Failure prediction in crash simulations with the GISSMO model

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Motivation

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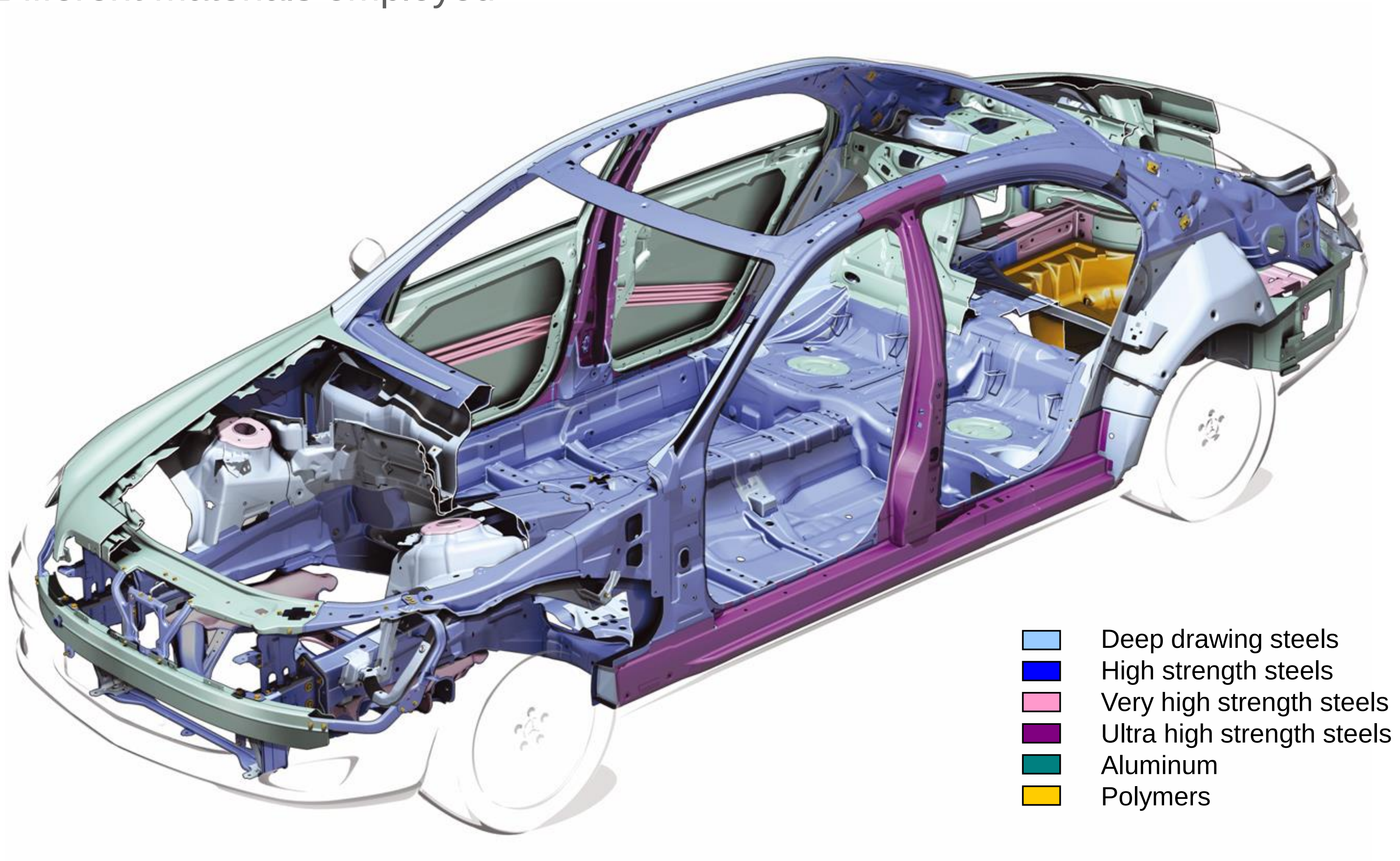
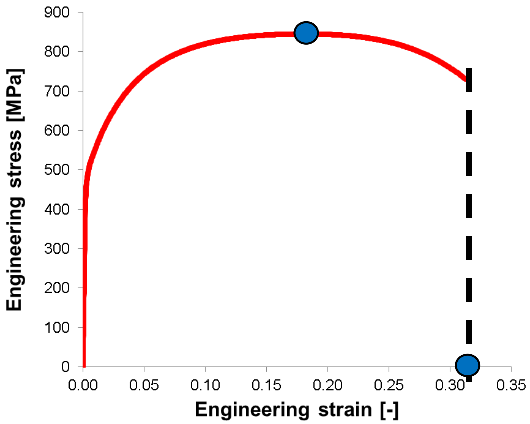
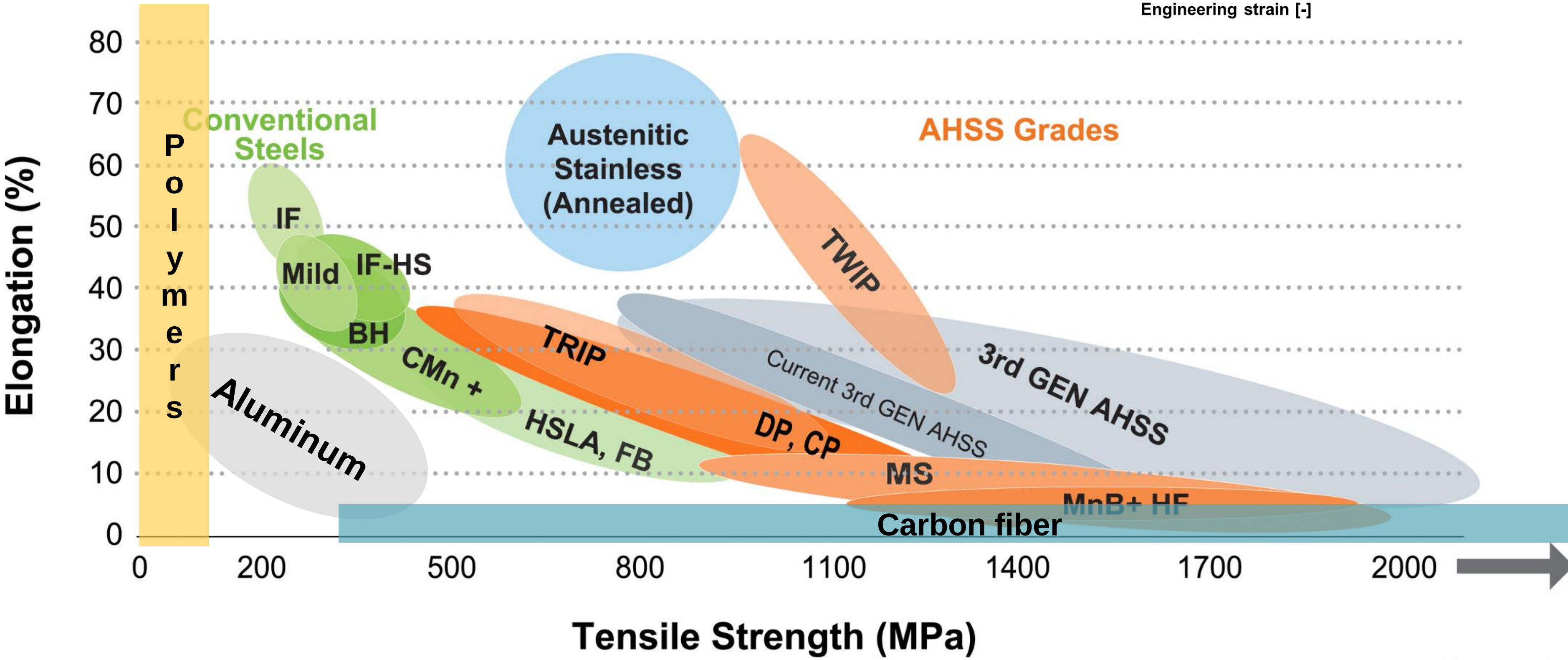
Different materials employed



Motivation

Different materials employed





Source: WorldAutoSteel

How to foretell the future?

A method for prediction of failure

Is it gonna break?

Observe failure
Perform experiments
Report observations

Make assumptions
Formulate equations
Create models

Check if models can reproduce experiments and predict future behavior

e.g., GISSMO

Use validated models in the application

Ductile failure

Factors of influence

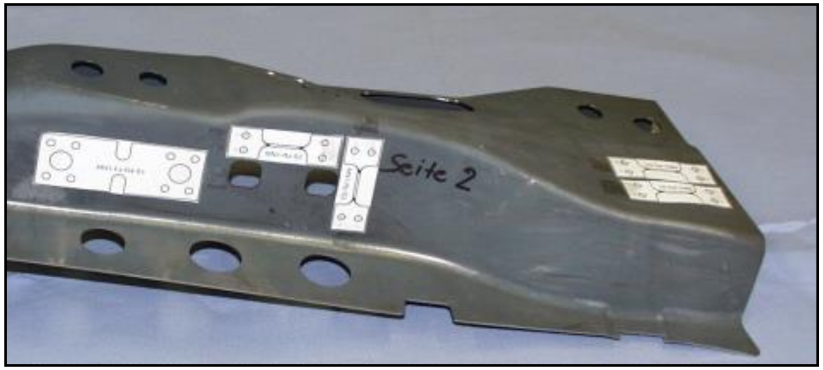
- Plastic strain
- Loading type (tension, shear, compression, …)
- Nonlinear strain paths
- Material instability → (Spurious mesh dependence)
- Discretization (shells, solids, under/fully integrated, …)
- Pre-strain and pre-damage
- Previous heat treatments
- Anisotropy
- Strain rate dependence
- Heat affected zones due to welding
- Other temperature related effects
- Scattering of material properties
- …

Plastic strain

Plastic strain

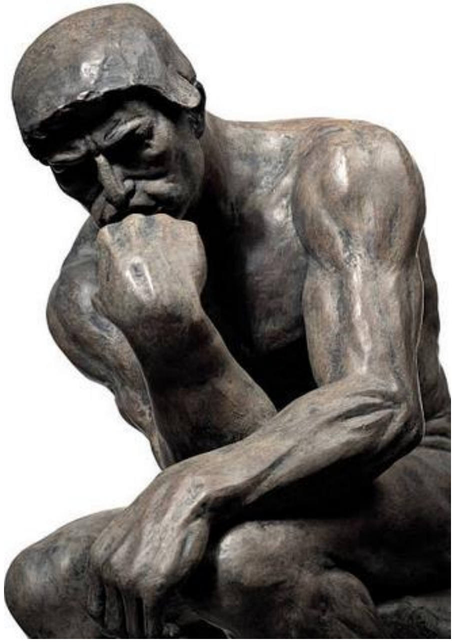
Influence on ductile failure

- No plastic strain
  → no ductile failure



- Severe plastic strain
  → (might lead to) ductile failure

What is strain?



A valid strain measure has to fulfill two conditions:

- It has to vanish in presence of pure rigid deformations
- It has to reduce to infinitesimal strains when small enough

Two strain measures commonly adopted in engineering (in one dimension):

Engineering strain: $$\varepsilon_{eng} = \frac{l - l_o}{l_o}$$

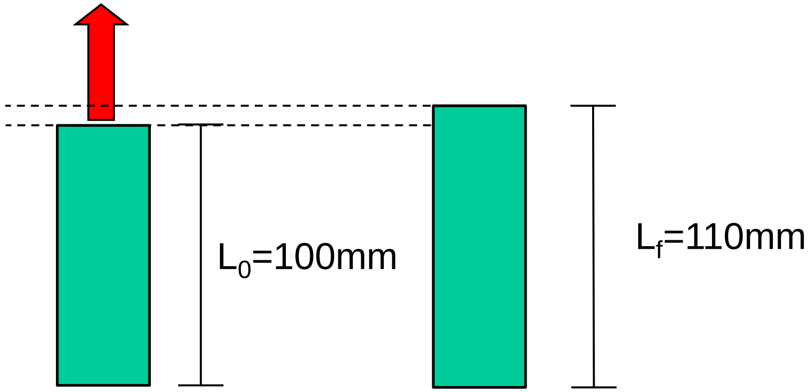
Generally more intuitive

True strain: $$\varepsilon_{true} = \ln\left(\frac{l}{l_0}\right)$$

General input/output in LS-DYNA!

