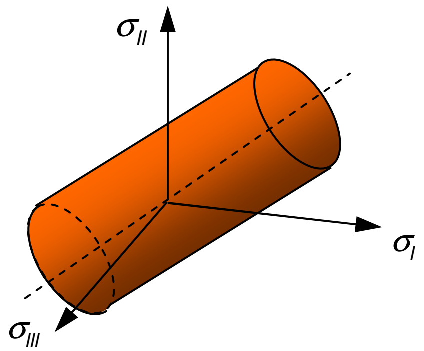
Threepart failure concept

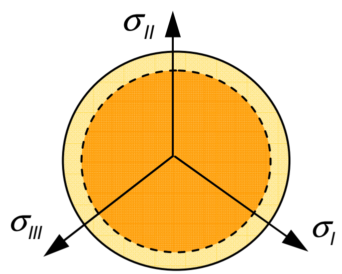
Damage and failure concept

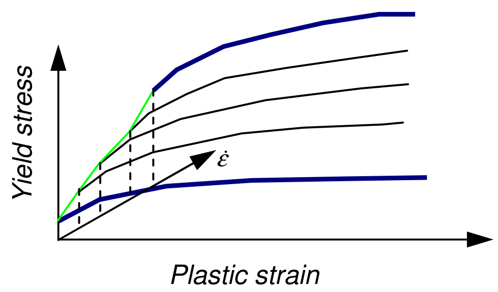
New implementation of a threepart failure model

- By using the basic software architecture available since the implementation of GISSMO another client driven threepart failure and damage model has been implemented.
- The model will be available in *MAT_ADD_EROSION starting with LS-DYNA V971 R5.
- The concept allows (theoretically) the combination with any available constitutive model in LS-DYNA. Hence the same idea for closing the gap between forming and crash simulations apply.
- The individual criteria deliver strain rate dependent failure accumulation that is being input in tabulated from.
- Using the accumulated data in subsequent simulations (multi-stage) simulations, the well established method of using the DYNAIN-files is chosen. Hence *INCLUDE_STAMPED_PART will be able to handle the new option.

Basis material model: e.g. MAT_24



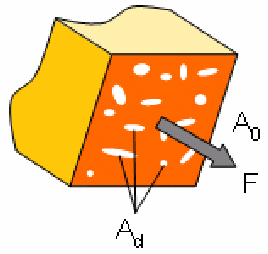




Damage and failure concept

- Three individual criteria may predict failure in thin sheet metal.
- Post-critical behavior is defined by allowance of an additional displacement in each element.
- The element is deleted if a defined number of integrations points is flagged as „failed“.

Idea of scalar damage



$D = \frac{A_d}{A_0}$ with $0.0 \leq D \leq 1.0$

Ductile failure

For the ductile initiation option a function

$$\varepsilon_D^p = \varepsilon_D^p(\eta, \dot{\varepsilon}^p)$$

represents the plastic strain at onset of damage (P1). This is a function of stress triaxiality defined as

$$\eta = -p / q$$

with p being the pressure and q the von Mises equivalent stress. Optionally this can be defined as a table with the second dependency being on the effective plastic strain rate $\dot{\varepsilon}^p$.

The damage initiation history variable evolves according to

$$\omega_D = \int_0^{\varepsilon^p} \frac{d\varepsilon^p}{\varepsilon_D^p}$$

Shear failure

For the shear initiation option a function

$$\varepsilon_D^p = \varepsilon_D^p(\theta, \dot{\varepsilon}^p)$$

represents the plastic strain at onset of damage (P1). This is a function of a shear stress function defined as

$$\theta = (q + k_S p) / \tau$$

with p being the pressure, q the von Mises equivalent stress and τ the maximum shear stress defined as a function of the principal stress values

$$\tau = \left(\sigma_{\text{major}} - \sigma_{\text{minor}}\right) / 2$$

Introduced here is also the pressure influence parameter k_S (P2). Optionally this can be defined as a table with the second dependency being on the effective plastic strain rate $\dot{\varepsilon}^p$. The damage initiation history variable evolves according to

$$\omega_D = \int_0^{\varepsilon^p} \frac{d\varepsilon^p}{\varepsilon_D^p}$$

Instability criteria

For the MSFLD initiation option a function

$$\varepsilon_D^p = \varepsilon_D^p(\alpha, \dot{\varepsilon}^p)$$

represents the plastic strain at onset of damage. This is a function of the ratio of principal plastic strain rates defined as

