Ductile material failure in LS-DYNA

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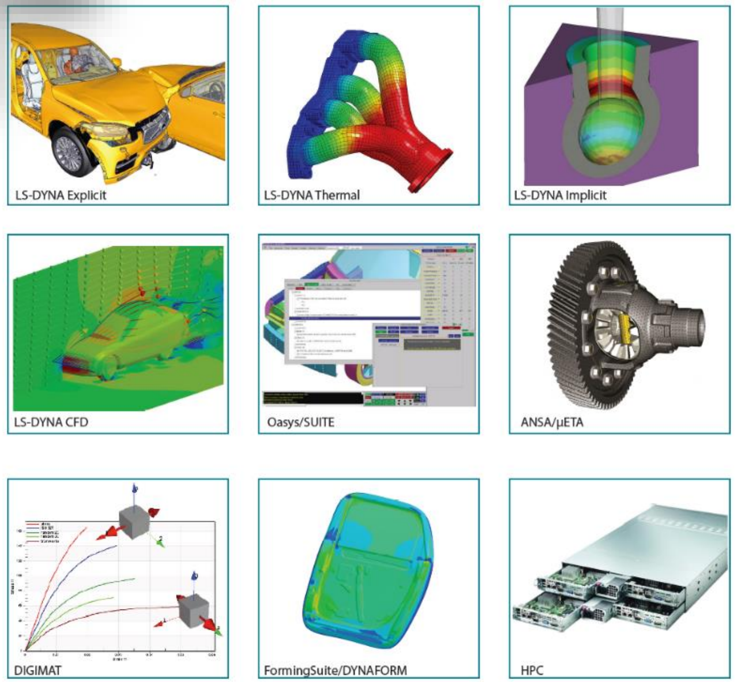
- www.dynaexamples.com – LS-DYNA example models from crash to DEM

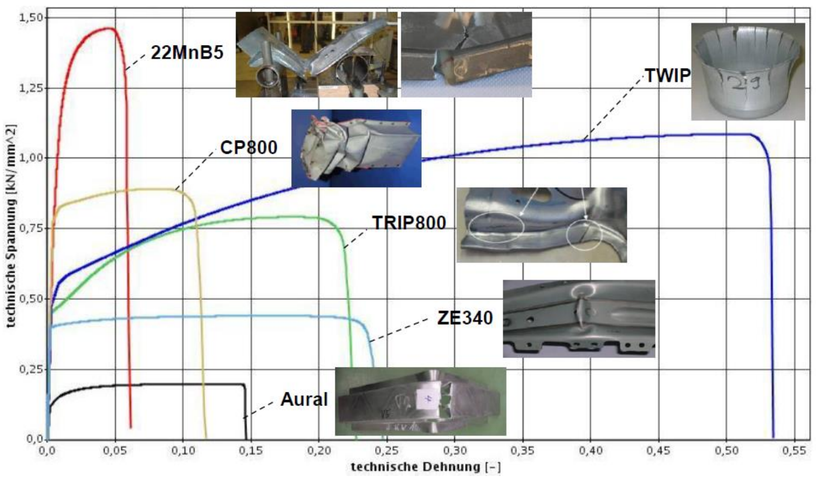


Agenda

- Introduction
  - Motivation
  - Path dependency
  - Stress Triaxiality and Lode Parameter
- Material instability/Diffuse necking
- Mesh dependency/Regularisation
- Failure criteria
  - Ductile
  - Instability
  - Shear
- Fracture models
  - Continuum Damage Mechanics
  - GISSMO
  - DIEM
  - Material Calibration

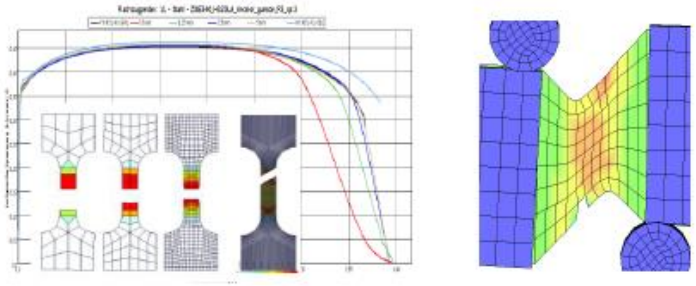
Introduction/Motivation

- The automotive industry is facing demands on emissions which has lead to a weight reduction race of the BIW
- The weight is reduced by using optimized material behaviour, e.g. high strength steels, but also mixing different material types.

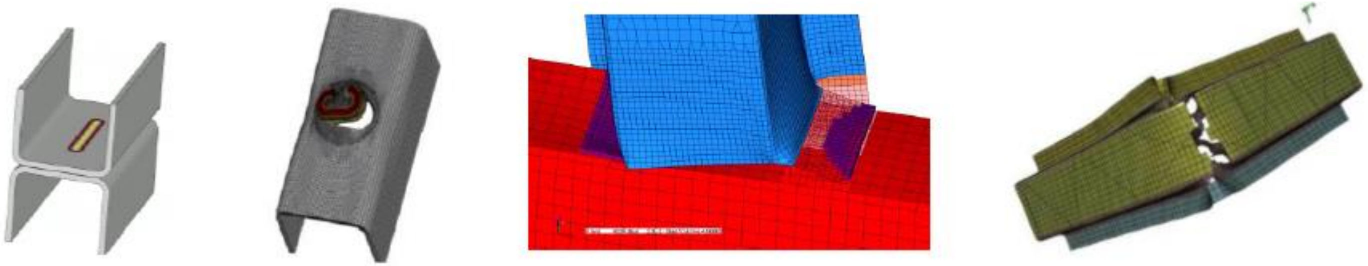


Introduction/Motivation

- The material shows different types of failures



- Failure of subsystems, e.g. connections



- Manufacturing history has an influence on the failure

Introduction/Motivation

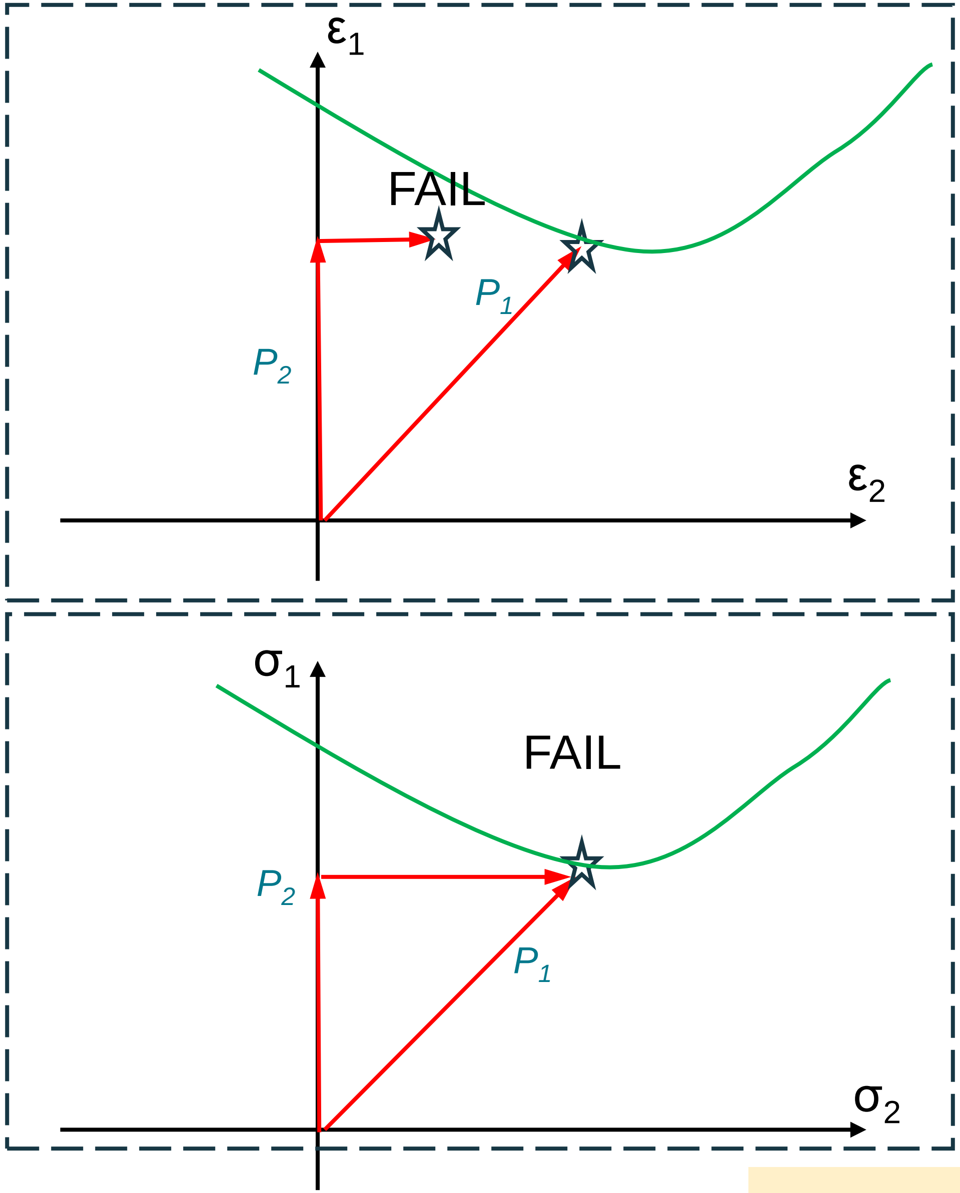
- The demands on a failure model are several
  - Material history/Path dependency
  - Mesh dependency
  - Capture several different failure modes
  - Easy to calibrate
  - Require a minimum of (expensive) tests
  - Possible to map between different material models and mesh sizes.

Path dependency

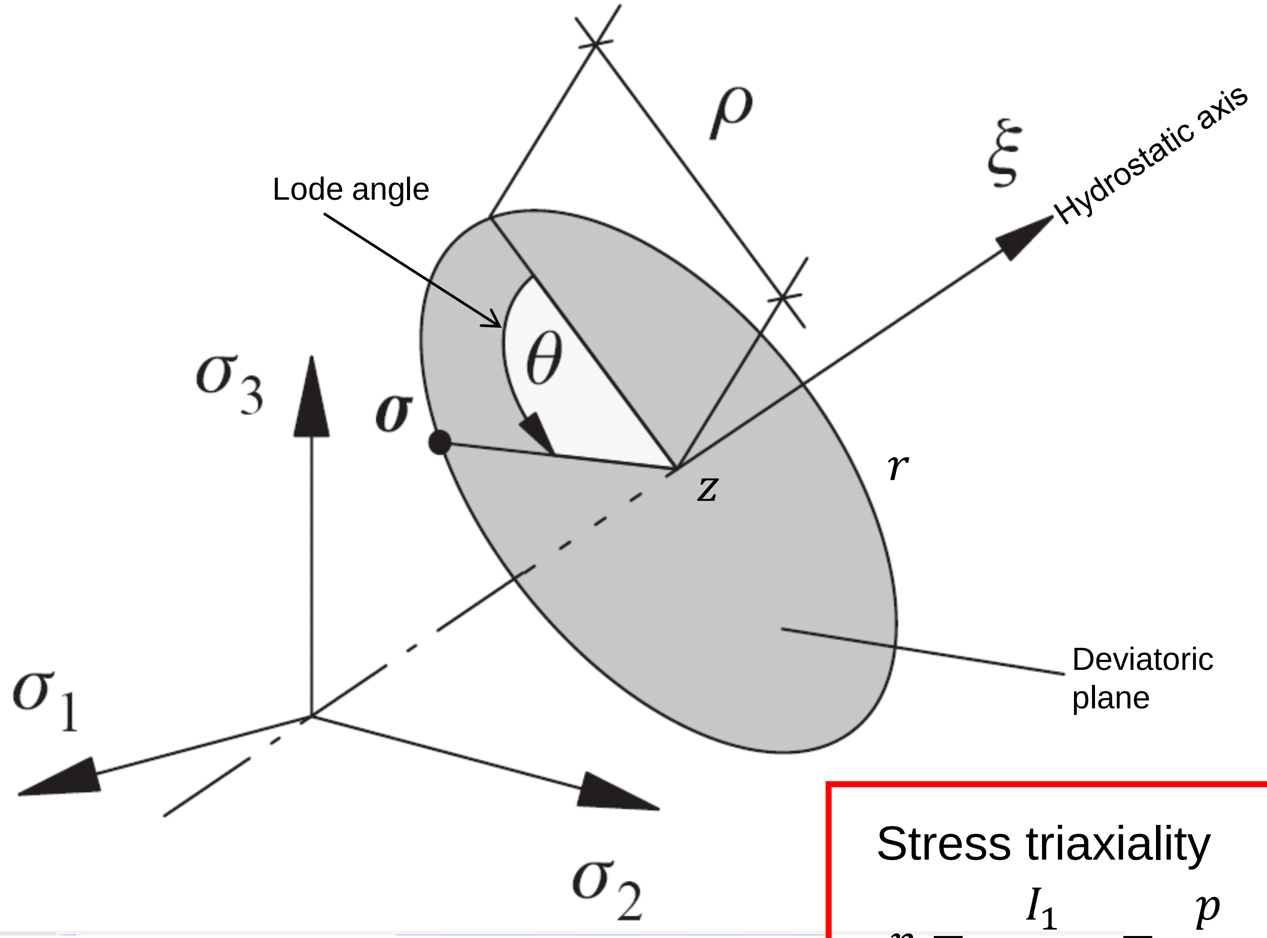
- If the failure criteria is path dependent, the load path has an influence on the failure point.
- However, the criteria can be path dependendent in strain space. But, if the stress space is used, then the final stress state is path in-dependent since:

$$\sigma = E\varepsilon^e$$

and the elastic strain is path independent.