Engineering vs. true strain

Example – one dimensional bar

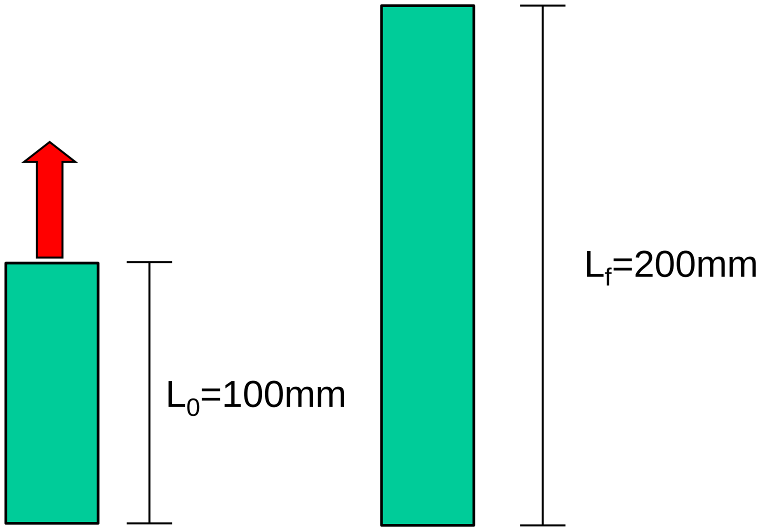


$$\varepsilon_{eng} = \frac{l - l_o}{l_o} = \frac{110 - 100}{100} = 0.1$$

$$\varepsilon_{true} = \ln\left(\frac{l}{l_0}\right) = \ln\left(\frac{110}{100}\right) = 0.0953$$

Engineering vs. true strain

Example – one dimensional bar (cont'd)



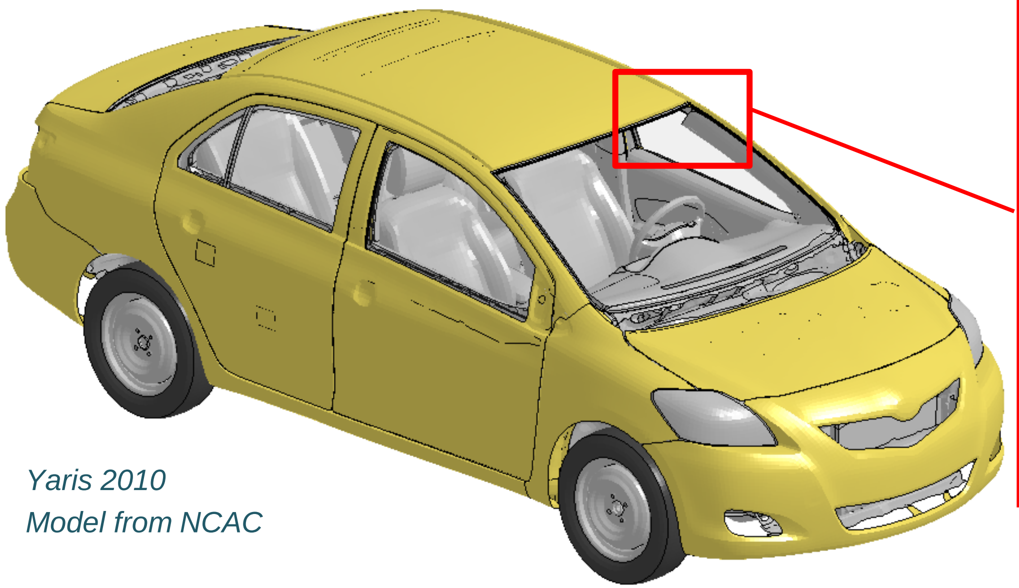
$$\varepsilon_{eng} = \frac{l - l_o}{l_o} = \frac{200 - 100}{100} = 1.0$$

$$\varepsilon_{true} = \ln\left(\frac{l}{l_0}\right) = \ln\left(\frac{200}{100}\right) = 0.693$$

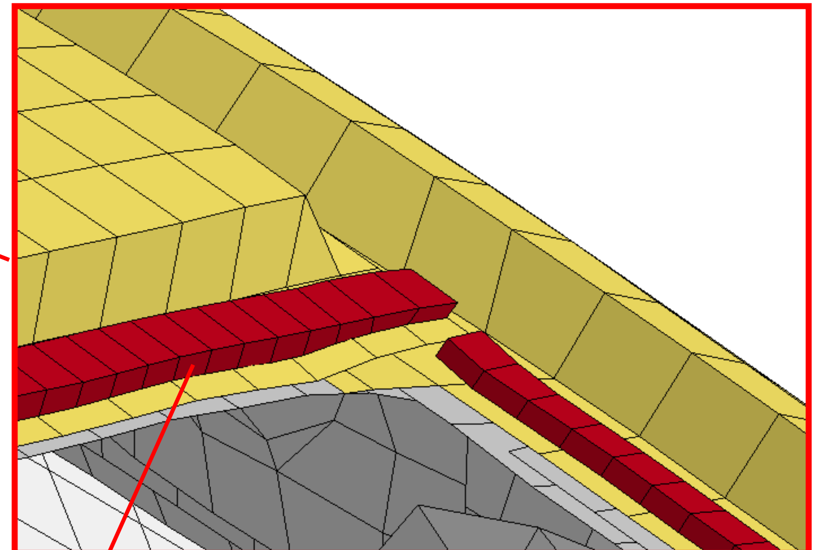
The deformation is exactly the same! The strain, however, is different depending on which strain measure is used.

Example

Windshield adhesive



Yaris 2010
Model from NCAC



```
*MAT_ADD_EROSION
$       MID       EXCL     MXPRES      MNEPS     EFFEPS     VOLEPS     NUMFIP
                                                    1.0
```

```
*MAT_ADD_EROSION
$       MID       EXCL     MXPRES      MNEPS     EFFEPS     VOLEPS     NUMFIP          NCS
                                                    2.0
```

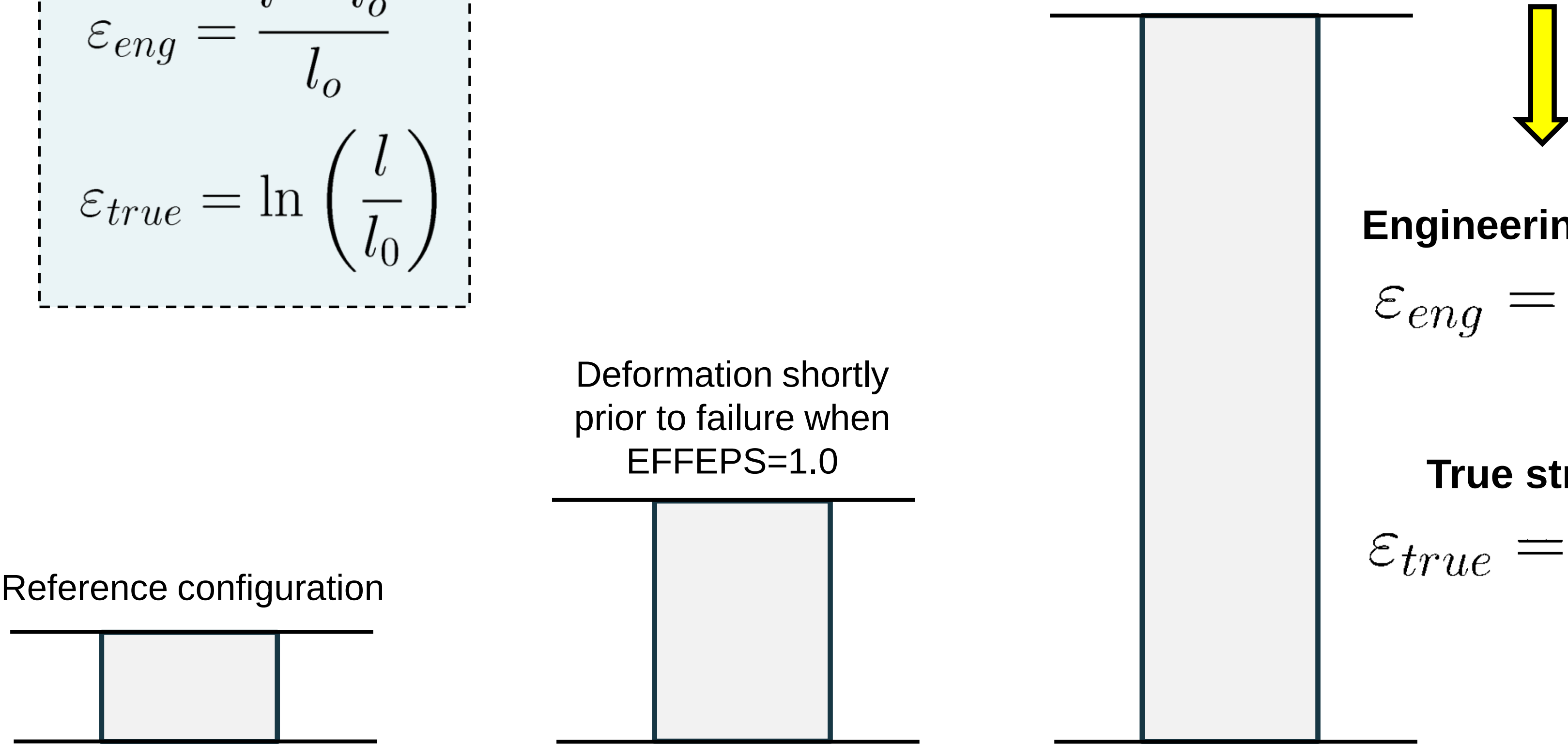
true strain in the input!

Example

Windshield adhesive

$$\varepsilon_{eng} = \frac{l - l_o}{l_o}$$

$$\varepsilon_{true} = \ln\left(\frac{l}{l_0}\right)$$



Unrealistic large deformation and still no failure when EFFEPS=2.0!!

