Introduction to Material Characterization

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  - Isotropic (*MAT_024)
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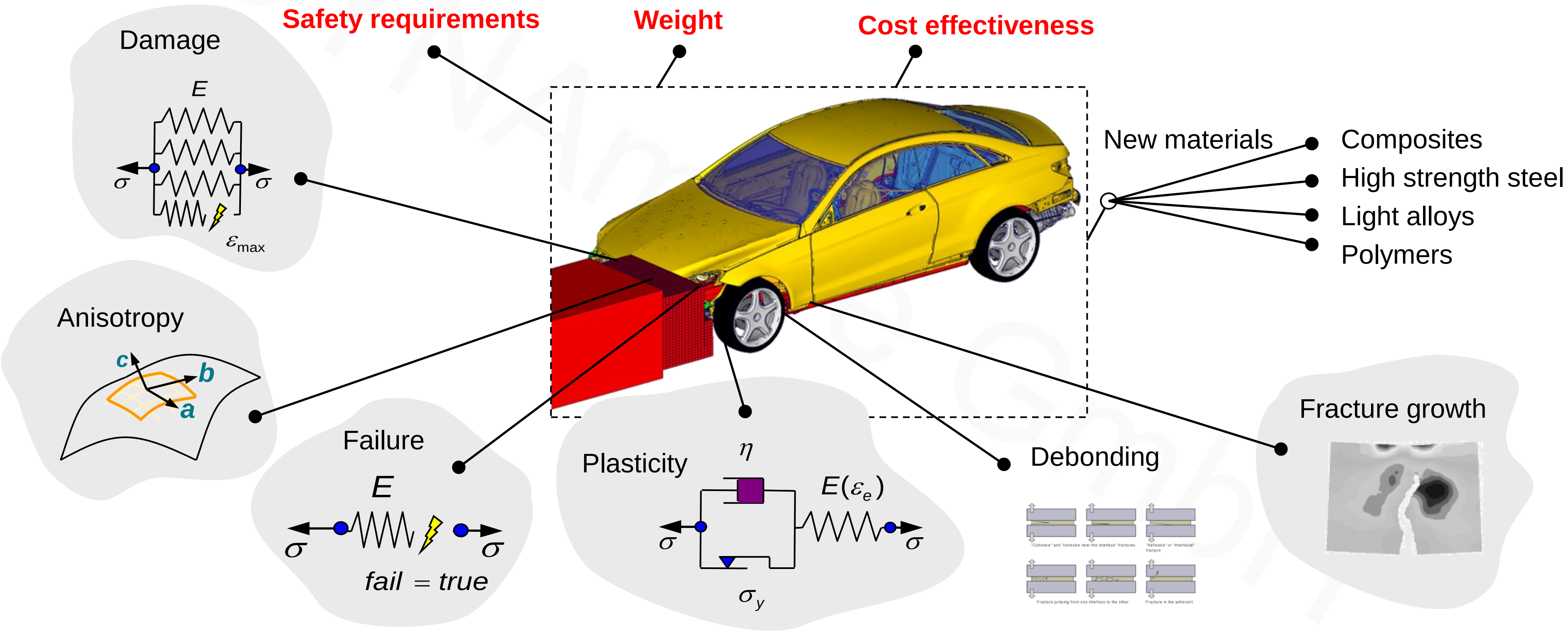
  - SAMP-1
  - SAMP-Light

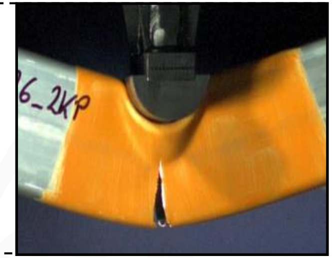
Motivation

Challenges in the automotive industry for efficient lightweight structures



Some typical materials and observed phenomena

Metals
- linear elasticity
- isochoric plasticity
- isotropy/anisotropy
- strain rate dependence
- damage/softening

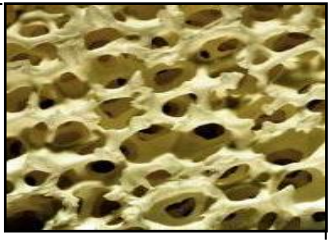


Quasi-brittle
- linear/non-linear elasticity
- anisotropy
- damage/softening

Plastics
- viscous elasticity
- non-isochoric plasticity
- strain rate dependence
- damage/softening

Rubbers
- hyperelasticity
- viscous elasticity
- nearly incompressible
- *Mullin*‘s effect

Foams
- viscous elasticity
- low stiffness
- low strength
- low *Poisson*‘s ratio



Composites
- non-linear elasticity
- anisotropy
- strain rate dependence
- heterogeneous structure
- damage

Constitutive law

The relation between stress and strain

- the constitutive law defines the response of a given material to external loads
- within the framework of continuum mechanics, the constitutive law is the relation between the strains and stresses in a material point, which in the general three-dimensional case can be expressed as

$$\boldsymbol{\sigma} = \mathbb{D} : \boldsymbol{\varepsilon} \qquad \text{where} \qquad \boldsymbol{\sigma} = \begin{bmatrix} \sigma_{11} & \sigma_{12} & \sigma_{13} \\ \sigma_{21} & \sigma_{22} & \sigma_{23} \\ \sigma_{31} & \sigma_{32} & \sigma_{33} \end{bmatrix}, \quad \boldsymbol{\varepsilon} = \begin{bmatrix} \varepsilon_{11} & \varepsilon_{12} & \varepsilon_{13} \\ \varepsilon_{21} & \varepsilon_{22} & \varepsilon_{23} \\ \varepsilon_{31} & \varepsilon_{32} & \varepsilon_{33} \end{bmatrix}$$

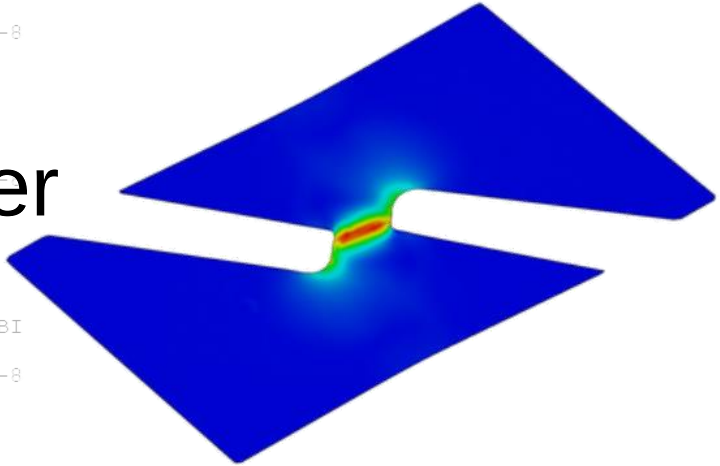
Constitutive operator

- for a uniaxial stress state and an elastic material with Young's modulus E, the equation above can be reduced to

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

- for most materials, the constitutive law is nonlinear and a function of other variables such as plastic strain, strain rate, temperature, etc.
- when you define the material parameters (e.g., hardening curve) for a material model in LS-DYNA, you are actually indirectly prescribing the constitutive law

DYNAmore
Material Competence Center



Our MCC offers you calibrated material cards and the best possible model techniques

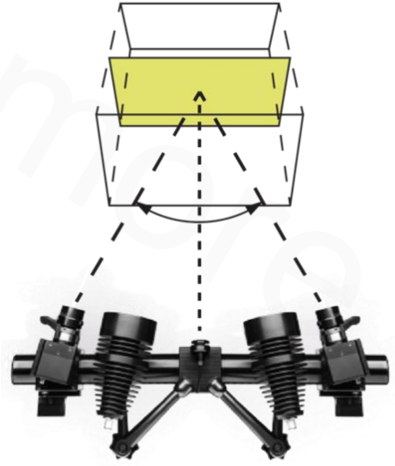
- Metallic materials up to failure prediction (GISSMO, eGISSMO, DIEM, etc.)
- Polymers and composites (non-reinforced, short fiber-reinforced, continuous fiber-reinforced)
- Elastomers
- Glass (float, thermally or chemically tempered) and ceramic materials
- Connection technology (punctiform, linear, flat)

On site material testing
Testing equipment

Universal testing machine for quasi-static tests (<100kN)

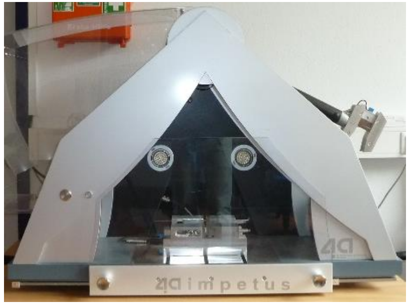
- Tension
- Compression
- Shear
- Biaxial
- Bending
- Cyclic

Optical measurement (DIC)



- Measurement of the strain field during the test
- Evaluation of the engineering strain in post-processing

4a Pendulum dynamic tests (<4.3 m/s)



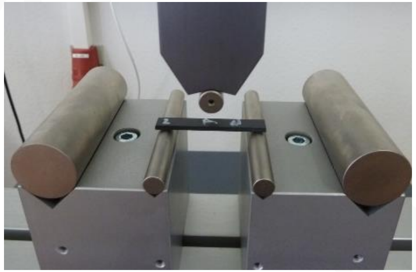
- Bending (plastics, composites)
- Compression (foam)