Haigh-Westergaard coordinates in principle stress space



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

$$r = \sqrt{2J_2} = \sqrt{s:s}$$

$$\theta = \frac{1}{3}\cos^{-1}\left(\frac{27}{2}\frac{J_3}{\sigma_{vm}^3}\right)$$

$$\begin{bmatrix}\sigma_1\\ \sigma_2\\ \sigma_3\end{bmatrix} = \frac{z}{\sqrt{3}}\begin{bmatrix}1\\1\\1\end{bmatrix} + \sqrt{\frac{2}{3}}r\begin{bmatrix}\cos(\theta)\\ \cos(\theta - \frac{2\pi}{3})\\ \cos(\theta + \frac{2\pi}{3})\end{bmatrix}$$

Stress triaxiality

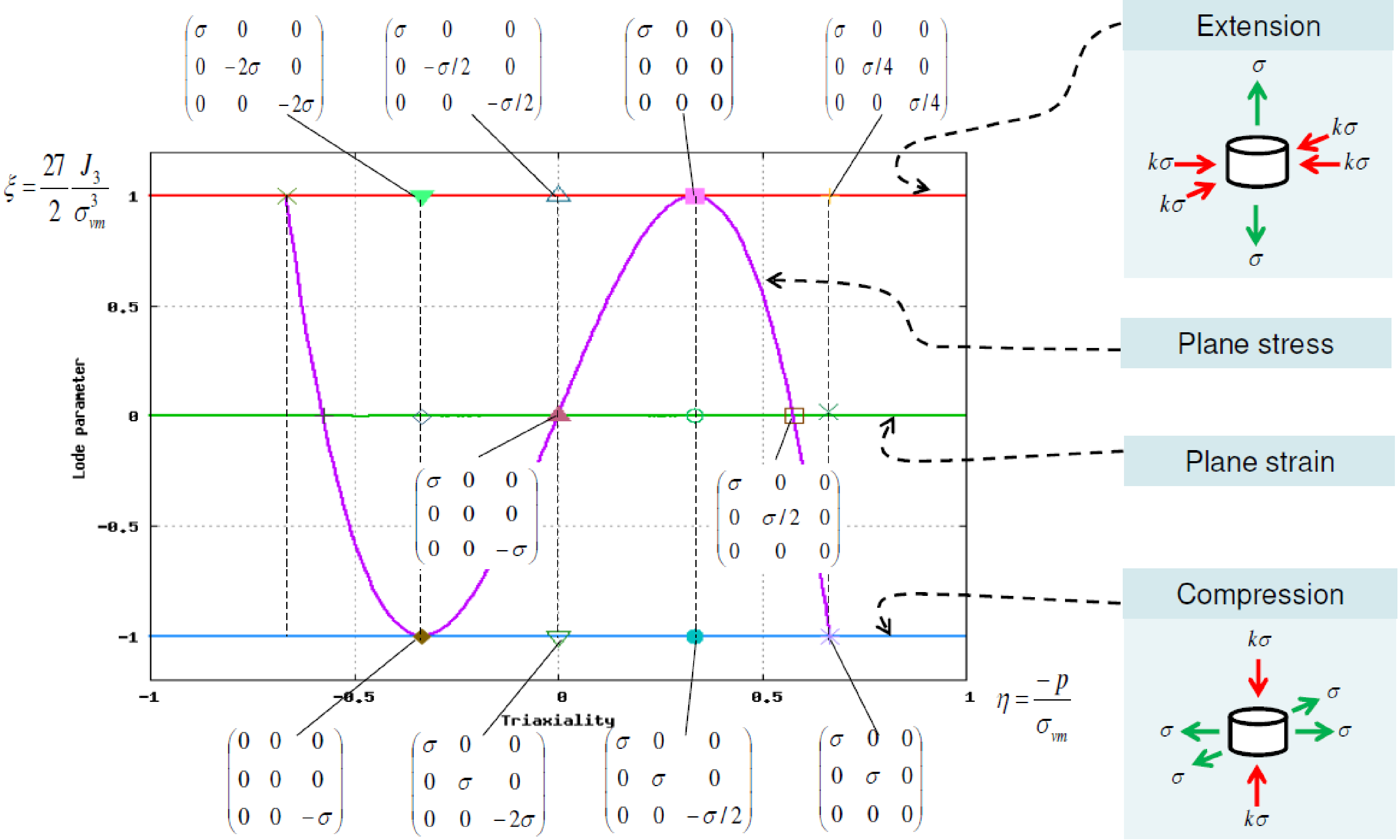
$$\eta = \frac{I_1}{3\sqrt{3J_2}} = \frac{p}{\sigma_{vm}}$$

Lode parameter

$$L = \frac{\sigma_1 + \sigma_3 - 2\sigma_2}{\sigma_1 - \sigma_3} = \frac{27}{2}\frac{J_3}{\sigma_{vm}^3}$$

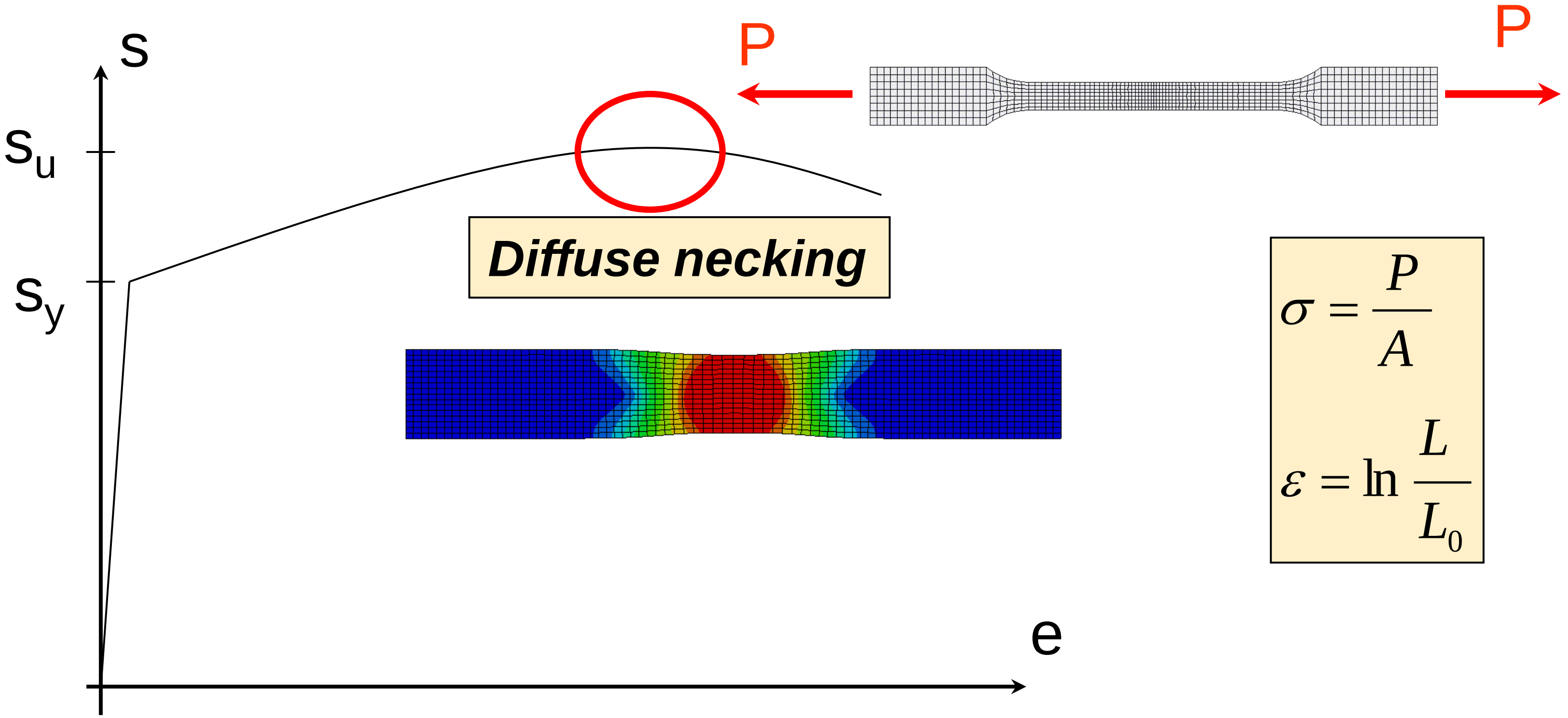
Lode angle parameter and stress triaxiality

- Any 3D stress state can be described using the Lode parameter and stress triaxiality.
- For a plane stress condition, every stress state can be described by the triaxiality value, i.e. shells.
- Stress states are often used in damage and failure models since it can describe a unique material state and is path independent.



Diffuse instability

The tensile test

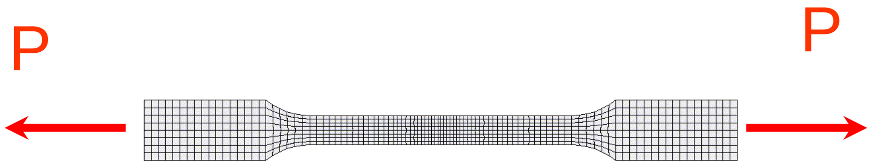


$$\sigma = \frac{P}{A}$$

$$\varepsilon = \ln \frac{L}{L_0}$$

At the point of necking, the hardening of the material can no longer compensate for the decrease in area and increase in load.
The softening behavior is due to the engineering measures, instead true values of stress and strain should be used.

The diffuse instability limit

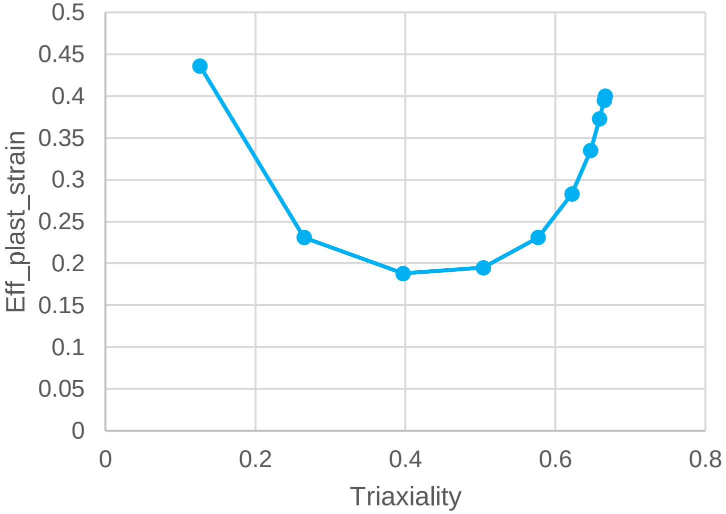


$$P = \sigma A$$

At the diffuse instability limit, the force has a maximum point. Thus,

$$dP = d\sigma A + \sigma dA = 0$$

$$\frac{d\sigma}{\sigma} = -\frac{dA}{A}$$



Plastic incompressibility yields,

$$dlA + LdA = 0$$

$$\frac{dl}{L} = -\frac{dA}{A} = \mathrm{d}\varepsilon$$

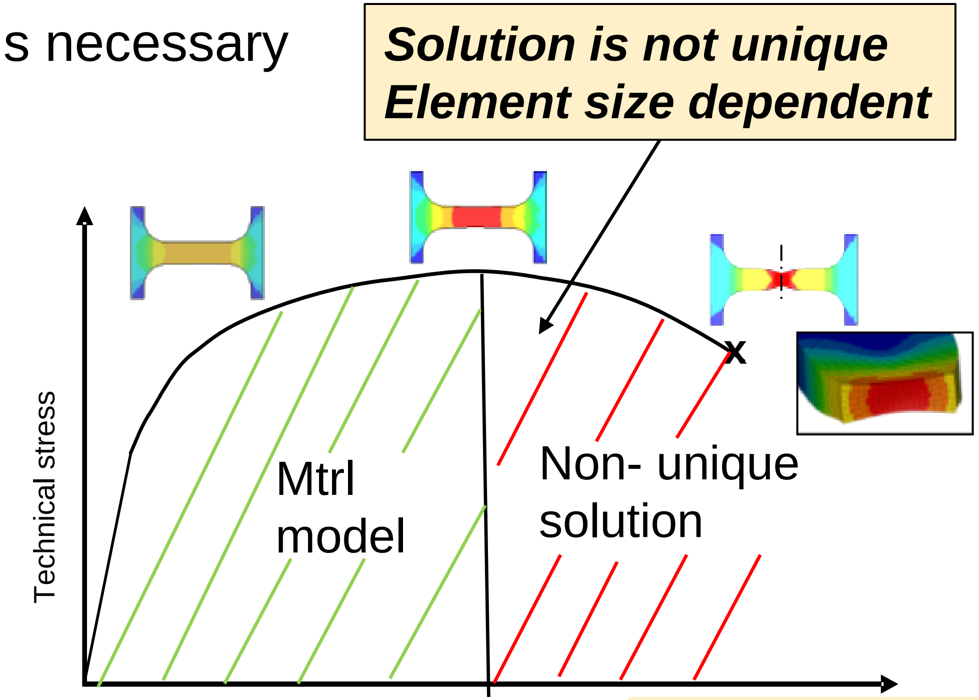
Thus, diffuse instability occurs when:

$$\frac{d\sigma}{d\varepsilon} = \sigma$$

Instability can be described by the hardening and yield criteria alone

General problem beyond necking

- Up to the material instability, the material behaviour can be described by the yield criteria and the hardening.
- Beyond the point of necking, the model shows softening.
- The solution is not unique.
- The solution will be mesh dependent – Regularisation is necessary