Engineering strain

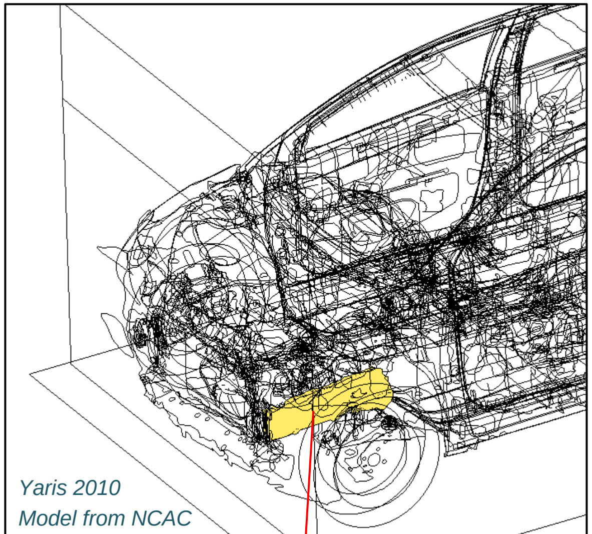
$$\varepsilon_{eng} = 500\%$$

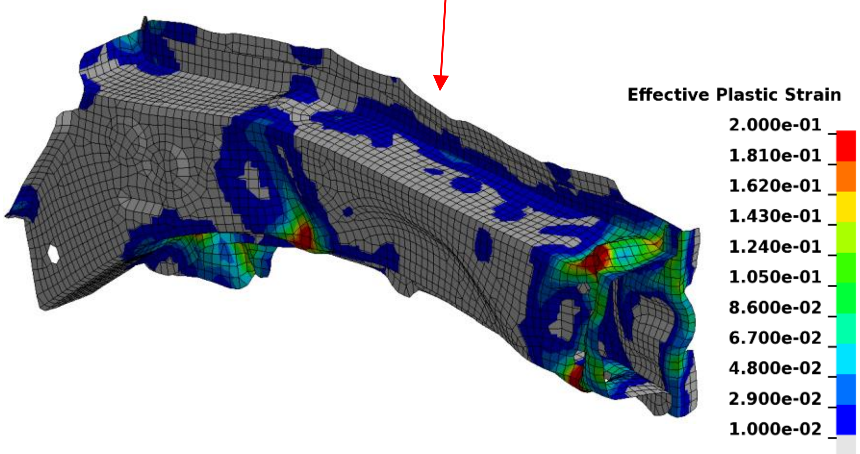
True strain

$$\varepsilon_{true} = 160\%$$

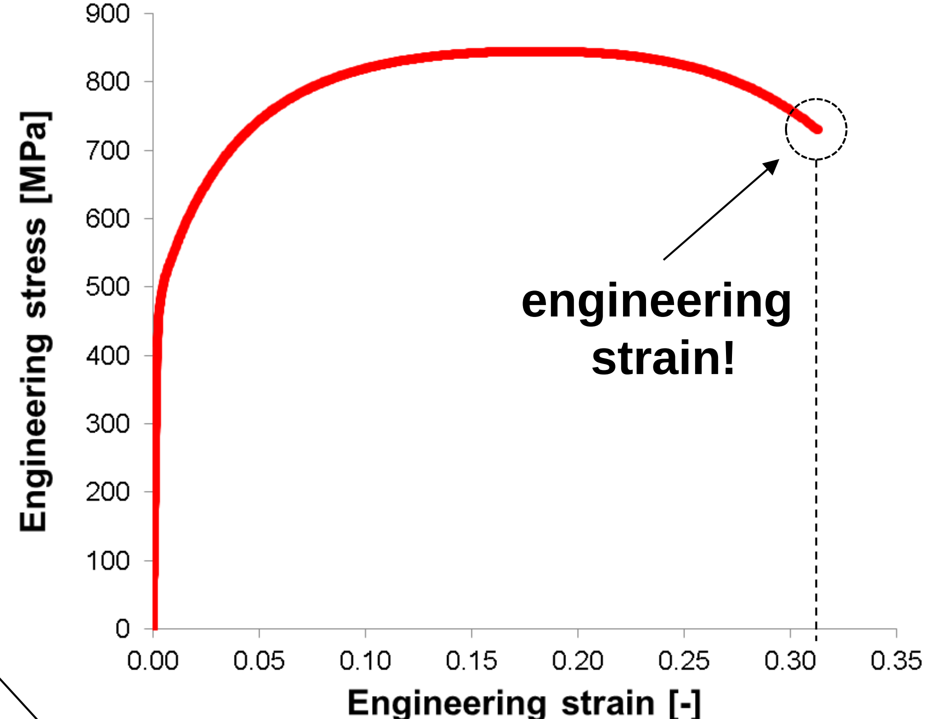
Engineering vs. true strain

$$\varepsilon_{eng} = \frac{l - l_o}{l_o}$$





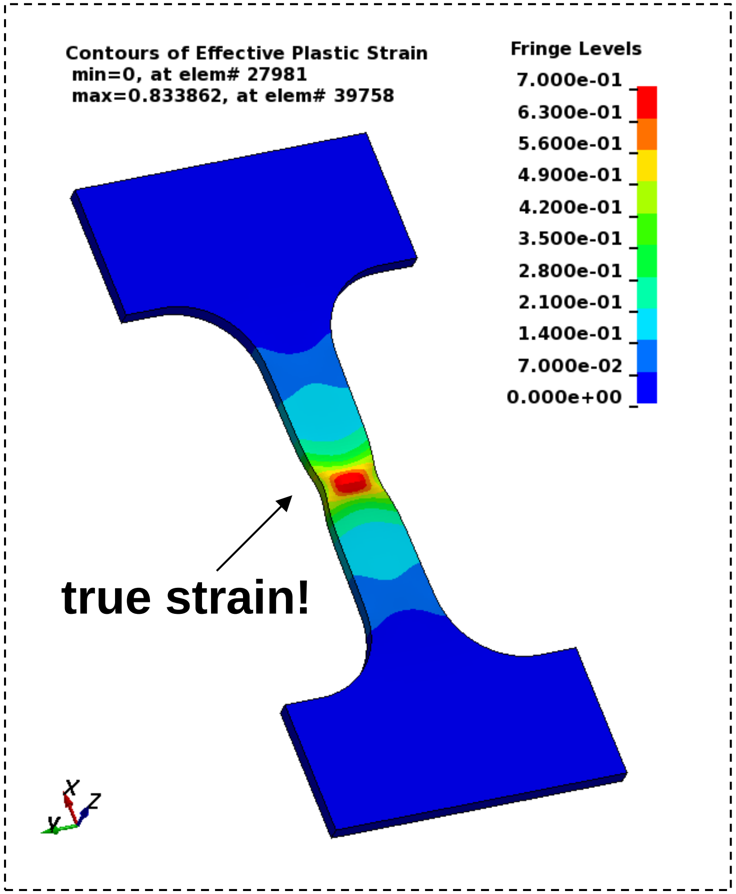
true strain!

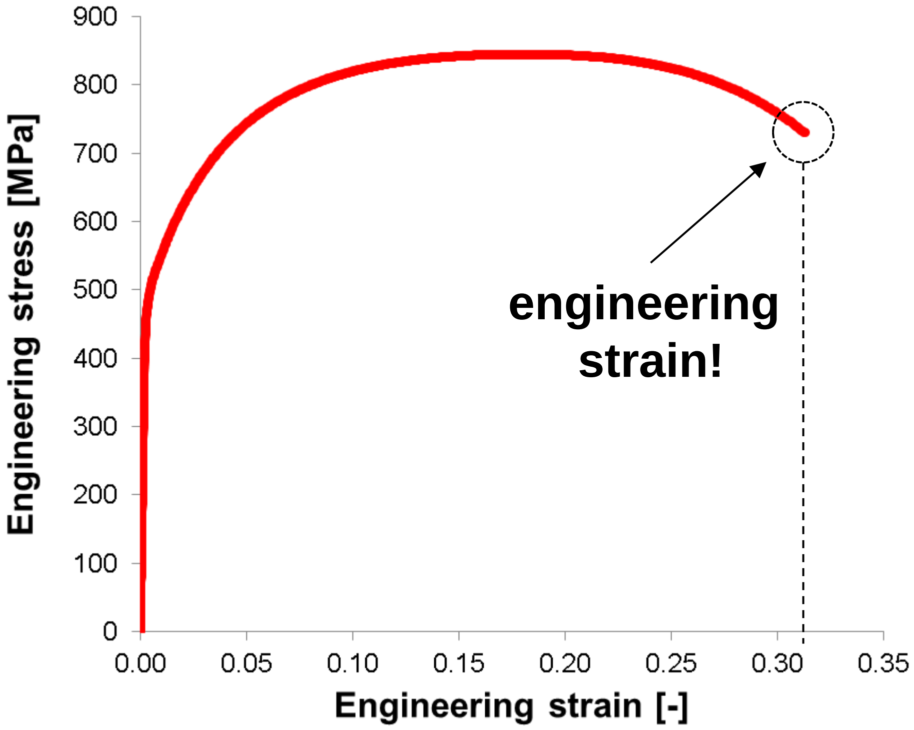


engineering strain!

Engineering vs. true strain

$$\varepsilon_{eng} = \frac{l - l_o}{l_o}$$





In this example, the **engineering strain is around 31%** meanwhile the **true plastic strain** has a maximum value of **about 83%** in the necking zone.

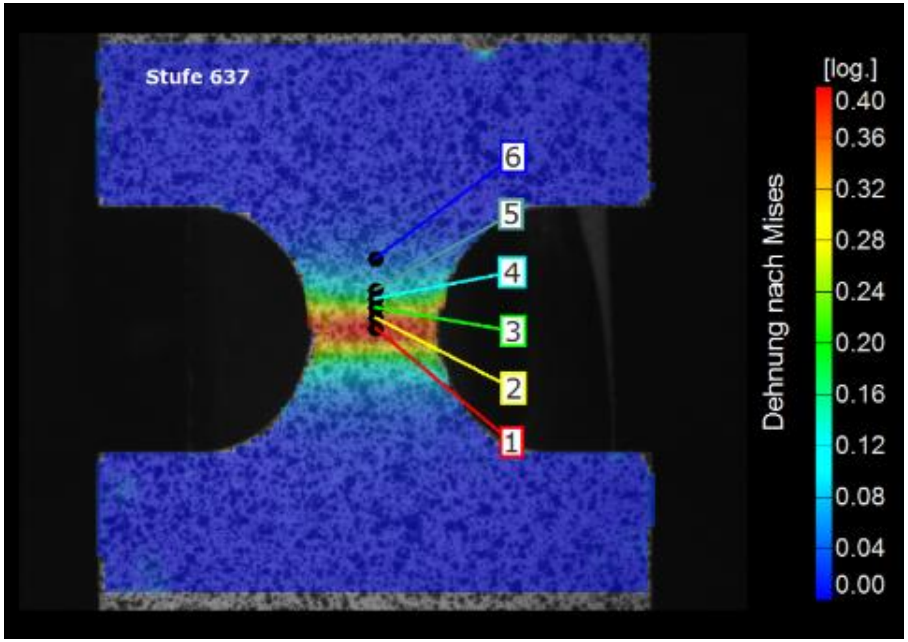
Strain

Elastic and plastic strains

Material model:
**MAT_024, *MAT_036, *MAT_SAMP-1, etc.*

$$\boldsymbol{\varepsilon} = \overbrace{\boldsymbol{\varepsilon}^{e} + \boldsymbol{\varepsilon}^{p}}$$

DIC measurement of (total) strain



Plastic strain

Influence on failure

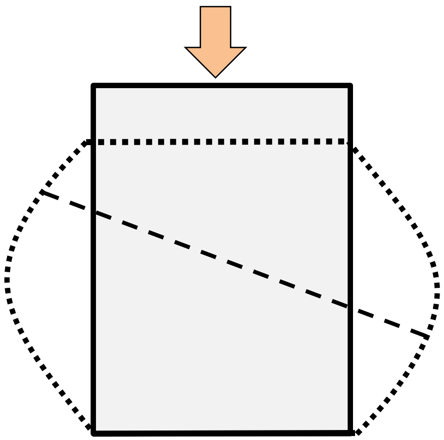
- The difference between engineering and true strain is important
- Input and output in LS-DYNA is true strain (except when otherwise noted)
- Ductile failure is strongly dependent on the plastic strain
- Different material models (*MAT_024, *MAT_036, *MAT_SAMP, etc.) basically consider different equations for describing plastic deformation
- The more complex the model, the more accurate it tries to predict plastic strain
- **The plastic strain at failure strongly depends on the loading type**

Loading type

Loading type

Effect on failure prediction

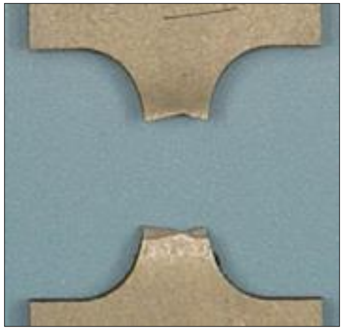
Experimental evidence: the strain at fracture is not constant for different loading types.



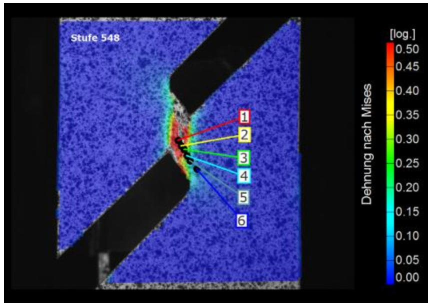
shear

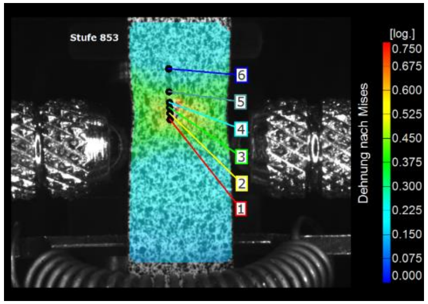
tension

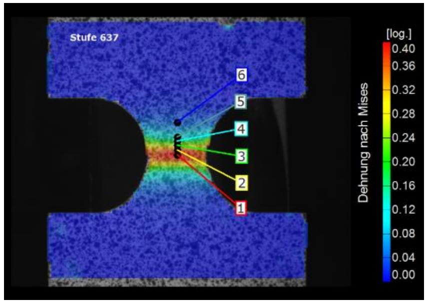
tensile test with notch



Today, local (true) strain can be measured with DIC:



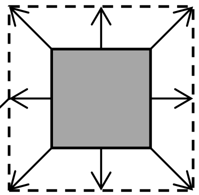




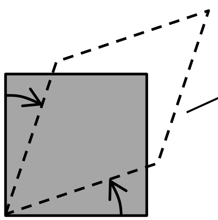
Stress tensor

Deviatoric/volumetric split

pure volumetric:
no shape modification



$$\boldsymbol{\sigma} = \begin{bmatrix} \sigma_{11} & \sigma_{12} & \sigma_{13} \\ & \sigma_{22} & \sigma_{13} \\ & & \sigma_{33} \end{bmatrix} = \begin{bmatrix} s_{11} & s_{12} & s_{13} \\ & s_{22} & s_{13} \\ & & s_{33} \end{bmatrix} + \sigma_m \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$



pure deviatoric:
no volume change
(isochoric)

Equivalent stress

$$\sigma_{eq} = f(\mathbf{s})$$

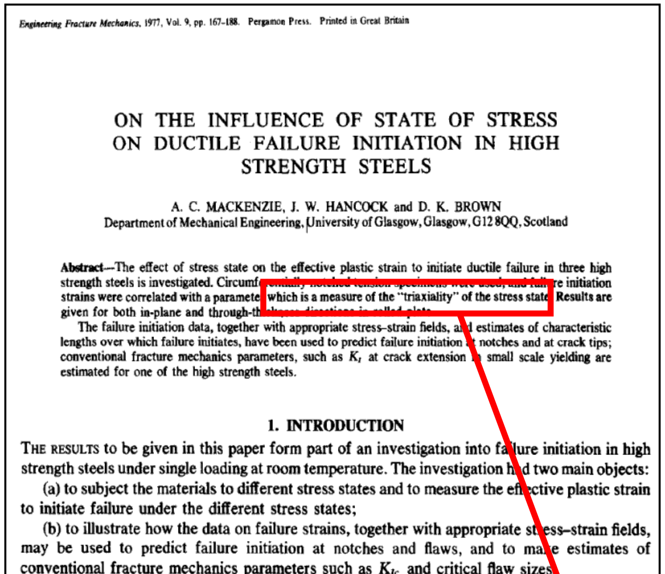
Mean stress

$$\sigma_m = \frac{\sigma_{11} + \sigma_{22} + \sigma_{33}}{3}$$

Stress triaxiality ratio

Original definition

A paper by Mackenzie, Hancock and Brown in 1977



Engineering Fracture Mechanics, 1977, Vol. 9, pp. 167–188. Pergamon Press. Printed in Great Britain

ON THE INFLUENCE OF STATE OF STRESS ON DUCTILE FAILURE INITIATION IN HIGH STRENGTH STEELS

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Abstract—The effect of stress state on the effective plastic strain to initiate ductile failure in three high strength steels is investigated. Circumferentially notched tension specimens were used, and failure initiation strains were correlated with a parameter which is a measure of the "triaxiality" of the stress state. Results are given for both in-plane and through-thickness directions in rolled plate.

The failure initiation data, together with appropriate stress–strain fields, and estimates of characteristic lengths over which failure initiates, have been used to predict failure initiation at notches and at crack tips; conventional fracture mechanics parameters, such as K_I at crack extension in small scale yielding are estimated for one of the high strength steels.

