WORKSHOP: Material Failure of Metals

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Agenda

- Motivation
- Preliminaries (experimental evidence, triaxiality, …)
- Aspect that influence failure prediction
- Short description of the GISSMO model
  - Stress state dependence
  - Plasticity model
  - Non-proportional loadings
- Calibration of a GISSMO material card
  - Usual methods
  - Live demo (reverse engineering)
- Mesh dependence/regularization in GISSMO
- Summary

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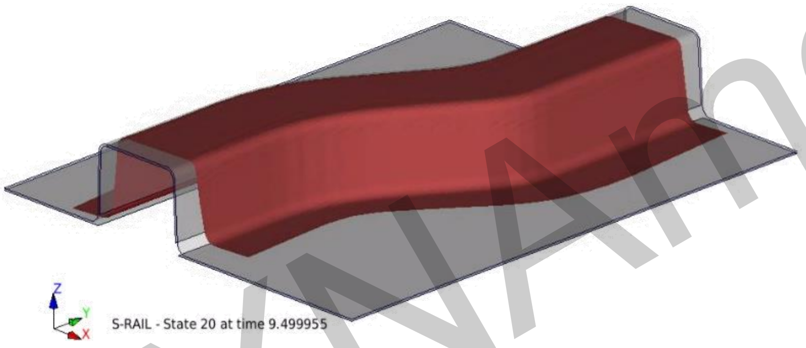
Motivation

Damage and failure play an important role in simulation

Focus on the application in crash simulation (and metal forming)



Courtesy of Daimler AG

What should I have in the input?

Does it fail or not?

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Material behavior

Aspects that influence failure and its prediction

- Stress state dependence
- Plastic yielding (yield surface shape) and plastic flow
- Non-proportional loading / strain path dependence
- Instability / localization issues / mesh dependence
- Element formulation (shells, solids, under/fully integrated, …)
- Pre-strain and pre-damage
- Anisotropy (in plasticity and in failure properties)
- Strain rate dependence (adiabatic process at high strain rates!)
- Heat affected zones due to welding
- Scattering of material properties
- …

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Ductile fracture

Experimental evidence regarding fracture of metals

Early works by authors like Bridgman, Rice, Tracey, Mackenzie, Hancock, Brown, among others, experimentally observed that fracture was dependent on the **triaxiality ratio of stress**.

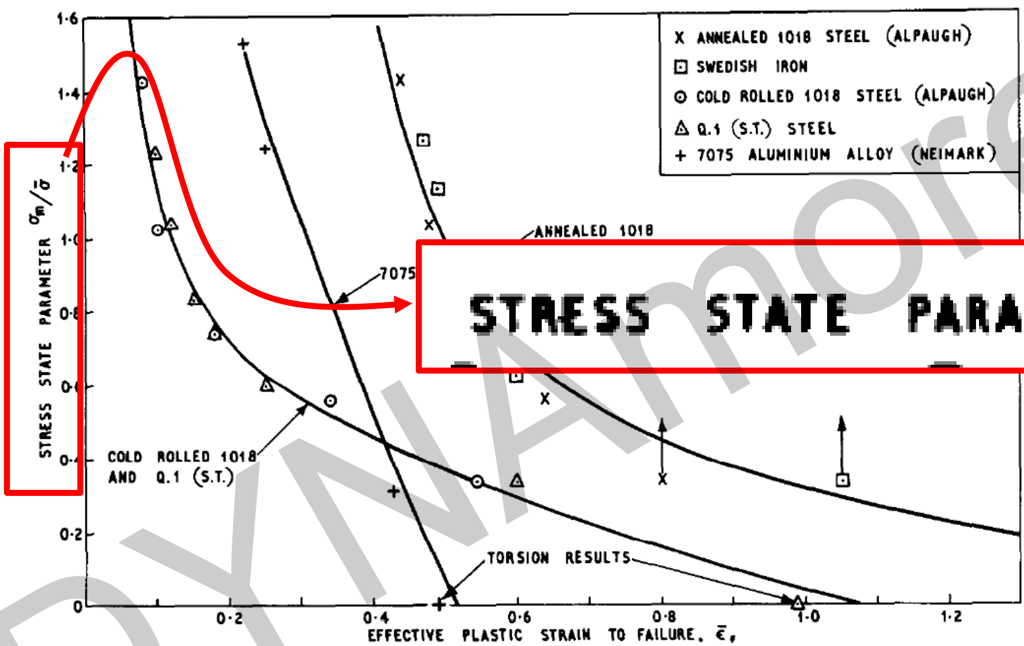

Fig. 19. Comparison of failure initiation curves.

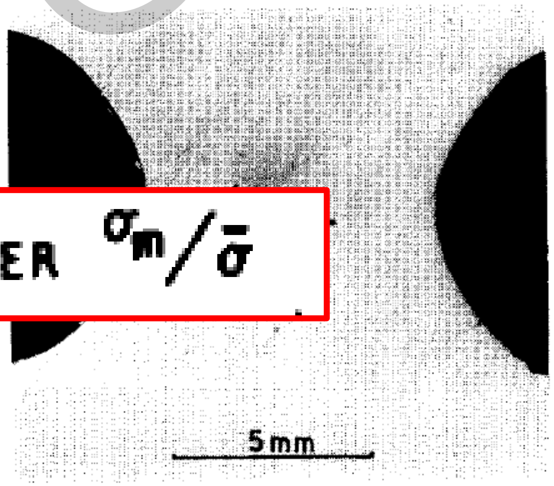

Fig. 1. Cracking in notch tension specimen.

Source: Mackenzie et al. 1977. On the influence of state of stress on ductile failure initiation in high strength steels.

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Preliminaries

Some usual definitions regarding the true stress tensor

The true stress tensor is symmetric and can be split in two parts, i.e.,

$$\boldsymbol{\sigma} = \begin{bmatrix} \sigma_{11} & \sigma_{12} & \sigma_{13} \\ & \sigma_{22} & \sigma_{13} \\ & & \sigma_{33} \end{bmatrix} = \mathbf{s} + \underbrace{\frac{1}{3}\mathrm{tr}(\boldsymbol{\sigma})}_{\text{mean stress}}\,\mathbf{I} = \underbrace{\begin{bmatrix} s_{11} & s_{12} & s_{13} \\ & s_{22} & s_{13} \\ & & s_{33} \end{bmatrix}}_{\text{stress deviator}} - p \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

mean stress

stress deviator

hydrostatic pressure (p)

The principal stress tensor and its invariants are given by

$$\boldsymbol{\sigma} = \begin{bmatrix} \sigma_1 & 0 & 0 \\ 0 & \sigma_2 & 0 \\ 0 & 0 & \sigma_3 \end{bmatrix}$$

$$I_1 = \sigma_1 + \sigma_2 + \sigma_3$$
$$I_2 = \sigma_1\sigma_2 + \sigma_2\sigma_3 + \sigma_1\sigma_3$$
$$I_3 = \sigma_1\sigma_2\sigma_3$$

$$J_1 = s_1 + s_2 + s_3 = 0$$
$$J_2 = \frac{1}{6}\left[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2\right]$$
$$J_3 = s_1 s_2 s_3 = \frac{2}{27}I_1^3 - \frac{1}{3}I_1 I_2 + I_3$$

The equivalent or von Mises stress is defined as

$$\sigma_{eq} = \sqrt{3J_2} = \sqrt{\frac{1}{2}\left[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2\right]}$$

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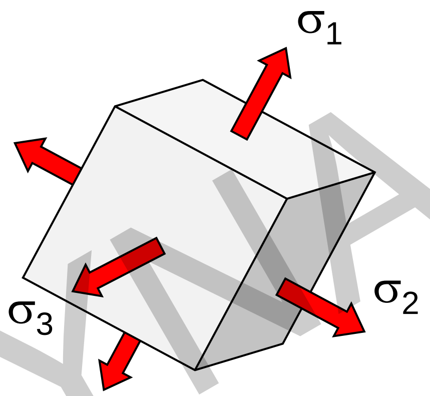
Stress state parameters

Triaxiality

- The term “triaxiality“ was apparently coined by Mackenzie, Hancock and Brown in 1977
- It quantifies the ratio among the three principal stresses (σ_1, σ_2, σ_3) through a single scalar
- It is a practical parameter for the characterization of material failure