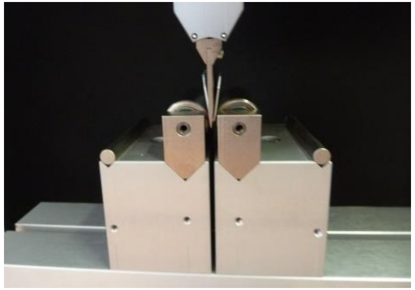
On site material testing

Testing equipment

Quasi-static tension

Quasi-static bending





Quasi-static compression

Quasi-static biax

Material modeling in LS-DYNA

A selection of LS-DYNA material models based on von Mises plasticity

- *MAT_PLASTIC_KINEMATIC (#003)
  Von Mises based model with bilinear isotropic and kinematic hardening

- *MAT_PIECEWISE_LINEAR_PLASTICITY (#024)
  Von Mises based elasto-plastic material model with isotropic hardening and strain rate effects;
  One of LS-DYNA's most used material models

*MAT_003

*MAT_PLASTIC_KINEMATIC

- bilinear elasto-plastic model
- kinematic, isotropic or mixed hardening
- Strain rate dependence
- element deletion possible
- very simple and fast material model

```
*MAT_PLASTIC_KINEMATIC
$      MID        RO         E        PR      SIGY      ETAN      BETA
         5    7.86E-6     210.0      0.33     310.0      50.0       0.5
$      SRC       SRP        FS        VP
       5.0
```

Please use this model instead of *MAT_ELASTIC!

- SIGY: Yield stress
- ETAN: Tangent modulus
- BETA: Hardening parameter (isotropic/kinematic hardening)
- SRC, SRP: Strain rate parameter C and P (*Cowper Symonds*)
- FS: Failure strain
- VP: Formulation for rate effects

*MAT_024

Keyword definition

```
*MAT_PIECEWISE_LINEAR_PLASTICITY
$      MID        RO         E        PR      SIGY      ETAN      FAIL      TDEL
         1  7.85E-06     210.0       0.3
$        C         P      LCSS      LCSR        VP
                           100                   1
$     EPS1      EPS2      EPS3      EPS4      EPS5      EPS6      EPS7      EPS8

$      ES1       ES2       ES3       ES4       ES5       ES6       ES7       ES8

```

- MID: Material identification
- RO: Density
- E: Young's modulus
- PR: Elastic Poisson's ratio
- SIGY: Yield stress (in case of linear hardening)
- ETAN: Hardening modulus (in case of linear hardening)

*MAT_024

Keyword definition

```
*MAT_PIECEWISE_LINEAR_PLASTICITY
$      MID        RO         E        PR      SIGY      ETAN      FAIL      TDEL
         1  7.85E-06     210.0       0.3
$        C         P      LCSS      LCSR        VP
                           100                   1
$     EPS1      EPS2      EPS3      EPS4      EPS5      EPS6      EPS7      EPS8

$      ES1       ES2       ES3       ES4       ES5       ES6       ES7       ES8

```

- EPS1-EPS8: Effective plastic strain values (optional, supersedes SIGY and ETAN)
- ES1-ES8: Corresponding yield stress values to eps1-eps8

*MAT_024

Keyword definition

```
*MAT_PIECEWISE_LINEAR_PLASTICITY
$      MID        RO         E        PR      SIGY      ETAN      FAIL      TDEL
         1  7.85E-06     210.0       0.3
$        C         P      LCSS      LCSR        VP
                           100                   1
$     EPS1      EPS2      EPS3      EPS4      EPS5      EPS6      EPS7      EPS8

$      ES1       ES2       ES3       ES4       ES5       ES6       ES7       ES8

```

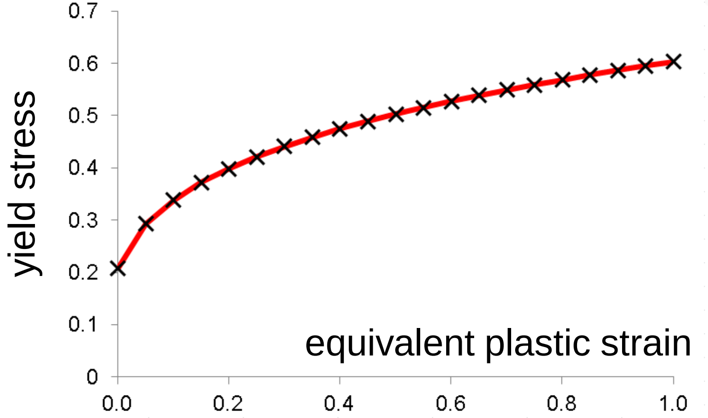
- FAIL: Failure flag
- TDEL: Minimum time step size for automatic element deletion
- C, P: Strain rate parameters C and P for Cowper-Symonds strain rate model
- LCSS: Load curve or table ID (yield curve, supersedes SIGY and ETAN)
- LCSR: Load curve ID defining strain rate effects on yield stress
- VP: Formulation for rate effects (1 for viscoplastic formulation)

*MAT_024

Working with load curves

Defining a hardening curve in *MAT_024

```
*MAT_PIECEWISE_LINEAR_PLASTICITY
$       MID        RO         E        PR
          1  7.85E-06     210.0       0.3
$         C         P      LCSS      LCSR
                            100
```




```
*DEFINE_CURVE
$     LCID      SIDR       SFA       SFO
       100         0     1.000     1.000
$                 A1                  O1
                0.00               0.208
                0.05               0.292
                0.10               0.338
                0.15               0.371
                0.20               0.398
                0.25               0.421
                0.30               0.441
                0.35               0.458
                0.40               0.474
                0.45               0.489
                0.50               0.502
                0.55               0.515
                0.60               0.527
                0.65               0.538
                0.70               0.549
                0.75               0.559
                0.80               0.568
                0.85               0.577
                0.90               0.586
                0.95               0.595
                1.00               0.603
```

*MAT_024

Some general remarks on *MAT_PIECEWISE_LINEAR_PLASTICITY

- “Work horse” in crash simulations
- Available for **shells** and **solids**
- **Load curve based input** makes this material model very **flexible**
- **No kinematic hardening** is considered
  (use *MAT_225 instead)
- The points between the rate-dependent curves are interpolated, either **linearly or logarithmically**

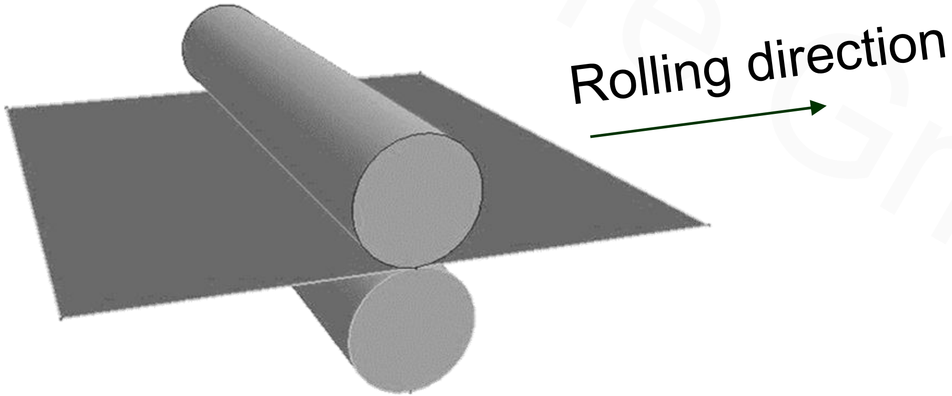
- The load curves are **extrapolated** in the direction of plastic strain by using the **last slope** of the curve
- **No extrapolation** is done in the direction of **strain rate**, i.e., the lowest (highest) curve defined is used if the current strain rate lies under (above) the input curves
- **Negative** and **zero slopes** are permitted but should generally **be avoided**