1. INTRODUCTION

THE RESULTS to be given in this paper form part of an investigation into failure initiation in high strength steels under single loading at room temperature. The investigation had two main objects:

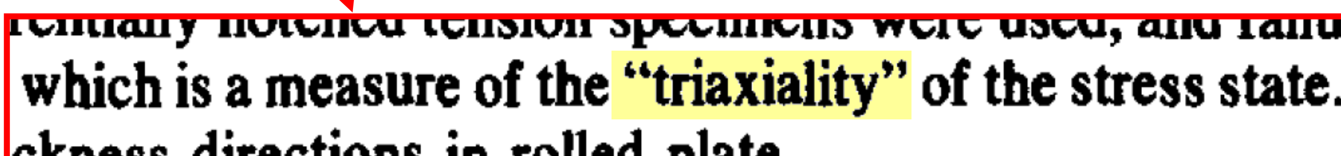
(a) to subject the materials to different stress states and to measure the effective plastic strain to initiate failure under the different stress states;

(b) to illustrate how the data on failure strains, together with appropriate stress–strain fields, may be used to predict failure initiation at notches and flaws, and to make estimates of conventional fracture mechanics parameters such as K_{Ic} and critical flaw sizes.

mean stress

pressure

$$\eta = \frac{\sigma_m}{\sigma_{eq}} = -\frac{p}{\sigma_{eq}}$$



which is a measure of the "triaxiality" of the stress state.

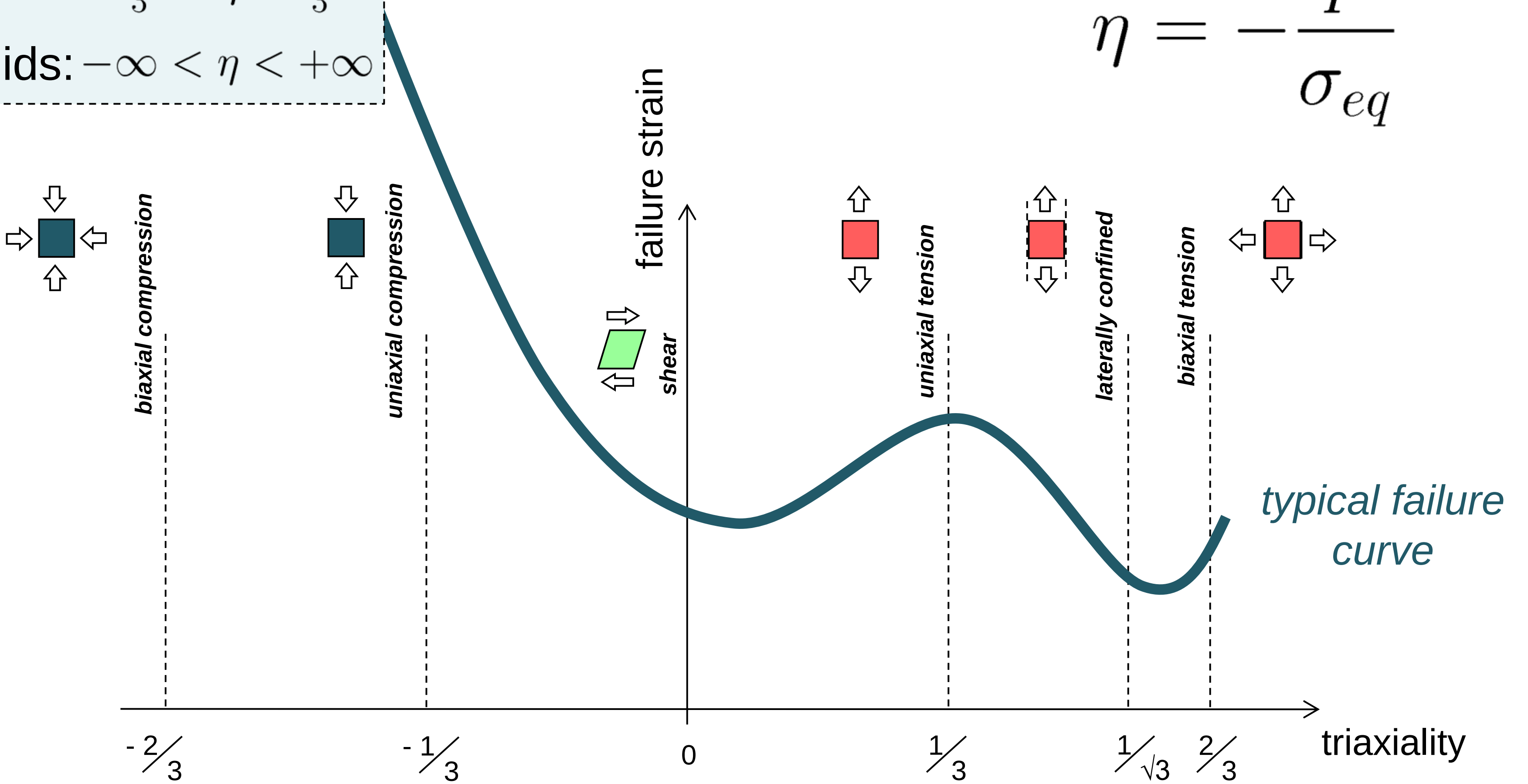
Typical failure description

Dependence on the stress triaxiality

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

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

$$\eta = -\frac{p}{\sigma_{eq}}$$



Input in LS-DYNA

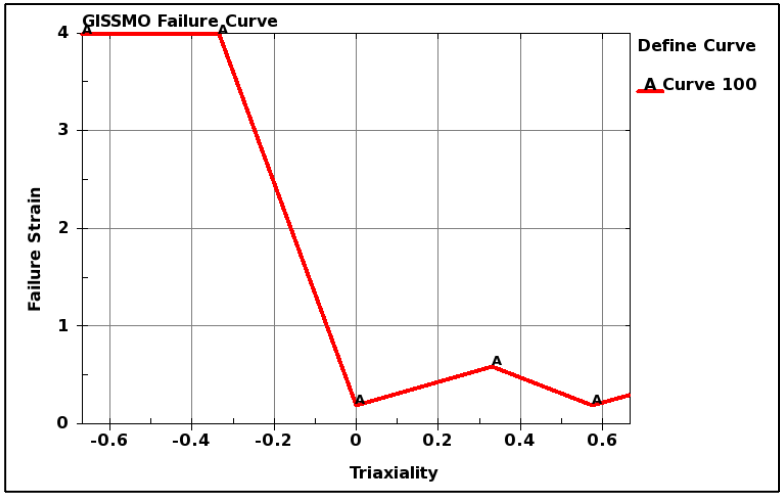
*MAT_ADD_EROSION

```
*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

*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
```

Main material model (e.g. *MAT_024)

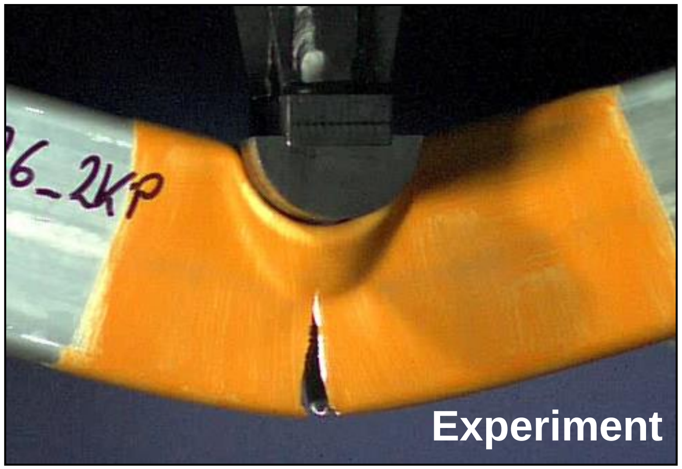
General parameters in *MAT_ADD_EROSION

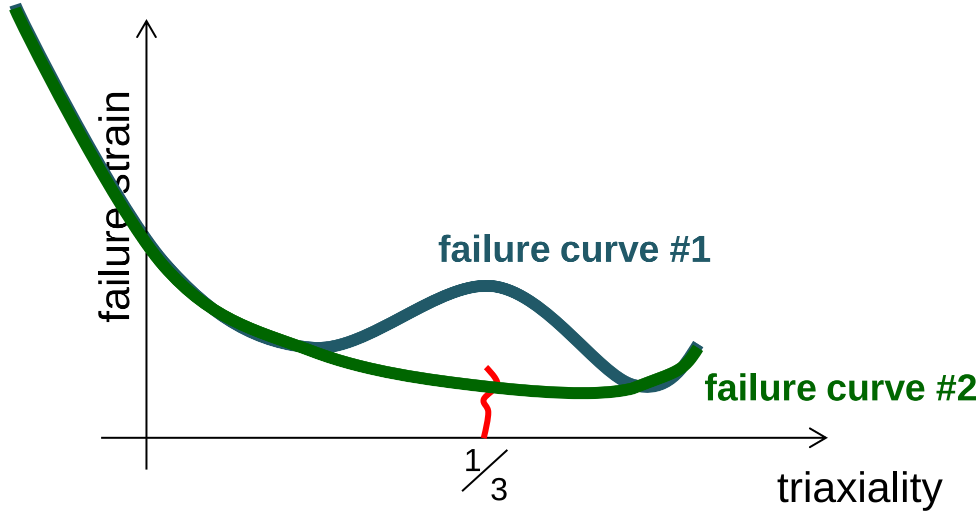
GISSMO failure parameters



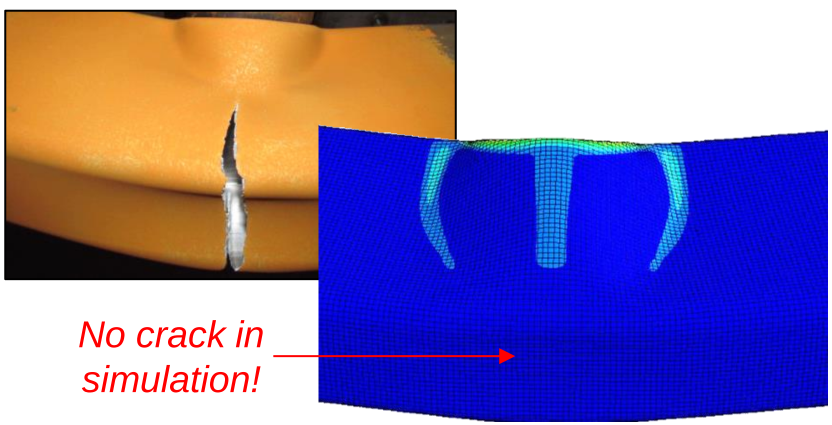
Example: Aluminum extrusion

Simulation of a three-point-bending experiment (*MAT_024+GISSMO)



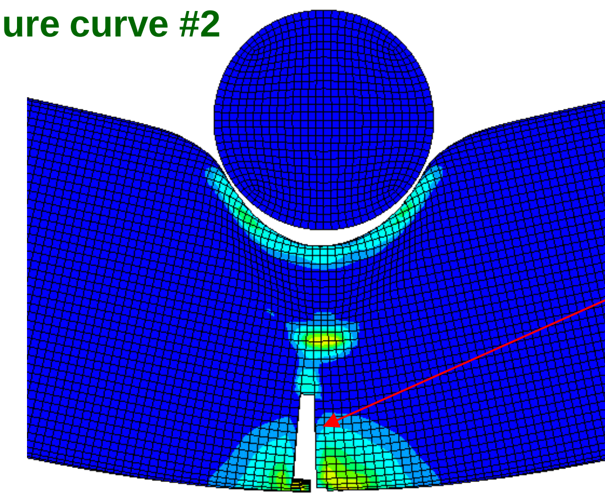


failure curve #1



No crack in simulation!