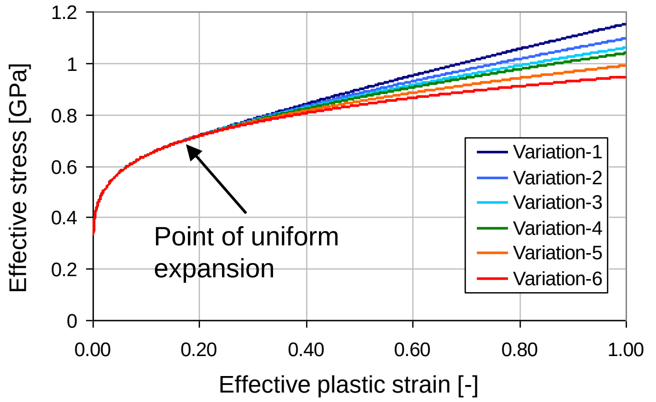


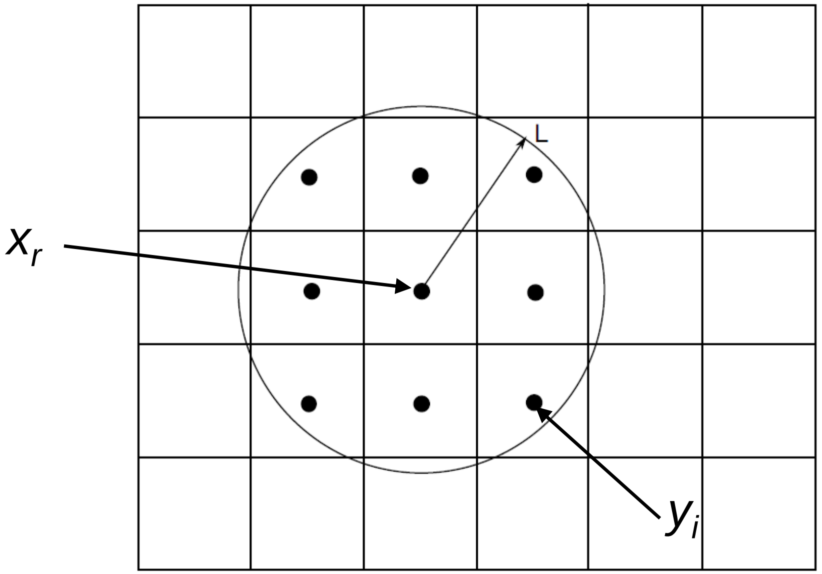
Regularisation in LS-DYNA

- ”Poor mans fit” – Fit your criteria for a specific element length.
- Some material models and failure criteria support element size dependent input.
- ***MAT_NON_LOCAL** distributes the material histories over several elements

$$w_{ri} = w(x_r - y_i) = \frac{1}{\left[1 + \left(\frac{\|x_r - y_i\|}{L}\right)^p\right]^q}$$

Iterations



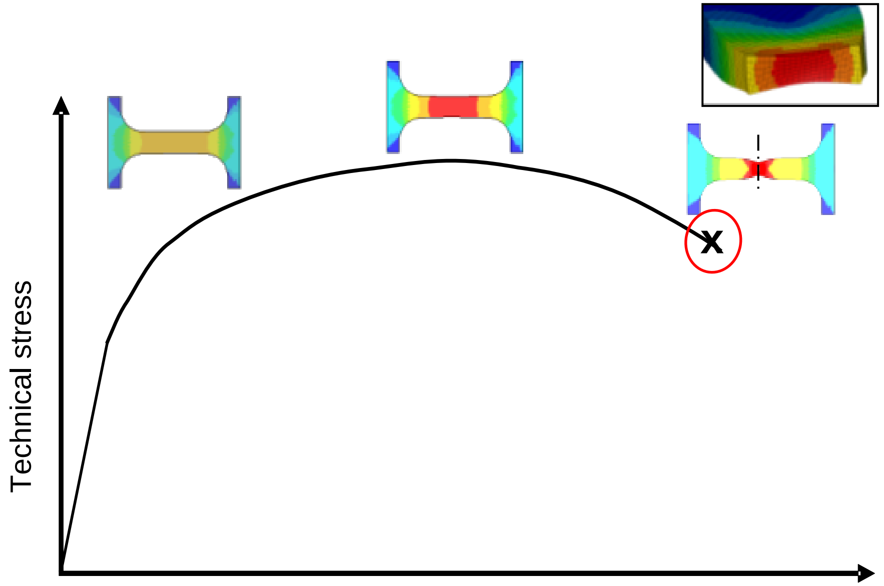


Failure criteria

Failure criteria

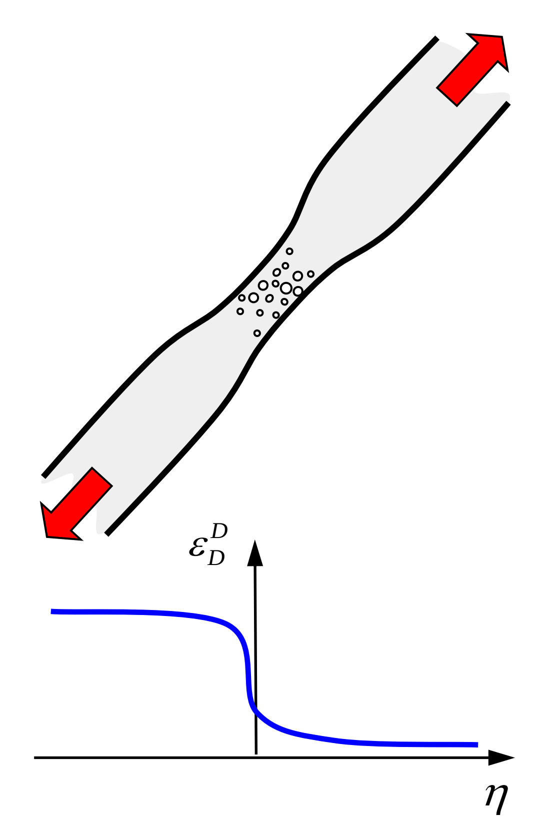
Definition: Failure criteria determines a point of failure and does not model the actual failure behaviour.

- However, the failure criteria theoretical basis can be found in failure models such as instability, damage etc.

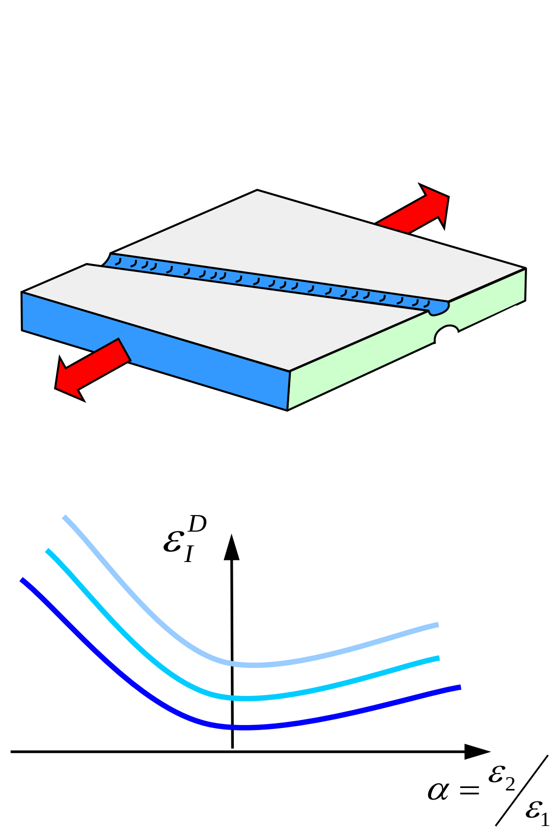


Failure criteria types

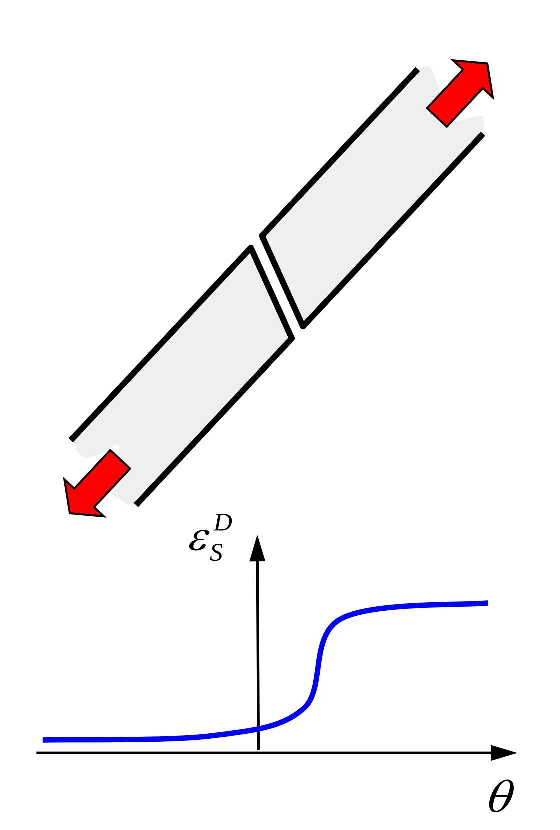
Ductile failure criteria



Instability failure criteria

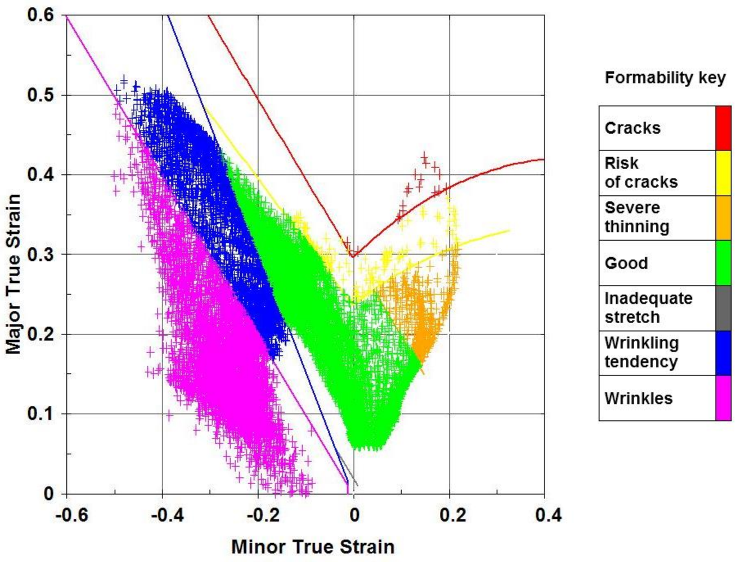


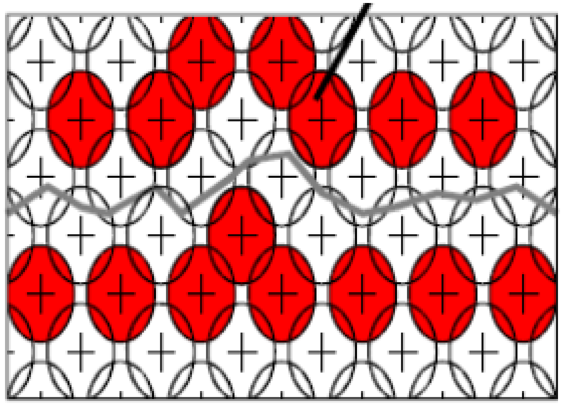
Shear failure criteria

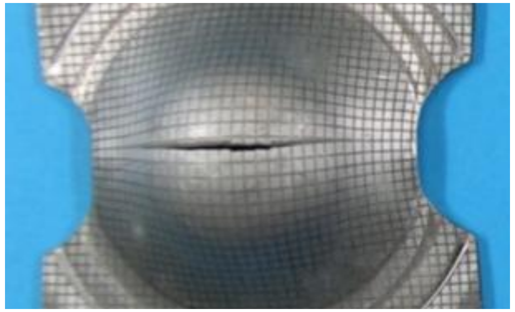


Failure criteria

- There are several failure criteria avialable:
  - Forming Limit Diagram (Instability)
    - **`*MAT39`**: Hill yield criterion with transverse anisotropy
    - **`*MAT_190`**: Barlat 3-parameter orthotropic yield criterion
  - FLSD (Instability) – Path independent FLD
    - **`*MAT_36`** and **`*MAT_37`** with **`_NLP_FAILURE`** option
  - Effective plastic strain (Ductile fracture)
    - E.G **`*MAT_24`**
  - Johnson Cook (Ductile fracture)
    - **`*MAT_15`**, **`*MAT_107`** and **`*MAT_224`**
  - Cockroft Latham (Ductile fracture)
    - **`*MAT_135: *MAT_WTM_STM`**
    - **`*MAT_107: *MAT_MODIFIED_JOHNSON_COOK`**
  - Bressan-Williams (Shear failure)
    - **`*MAT_135: *MAT_WTM_STM`**

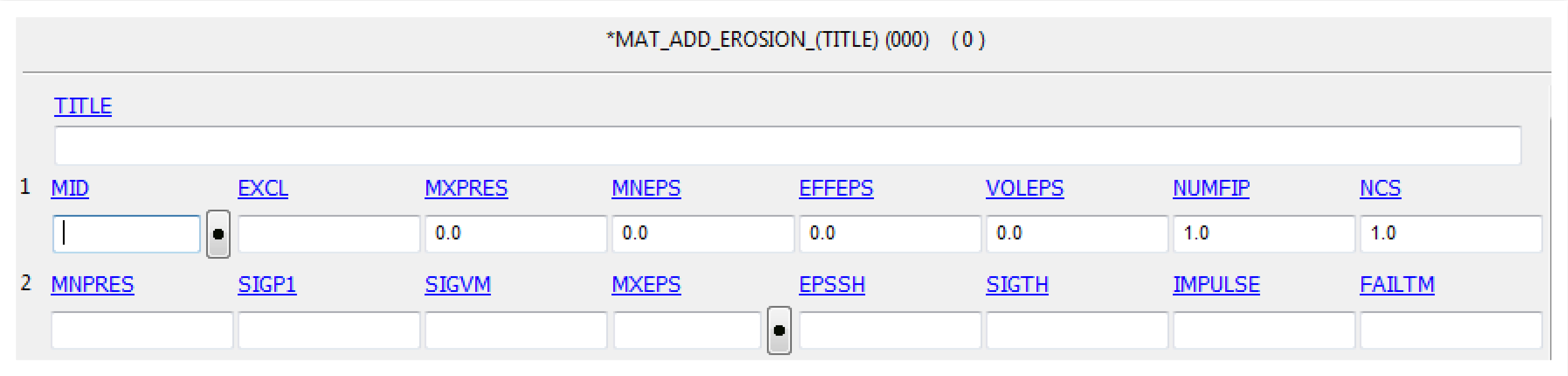






*MAT_ADD_EROSION

- Offers a way of adding various types of erosion criteria to material models in LS-DYNA
- Several criteria can be combined and used at the same time