Definition of stress triaxiality: $\eta = -\frac{p}{\sigma_{eq}}$

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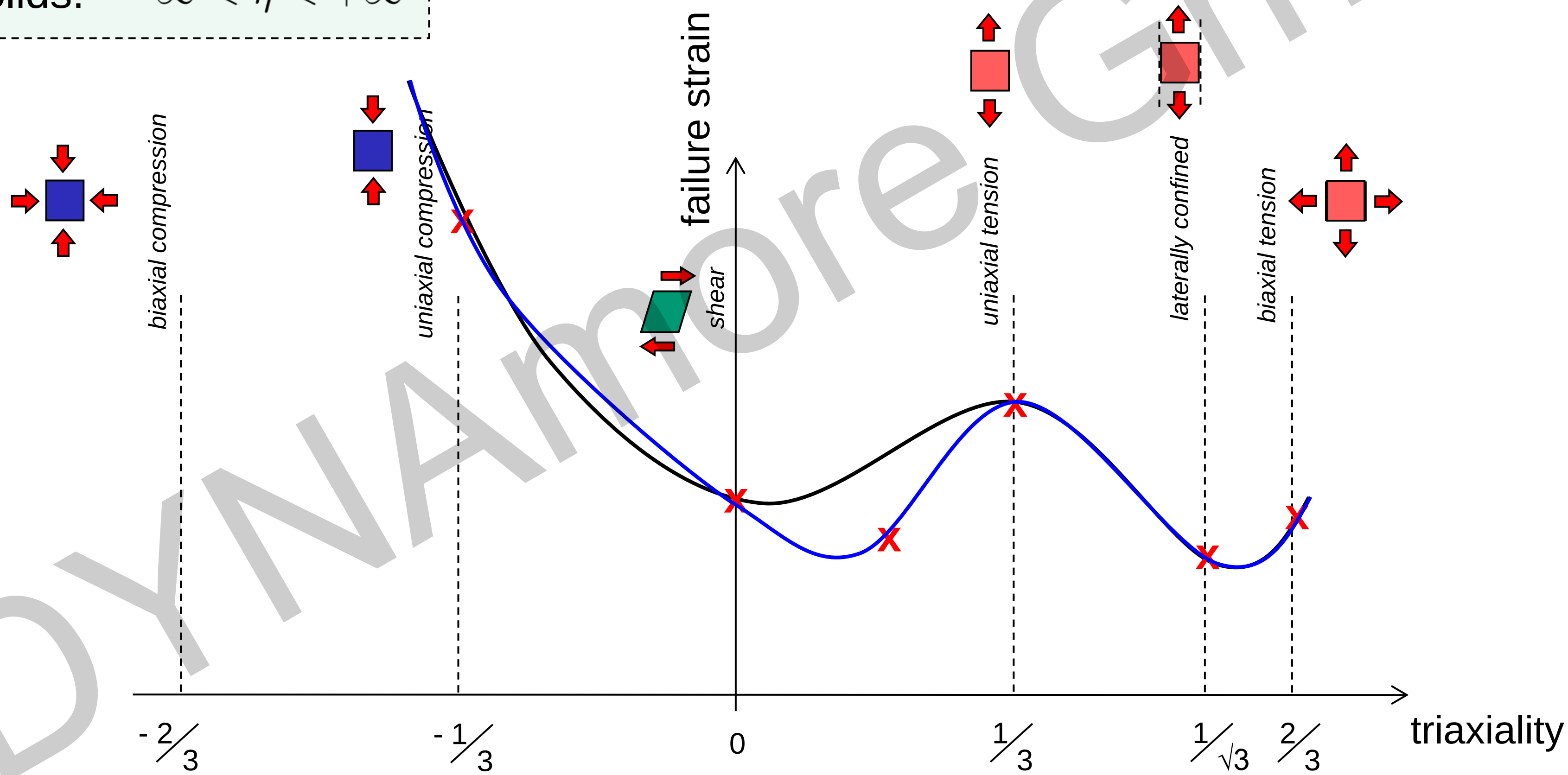
Stress state parameters

Triaxiality under plane stress

Shells: $-\frac{2}{3} < \eta < \frac{2}{3}$

Solids: $-\infty < \eta < +\infty$



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Short description of GISSMO

(Generalized Incremental Stress State dependent MOdel)

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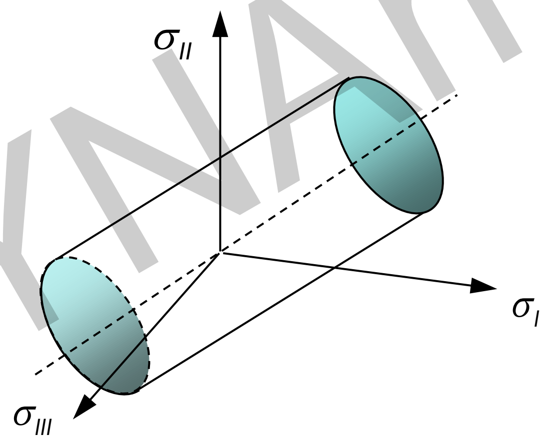
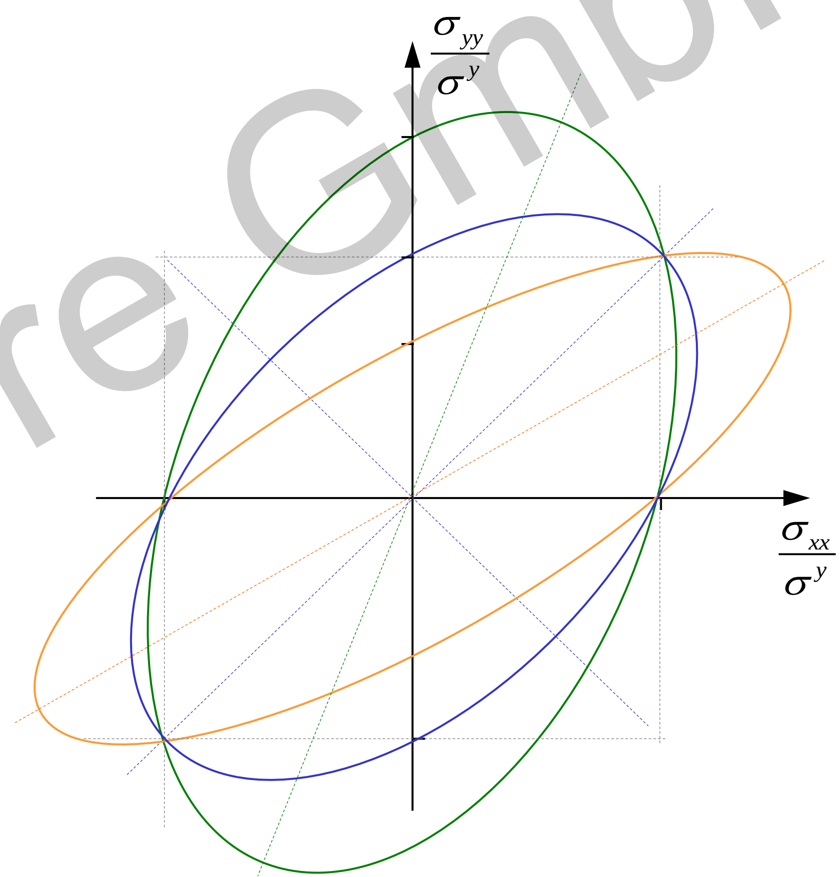
Plasticity

Many elasto-plastic models in LS-DYNA

*MAT_PLASTIC_KINEMATIC
*MAT_PIECEWISE_LINEAR_PLASTICITY
*MAT_BARLAT_ANISOTROPIC_PLASTICITY
*MAT_3-PARAMETER_BARLAT
*MAT_ANISOTROPIC_VISCOPLASTIC
*MAT_ORTHO_ELASTIC_PLASTIC
*MAT_HILL_3R
*MAT_BARLAT_YLD2000
*MAT_WTM_STM
*MAT_CORUS_VEGTER
*MAT_CAZACU_BARLAT
*MAT_HILL_90
……