failure curve #2

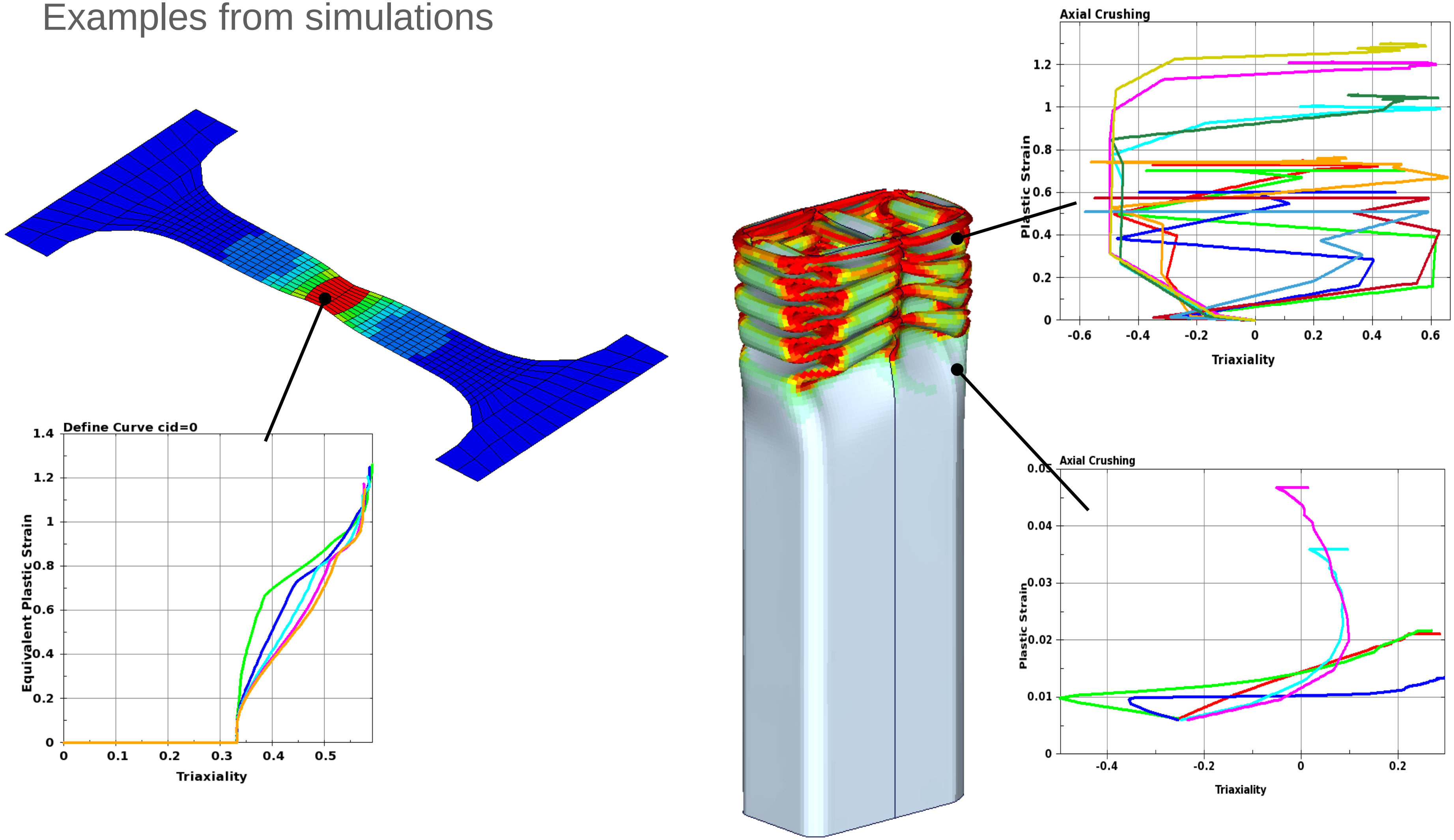


Crack can be reproduced

Nonlinear strain paths

Non-proportional loading

Examples from simulations



Non-proportional loading

How to deal with that?

The accumulation of a failure variable (usually called “damage”) intrinsically accounts for the effect of non-proportional loading. This feature is available in GISSMO (nonlinear accumulation)

GISSMO

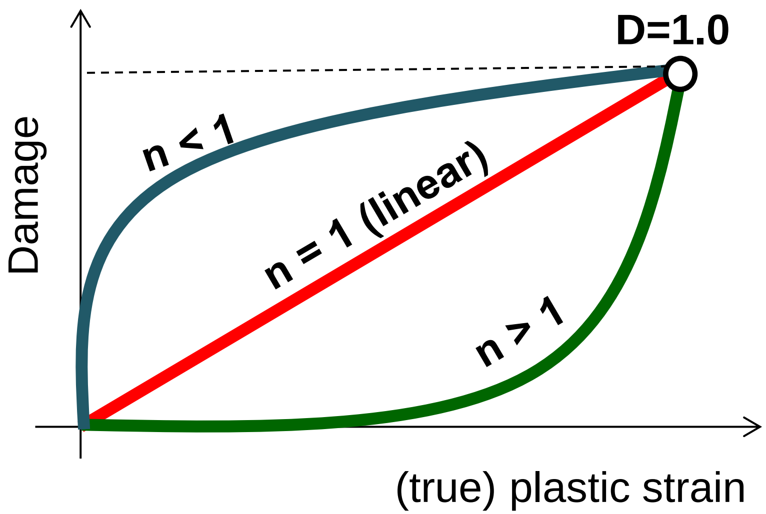
$$\Delta D = \frac{n}{\varepsilon_f(\eta)} D^{\left(1-\frac{1}{n}\right)} \Delta \varepsilon^p_{eq}$$

damage (***hisv #ND***)

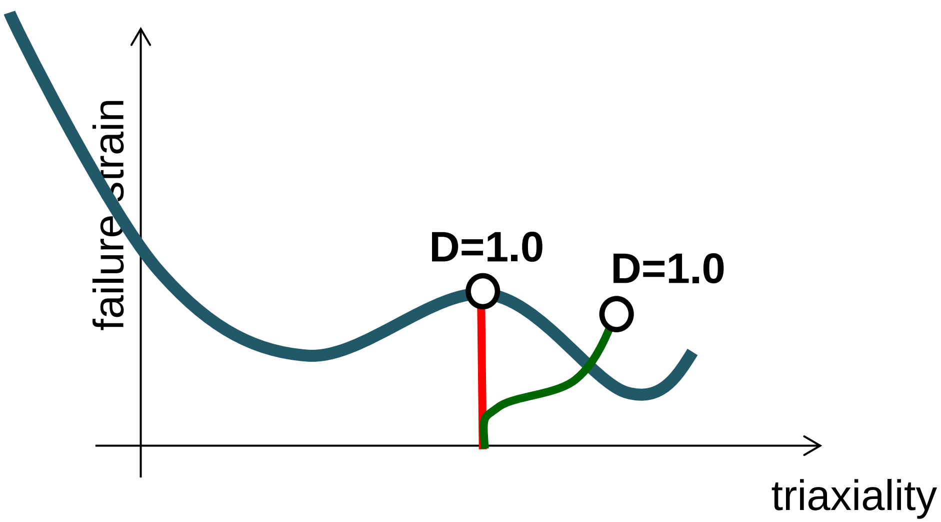
damage exponent

```
*MAT_ADD_EROSION
$      MID      EXCL    MXPRES     MNEPS    EFFEPS
        10
$   MNPRES     SIGP1     SIGVM     MXEPS     EPSSH

$     IDAM    DMGTYP     LCSDG     ECRIT    DMGEXP
         1         1       100      -200         2
$   SIZFLG     REFSZ     NAHSV     LCSRS      SHRF
                            14                 1.0
```

Damage accumulation



In GISSMO, the failure criterion is the damage, **not** the failure curve!

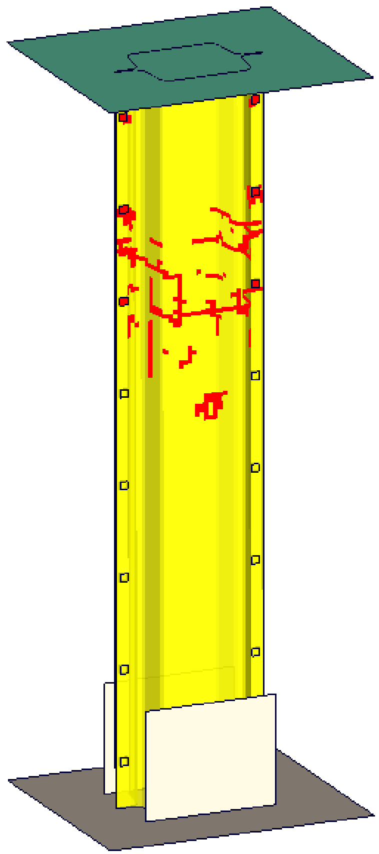


HINT: n=1.0 or n=2.0 might lead to faster computational times in large models

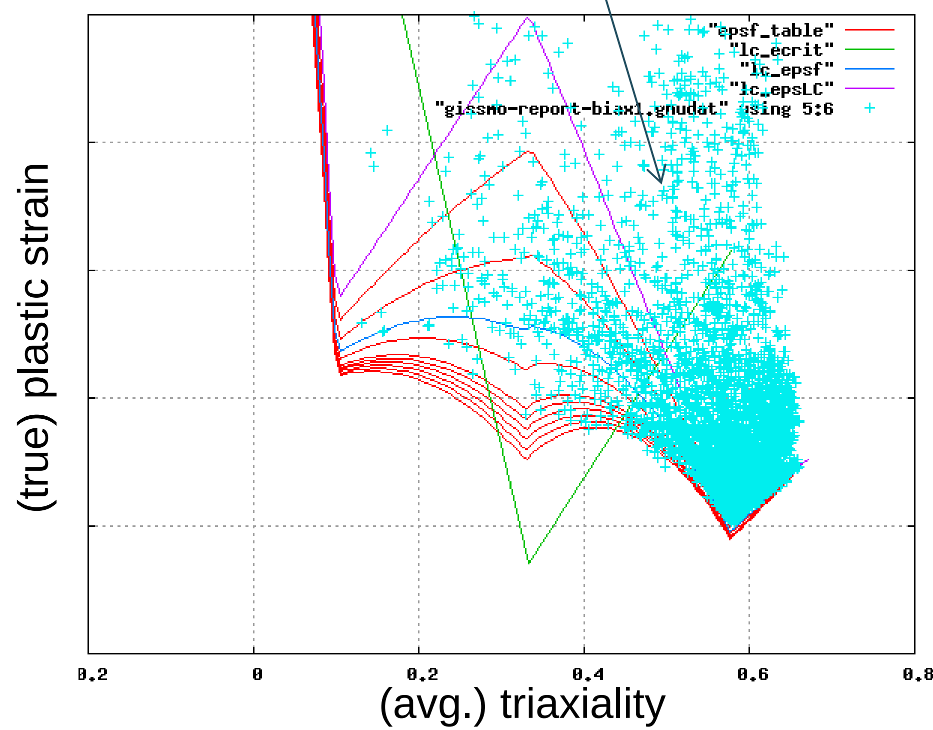
Example

Axial crushing of a side rail (*MAT_024 + GISSMO)

visualization of the failed elements



Failed integration points may lie above or under the failure curve



Non-proportional loading

Influence on failure

- Non-proportional loading happens all the time in crash load cases (although important, it's in comparison less significant in metal forming)

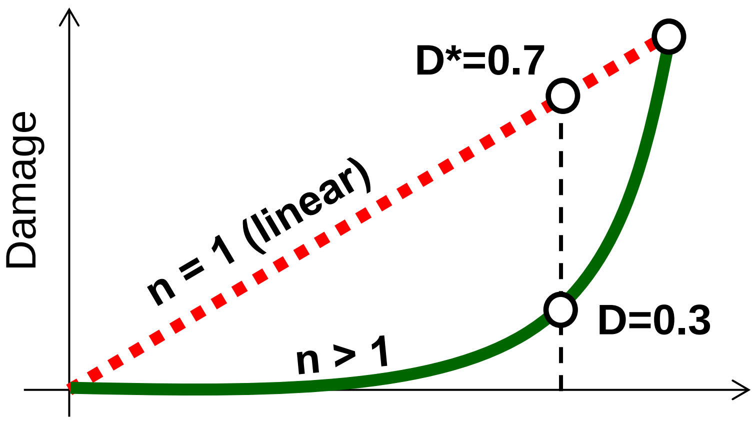
- Failure behavior is dependent on loading history:
  First tension and then shear generally leads to a different failure strain than **first shear and then tension**

- In GISSMO, an accumulated variable called "damage" is the failure criterion, **not the failure curve**! The failure curve is actually the criterion for **proportional loading**.

- **The user should evaluate the damage at the components of interest**

GISSMO output

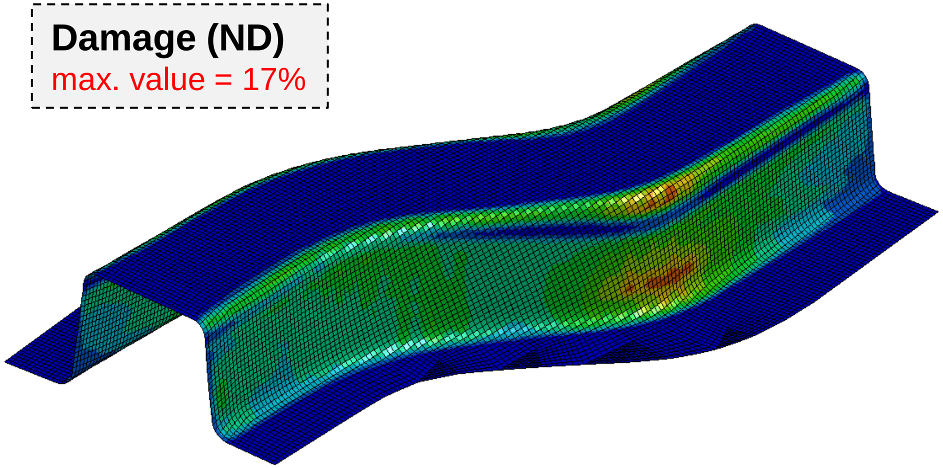
Evaluating the damage variable



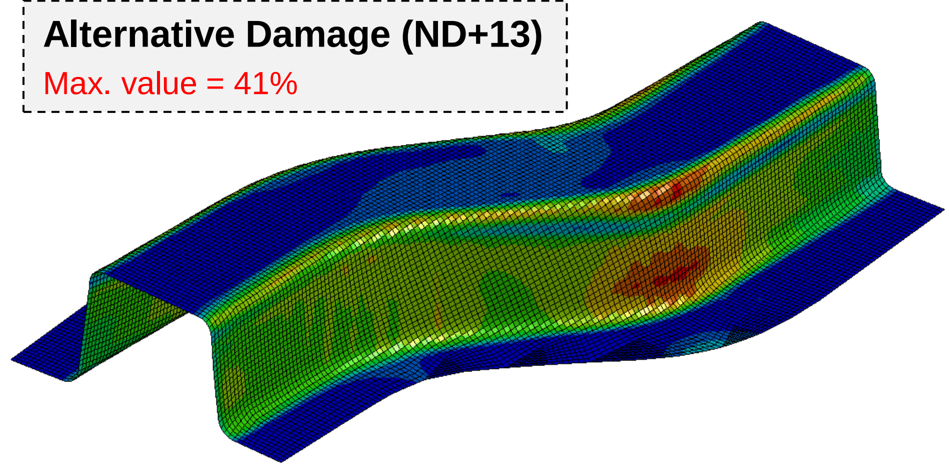
- **Damage:** ND
- **Alternative damage:** ND+13
  ($D_{alt} = D^{1/n}$)