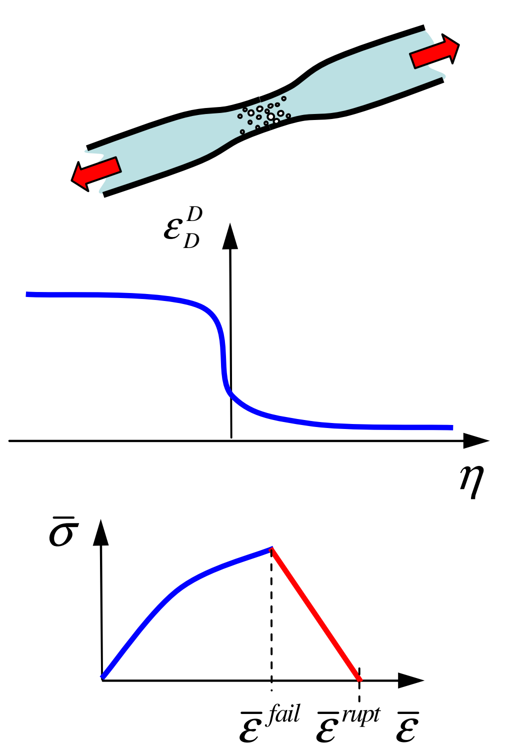
$$\alpha = \dot{\varepsilon}_{\text{minor}}^p / \dot{\varepsilon}_{\text{major}}^p$$

The MSFLD criterion is only relevant for shells and the principal strains should be interpreted as the in-plane principal strains. The damage initiation history variable evolves according to:

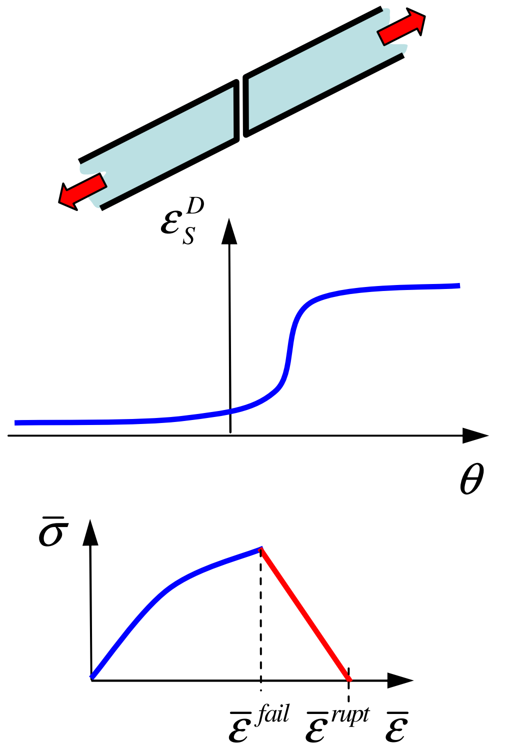
$$\omega_D = \max_{t \leq T} \frac{\varepsilon^p}{\varepsilon_D^p}$$

Failure mechanism in sheet metal deformation

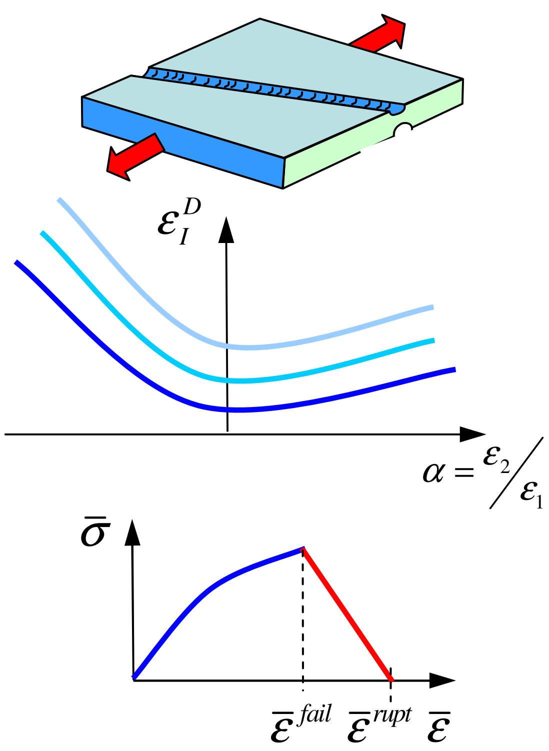
Ductile failure criteria



Shear failure criteria



Instability failure criteria



Thank you for your attention!

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