Anisotropic Plasticity

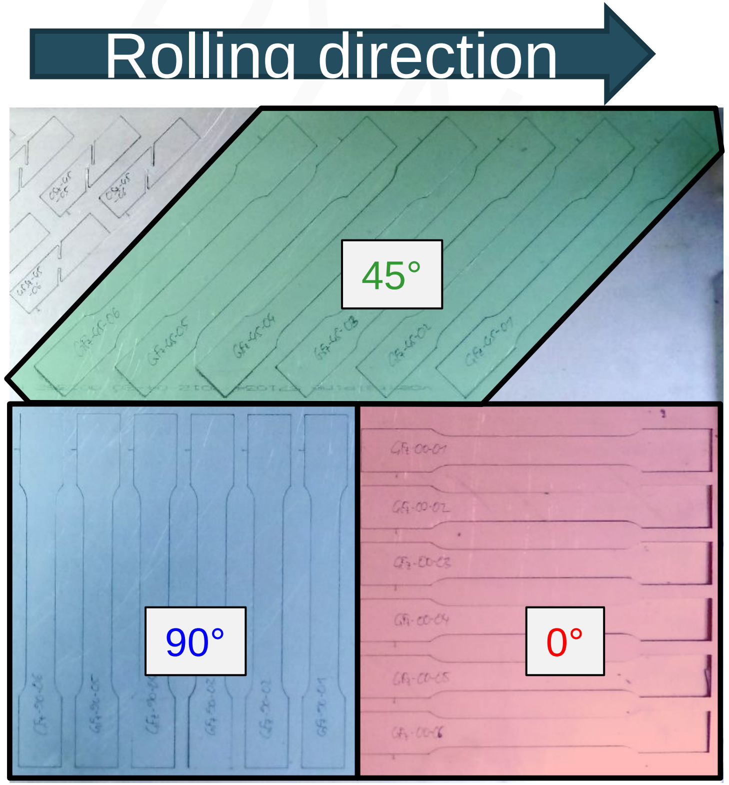
Anisotropy of metal sheets

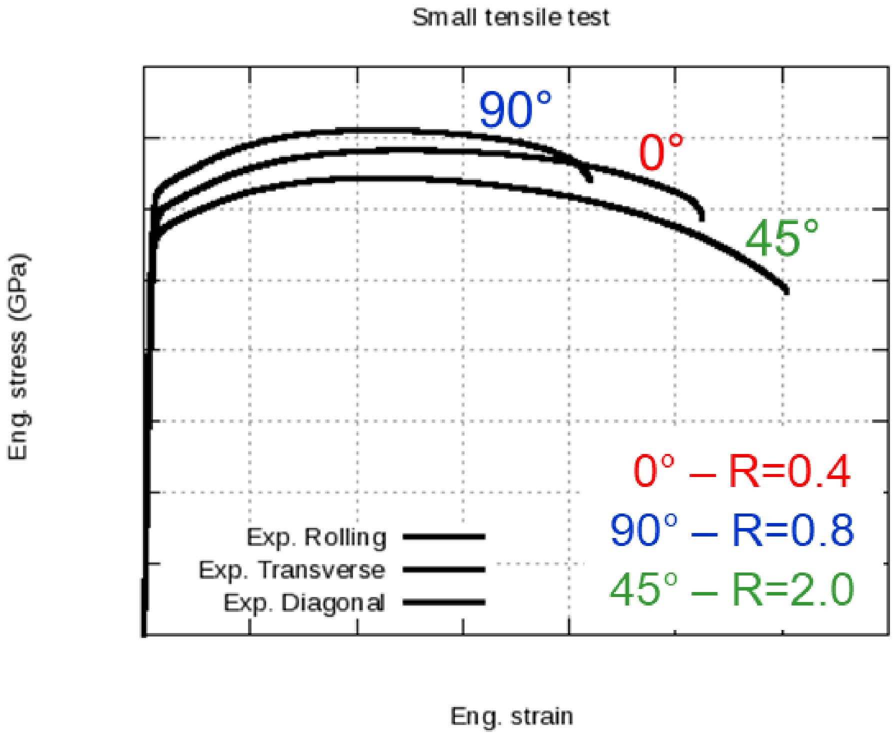
Deformation induced anisotropy

- Metals may show anisotropic behavior due to previous loading and irreversible deformations (classical phenomenon of plasticity)
- Most prominent examples are forming and stamping processes where major and minor plastic strains develop in areas where high deformation occurs
- Also pre-stretching of steel parts (rods, tubes, etc.) leads to anisotropy
- Anisotropy is usually characterized by the *Lankford parameter*



Anisotropy of metal sheets



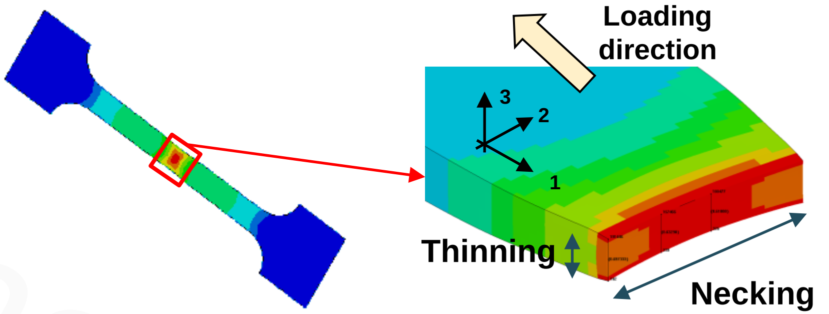


Anisotropy of metal sheets

The Lankford parameter (R-value)

- Definition

$$R = \frac{\dot{\varepsilon}_{22}^{p}}{\dot{\varepsilon}_{33}^{p}} = -\frac{\dot{\varepsilon}_{22}^{p}}{\dot{\varepsilon}_{11}^{p} + \dot{\varepsilon}_{22}^{p}}$$



- Interpretation

$R = 1.0 \rightarrow \dot{\varepsilon}_{22}^{p} = \dot{\varepsilon}_{33}^{p}$ ⟶ Necking and thinning are comparable

$R < 1.0 \rightarrow \dot{\varepsilon}_{22}^{p} < \dot{\varepsilon}_{33}^{p}$ ⟶ Less necking, **More thinning**

$R > 1.0 \rightarrow \dot{\varepsilon}_{22}^{p} > \dot{\varepsilon}_{33}^{p}$ ⟶ **More necking**, Less thinning

$R_{00} = R_{45} = R_{90} = 1$ ⟶ Isotropic material

$R_{00} = R_{45} = R_{90} \neq 1$ ⟶ Anisotropic behavior in thickness direction

$R_{00} \neq R_{45} \neq R_{90}$ ⟶ *Anisotropic behavior in the plane and in thickness direction*

Material modeling in LS-DYNA

A selection of anisotropic elasto-plastic models

- *MAT_3-PARAMETER_BARLAT (#036)
  Anisotropic plasticity model based on Barlat and Lian (1989)
- *MAT_TRANSVERSELY_ANISOTROPIC_ELASTIC_PLASTIC (#037)
  Elasto-plastic model for transverse anisotropy
- *MAT_ ORTHO_ELASTIC_PLASTIC (#108)
  Orthotropic material model in both elasticity and plasticity
- *MAT_HILL_3R (#122)
  Hill's 1948 planar anisotropic material model with 3 R-values
- *MAT_BARLAT_YLD2000 (#133)
  Elasto-plastic anisotropic plasticity model based on Barlat 2000
- *MAT_WTM_STM (#135)
  Anisotropic elasto-plastic model based on the work of Aretz et. al (2004)
- *MAT_CORUS_VEGTER (#136)
  Anisotropic yield surface construction based on the interpolation by second-order Bezier curves

Training:
Modeling Metallic Materials

*MAT_036

*MAT_3-PARAMETER_BARLAT

```
*MAT_3-PARAMETER_BARLAT
$      MID        RO         E        PR        HR        P1        P2      ITER
         1  7.85E-06     210.0       0.3         3
$        M    R00/AB    R45/CB    R90/HB      LCID        E0       SPI        P3
       8.0       0.8       0.9       1.1       100
$     AOPT         C         P     VLCID                  PB   NLP/HTA       HTB
         2
$                                     A1        A2        A3       HTC       HTD
                                    1.00       0.0       0.0
$       V1        V2        V3        D1        D2        D3      BETA
                                     0.0       0.0       0.0
```

- MID: Material identification
- RO: Density
- E: Young's modulus
- PR: Elastic Poisson's ratio
- HR: Hardening rule
- P1: Material parameter #1
- P2: Material parameter #2
- ITER: Iteration flag
- M: Exponent for yield surface
- AB: Parameter 'a' of yield function
- CB: Parameter 'c' of yield function
- HB: Parameter 'h' of yield function
- R00: R-Value in 0° degree direction
- R45: R-Value in 45° degree direction
- R90: R-Value in 90° degree direction
- LCID: Load curve or table if HR=3

*MAT_036 + HR=3

The original Barlat & Lian formulation (1989)

```
*MAT_3-PARAMETER_BARLAT
$       MID        RO         E        PR        HR        P1        P2      ITER
          1  2.70E-06      70.0       0.3         3
$         M       R00       R45       R90      LCID        E0       SPI        P3
        8.0       0.8       1.0       0.9       100
$...
```

???

$$\Phi(\boldsymbol{\sigma}) = \frac{1}{2}\left(a\,|K_1 + K_2|^m + a\,|K_1 - K_2|^m + c\,|2K_2|^m\right) - \sigma_y^m = 0$$

$R_{00} = 0.8$

$R_{45} = 1.0$

$R_{90} = 0.9$

σ_y, m

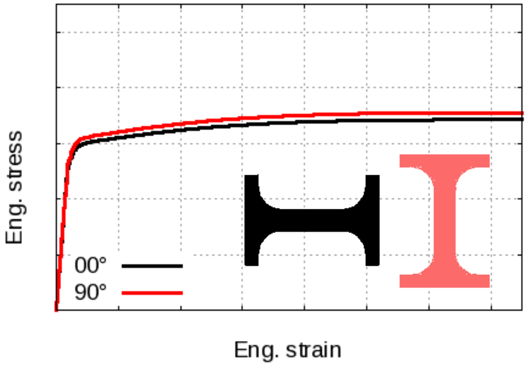
internal fitting

$a = \dots$

$c = \dots$

$h = \dots$

$p = \dots$



*MAT_036 + HR=3

The original Barlat & Lian formulation (1989)

R values differ significantly from each other

```
*MAT_3-PARAMETER_BARLAT
$       MID        RO         E        PR        HR        P1        P2      ITER
          1  2.70E-06      70.0       0.3         3
$         M       R00       R45       R90      LCID        E0       SPI        P3
        8.0       0.5       1.0       2.0       100
$...
```

$$\Phi(\boldsymbol{\sigma}) = \frac{1}{2}\left(a\,|K_1 + K_2|^m + a\,|K_1 - K_2|^m + c\,|2K_2|^m\right) - \sigma_y^m = 0$$