The alternative damage can be quite helpful in evaluating results when the damage accumulation is nonlinear

Damage (ND)
max. value = 17%

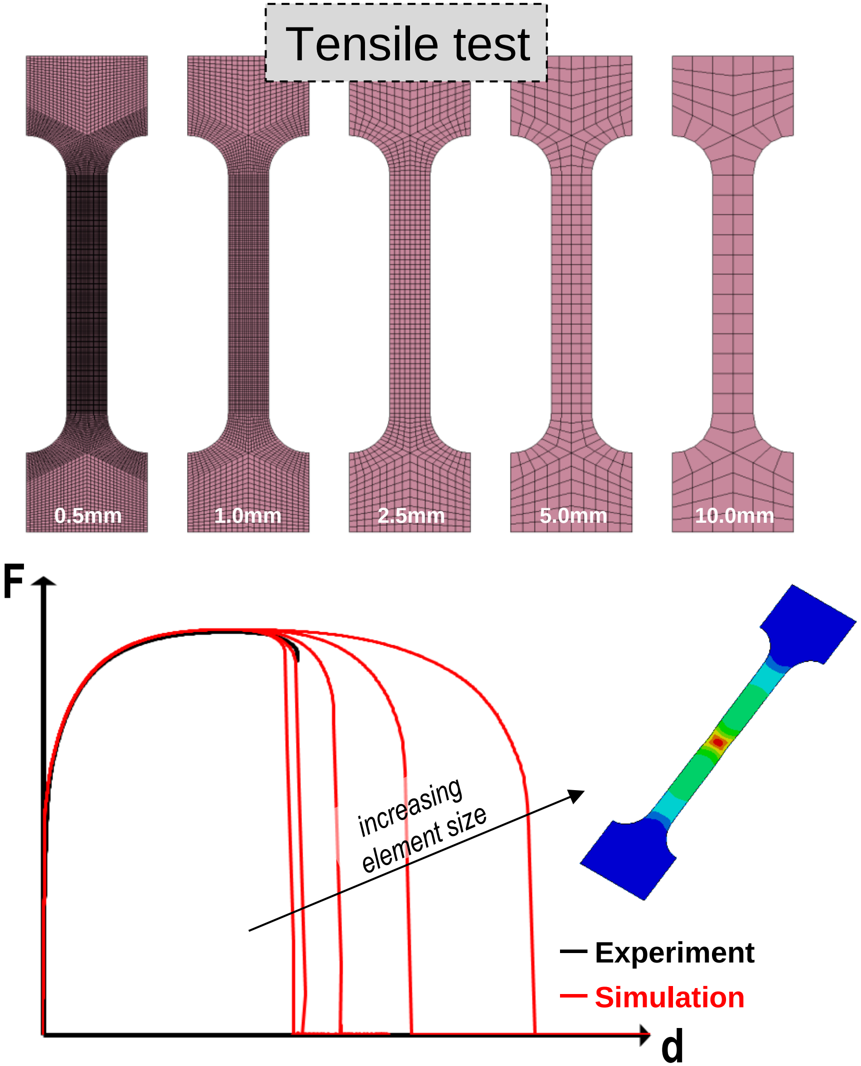


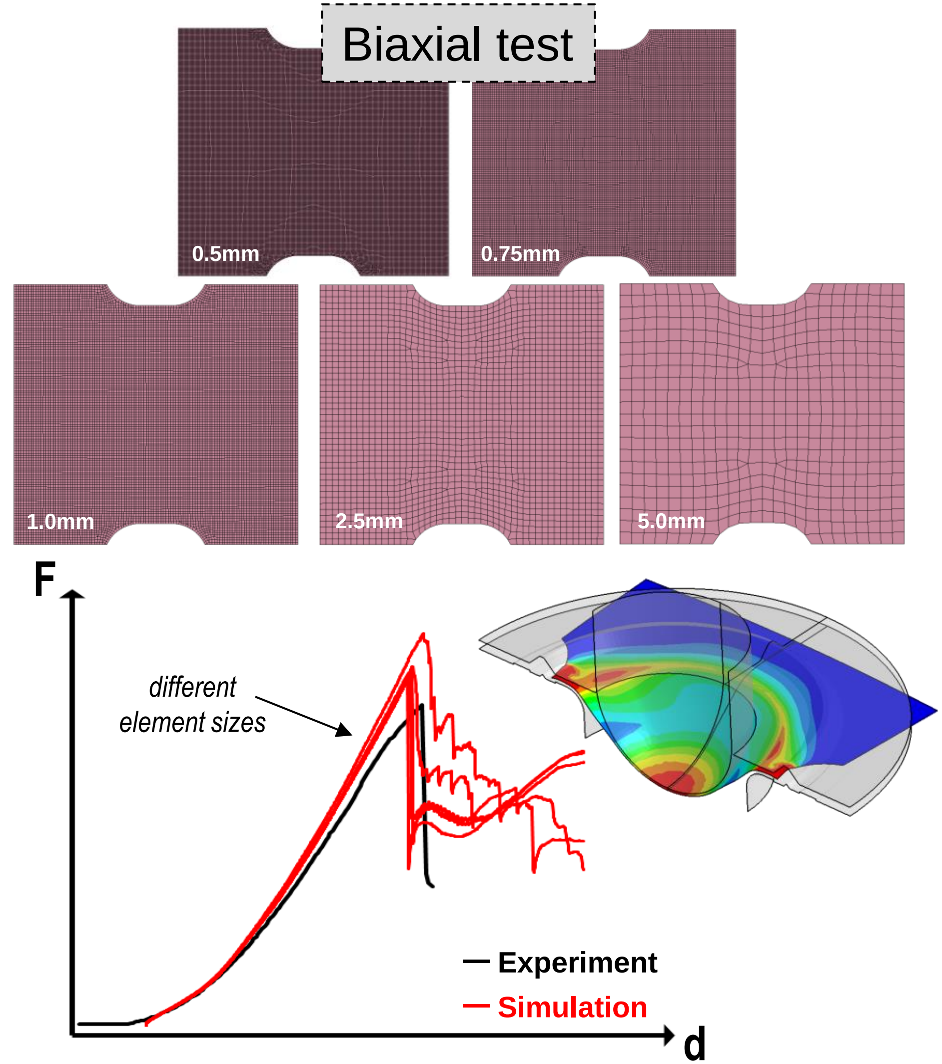
Alternative Damage (ND+13)
Max. value = 41%