*MAT_ADD_EROSION_(TITLE) (000) (0)

TITLE

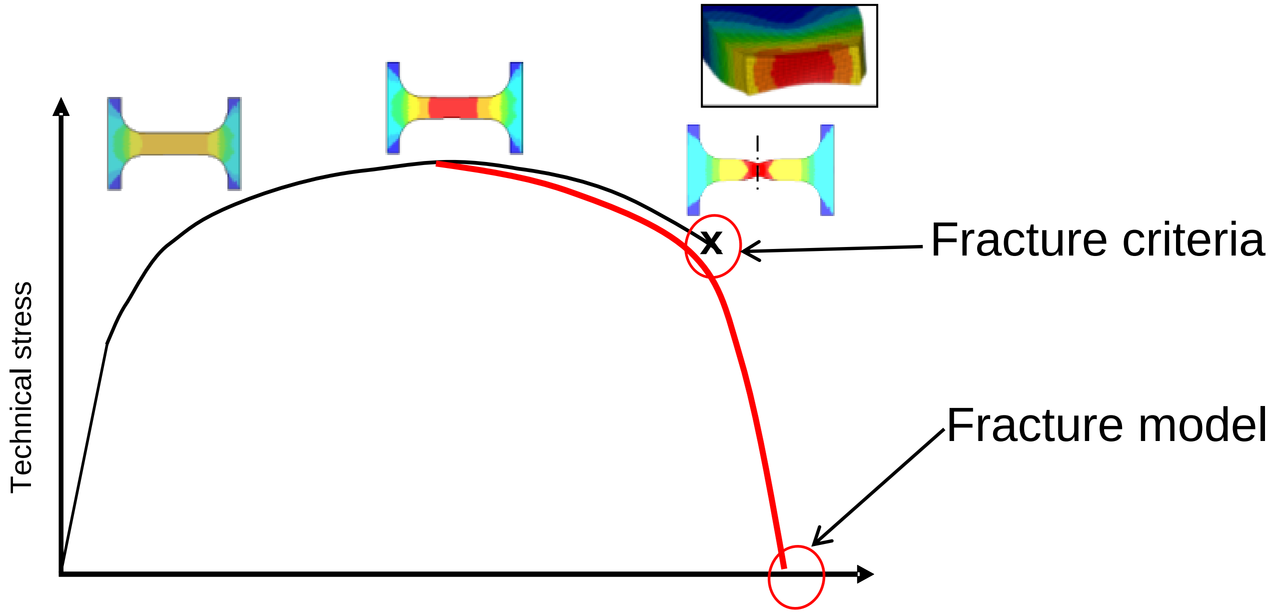
1	MID	EXCL	MXPRES	MNEPS	EFFEPS	VOLEPS	NUMFIP	NCS
			0.0	0.0	0.0	0.0	1.0	1.0
2	MNPRES	SIGP1	SIGVM	MXEPS	EPSSH	SIGTH	IMPULSE	FAILTM

- MID: Material number to which the **`ADD_EROSION`** card applies

Fracture models

Fracture models

Fracture models follows the material degradation until the stresses are zero in the element



Continuum Damage Mechanics (CDM)

- The concept of damage assumes growth of voids in the material
- The voids reduces the effective area.
- When the effective area equals 0 the damage will be 1 and then the material fails.
- The stress is scaled by the damage. This coupling enables the damage <u>modeling</u>.
- Since the true stress is related to the area, it will decrease. Thus,the material exhibits softening.

A = deformed or current cross section

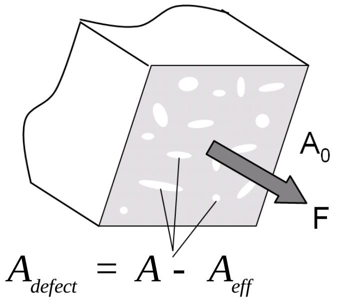
A_{eff} = effective cross section

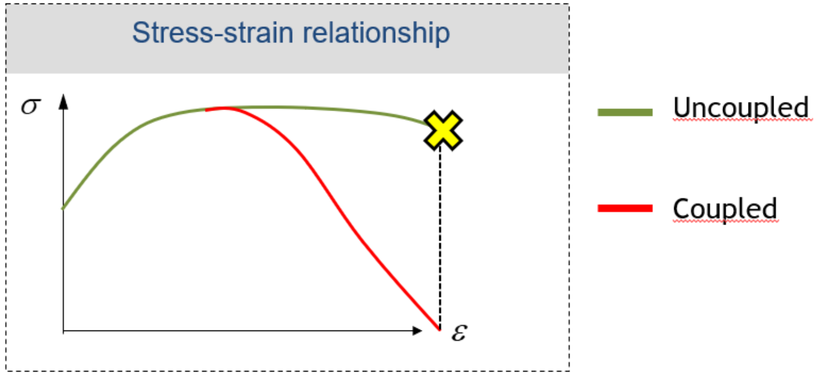
$$D = 1 - \frac{A_{eff}}{A} = \frac{A_{defect}}{A} \text{ = Damage}$$

$$\sigma = \frac{F}{A} \text{ = True stress}$$

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

Damage/Stress coupling





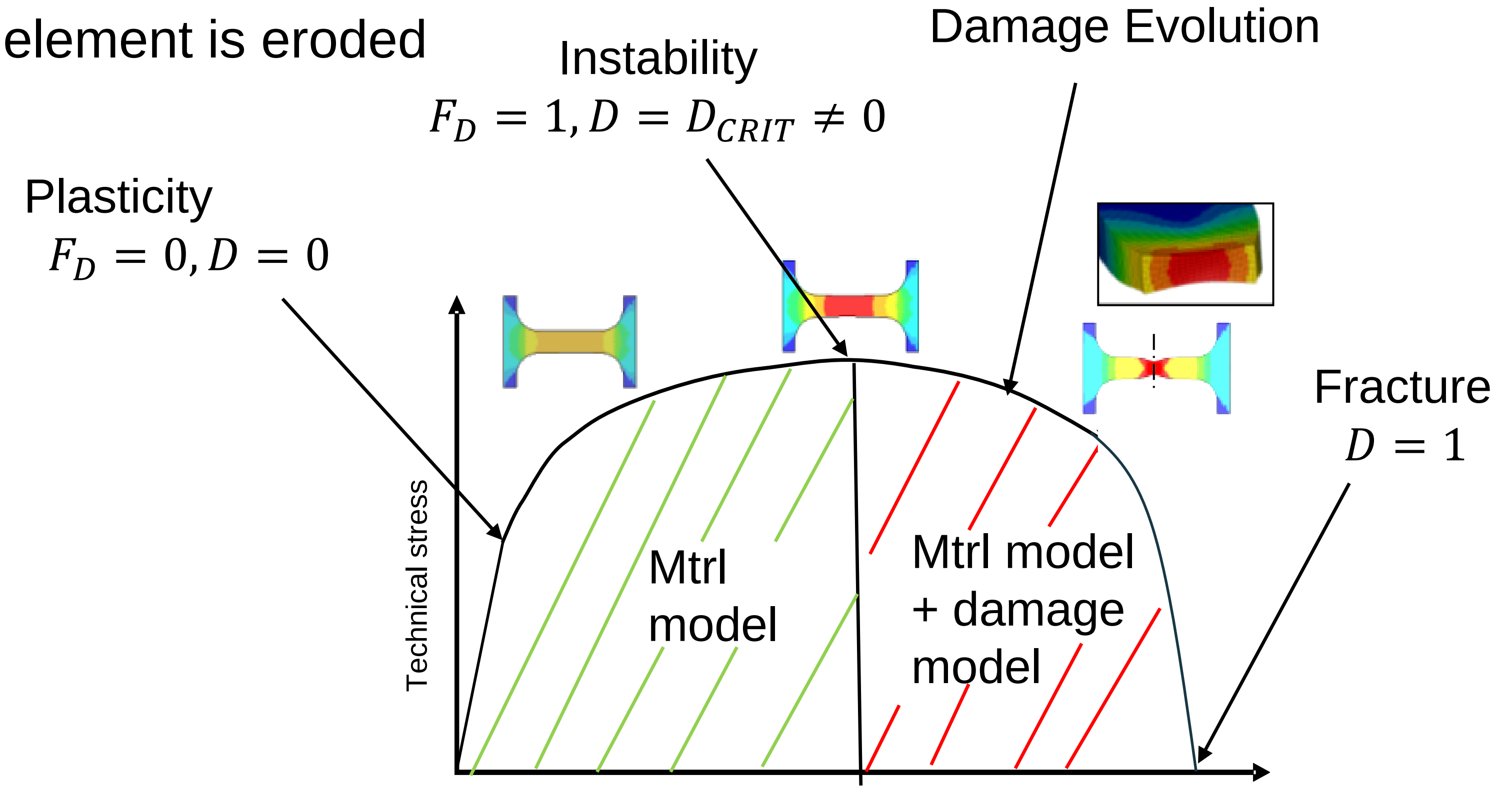
Damage models in LS-DYNA

- *MAT_81: *MAT_PLASTICITY_WITH_DAMAGE
- *MAT_104: *MAT_DAMAGE_1
- *MAT_105: *MAT_DAMAGE_2
- *MAT_120: *MAT_GURSON
- *....

GISSMO - Generalized Incremental Stress State dependent damage Model

GISSMO – Material instability and damage evolution

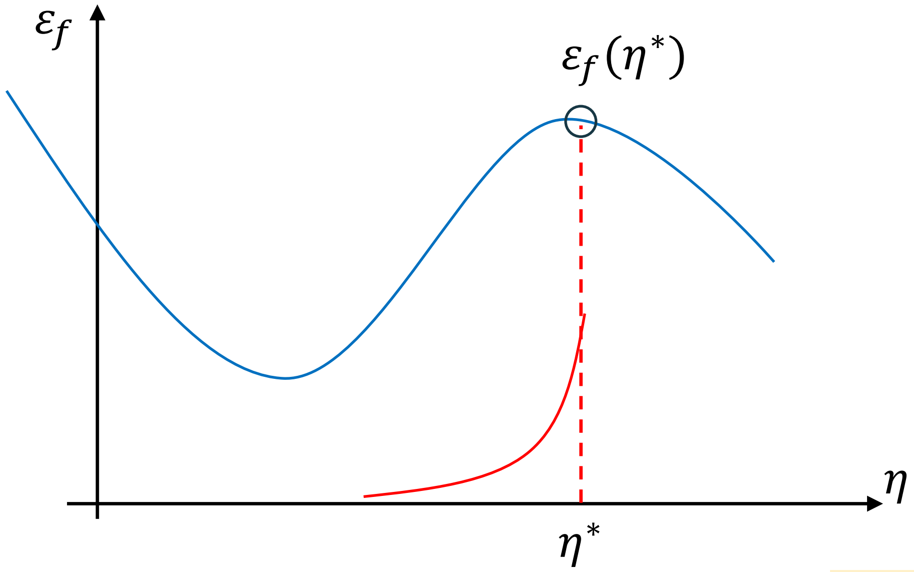
- Damage, *D,* starts to evolve at the start of plastic deformation
- Material instability, F_D, starts to evolve at the start of plastic deformation
- At material instability, $F_D=1$, the damage is coupled to the stress
- When $D=1$, the element is eroded



GISSMO – Damage evolution

- The damage evolves with effective plastic strain (default), or a material model history variable.
- The damage is isotropic.
- The effective plastic strain increment is scaled with the current failure strain.
- The damage evolution has a non-linear term *n.*
- The starts to evolve as soon as the material deforms plastically

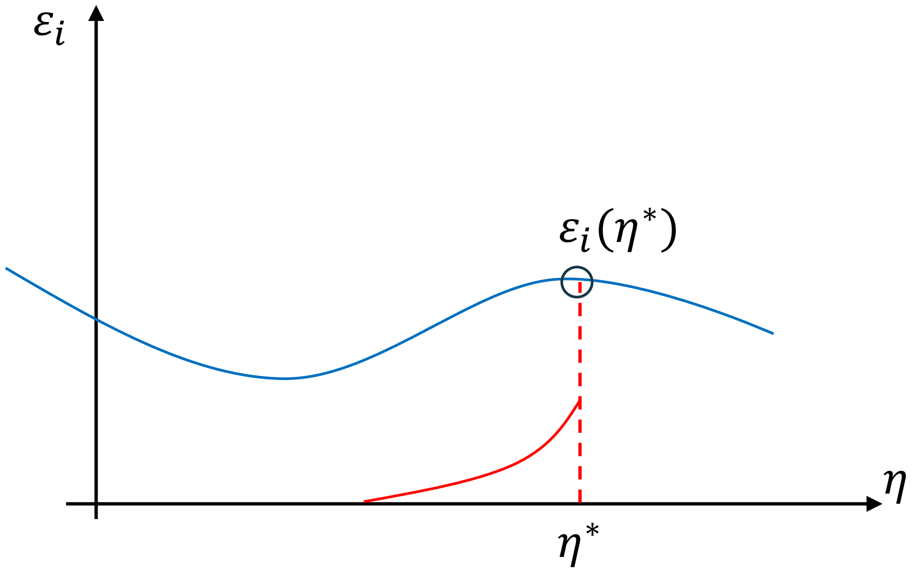
$$\Delta D = \frac{n}{\varepsilon_f(\eta^*)} D^{\left(1-\frac{1}{n}\right)} \Delta\varepsilon^p$$



GISSMO – Stress coupling

- The stress coupling is optional
- The stress coupling is activated by either of:
  - Constant effective plastic strain
  - Constant damage value
  - User input curve effective plastic strain curve as a function of stress triaxiality
- If coupling is determined by a user curve, an instability measure *F* determines the point of ”instability”
- *F* evolves according to the same equation as the damage.