$R_{00} = 0.5$

$R_{45} = 1.0$

$R_{90} = 2.0$

σ_y, m

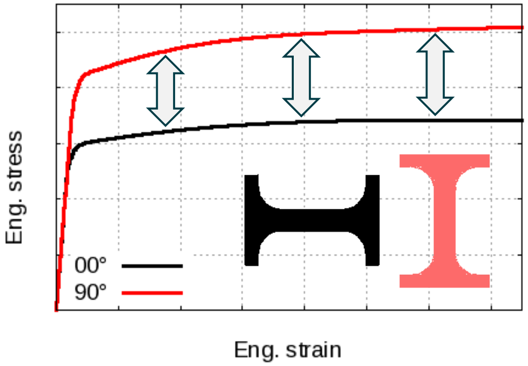
internal fitting

$a = \ldots$

$c = \ldots$

$h = \ldots$

$p = \ldots$



*MAT_036 + HR=7

Extended formulation based on Fleischer et al. (2007) – input example

HR=7 allows the definition of three hardening curves

Hardening curve in the 45° direction

Hardening curve in the 90° direction

```
*MAT_3-PARAMETER_BARLAT
$      MID        RO         E        PR        HR        P1        P2      ITER
         1  7.85E-06     210.0       0.3         7       145       190
$        M       R00       R45       R90      LCID        E0       SPI        P3
       8.0      -200      -245      -290       100
$     AOPT         C         P     VLCID                  PB   NLP/HTA       HTB
         2
$                                     A1        A2        A3       HTC       HTD
                                    1.00       0.0       0.0
$       V1        V2        V3        D1        D2        D3      BETA
                                     0.0       0.0       0.0
```

If negative values are defined, the absolute values indicate load curves where the R values in 0°, 45° and 90° directions are a function of the plastic strain

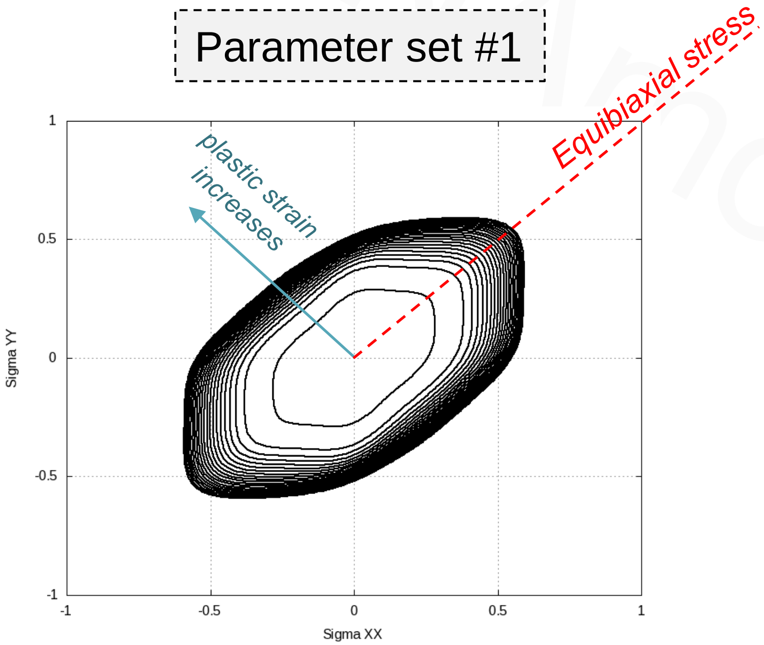
Hardening curve in the 0° direction

*MAT_036 + HR=7

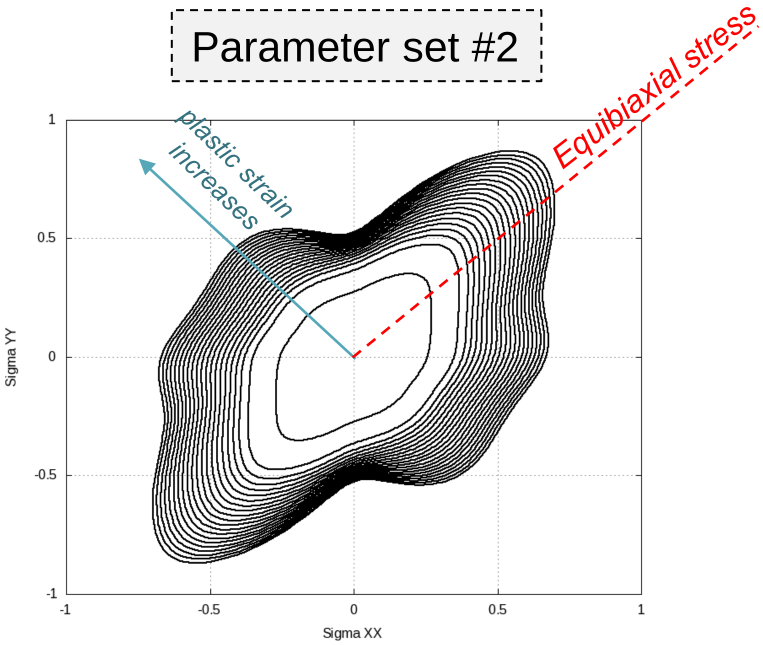
Yield surface

The extended formulation of *MAT_036 is very flexible and extremely useful in order to match experimental data. Nevertheless, different sets of parameters may lead to non-convex and non-monotonic yield surfaces.

Parameter set #1



Parameter set #2



*MAT_036E

Extended formulation with different input format (from R9 on)

Load curve IDs for the hardening curves in 0°, 45° and 90° directions

Load curve IDs for the hardening curves under biaxial and shear stress states

Exponent 'm' for the yield criterion

```
*MAT_EXTENDED_3-PARAMETER_BARLAT
$      mid        ro         e        pr
         1    2.7E-6      70.0       0.3
$    lch00     lch45     lch90     lchbi     lchsh      hosf
       100       145       190                             0
$    lcr00     lcr45     lcr90     lcrbi     lcrsh         m
      -0.5      -2.0      -0.8                             8
$     AOPT
         2
$                                       A1        A2        A3       HTC       HTD
                                      1.00       0.0       0.0
$       V1        V2        V3        D1        D2        D3      BETA
                                       0.0       0.0       0.0
```

HOSF=0: *Barlat-based effective stress (eq. to *MAT_036 + HR=7)*

HOSF=1: *Hosford-based effective stress*

Flag for the definition of the material directions

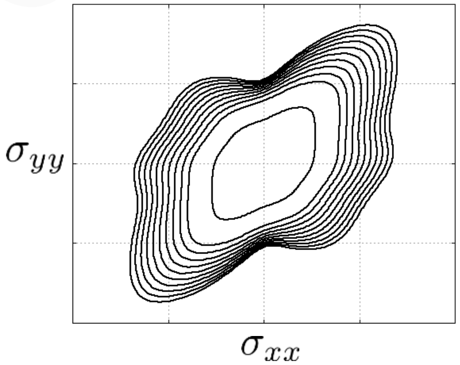
R-values in 0°, 45° and 90° directions:
- Negative values mean constant R-values
- Positive values correspond to the load curve IDs of variable R-values

R-values for biaxial and shear stress states:
- Negative values mean constant R-values
- Positive values correspond to the load curve IDs of variable R-values

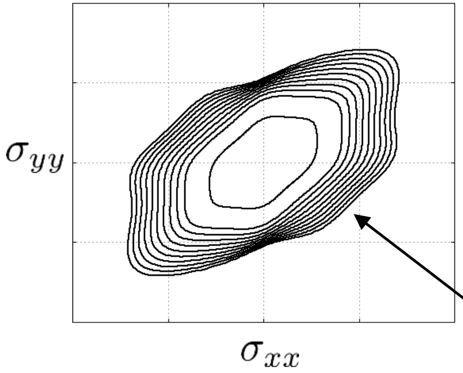
*MAT_036E

Comparison between Barlat- (HOSF=0) and Hosford-based (HOSF=1) formulations

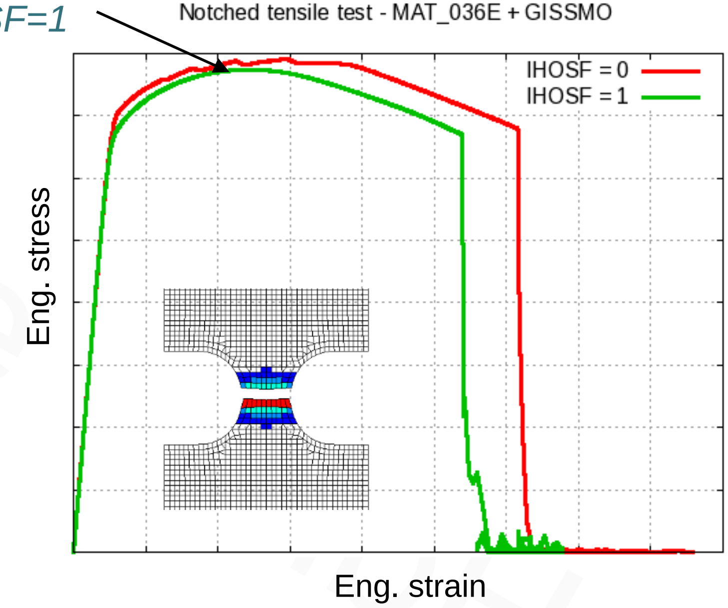
HOSF=0



HOSF=1



No oscillations with HOSF=1



Yield surface is much more well-behaved with HOSF=1

Material calibration

Material calibration

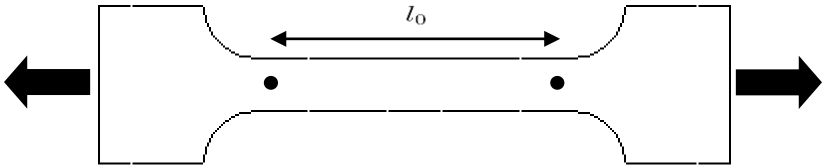
Overview of material models an the required tests