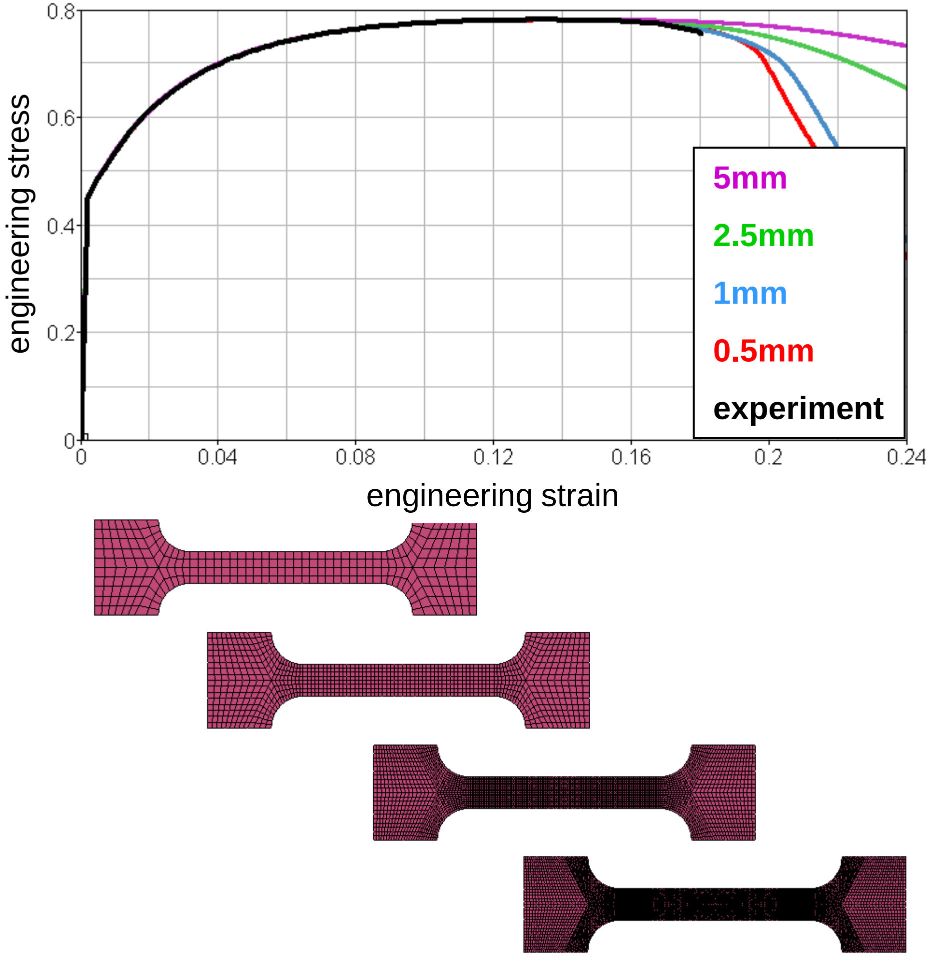
Mesh dependence

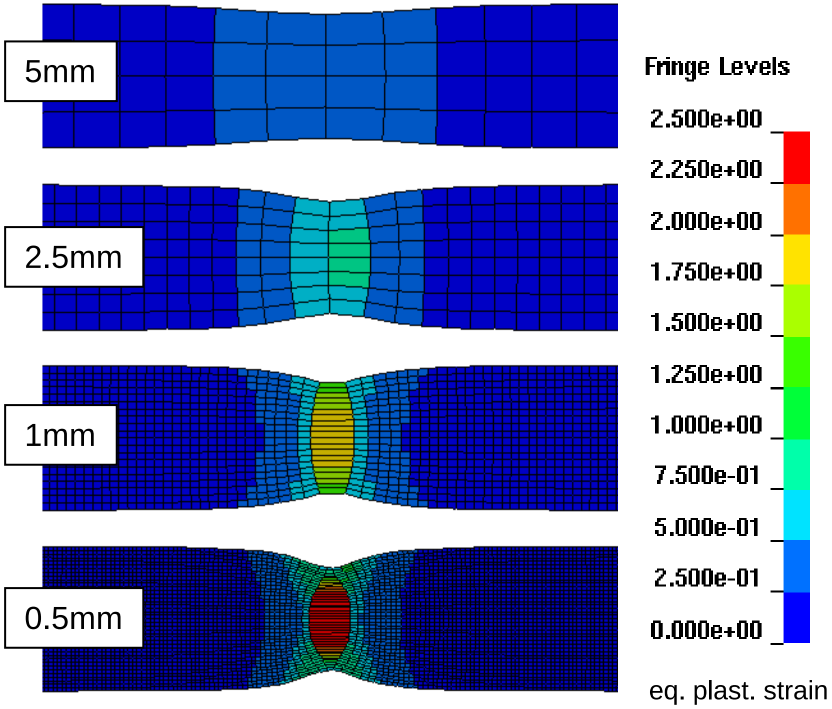
Effects of spurious mesh dependence





Effects of spurious mesh dependence

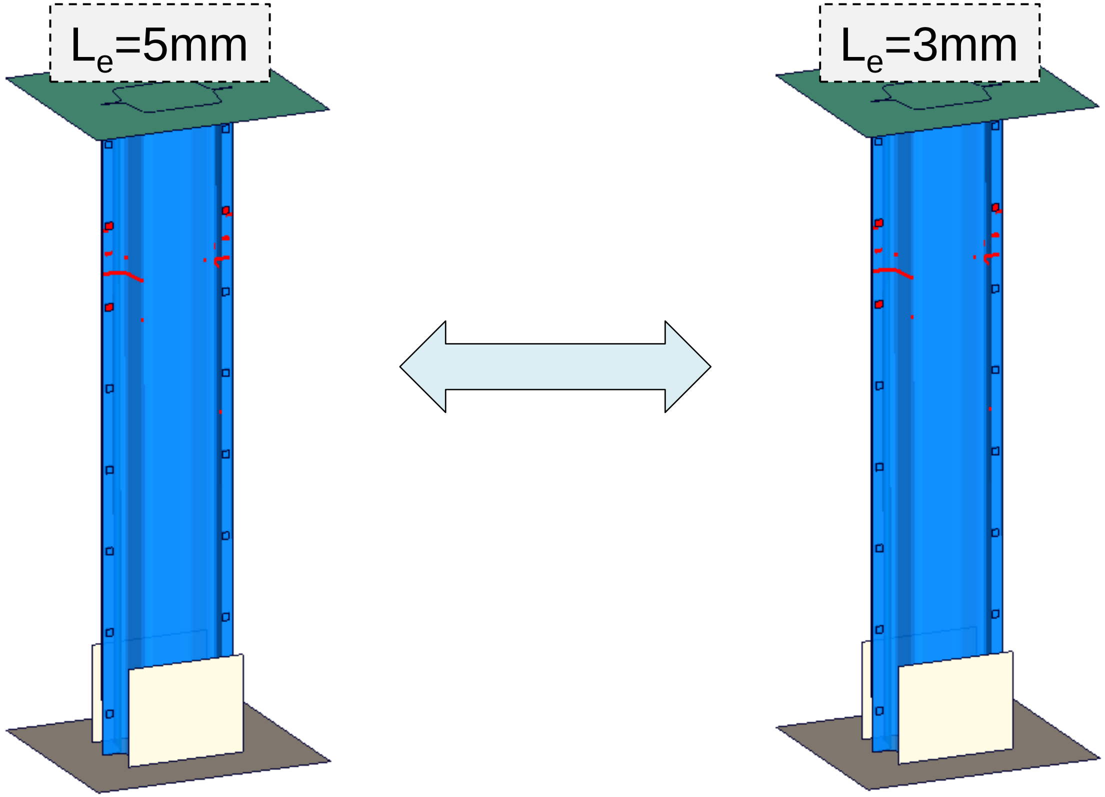




Local variation of the (true) plastic strain

Consequences for real life simulation

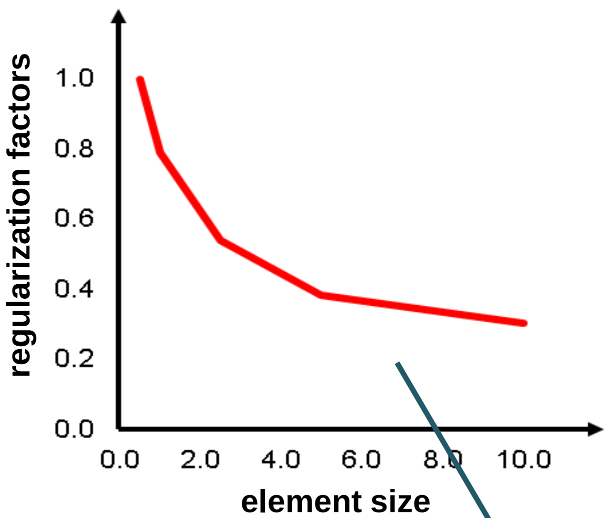
The local (true) plastic strain might be different if you run a simulation with 5mm or 3mm element size. It is difficult to say beforehand how significant this effect is for a particular application, but if spurious mesh dependence arises, then there is no mesh convergence.

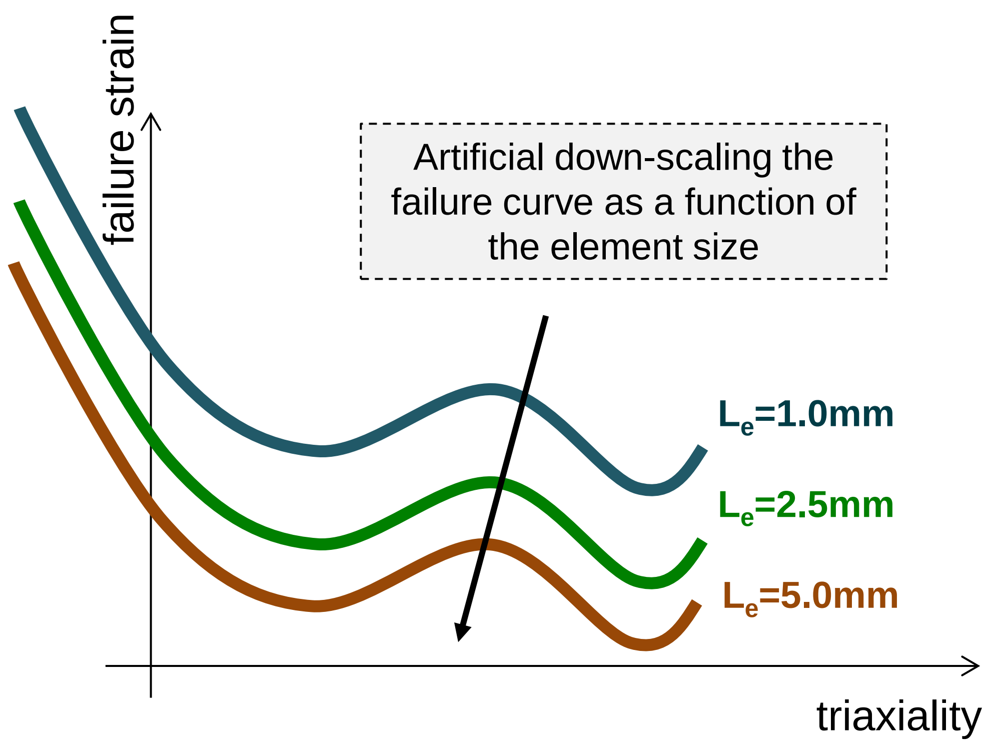


Effects of spurious mesh dependence

How we deal with that in GISSMO

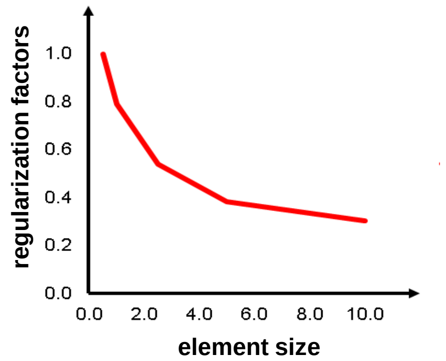
Both models allow the use of regularization factors (through a load curve defined with *DEFINE_CURVE) that modify the failure curve as a function of the element size

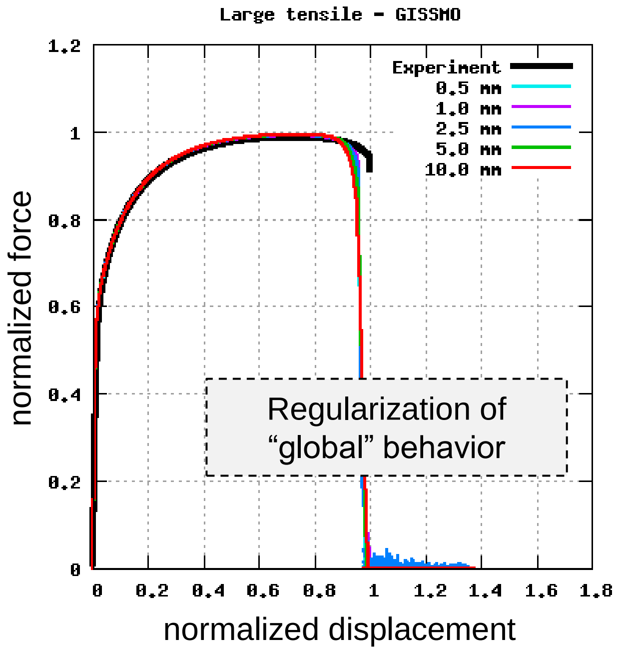


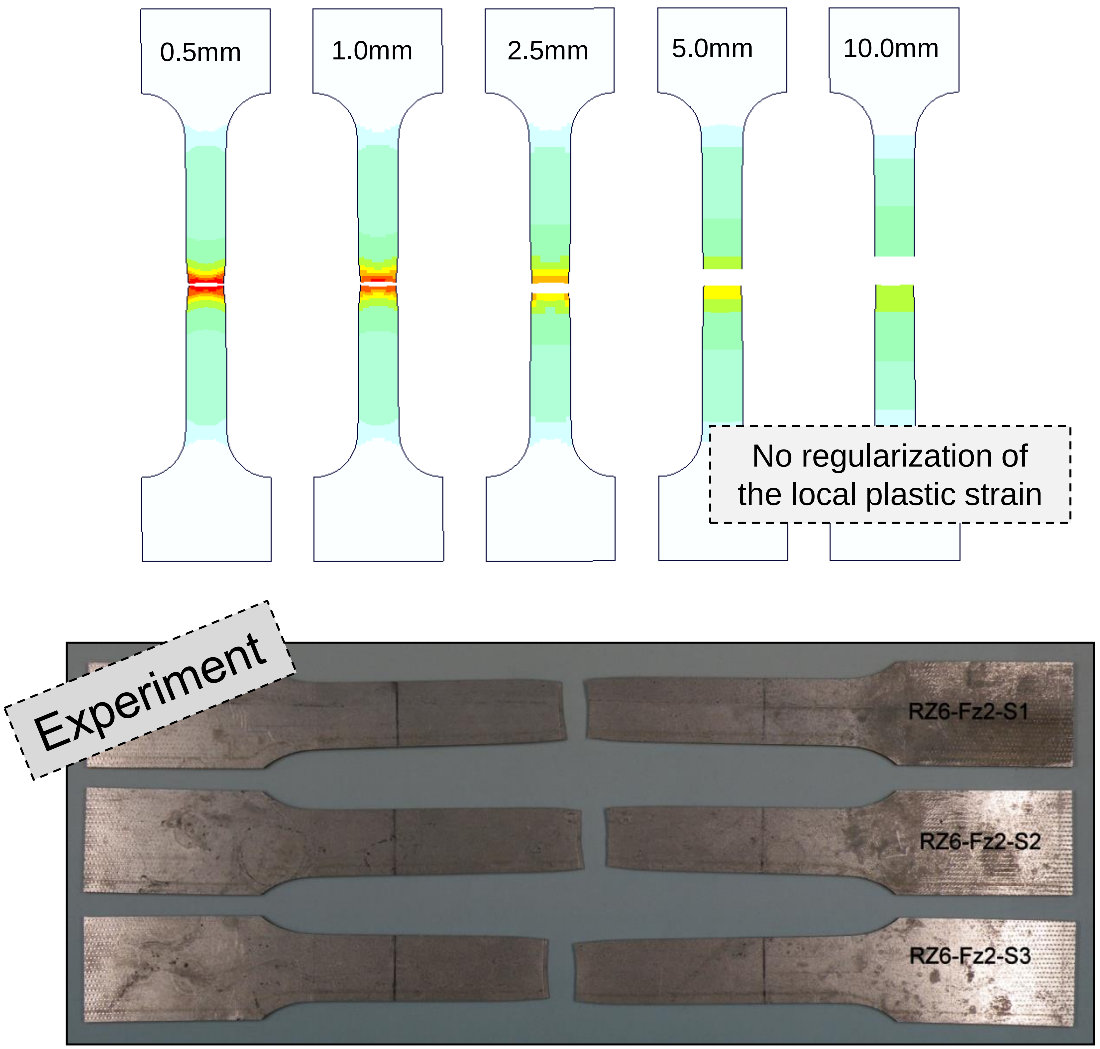


MNEPS	EFFEPS	VOLEPS	NUMFIP	NCS
MXEPS	EPSSH	SIGTH	IMPULSE	FAILTM
ECRIT	DMGEXP	DCRIT	FADEXP	LCREGD
-200	2		2.5	400
LCSRS	SHRF	BIAXF		
	1.0	0.0		

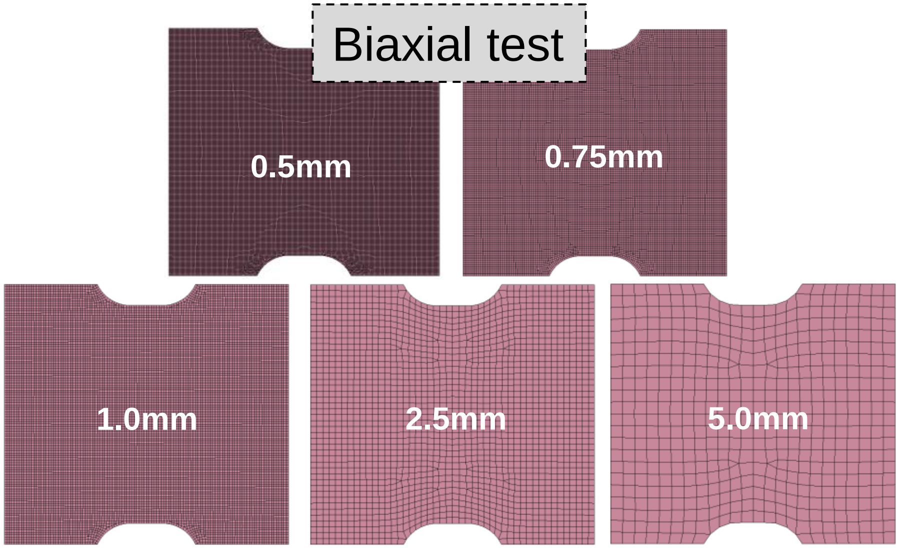
Regularization on the tensile test (GISSMO)



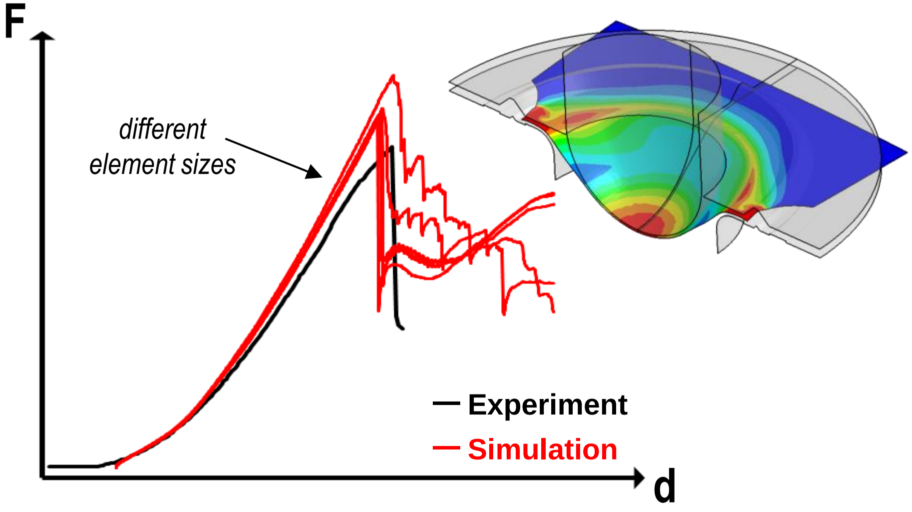




What about other loading types?