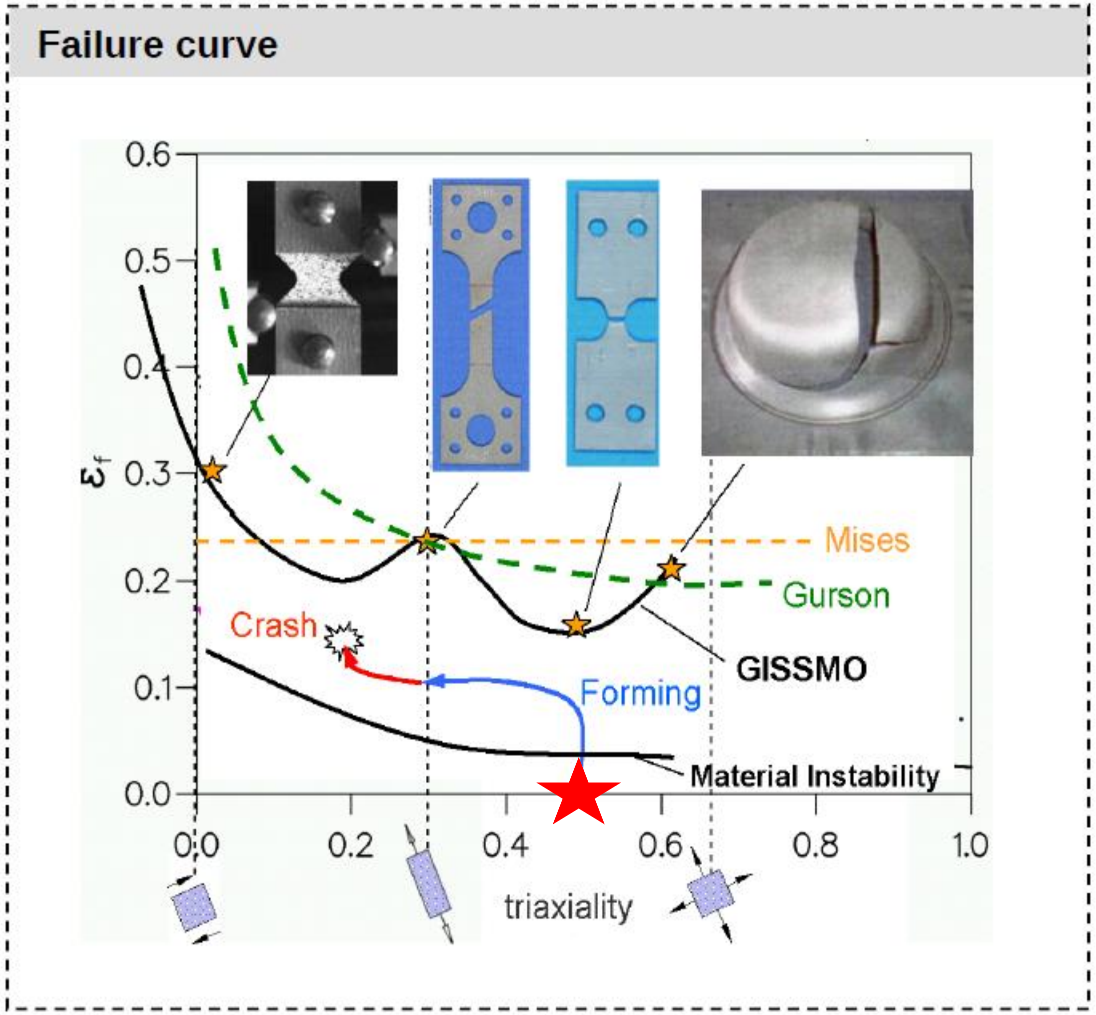
$$\Delta F = \frac{n}{\varepsilon_i(\eta^*)} F^{\left(1-\frac{1}{n}\right)} \Delta\varepsilon^p$$



- D_{CRIT} is the critical damage whe the coupling starts (F=1)

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

GISSMO Damage Model – step by step



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

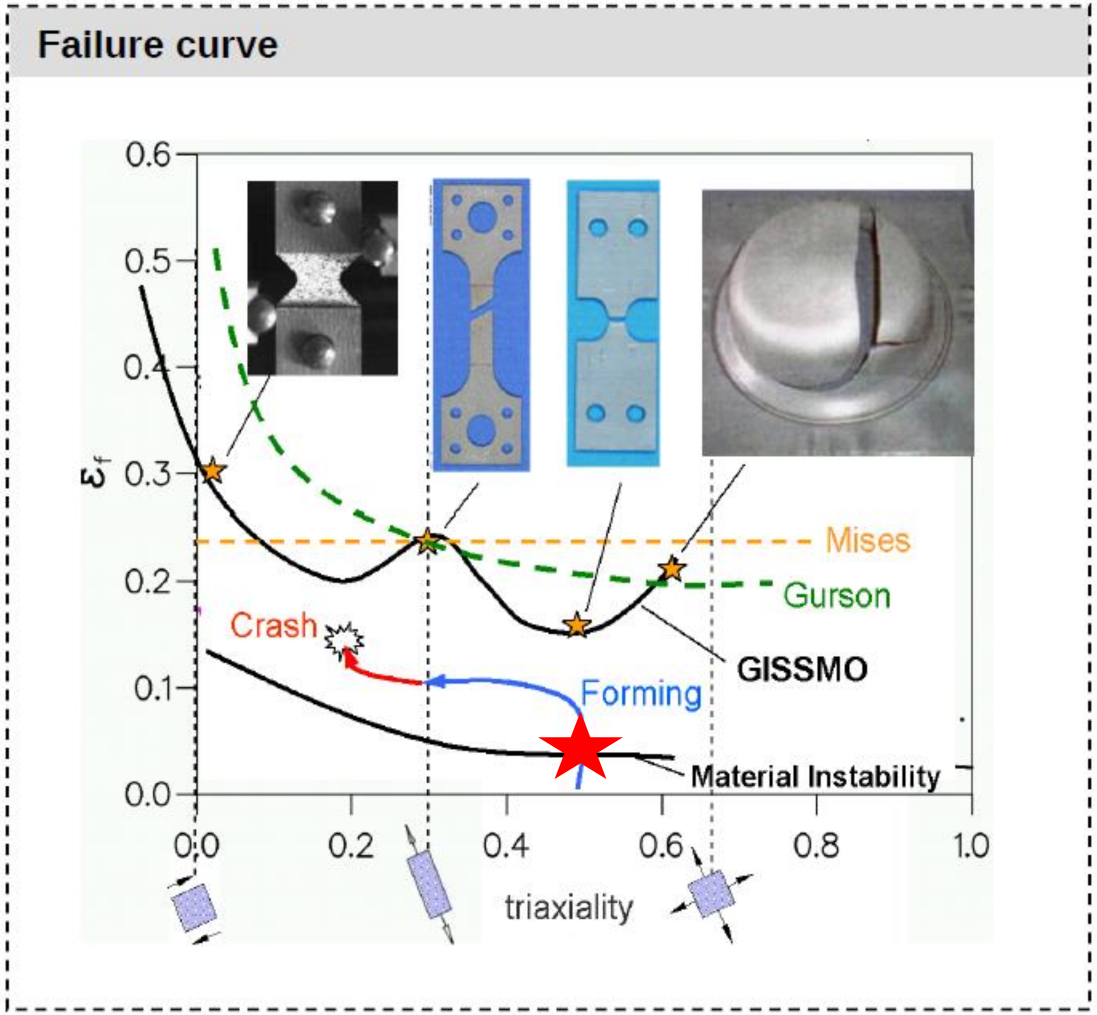
- Material instabilility, F, evolves with plastic strain through

$$\Delta F = \frac{n}{\varepsilon_i(\eta^*)} F^{\left(1-\frac{1}{n}\right)} \Delta\varepsilon^p$$

- At the instability limit F=1 and the material is assumed to reach a point of instability.
- Damage evolves through

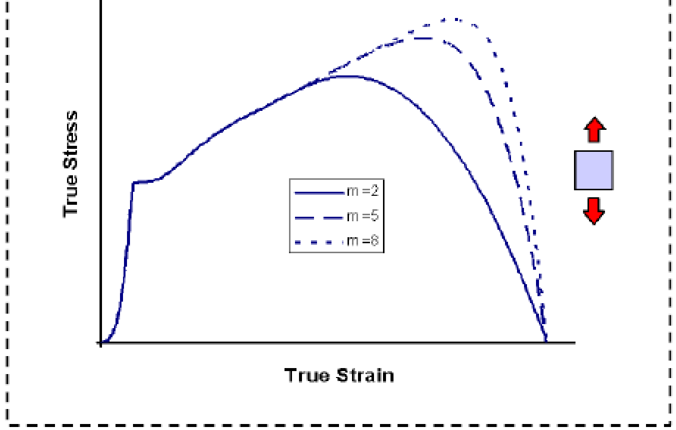
$$\Delta D = \frac{n}{\varepsilon_f(\eta^*)} D^{\left(1-\frac{1}{n}\right)} \Delta\varepsilon^p$$

GISSMO Damage Model – step by step



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

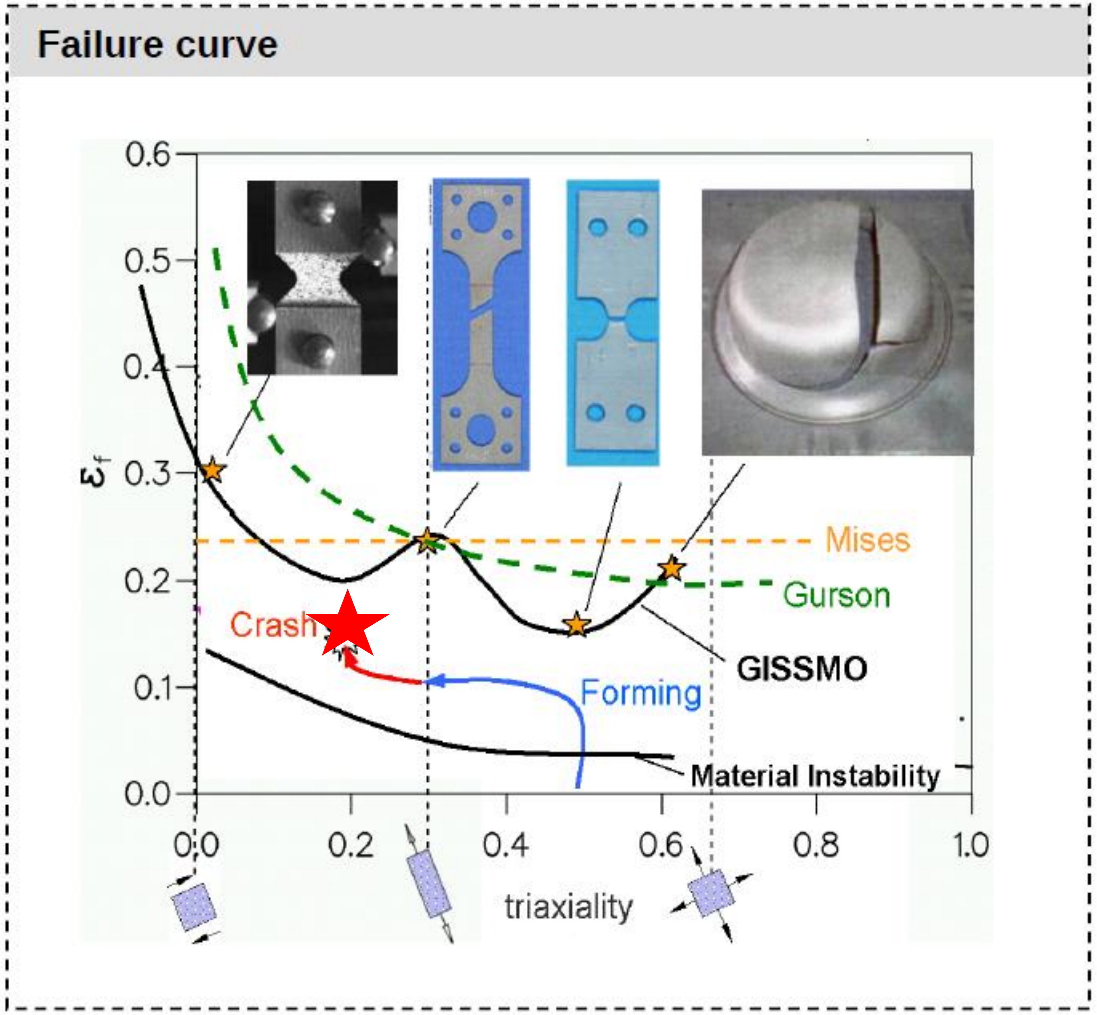
- Beyond the point of instability, the stresses can be coupled to the damage through:



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

- D_{CRIT} is the D value at Material instability

GISSMO Damage Model – step by step



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

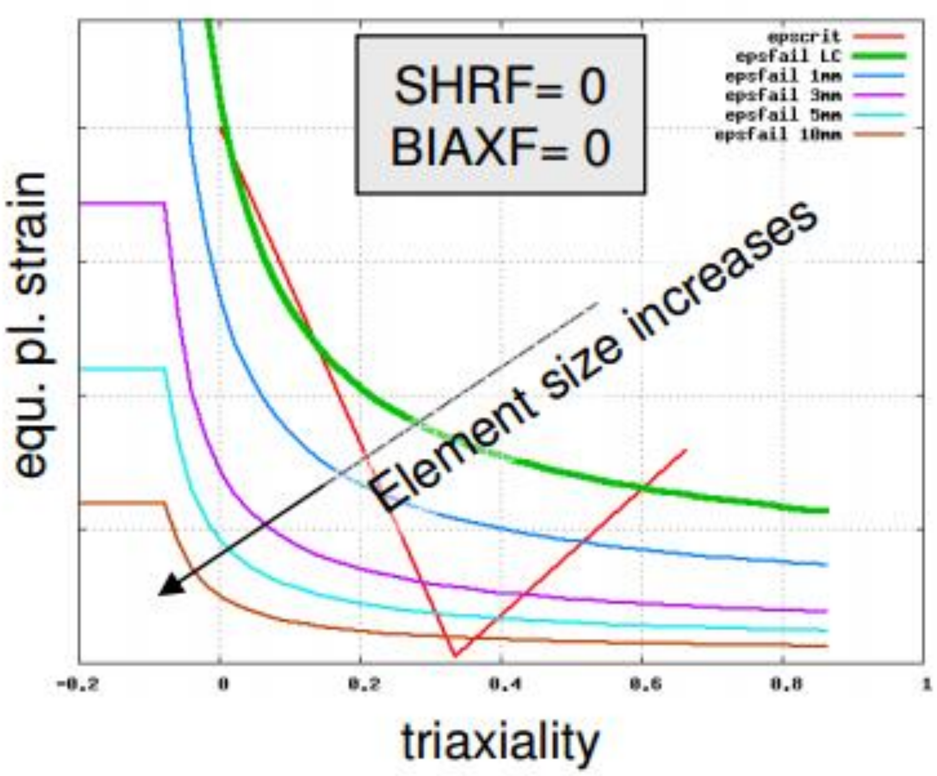
- Damage is increasing through:

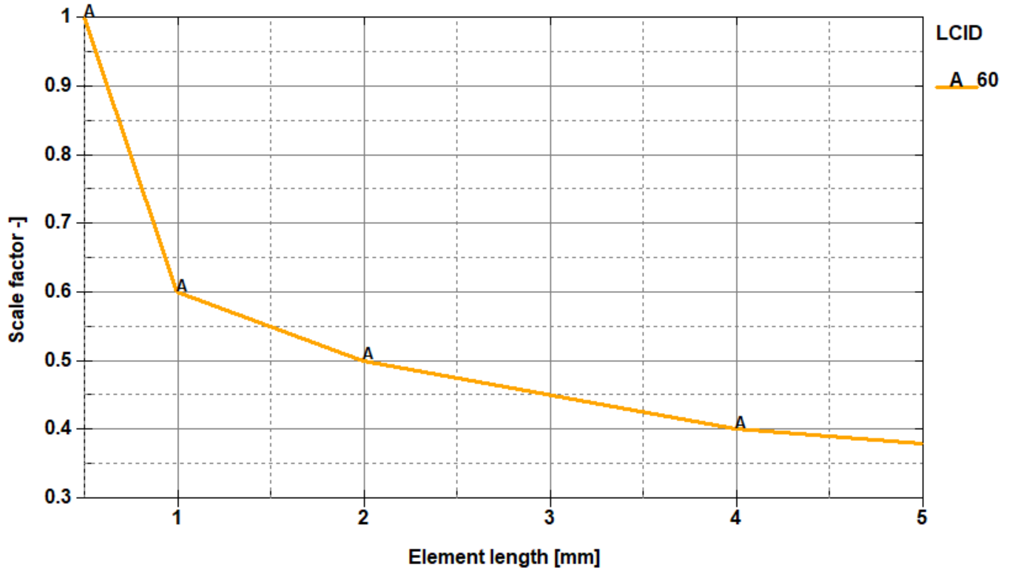
$$\Delta D = \frac{n}{\varepsilon_f(\eta^*)} D^{\left(1-\frac{1}{n}\right)} \Delta\varepsilon^p$$

- When the material is fully damaged, D=1, the stress in the integration point is 0.
- When a user defined number of integration points has failed, the element is deleted.

Mesh Regularisation

- Regularisation curve that scales the failure strains as a function of the element size.

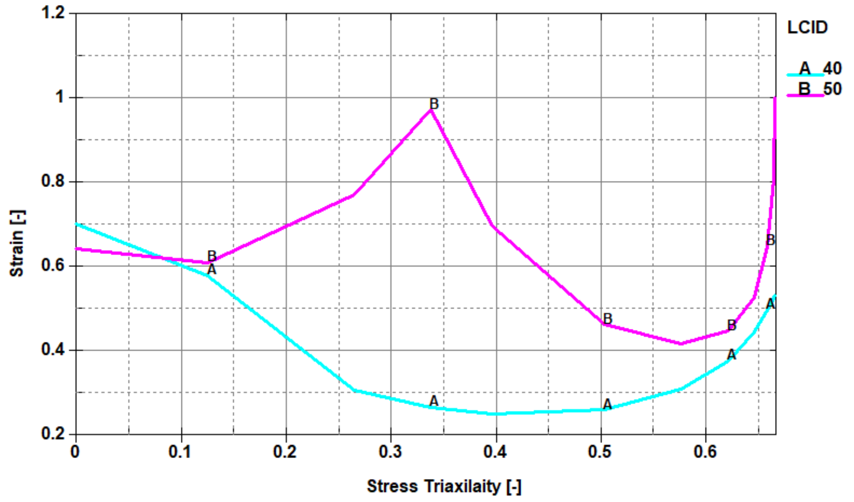




GISSMO example card

% of NIP where D=1 before erosion

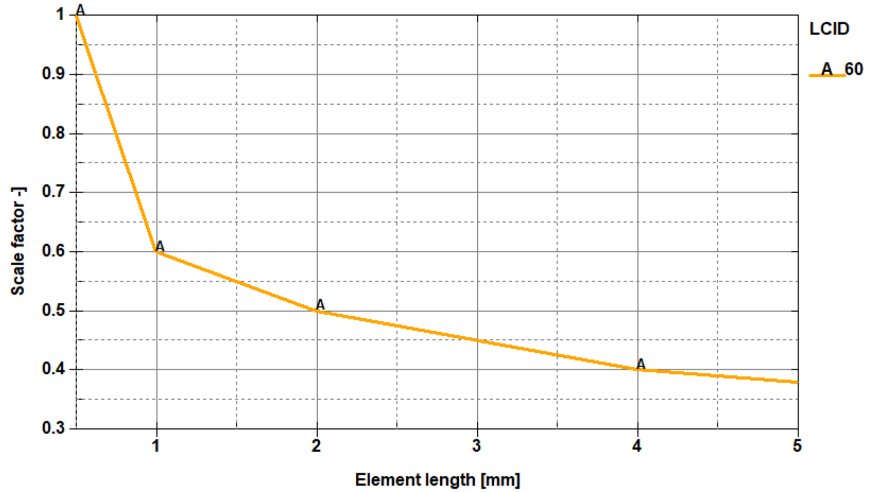
```
*MAT_ADD_DAMAGE_GISSMO
$#       mid         -      dtyp     refsz    numfip
           1         0       1.0       0.0     -80.0
$#     lcsdg     ecrit    dmgexp     dcrit    fadexp    lcregd
          50       -40       1.0       0.0       1.0        60
$#     lcsrs      shrf     biaxf    lcdlim   midfail
           0       0.0       0.0         0       0.0
```



$$\dot{F} = \frac{n}{\varepsilon_{loc}(\eta)} F^{(1-1/n)} \dot{\varepsilon}_p$$

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

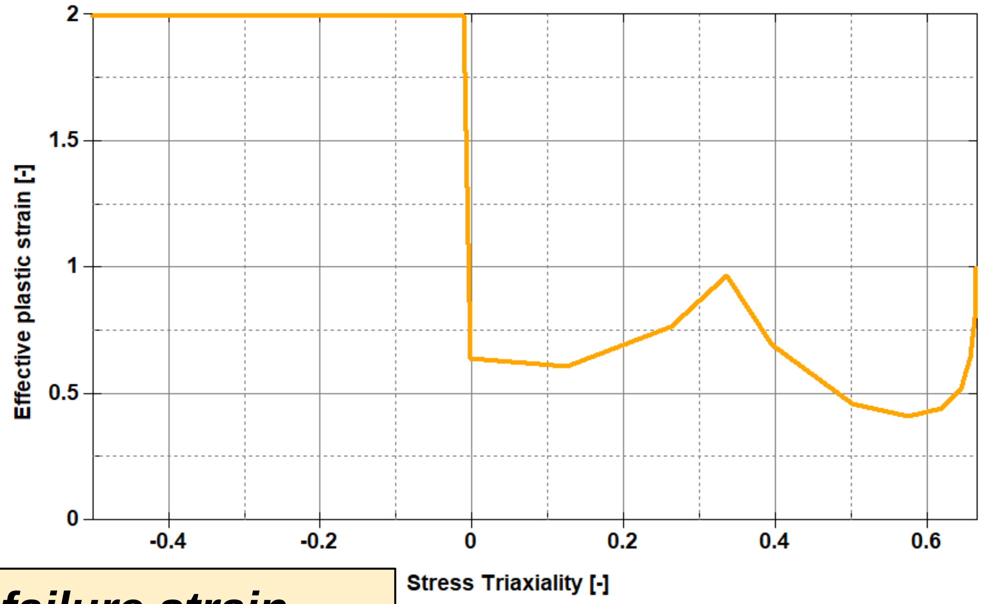
$$\sigma^* = \sigma \left(1 - \left(\frac{D - D_{CRIT}}{1 - D_{CRIT}}\right)^{FADEXP}\right)$$



GISSMO input

- Additional input parameters that could be useful are:
  - LCDLIM: Possibility to limit the damage values as a function of triaxiality.
    - Limit the damage evolution in compression
    - Avoiding element deletion

- MIDFAIL (shells): Only check the mid IP for damage.
  - Only checking for membrane types/Instability type of failure
  - Damage is calculated in all IP’s, but no coupling occurs.
  - When Mid IP is coupled, all IP’s are coupled

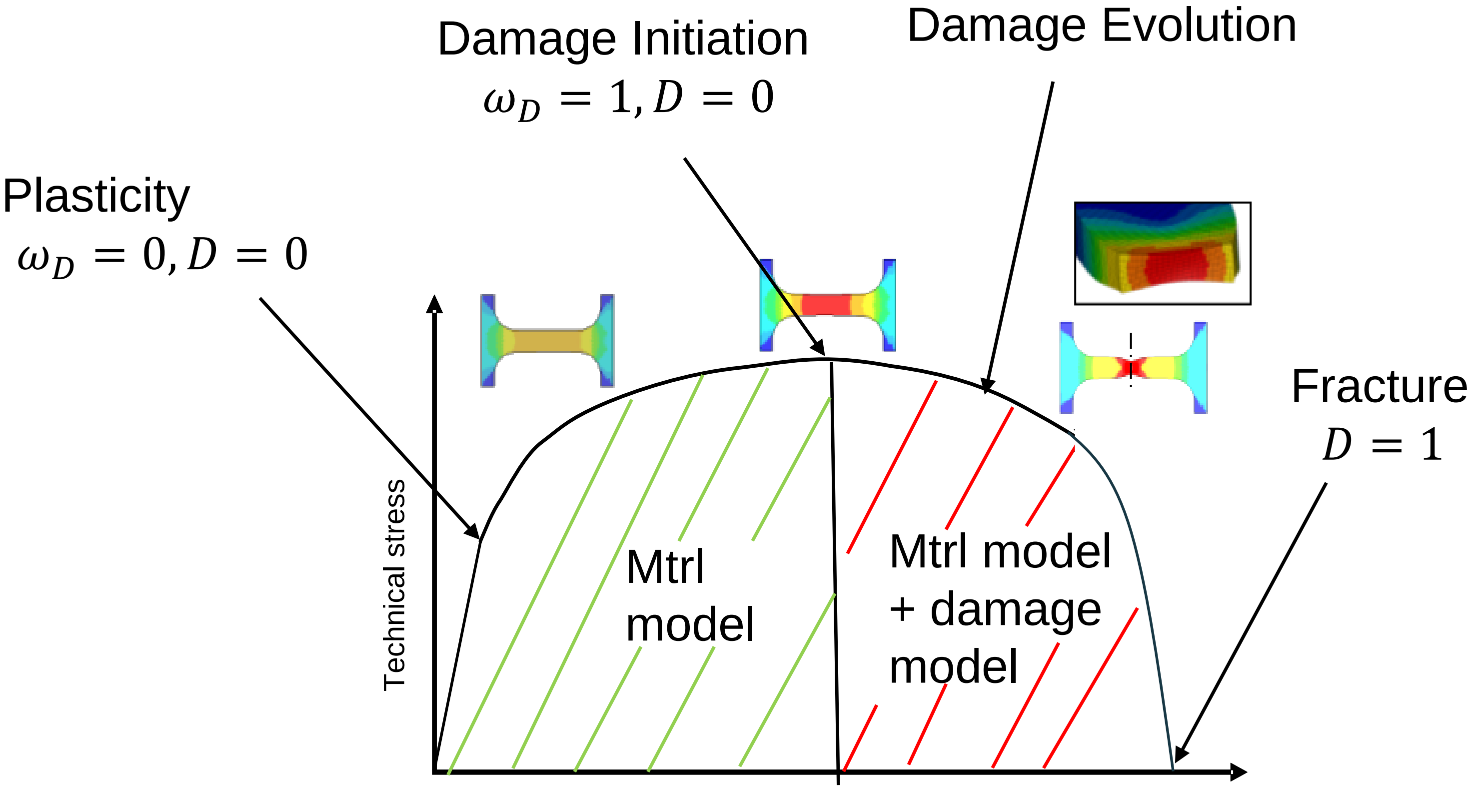


High failure strain to avoid compressive damage.