Material behavior \ Test	Quasi-static tensile	Quasi-static compression	Quasi-static Shear/biax	Dynamic tensile/bending	Cyclic tensile/bending/ compression
Elasticity	✓	(✓)	(✓)		
Visco-elasticity	✓	(✓)	(✓)	✓	✓
Plasticity	✓	(✓)	(✓)		
Visco-plasticity	✓	(✓)	(✓)	✓	
Damage	✓		✓	(✓)	

Calibration of yield curves

Tensile test

- it is a very common and very important test
- with the tensile test it is possible to identify many important mechanical properties such as elastic modulus, yield stress, ultimate tensile strength and elongation
- different specimens available (flat and round specimens, different strain gauges)

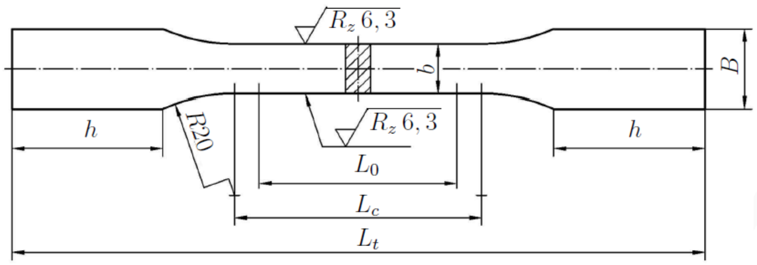


- different standards, e.g., for metallic materials DIN EN 10002

Calibration of yield curves

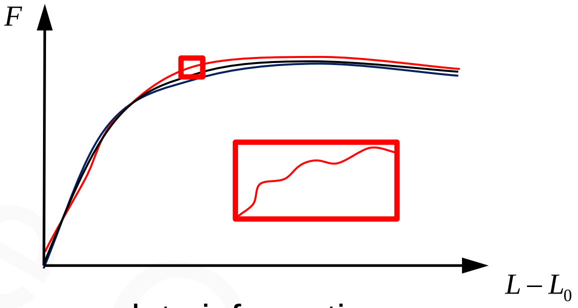
From test data to material input

- tensile test – necessary information and raw data processing
  - specimen geometry and boundary conditions
  - raw data



for each test:

- geometry dimensions
- gauge length
- fixed support
- velocity/strain rate



raw data information

$$F \Rightarrow \sigma_{eng} \qquad L - L_0 \Rightarrow \varepsilon_{eng}$$

raw data processing

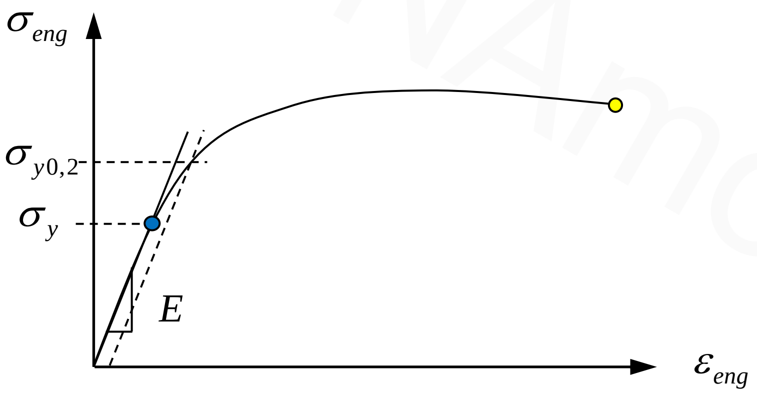
- smoothing, filtering and averaging
- start at (0, 0)

averaging of all test curves

Calibration of yield curves

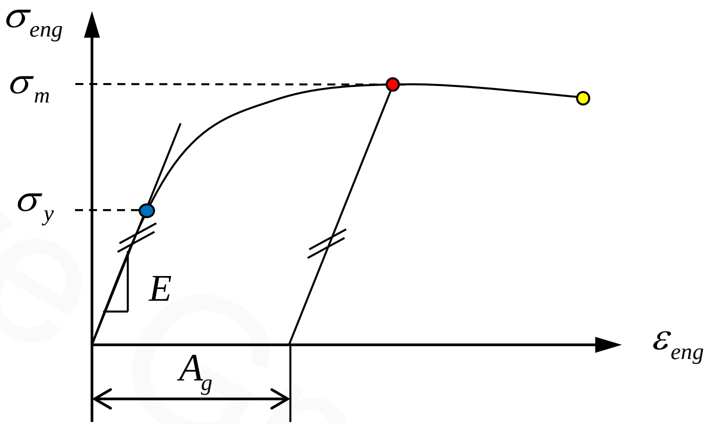
From test data to material input

- Young's Modulus and yield stress



Young's modulus → initial slope
yield stress → beginning of plastic deformation

- Ultimate Strength and necking point



Necking initiation is related to the maximum of the engineering stress-strain curve:

$$\frac{\partial \sigma_{eng}}{\partial \varepsilon_{eng}} = 0$$

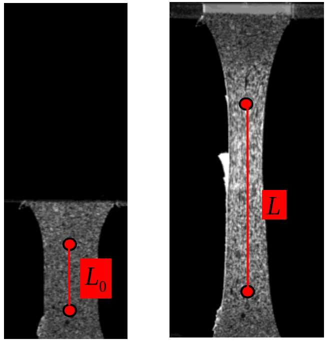
Calibration of yield curves

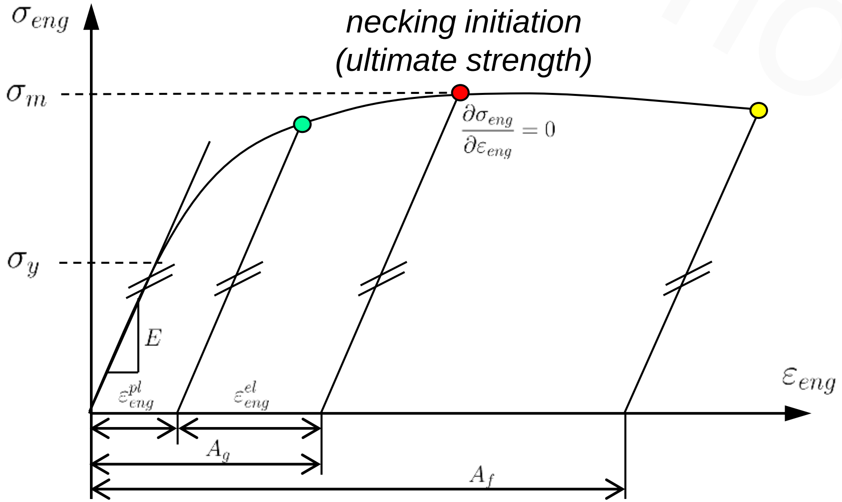
From test data to material input

- engineering (or nominal) stress-strain curve
  - engineering stress: axial force per initial area
  - engineering strain: elongation per initial length
  - the engineering stress-strain curve is a usual result from experiments

$$\sigma_{eng} = \frac{F}{A_0}$$

$$\varepsilon_{eng} = \frac{l - l_0}{l_0}$$





Behavior after necking initiation is unstable:

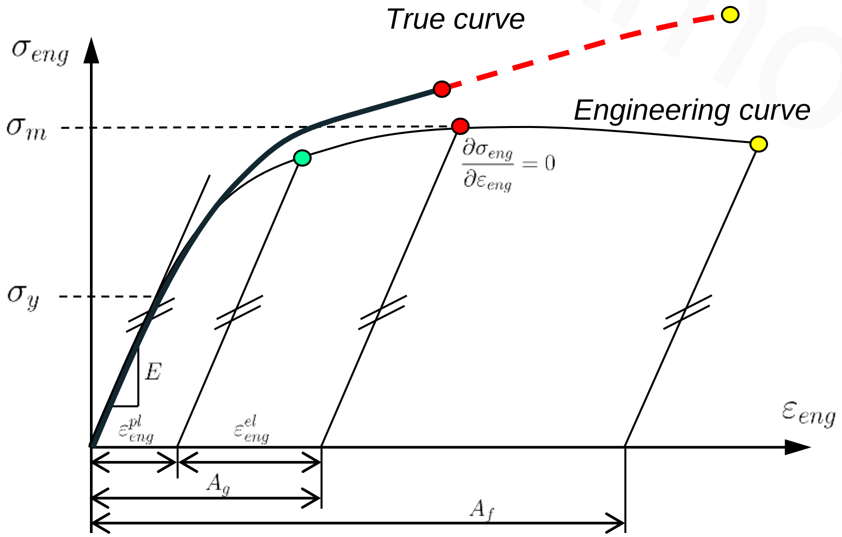
- further deformation without increasing load
- stress not uniformly distributed over necking region
- triaxial state of stress is unknown
- localization of strain manifested by local necking

Calibration of yield curves

From test data to material input

Standard tensile test: current area A is unknown!