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Plasticity

Modular concept with *MAT_ADD_EROSION

```
*MAT_3-PARAMETER_BARLAT
$      MID        RO         E        PR        HR        P1        P2      ITER
        10    7.85E-6    210.0       0.3       3.0       0.0       0.0       0.0
$        M    R00/AB    R45/CB    R90/HB      LCID        E0       SPI        P3
         8      0.75      0.85      1.05       500
$     AOPT         C         P     VLCID                  PB
         2
$                                     A1        A2        A3
                                     1.0       0.0       0.0
$       V1        V2        V3        D1        D2        D3      BETA
                                     0.0       0.0       0.0
$
*MAT_ADD_EROSION
$      MID      EXCL    MXPRES     MNEPS    EFFEPS    VOLEPS    NUMFIP       NCS
        10
$   MNPRES     SIGP1     SIGVM     MXEPS     EPSSH     SIGTH   IMPULSE    FAILTM

$     IDAM    DMGTYP     LCSDG     ECRIT    DMGEXP     DCRIT    FADEXP    LCREGD
         1         1       100      -200         2                 2.5       400
$   SIZFLG     REFSZ     NAHSV     LCSRS    REGSHR   REGBIAX
                            14                 1.0       0.0
```

The modular concept of *MAT_ADD_EROSION allows the user to combine GISSMO with any other elasto-plastic model in LS-DYNA

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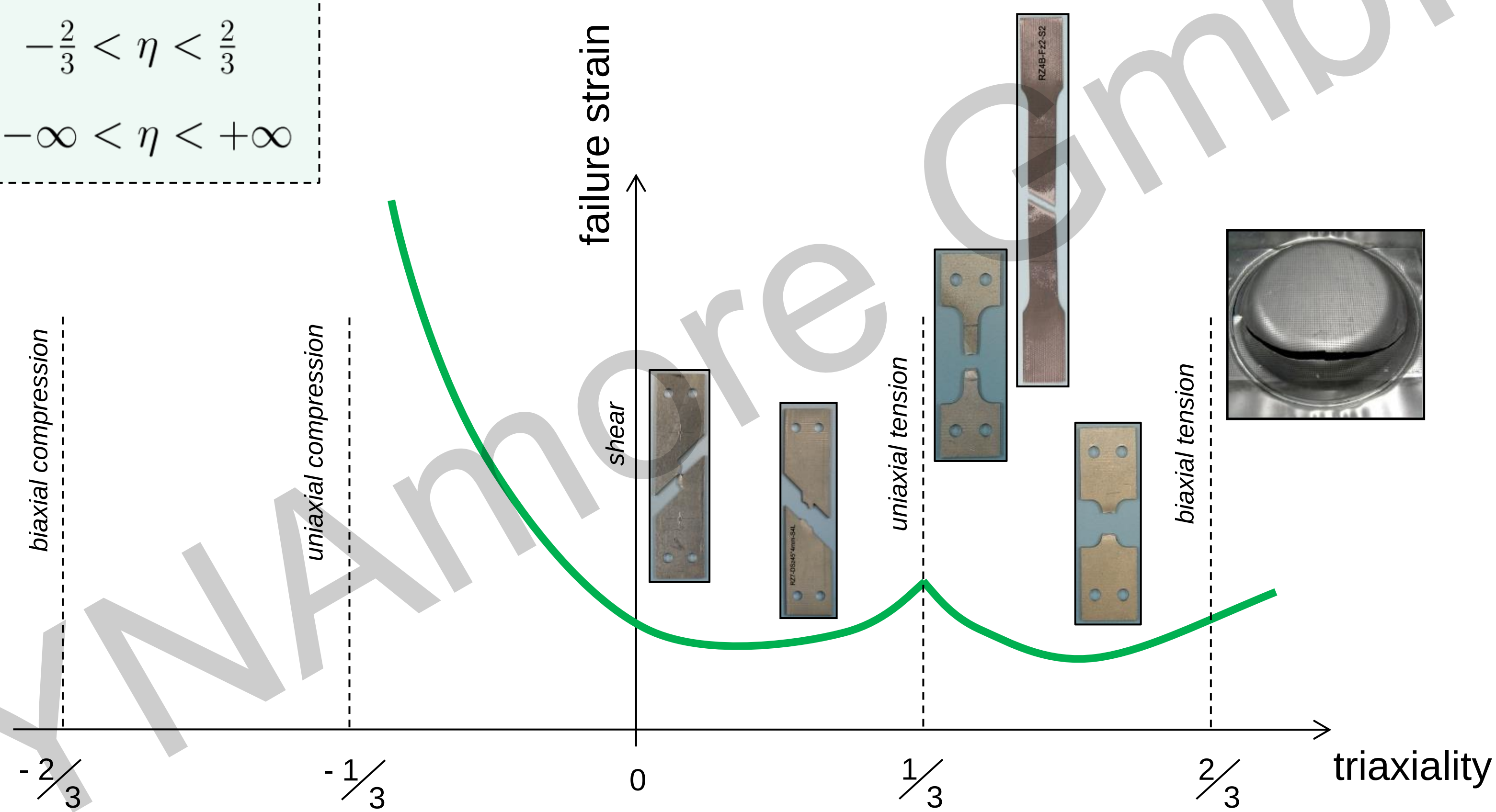
Stress state dependence

Material failure strongly depends on the stress state

Shells: $-\frac{2}{3} < \eta < \frac{2}{3}$

Solids: $-\infty < \eta < +\infty$



Suitable specimens are generally preferred for the accurate calibration of material failure

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Stress state dependence

Defining a failure curve (only triaxiality)

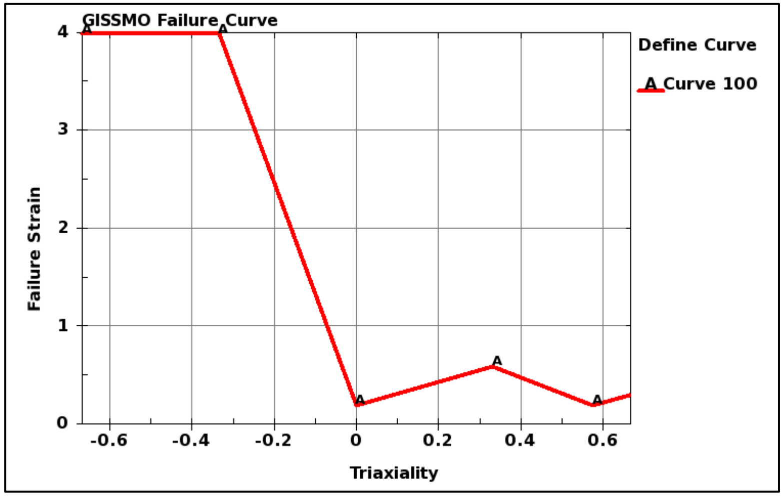
```
*MAT_PIECEWISE_LINEAR_PLASTICITY
$      MID        RO         E        PR      SIGY      ETAN      FAIL      TDEL
        10
$        C         P      LCSS      LCSR        VP

...

*MAT_ADD_EROSION
$      MID      EXCL    MXPRES     MNEPS    EFFEPS    VOLEPS    NUMFIP       NCS
        10
$   MNPRES     SIGP1     SIGVM     MXEPS     EPSSH     SIGTH   IMPULSE    FAILTM

$     IDAM    DMGTYP     LCSDG     ECRIT    DMGEXP     DCRIT    FADEXP    LCREGD
         1         1       100      -200         2                 2.5       400
$   SIZFLG     REFSZ     NAHSV     LCSRS    REGSHR   REGBIAX
                            14                 1.0       0.0
```

Main material model (e.g. *MAT_024)

General parameters in *MAT_ADD_EROSION

GISSMO failure parameters

```
*DEFINE_CURVE
$     LCID      SIDR      SCLA      SCLO
       100         0       1.0       1.0
$                eta                epsf
             -0.6666                 4.0
             -0.3333                 4.0
              0.0000                 0.2
              0.3333                 0.6
              0.5775                 0.2
              0.6666                 0.3
```