DIEM - Damage Initiation and Evolution Model

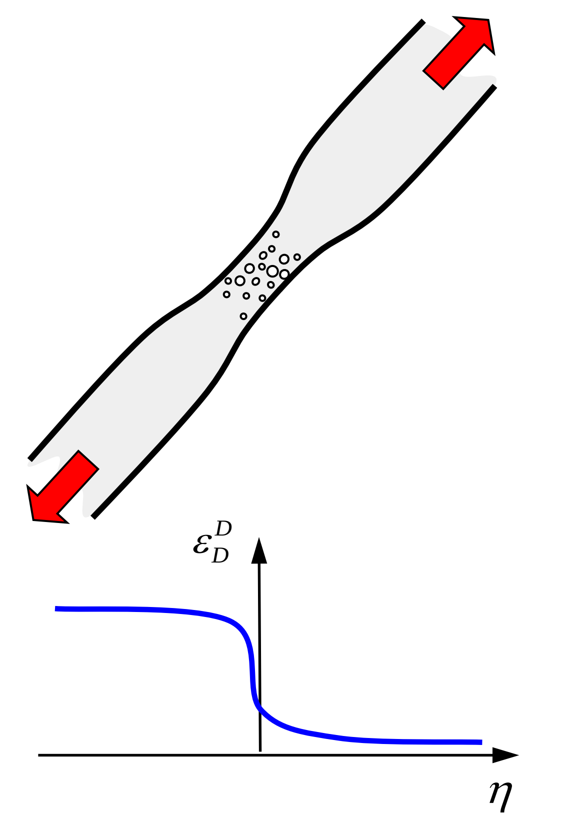
DIEM – Damage Initiation and evolution

- The failure is divided into Initiation and Evolution
  - Initiation is triggered by the history variable ω_D

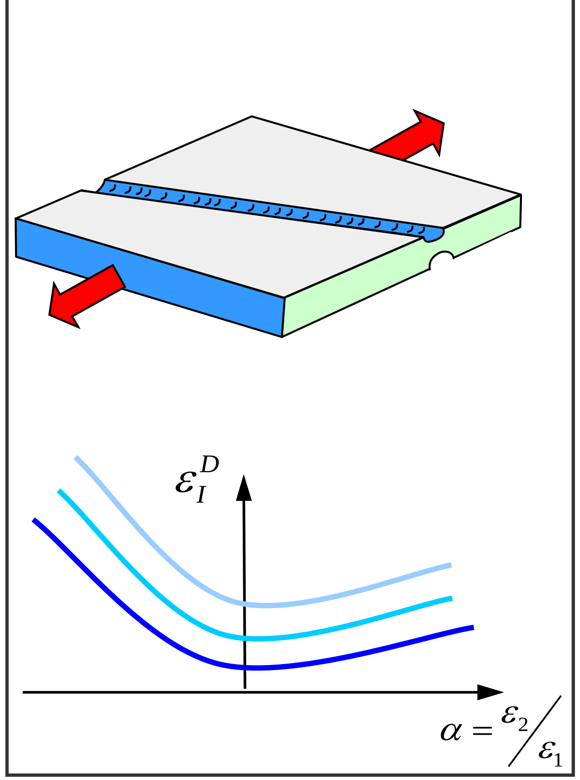


DIEM – Damage initation

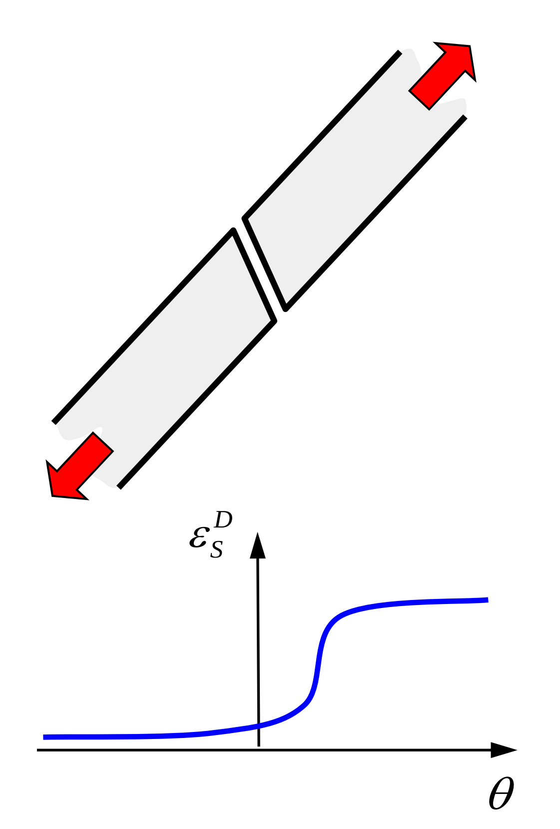
Ductile Initiation criteria



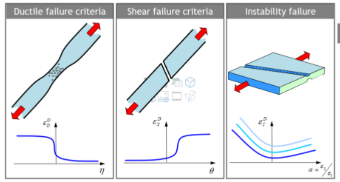
Instability Initiation criteria



Shear Initiation criteria



DIEM – Damage initation



Ductile (DITYP=0)

- Damage initiation curve as a function of stress triaxiality (and strainrate)

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

- The damage initiation history variable evolves according to

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

Shear (DITYP=1)

- Damage initiation curve as a function of θ (and strainrate)

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

- θ is a function of the von Mises stress σ_{vm}, pressure *p*, and maximum shear stress τ , k_s is a constant.

$$\theta = (\sigma_{vm} + k_s p)/\tau$$

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

- The damage initiation history variable evolves according to

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

Instability (DITYP=2)

- Damage initiation curve as a function of the principal strain rate ratio α (and strainrate)

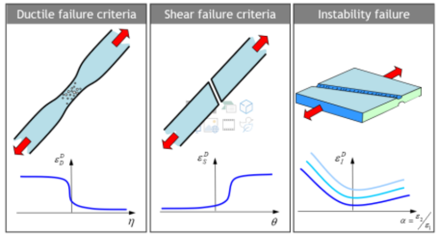
$$\varepsilon_D^p = \varepsilon_D^p(\alpha, \dot{\varepsilon}^p)$$

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

- The damage initiation variable does only evolve in tension

- The criteria can be set to only be evaluated at the middle through thickness integration point

DIEM – Damage initation



Instability (DITYP=3)

- This initiation option is very similar to DITYP=2, the only difference being the damage initiation history considers damage initiation both in tension and compression.
- The criteria can be set to only be evaluated at the middle through thickness integration point

Ductile (DITYP=4)

- Damage initiation curve as a function of β (and strainrate)

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

- β is a function of the von Mises stress σ_{vm}, pressure *p*, and major principal stress σ_1, k_d is a constant.

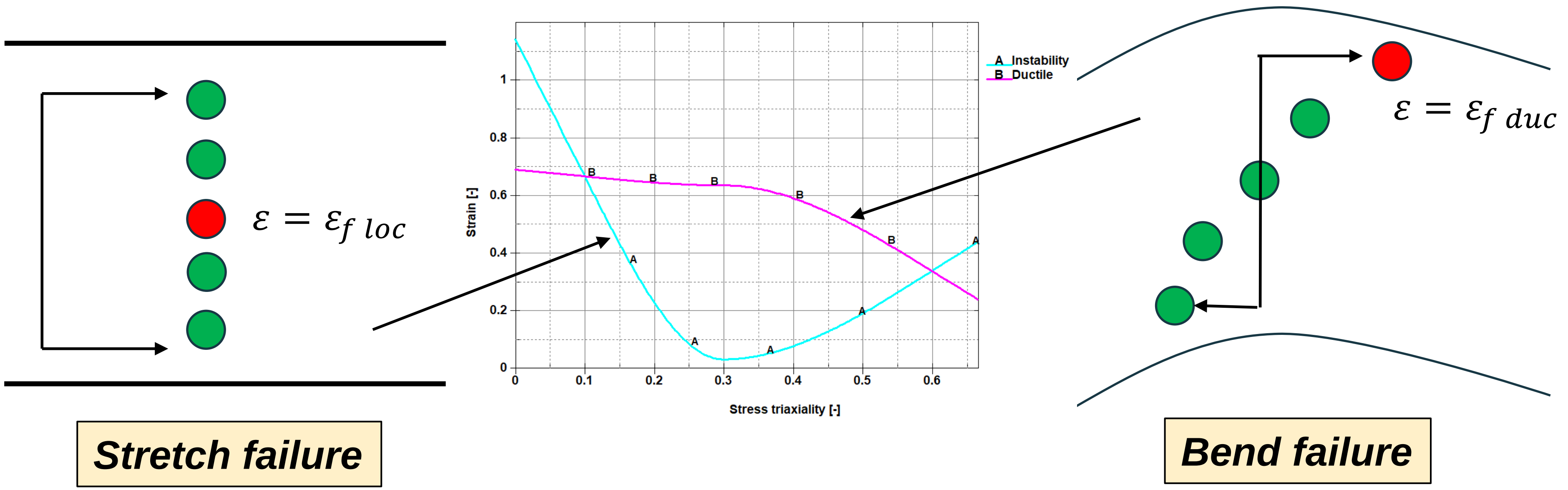
$$\beta = (\sigma_{vm} + k_d p)/\sigma_1$$

- The damage initiation history variable evolves according to

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

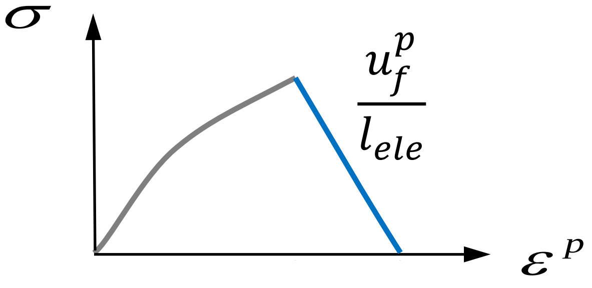
Combining multiple initiation criteria

- In DIEM, several initiation criteria can be active at the same time
- For instance, a ductile criteria can be used to capture the failure in bending and an instability criteria can be used to cover the stretch failure.
- Together with the possibility to assign evaluation of the instability criteria only at the mid gauss point through thickness this offers a way to distinguish between a stretch and bending failure.



Damage evolution model

- After the damage is initiated ($\omega_D = 1$), an evolution model is activated
- Damage is coupled to the stress
- Damage evolves with a plastic displacement u^p



$$\dot{D} = \frac{\dot{u}^p}{u_f^p}$$

where u_f^p is a user input failure plastic displacement

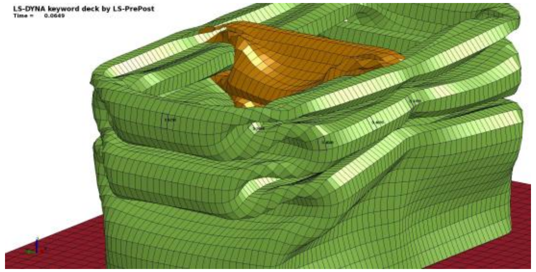
The plastic displacement is dependent on the element length. Hence, a linear regularization is applied.

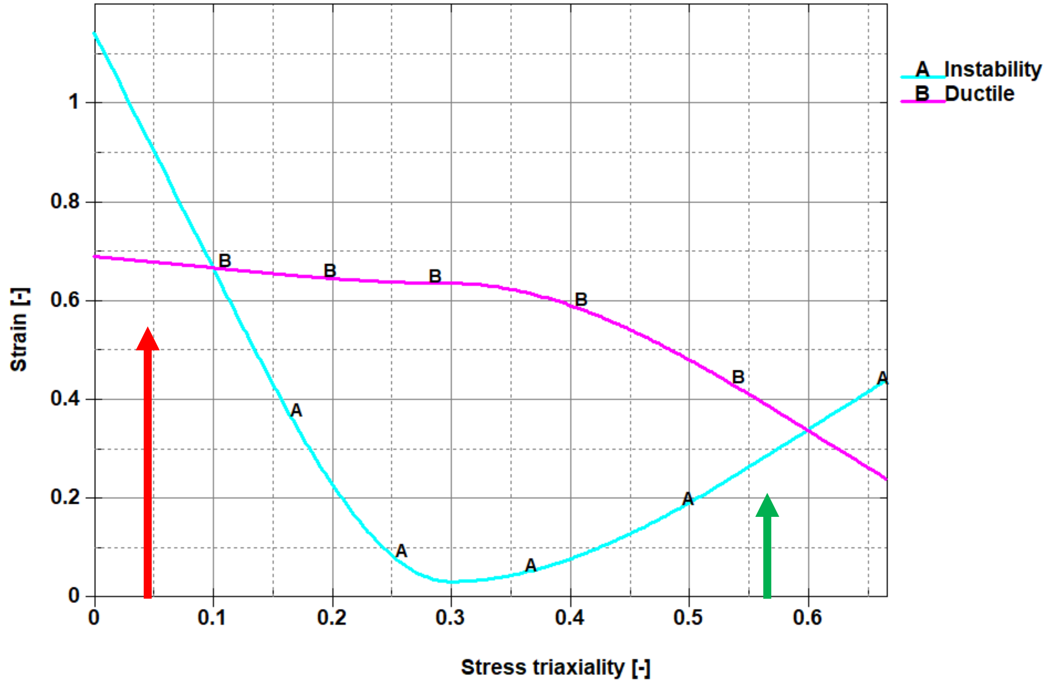
$$\dot{u}^p = \begin{cases} 0 & \omega_D < 1 \\ l_{ele}\dot{\varepsilon}^p & \omega_D \geq 1 \end{cases}$$

- In its simplest form, the damage evolution is linear.
- The failure plastic displacement can however be input as a table of damage and triaxiality.
  Thus, the damage evolution is then non-linear.