- True stress-strain curve
  - True stress: axial force per current unit area ⇨ $\sigma_{true} = \frac{F}{A}$
  - True (logarithmic) strain ⇨ $\varepsilon_{true} = \ln\frac{l}{l_0} = \ln(1+\varepsilon_{eng})$



True stress **before necking initiation**: Calculation with the assumption of constant volume

$$\sigma_{true} = \frac{F}{A} = \frac{F}{A_0}\frac{A_0}{A} = \frac{F}{A_0}\frac{l}{l_0} = \sigma_{eng}(1+\varepsilon_{eng})$$

True stress **after necking initiation**: Extrapolation is necessary!

Calibration of yield curves

Extrapolation strategies after the necking point

In order to identify the **true stress strain curve** after the necking point, several methods are normally used, among then:

- Using information from a shear test
- Using information from a biaxial test
- Through Digital Image Correlation (DIC)
- Reverse engineering

Irrespective of the method adopted for the extrapolation, a suitable model can be used to generate the **hardening curve**. Some of the most commonly used extrapolation equations are:

- Ludwig: $\sigma_y^{true} = k(\varepsilon_{true}^{pl})^n$
- Swift: $\sigma_y^{true} = k(\varepsilon_0 + \varepsilon_{true}^{pl})^n$
- Gosh: $\sigma_y^{true} = k(\varepsilon_0 + \varepsilon_{true}^{pl})^n - p$
- Voce: $\sigma_y^{true} = a - be^{-c\varepsilon_{true}^{pl}}$
- Hocket-Sherby: $\sigma_y^{true} = a - be^{-c(\varepsilon_{true}^{pl})^n}$

Calibration of yield curves

Parametrization of the yield curve

Direct *calculation* of the yield curve until A_g for isochoric materials

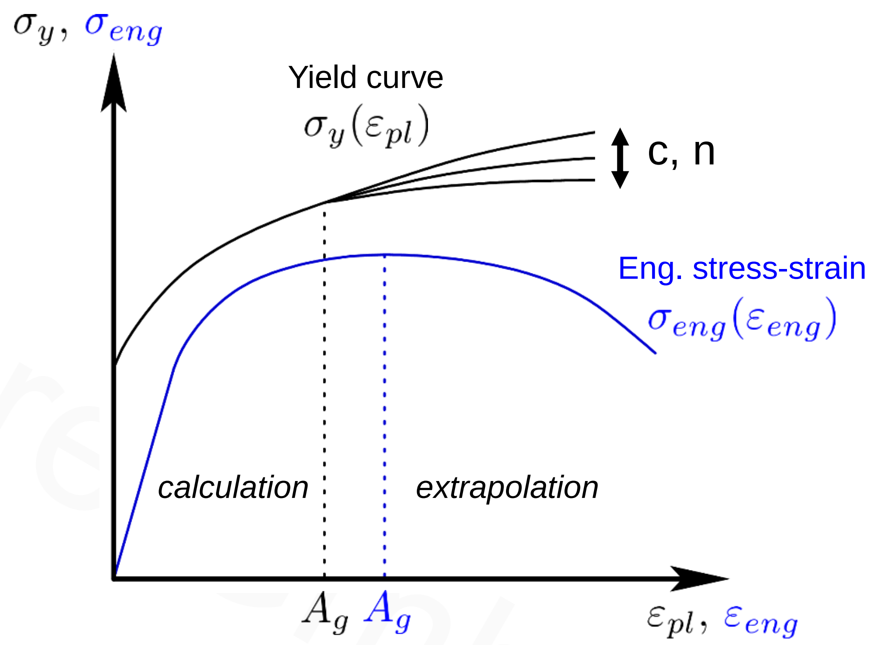
$$\sigma_y = \sigma_{eng}(1+\varepsilon_{eng})$$
$$\varepsilon_{pl} = \ln(1+\varepsilon_{eng}) - \frac{\sigma_{eng}}{E}$$

Extrapolation from A_g with Hockett-Sherby

$$\sigma_y(\varepsilon_{pl}) = A - B\,e^{(-c\,\varepsilon_{pl}^n)}$$

C^1-continuity at A_g:

- Reduction of the function by two variables

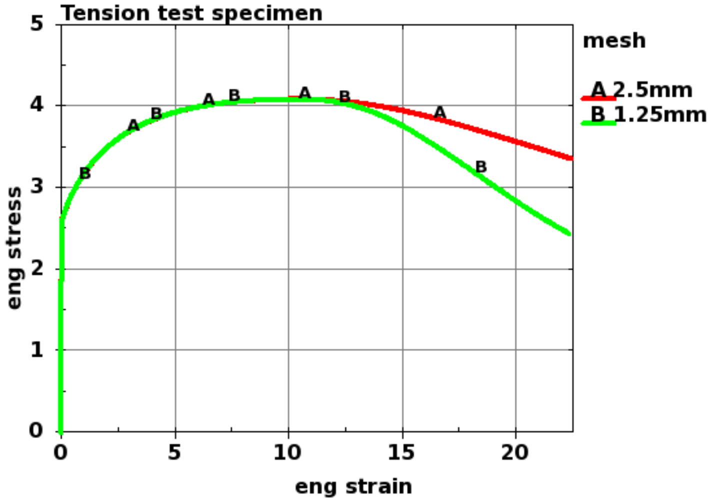


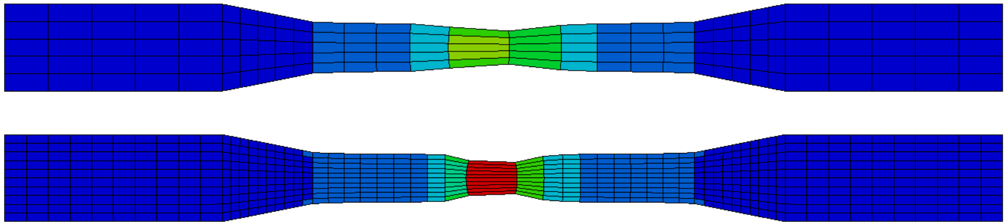
- Remaining variables c and n are the remaining free parameters

Calibration of yield curves

Element size dependence

After the necking point the result depends on the element size





Don't forget!

$$\varepsilon_{eng} = \frac{l - l_0}{l_0}$$

$$\sigma_{eng} = \frac{F}{A_0}$$

After the necking point:

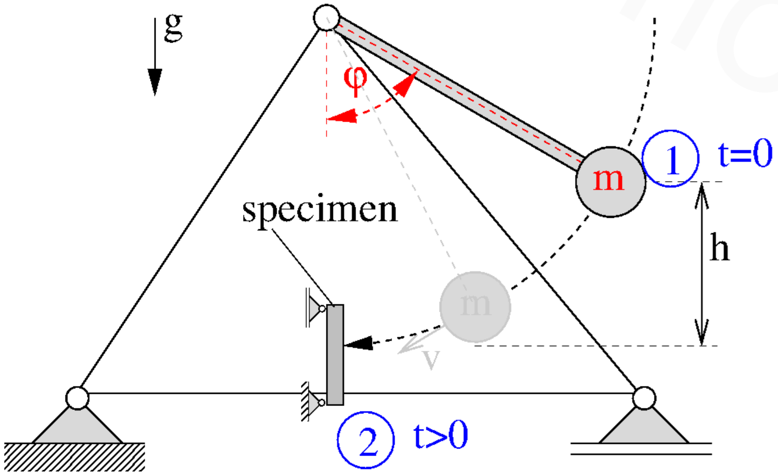
- For most material models the characterization only applies to a certain element size!