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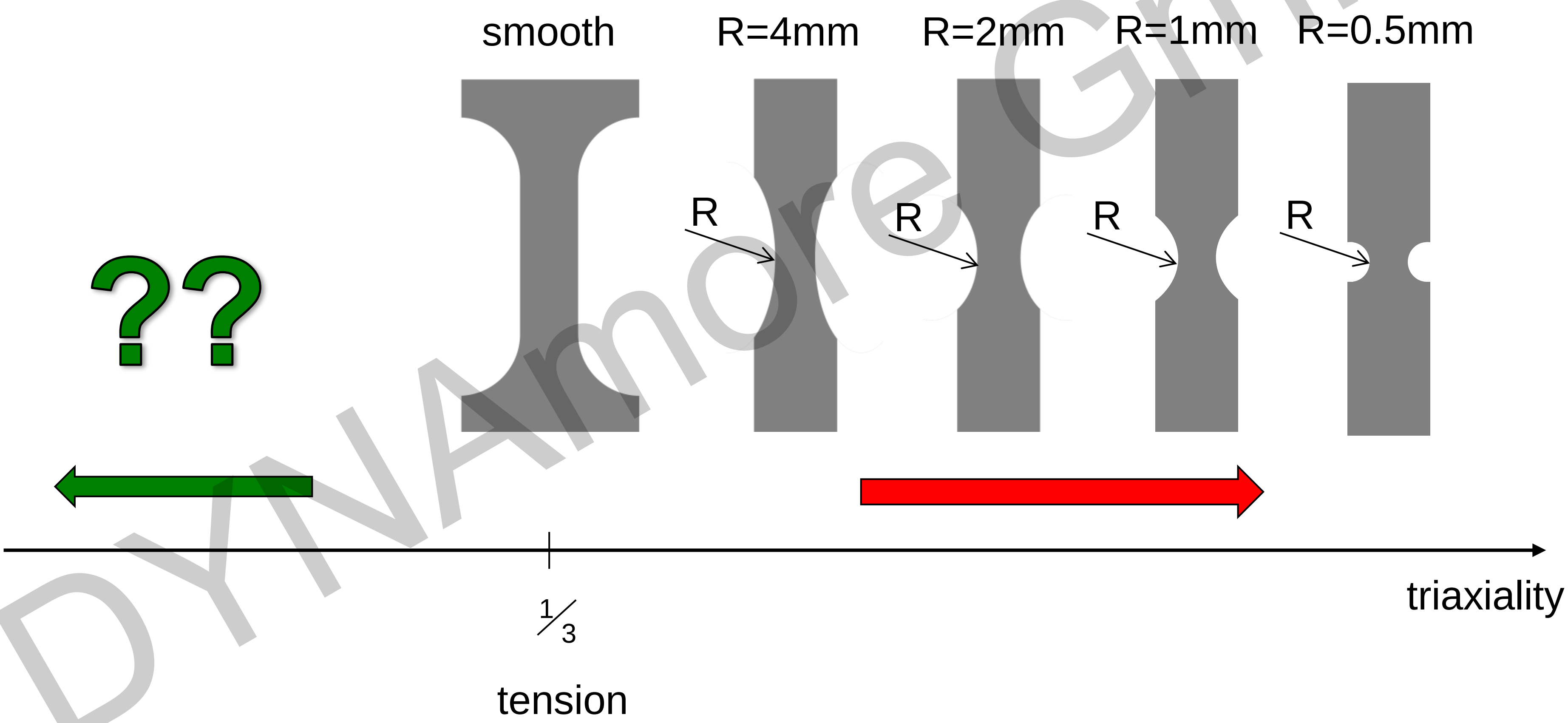
Stress state dependence

How to vary the triaxiality in experiments?



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Non-proportional loading

(very important in crash simulations)

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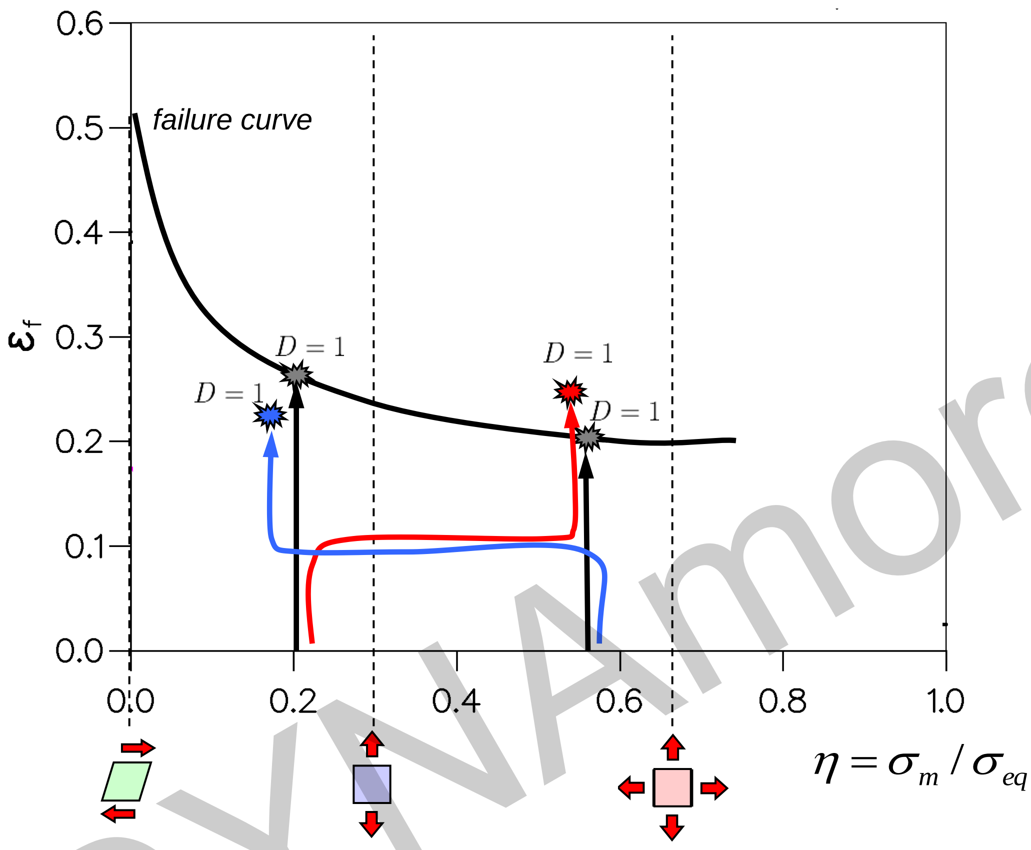
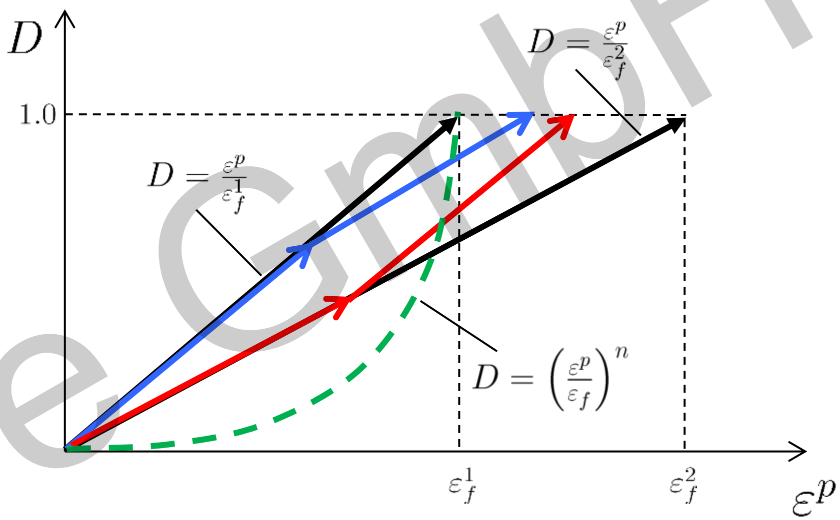
Non-proportional loading

Accumulation of damage in GISSMO





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

Differentiated under constant triaxiality

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

Damage is incrementally accumulated as a function of the plastic strain increment and of the failure curve. **Failure occurs when D = 1!**