DIEM Step by step

- Damage is zero during damage initiation
- Initiation parameter is zero and evolves with the plastic strain
  - Instability criteria, $\omega_{D,loc}$, is evaluated at the mid surface
  - Ductile failure criteria, $\omega_{D,duc}$, is evaluated at all integration points



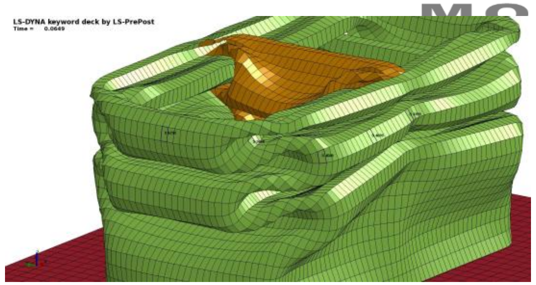


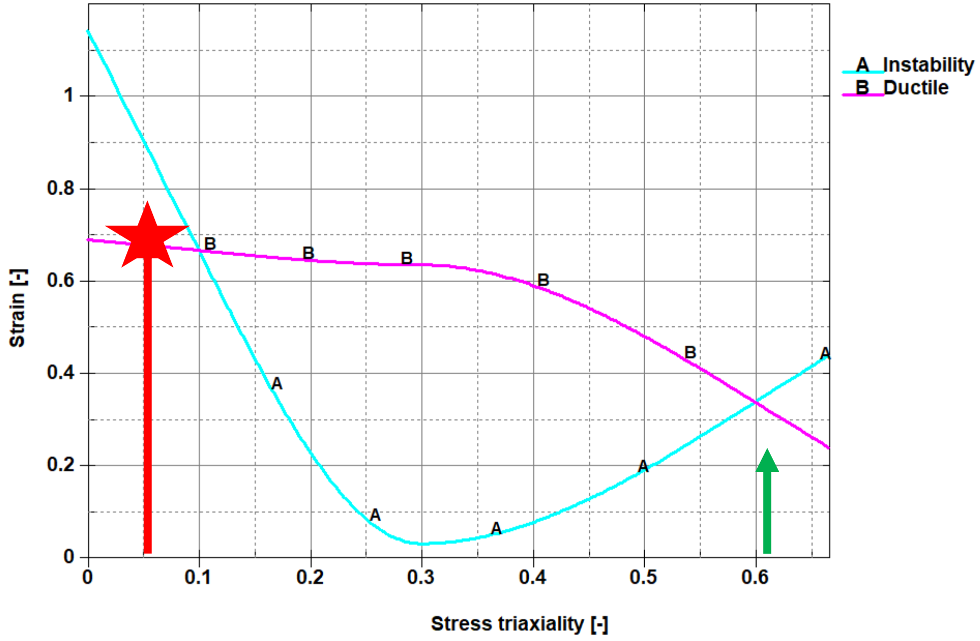
$$\omega_{D,loc} = \int_0^{\varepsilon^p} \frac{d\varepsilon^p_{mid}}{\varepsilon_{f,loc}(\eta)}$$

$$\omega_{D,duc} = \int_0^{\varepsilon^p} \frac{d\varepsilon^p_{i}}{\varepsilon_{f,duc}(\eta)}$$

DIEM Step by step

- As any of the initiation criteria reaches unity the damage evolution part begins
- The damage, D, evolves with the plastic displacement u^p
- The damage is coupled to the stress model the softening
- When the damage, D, reaches unity, the element is deleted





$$\dot{u}^p = \begin{cases} 0 & \omega_D < 1 \\ l_{ele}\dot{\varepsilon}^p & \omega_D \geq 1 \end{cases}$$

$$\dot{D} = \frac{\dot{u}^p}{u_f^p}$$

$$\boldsymbol{\sigma} = (1 - D)\mathbf{C}^{ep} : \boldsymbol{\varepsilon}$$

DIEM example card

Number of initiaton criteria

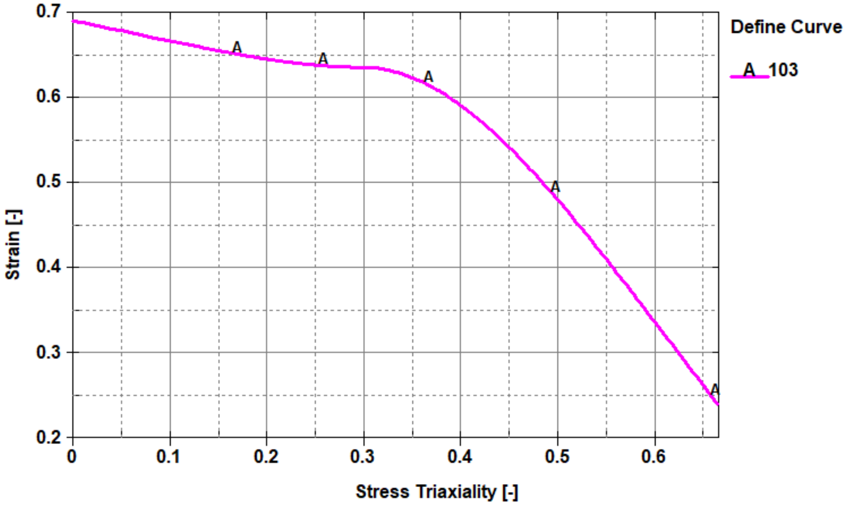
% of NIP where D=1 before erosion

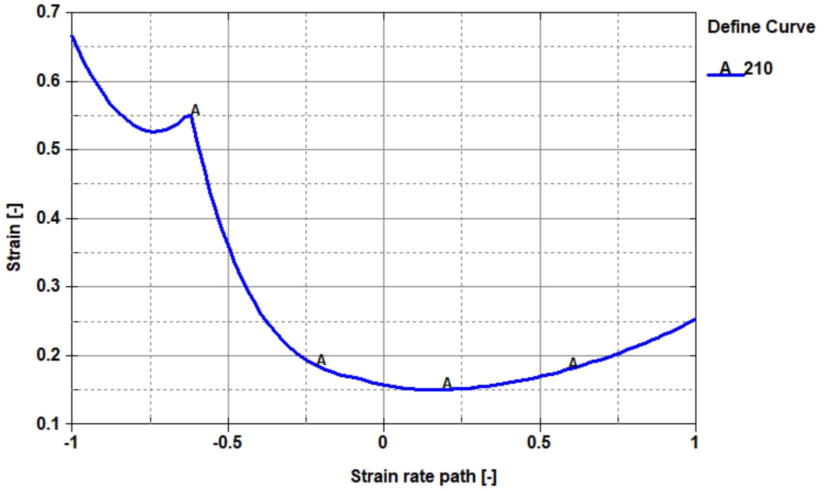
```
*MAT_ADD_DAMAGE_DIEM
$#      mid    ndiemc      dinit       deps     numfip
          1         2          0        0.0      -80.0
$# DITYP=0., Ductile failure criteria
        0.0       103        0.0        0.0
        0.0       0.0        0.1
$# DITYP=3., Instability failure criteria
        3.0       210        0.0        0.0
        0.0       0.0        0.1        0.0
```

INIT

DAMAGE

$$\dot{D} = \frac{\dot{u}^p}{u_f^p}$$



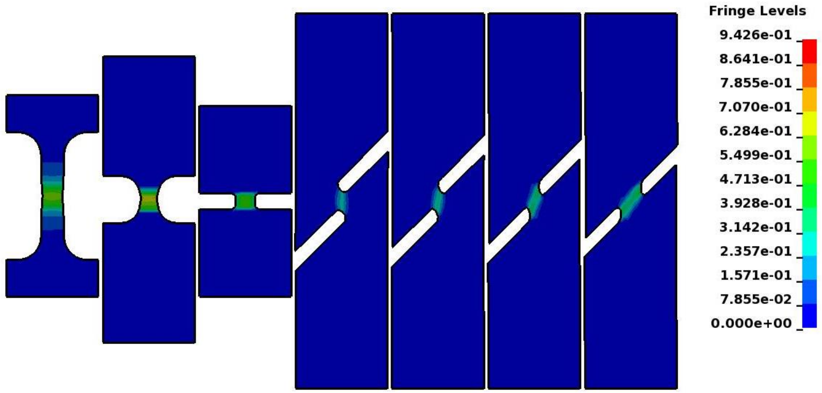


Comparison DIEM and GISSMO

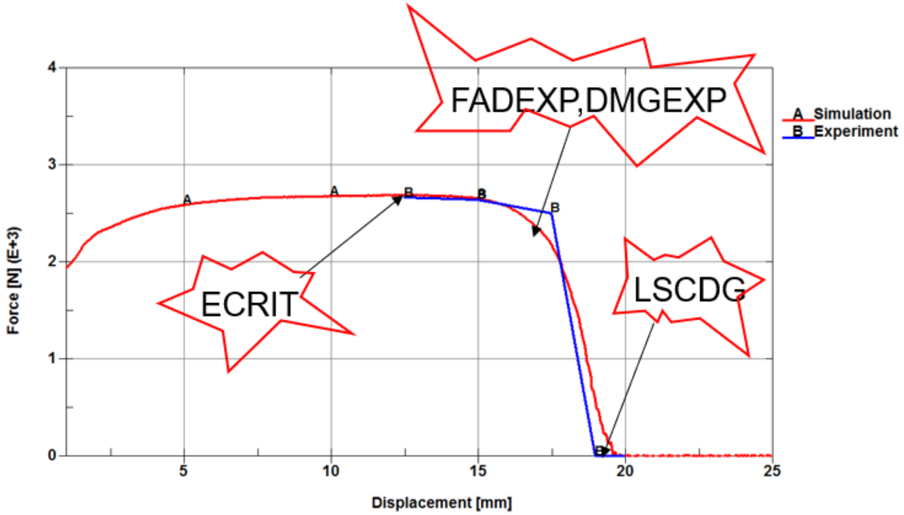
- GISSMO only has one initiation and damage models where DIEM has several that evolve simultaneously.
- In GISSMO, the damage starts to evolve from the beginning while D starts to evolve after intitiation in DIEM.
- In the instability criteria of DIEM, only the middle surface is regarded.
- From R11, GISSMO can be defined to only evaluate the middle surface, otherwise all integration points are included in the failure model.
- In DIEM, the damage evolution can be defined as a table (damage, triaxiality and plastic displacement) where in GISSMO it is governed by DMGEXP.
- In GISSMO, the mesh regularization is handeled by scaling the failure curve. In DIEM, a plastic displacement is used which is scaled by the element length, thus linear.

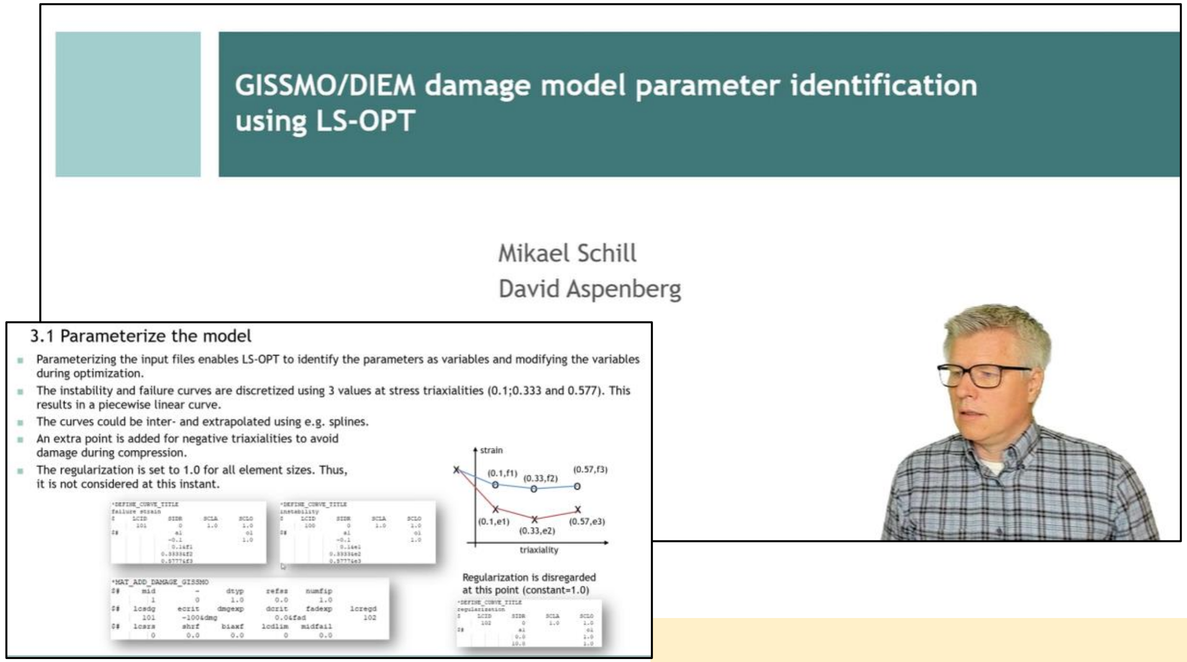
- Input to DIEM and GISSMO is based on the same principles. Thus, calibration is similar between the two methods.

GISSMO/DIEM - Input



- Parameters are determined from experiments through inverse modeling
- If necessary, the test data needs to be filtered to get a smooth result
- Any engineering measure will do for the optimization, e.g. engineering stress/strain or Force/displacement.



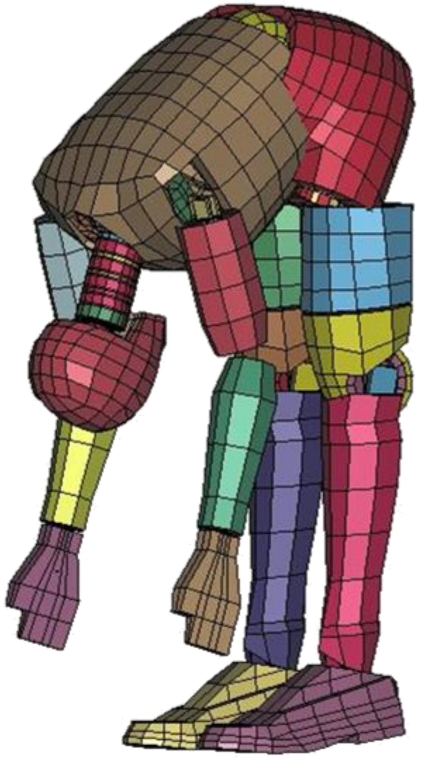


- Parameter Identification Webinar on Client Area

Conclusions

- Diffuse necking
  - Maximum Force criteria
  - Described by the yield criterion and the hardening of the material
- Beyond the point of diffuse necking, the solution becomes mesh dependent. Regularisation through:
  - Element size dependent material/failure data
  - Non-local criteria
- Failure criteria determines the point of failure, while a failure model also describes the failure, i.e. Damage
- General failure criteria can be added to any material model through **`*MAT_ADD EROSION`**
- GISSMO – General Damage model that can be added to any material model
- Input to GISSMO can be based on either experiments or analytical failure models.
- DIEM – Ductile, shear and instability failure model that can be added to “any” material model in LS-DYNA.
- Multiple DIEM failures can be combined and failure will be based on a multiplicative or maximum value.
- Identification of GISSMO/DIEM parameters are made through inverse modeling
- Note! In versions prior to R11, GISSMO and DIEM are part of *MAT_ADD_EROSION

Thank You



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