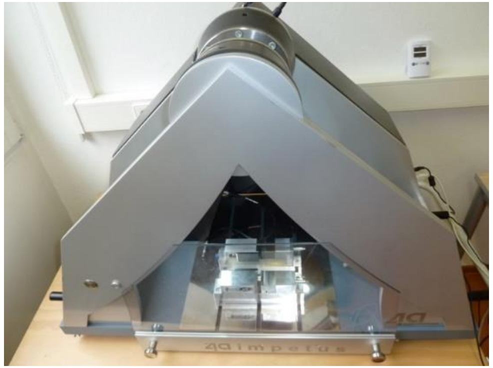
Testing and modelling of foams using

*MAT_FU_CHANG_FOAM (*MAT_083)

Dynamic Tests with pendulum – experimental setup

- 4a impetus testing machine:
  - single pendulum
  - dynamic velocities 0.5-4.3 m/s
  - measurement of angle and acceleration at impactor with mass m





t=0: position of m is fixed at 1
with an initial $W_{pot} = mgh$

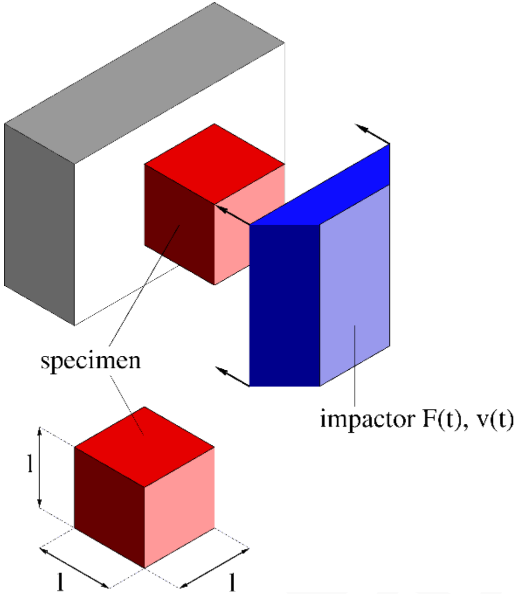
t>0: m moves from 1 to 2
W_{pot} changes to $W_{kin} = \frac{1}{2}mv^2$

at 2: min W_{pot} and max W_{kin}
impactor hits specimen with
$\vec{p} = m\vec{v}$

Compression test – experimental setup

- compression test:
  - specimen is fixed by adhesive tape
- variation of nominal strainrate $\dot{\varepsilon}$ due to
  - different specimen size l
  - different initial velocities v

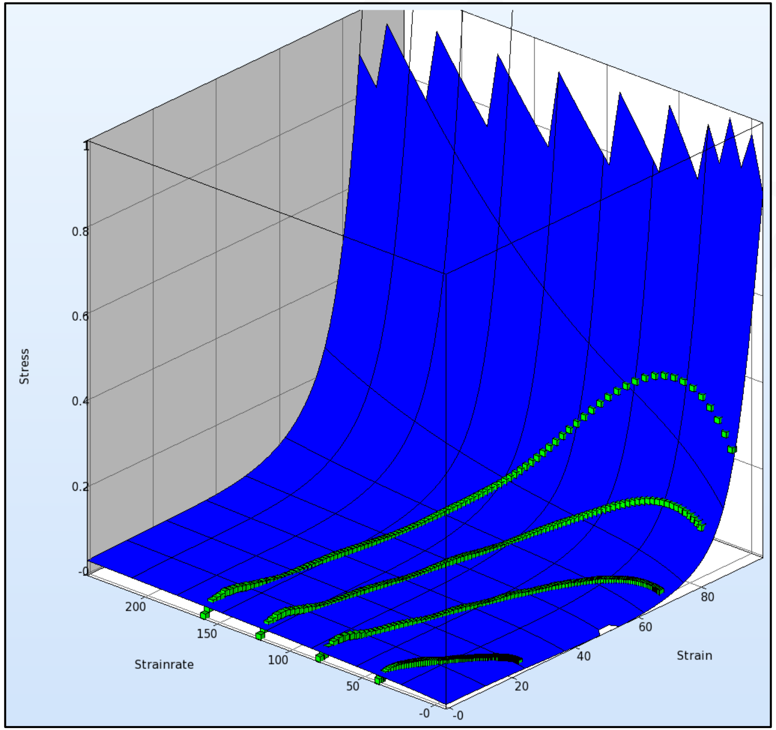
strain rate in 1/s	l in mm	v in m/s
0.001	20	0.00002
0.01	20	0.0002
0.1	15	0.0015
0.3	15	0.0045
40	20	0.8
100	15	1.5
200	20	4.0



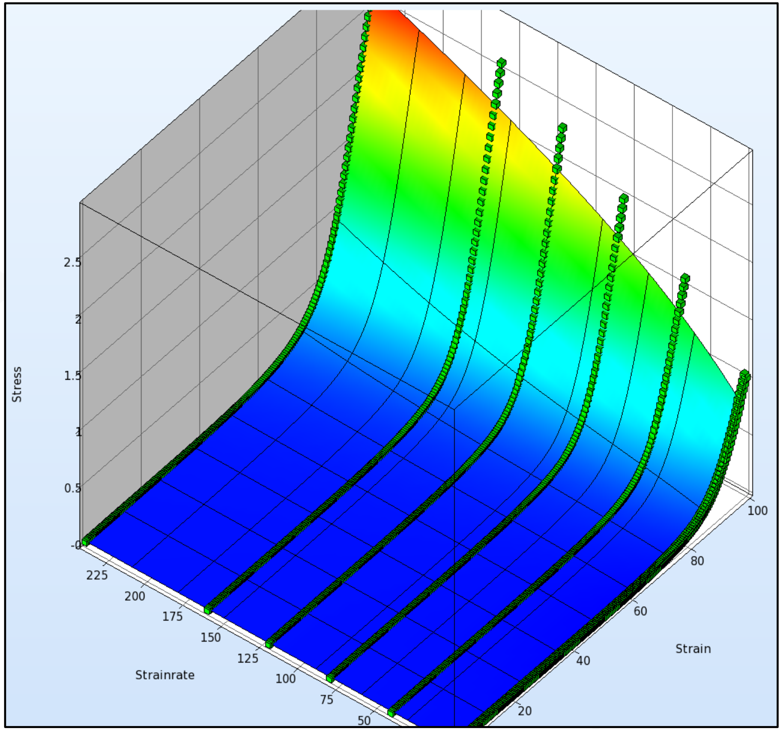
nominal strain rate: $\dot{\varepsilon} = \frac{v}{l}$

Example: LS-OPT meta model

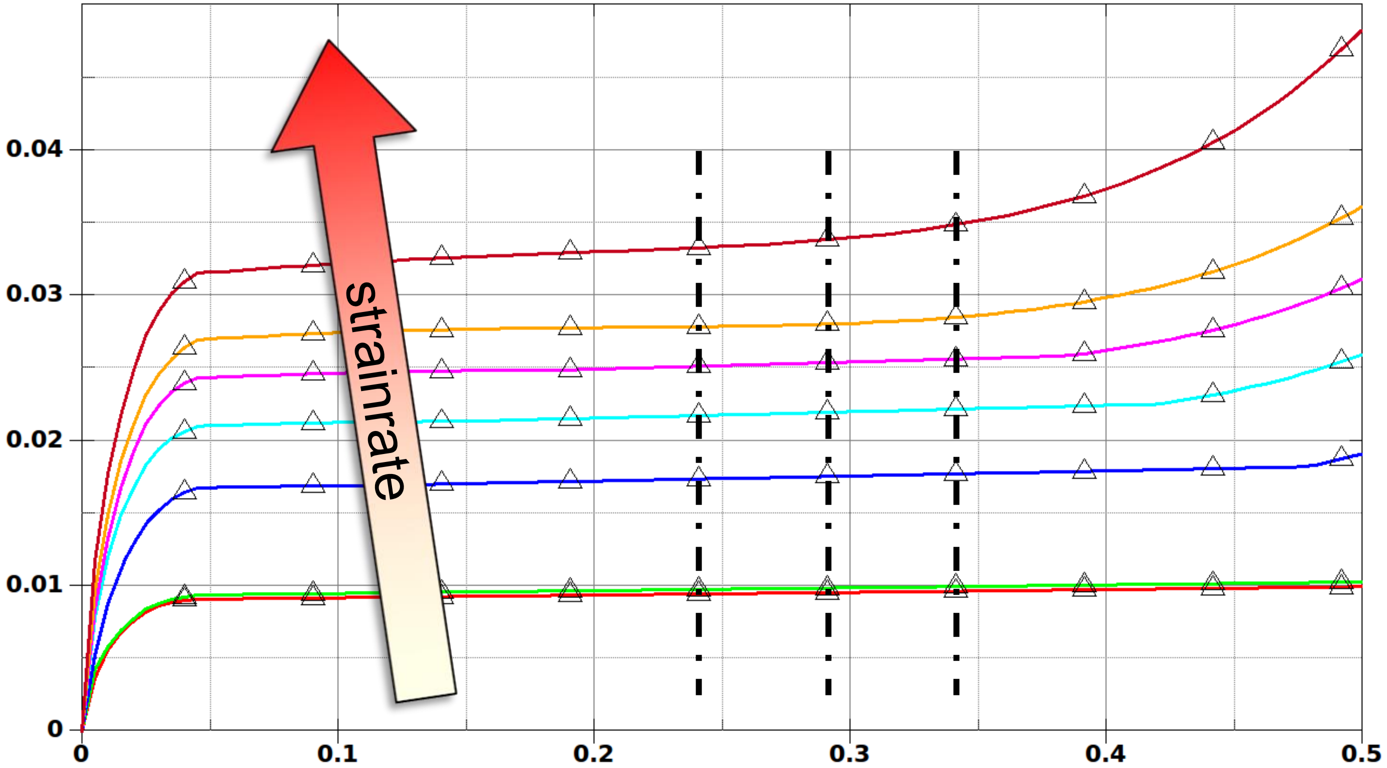
Stress strain cuves from Experiment

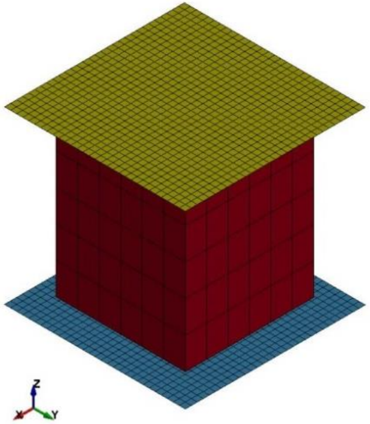


Stress Strain curves with constant strain rates



Example: Fu-Chang-Foam





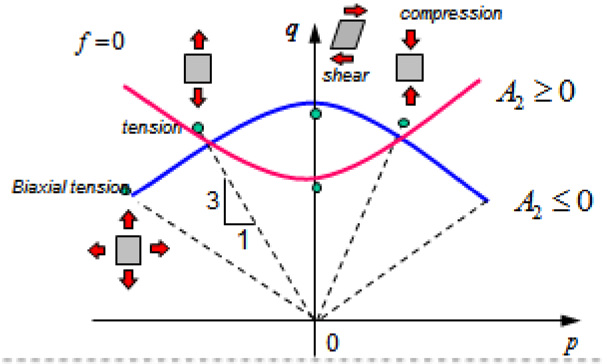
Testing and modelling of Polymers using

*MAT_SAMP-1 (*MAT_187)
*MAT_SAMP_Light (*MAT_187L)

semi-**a**nalytical **m**odel for **p**olymers

Material modelling of polymers in LS-DYNA

Isotropic plasticity with SAMP-1 (*MAT_187)