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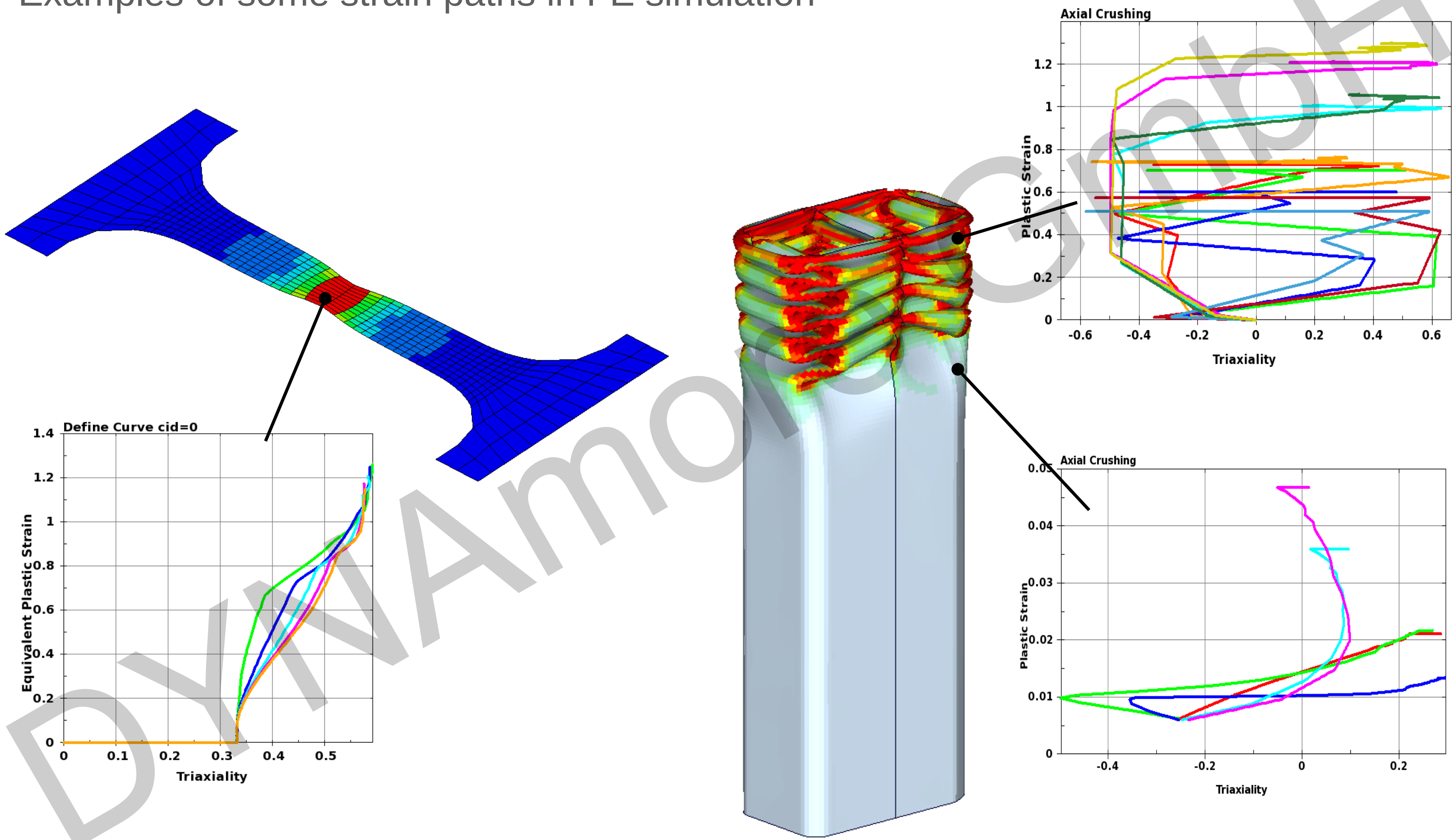
Non-proportional loading

Examples of some strain paths in FE simulation



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Calibration of a GISSMO material card

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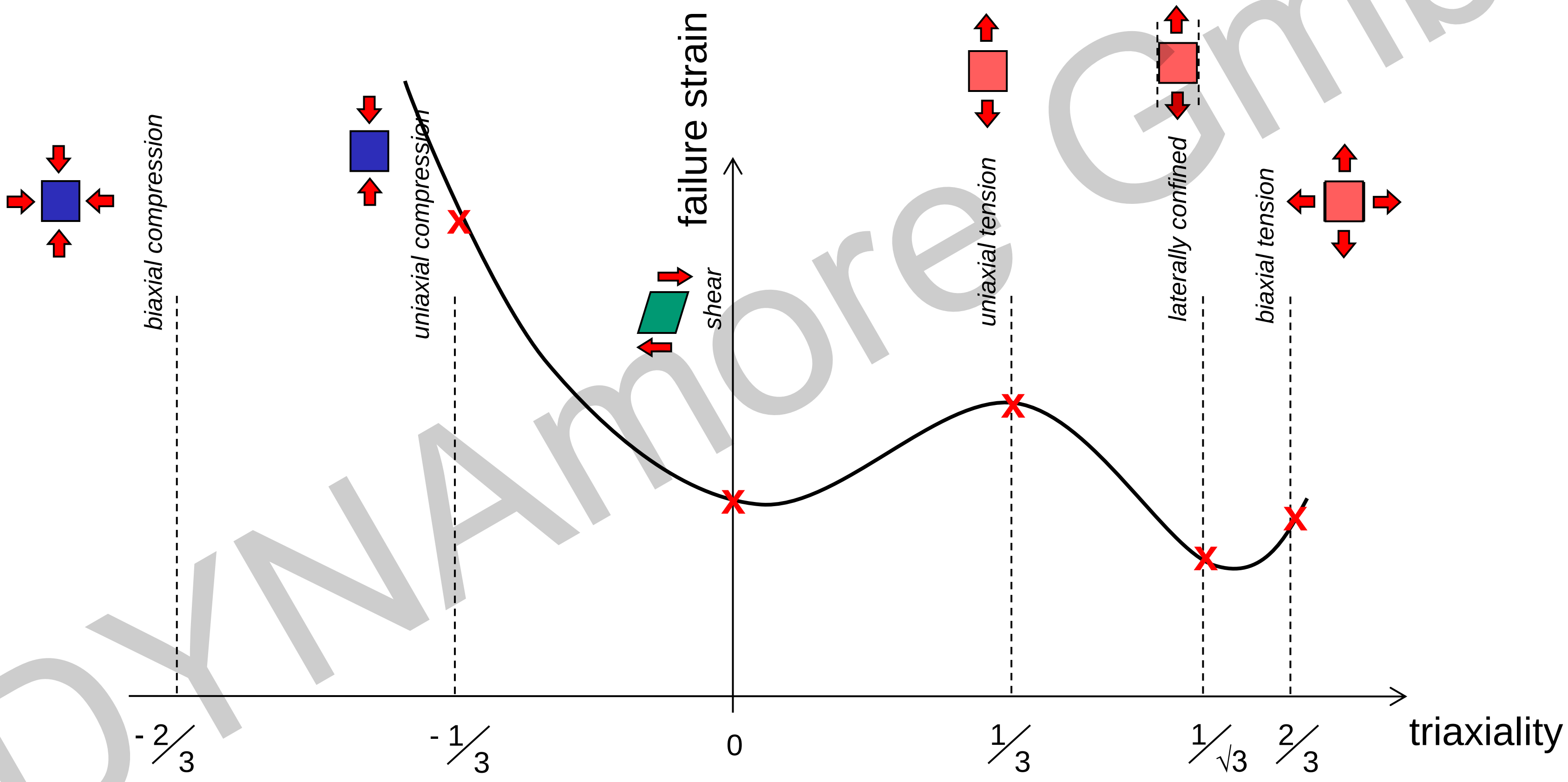
Plane stress case (e.g. standard shells)

Identification of failure strain for various triaxialities



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Calibration of GISSMO

Usual methods for the identification of the failure strains

Method	Advantages	Disadvantages
Geometrical measurement of the failure strain	• No or few simulations needed for the model calibration • Results are often good enough	• Somewhat limited precision • Plasticity model assumed accurate • Non-proportionality disregarded • Influence of numerical parameters when simulating real parts
Optical measurement of the failure strain	• No or few simulations needed • Higher measurement precision than above method	• Plasticity model assumed accurate • Non-proportionality disregarded • Influence of numerical parameters
Reverse engineering for failure strain identification	• Influence of numerical parameters inherently considered • Non-proportionality considered • Limitations of plasticity model can be somewhat compensated	• More simulations needed • Only valid for the numerical parameters used in the calibration • Numerical calibration may still not be accurate enough

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LIVE DEMO:
Reverse engineering method