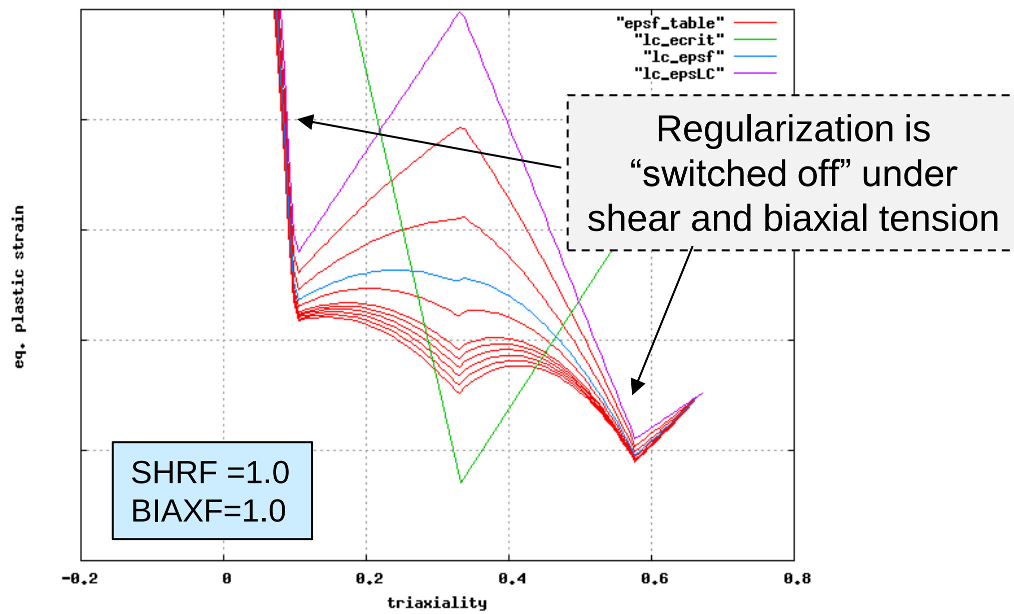
No spurious mesh dependence under biaxial loading!



Effects of spurious mesh dependence

GISSMO only – triaxiality-dependent regularization

```
$===============================================================================
*MAT_ADD_EROSION
$      MID      EXCL    MXPRES     MNEPS    EFFEPS    VOLEPS    NUMFIP       NCS
         1
$   MNPRES     SIGP1     SIGVM     MXEPS     EPSSH     SIGTH   IMPULSE    FAILTM

$     IDAM    DMGTYP     LCSDG     ECRIT    DMGEXP     DCRIT    FADEXP    LCREGD
       1.0         1       100      -200         2               2.5       400
$   SIZFLG     REFSZ     NAHSV     LCSRS      SHRF     BIAXF
                            14                  1.0       1.0
$===============================================================================
```

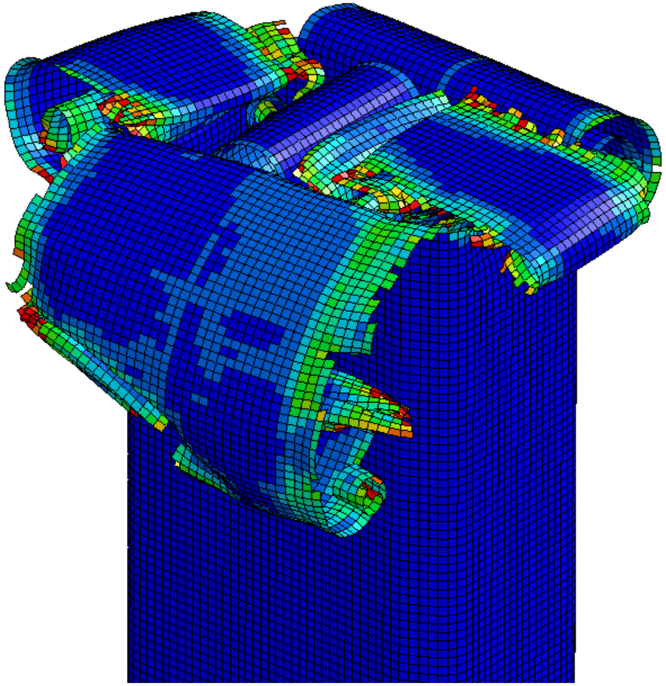


Application – Aluminum extrusion

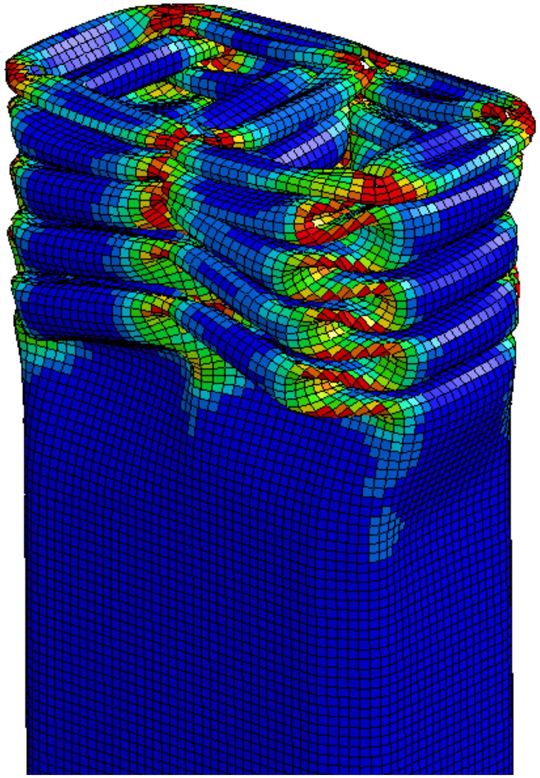
(Possible) effect of flags SHRF and BIAXF

Mesh size by calibration: **0.5mm**
Mesh size of component: **3.0mm**

SHRF =0.0
BIAXF=0.0



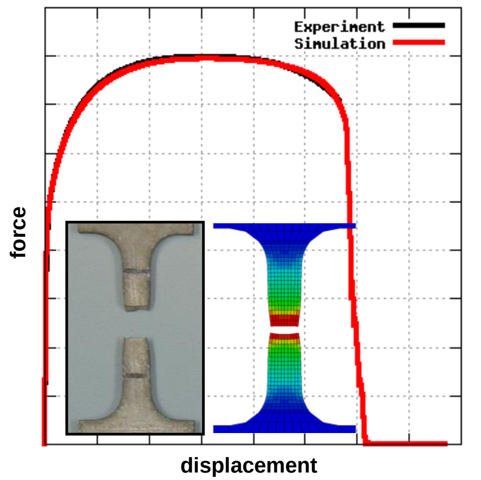
SHRF =1.0
BIAXF=0.0



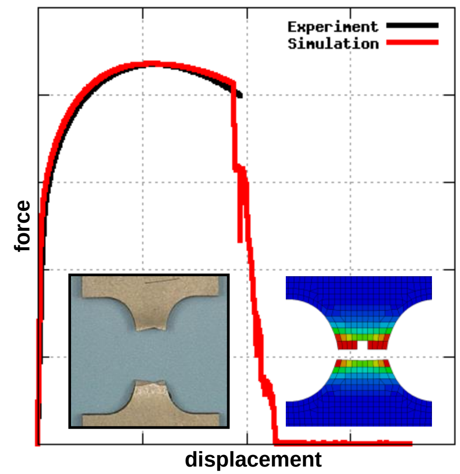
Material card calibration

Example of a dual-phase steel

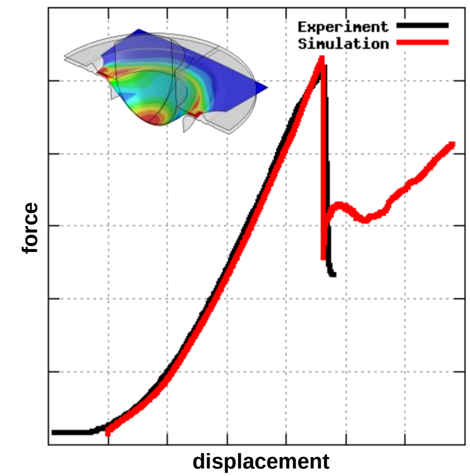
Small tensile test



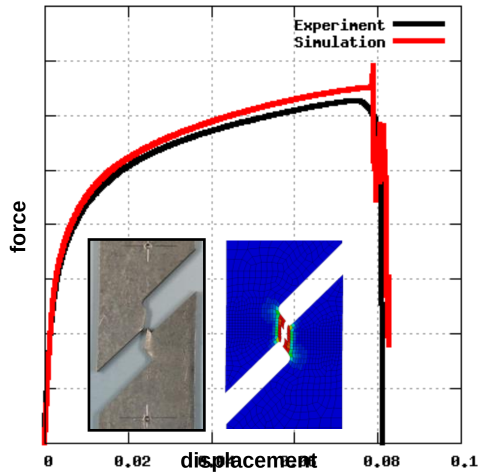
Notched specimen



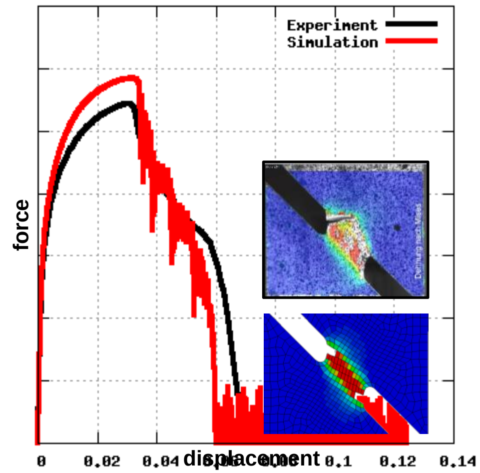
Biaxial test



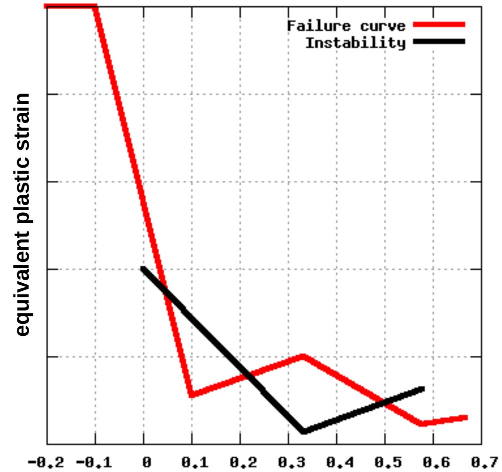
Shear test 0°



Shear test 45°



GISSMO curves



We are coming to the end…

I’m convinced!

Where to get more information?

- From previous conference papers at www.dynalook.com

- Further literature:
  - F. Neukam. *Lokalisierung und Versagen von Blechstrukturen*. PhD Thesis, 2018
  - Andrade, Feucht, Haufe, Neukamm. *An incremental stress state dependent damage model for ductile failure prediction*. Int Journal of Fracture, 2016.

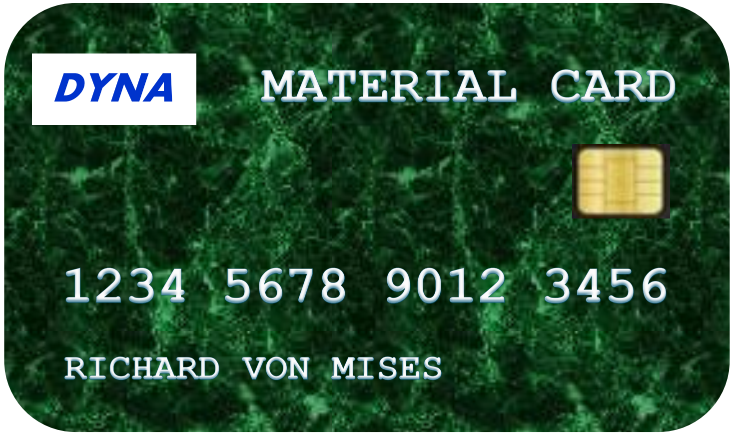
- Presentations in this conference, e.g.:
  Koch, Andrade, Haufe, DuBois, Feucht. *On the Development of a new Generalized Orthotropic Damage and Fracture Model*.

- Upcoming training classes:
  “**Material Failure”**, Stuttgart, Nov 15th 2018

I need a material card!

www.dynamore.de
DYNAmore GmbH
Industriestr. 2
70565 Stuttgart

Δt



Thank you for your attention!