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Spurious mesh dependence

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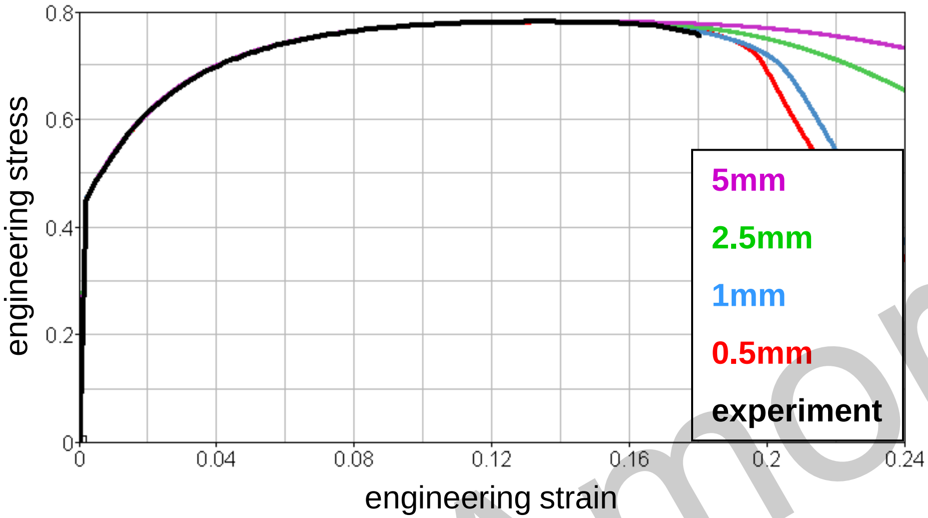
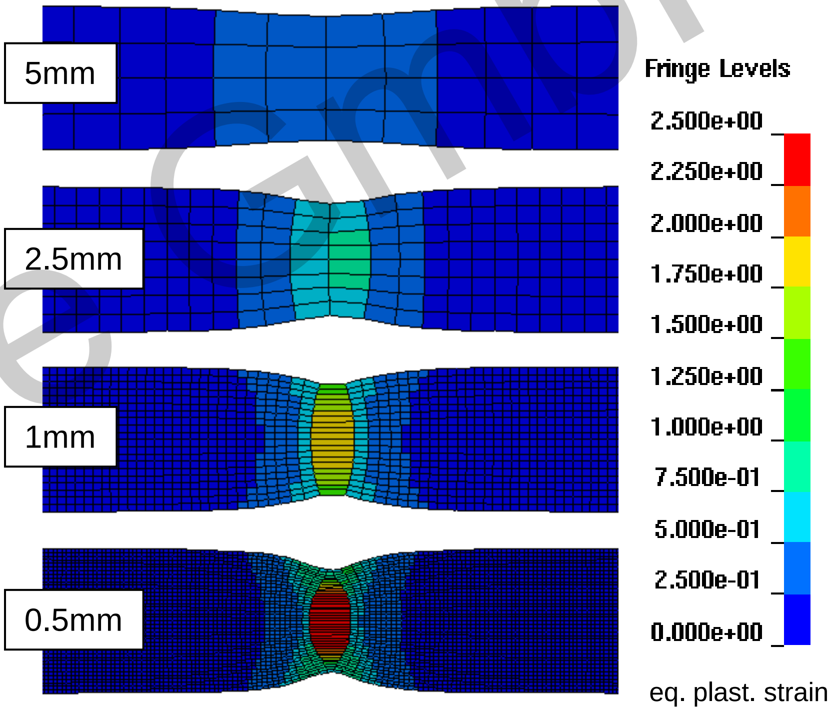
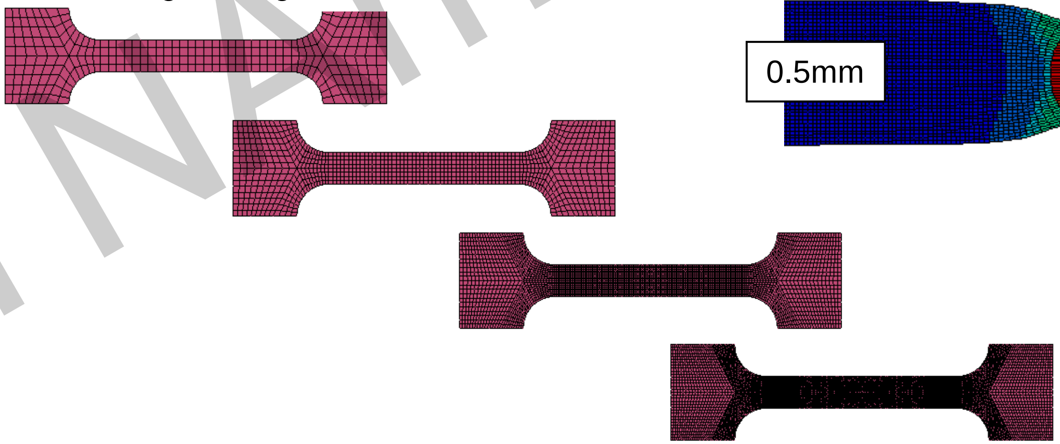
Mesh dependence

FE solution is spuriously mesh dependent after the necking point







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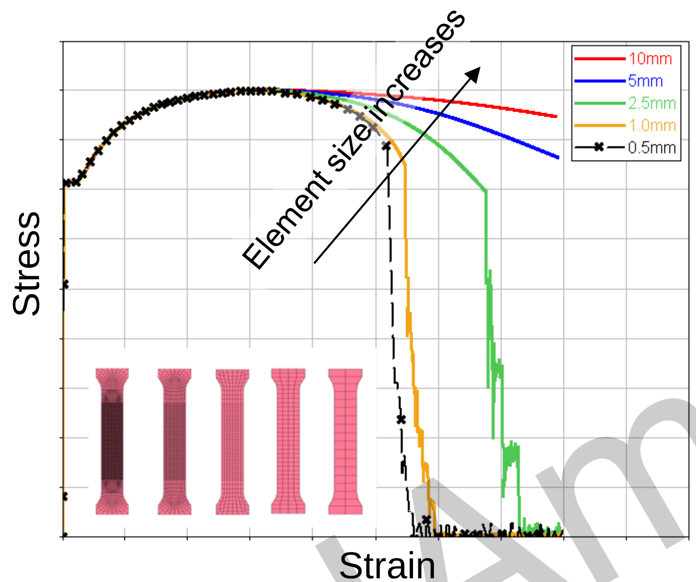
Mesh dependence

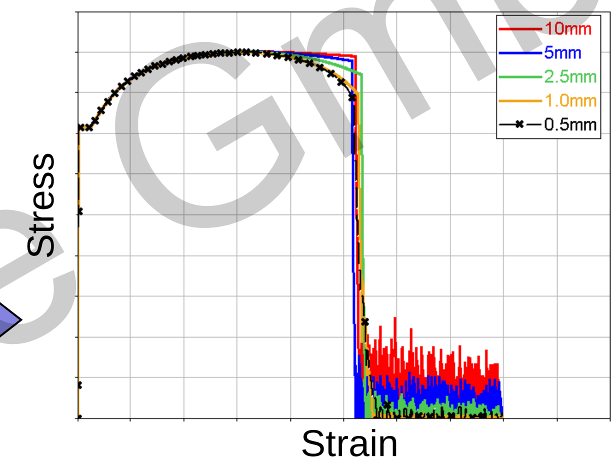
Regularization for different mesh sizes

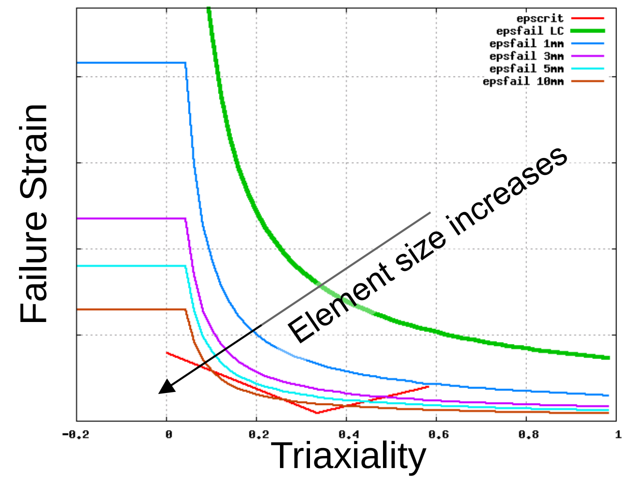
Mesh size dependence



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

Simple regularization





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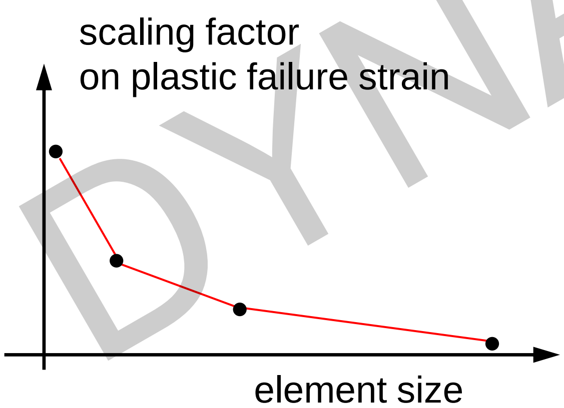
Mesh dependence

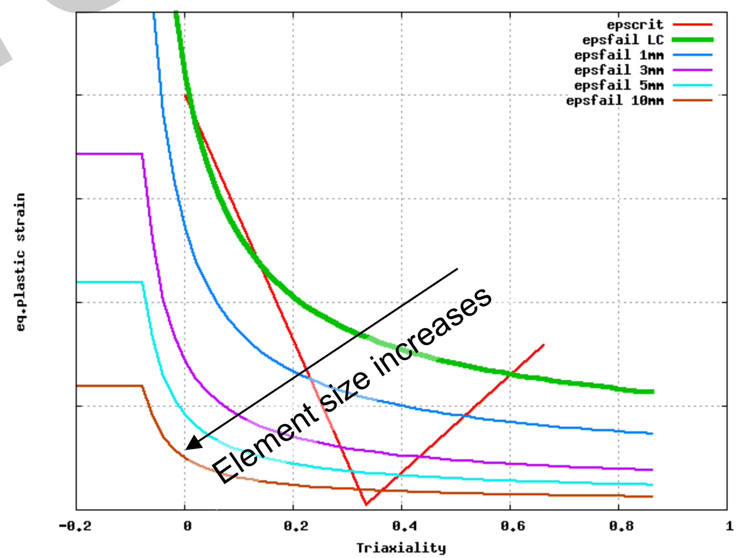
Regularization for different mesh sizes

```
*MAT_ADD_EROSION
$      MID      EXCL    MXPRES     MNEPS    EFFEPS    VOLEPS    NUMFIP       NCS
        10
$   MNPRES     SIGP1     SIGVM     MXEPS     EPSSH     SIGTH   IMPULSE    FAILTM

$     IDAM    DMGTYP     LCSDG     ECRIT    DMGEXP     DCRIT    FADEXP    LCREGD
         1         1       100      -200         2                 2.5       400
$   SIZFLG     REFSZ     NAHSV     LCSRS    REGSHR   REGBIAX
                            14                 1.0       0.0

*DEFINE_CURVE
$     LCID      SIDR      SCLA      SCLO
       400         0       1.0       1.0
$                 LE              regfac
                0.25                1.00
                0.50                0.80
                1.00                0.65
                2.50                0.52
                5.00                0.40
               10.00                0.31
```





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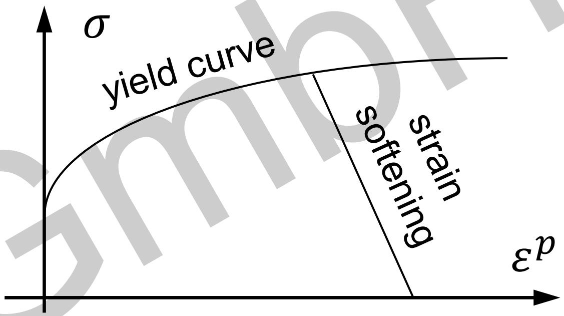
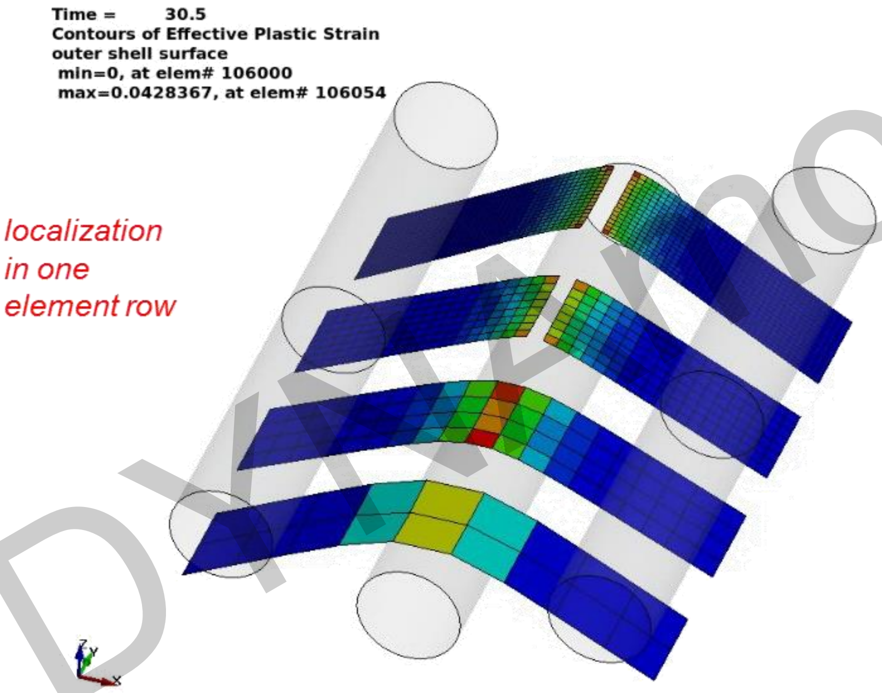
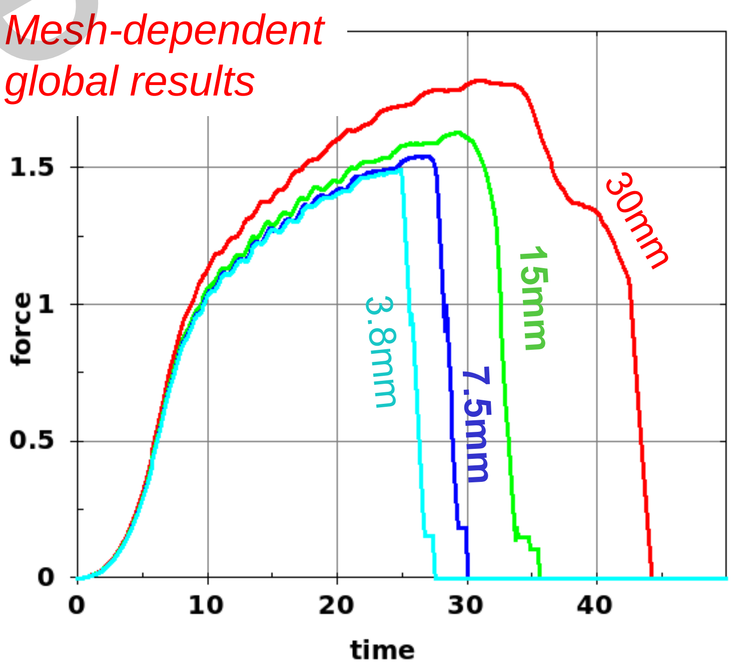
Mesh dependence

Bending example – without regularization

- *MAT_ADD_EROSION with IDAM=1, LCSDG with const. value of 0.055 and ECRIT=0.045
- 3-point bending with different mesh sizes
- Mesh dependent results **without regularization**:







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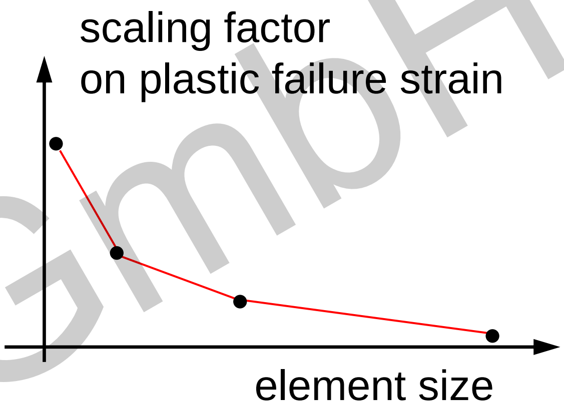
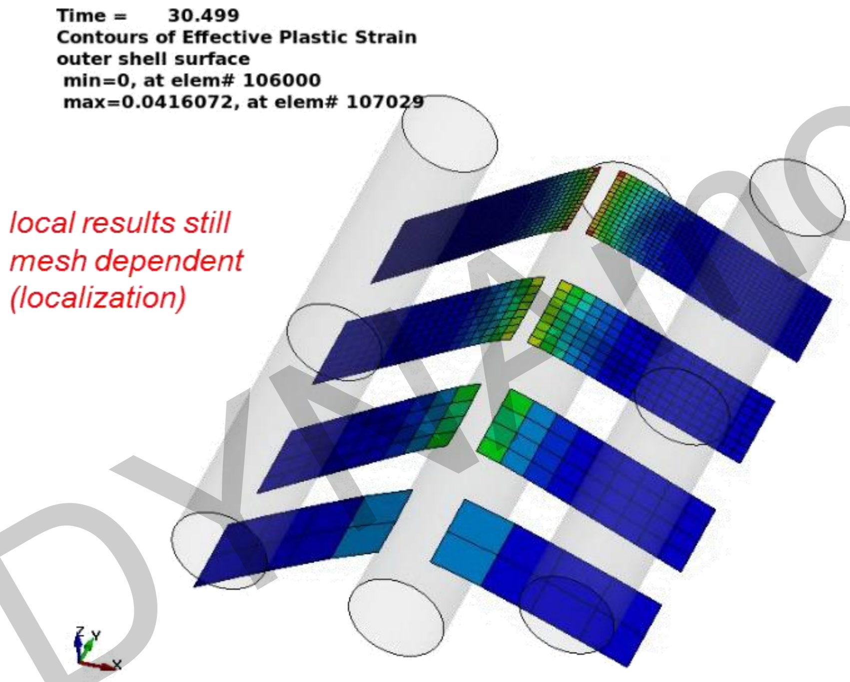
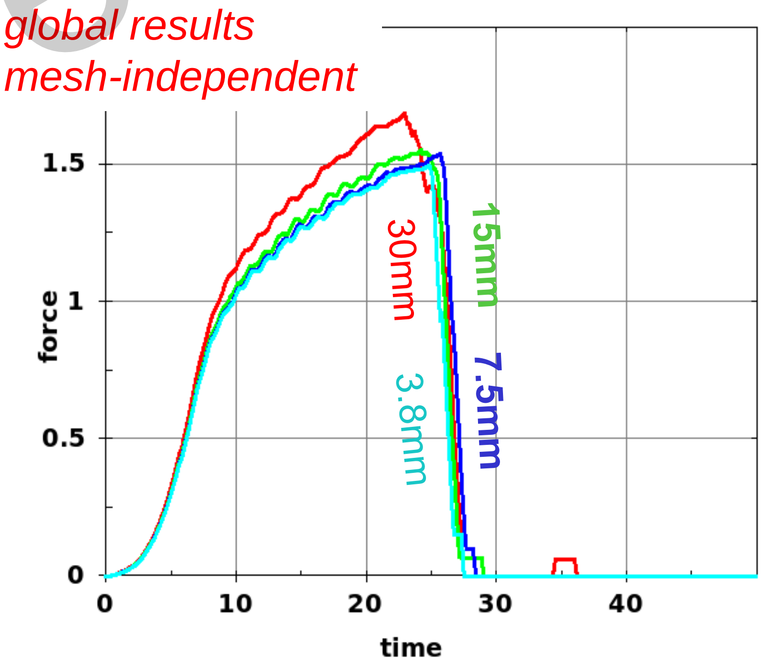
Mesh dependence

Bending example – with regularization

- *MAT_ADD_EROSION with IDAM=1, LCSDG with const. value of 0.055 and ECRIT=0.045
- 3-point bending with different mesh sizes
- Results **with regularization (LCREGD)**:







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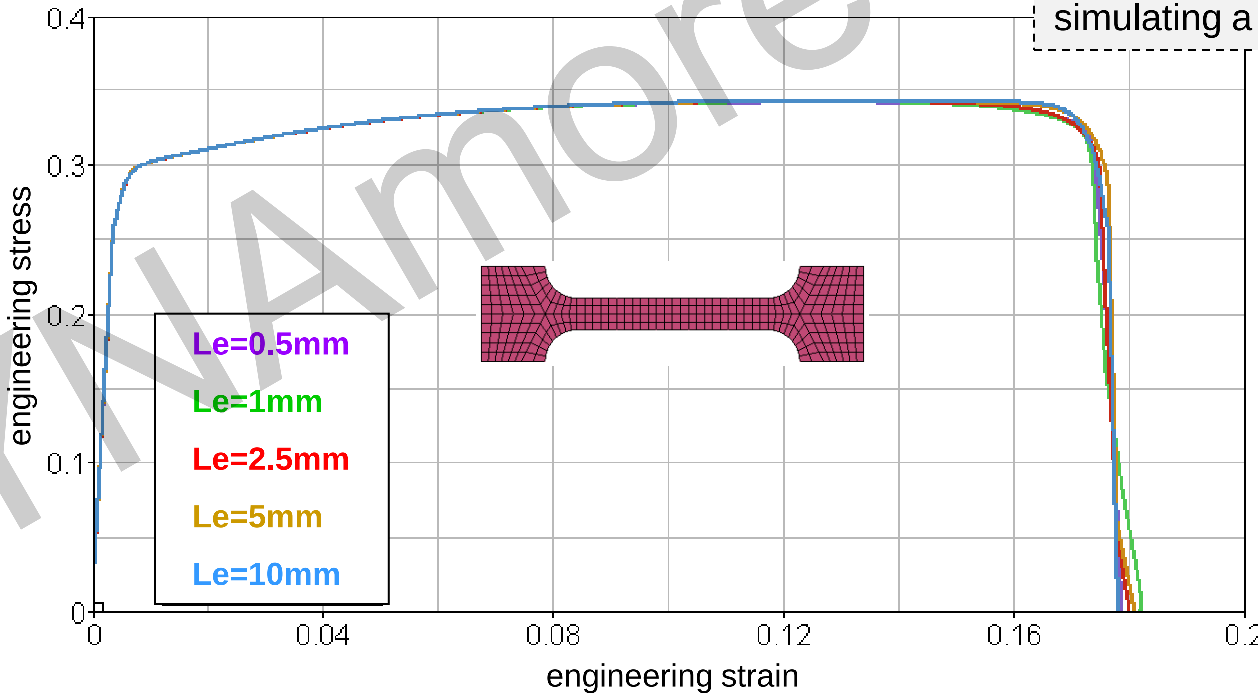
Calibration of GISSMO

Regularization

```
*DEFINE_CURVE
$ Regularizing factors (LCREGD)
$      LCID      SIDR      SCLA      SCLO
        400         0       1.0       1.0
$                 eta                epsf
                 0.50                1.00
                 1.00                0.72
                 2.50                0.49
                 5.00                0.35
                10.00                0.28
```

A GISSMO material card can be iteratively regularized by simulating a tensile test!



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Summary

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Summary

Final comments

Although the subject of metal failure prediction seems to be far from settled, LS-DYNA currently provides state-of-the-art failure and damage models for the prediction of material ductile fracture. GISSMO belongs to the most advanced of these models and is generally recommended for metal failure prediction in LS-DYNA.

General features of GISSMO:

- Modular structure
- Dependence of the stress state
- Failure as a function of the triaxiality as well as of the Lode angle (shells and volume elements)
- Non-proportional loading is considered through damage accumulation
- Coupling of damage/stress → more realistic strains for large elements
- Numerical tools for treatment of mesh dependence
- Strain rate may be considered
- Possibility of mapping damage from a previous simulation

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Summary

Where to get more information

- Presentations at this conference, e.g.:
  - F. Andrade, M. Feucht, A. Haufe:
    On the Prediction of Material Failure in LS-DYNA:
    A Comparison Between GISSMO and DIEM
    (Tuesday, 2:50 pm, Crash I – Materials)

- DYNAmore training courses (www.dynamore.de/en/training/seminars)
  - Modeling of metallic materials (10^{th}–11^{th} Nov 2014, Stuttgart)
  - Material failure (12^{th}–13^{th} Nov 2014, Stuttgart)

- LS-DYNA upcoming conferences
  - 2015 European LS-DYNA Conference in Würzburg, Germany

- Papers from previous conferences (www.dynalook.com)

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END

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