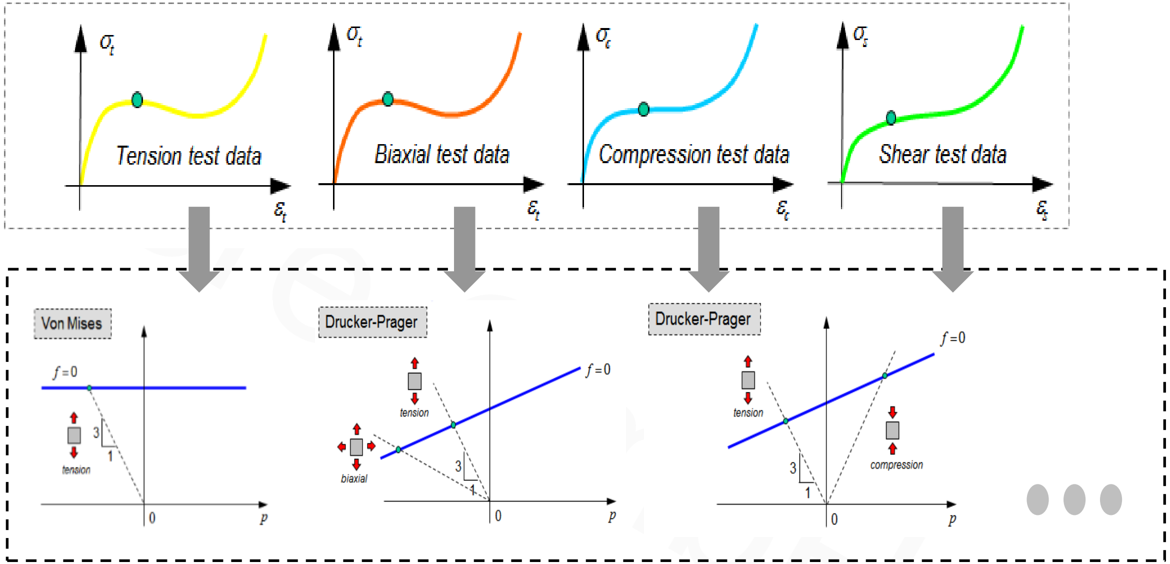


Yield surface:

$$f(p,\sigma_{vm},\bar{\varepsilon}^{pl}) = \sigma_{vm}^2 - A_0 - A_1 p - A_2 p^2 \le 0$$

Condition for convexity :

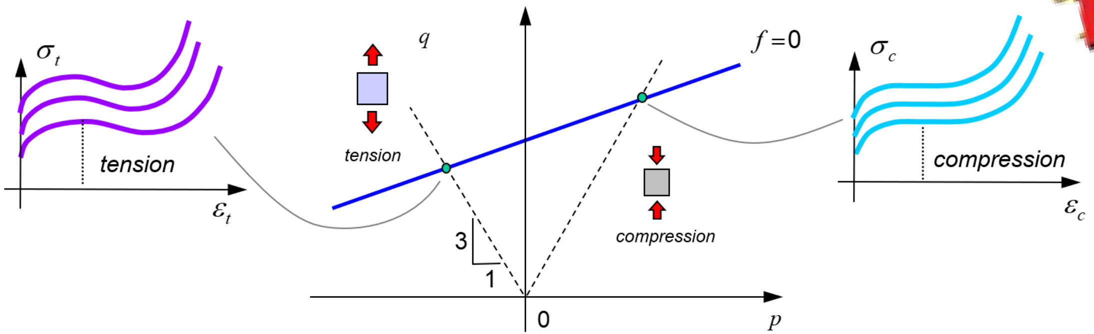
$$A_2 \le 0 \Leftrightarrow \sigma_s \ge \frac{\sqrt{\sigma_t \sigma_c}}{\sqrt{3}}$$



➤ Dependency of plastic poisson ratio

Material modelling of polymers in LS-DYNA

Isotropic plasticity with SAMP_LIGHT (*MAT_187L)



- a slimmed-down form of Material Type 187
- rate independent or rate dependent flow in tension and compression
- constant or variable plastic Poisson's ratio
- shear and biaxial test data are **not** incorporated
- damage and failure is **not** available
- SAMP-1 cards usually cannot be transferred directly to SAMP-L

Example of a *SAMP-1 Material card

LCID-T — Load curve or table ID giving the yield stress as a function of plastic strain. These curves should be obtained from quasi-static and (optionally) dynamic uniaxial tensile tests. This input is mandatory, and the material model will not work unless at least one tensile stress-strain curve is given. If LCID-T is a table ID, the table values are plastic strain rates, and a curve of yield stress versus plastic strain must be given for each of those strain rates. If the first value in the table is negative, LS-DYNA assumes that all the table values represent the natural logarithm of plastic strain rate. When the highest plastic strain rate is several orders of magnitude greater than the lowest strain rate, it is recommended that the natural log of plastic strain rate be input in the table. See Remark 4.

LCID-C — Optional load curve ID giving the yield stress as a function of plastic strain. This curve should be obtained from a quasi-static uniaxial compression test.

LCID-S — Optional load curve ID giving the yield stress as a function of plastic strain. This curve should be obtained from a quasi-static shear test.

LCID-B — Optional load curve ID giving the yield stress as a function of plastic strain, this curve should be obtained from a quasi-static biaxial tensile test.

NUEP — Plastic Poisson's ratio: an estimated ratio of transversal to longitudinal plastic rate of deformation under uniaxial loading should be given.

LCID-P — Load curve ID giving the plastic Poisson's ratio as a function of plastic strain during uniaxial tensile and uniaxial compressive testing. The plastic strain on the abscissa is negative for compression and positive for tension. It is important to cover both tension and compression. If LCID-P is given, NUEP is ignored.

```
$---+----1----+----2----+----3----+----4----+----5----+----6----+----7----+----8
*KEYWORD
$---+----1----+----2----+----3----+----4----+----5----+----6----+----7----+----8
*MAT_SAMP-1
$      mid        ro      BULK      GMOD      EMOD       nue    rbcfac    numint
       100  1.00e-06                          2.50        .3                -75.
$   LCID_T    LCID_C    LCID-S    LCID-B      NUEP    LCID-P              incdam
       100       200       300       400        .3       500
$   LCID_D    EPFAIL    DEPRPT  LCID_TRI   LCID_LC
              0.10       0.1       600
$  MAXITER      MIPS              incfail     ICONV      ASAF    iprint     nhisv
       400        20                   1         0                             5
$---+----1----+----2----+----3----+----4----+----5----+----6----+----7----+----8
*DEFINE_TABLE
$#    tbid
       100
$#                 value      lcid
                  1.0e-7       101
                  1.0e-5       102
                  1.0e-3       103
                  1.0e00       104
$---+----1----+----2----+----3----+----4----+----5----+----6----+----7----+----8
*DEFINE_CURVE
$#    lcid      sidr       sfa       sfo      offa      offo    dattyp
       101
$#                  a1                  o1
                   0.0               0.200
```

damage parameter

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Example of *SAMP-L Material card

LCID-T	Load curve or table ID giving the yield stress as a function of plastic strain. These curves should be obtained from quasi-static and (optionally) dynamic uniaxial tensile tests. This input is mandatory. If LCID-T is a table ID, the table values are effective strain rates, and a curve of yield stress as a function of plastic strain must be given for each of those strain rates. If the first value in the table is negative, LS-DYNA assumes that all the table values represent the natural logarithm of effective strain rate. When the highest effective strain rate is several orders of magnitude greater than the lowest strain rate, it is recommended that the natural log of strain rate be input in the table.
LCID-C	Optional load curve (or table) ID giving the yield stress as a function of plastic strain (and strain rate). This curve (or table) should be obtained from uniaxial compression tests. If LCID-C is defined as a curve and LCID-T given as a table, then the rate dependence from the tension table is adopted in compression as well.
NUEP	Plastic Poisson's ratio: an estimated ratio of transversal to longitudinal plastic rate of deformation under uniaxial loading should be given.
LCID-P	Load curve ID giving the plastic Poisson's ratio as a function of plastic strain during uniaxial tensile and uniaxial compressive testing. The plastic strain on the abscissa is negative for compression and positive for tension. It is important to cover both tension and compression. If LCID-P is given, NUEP is ignored.

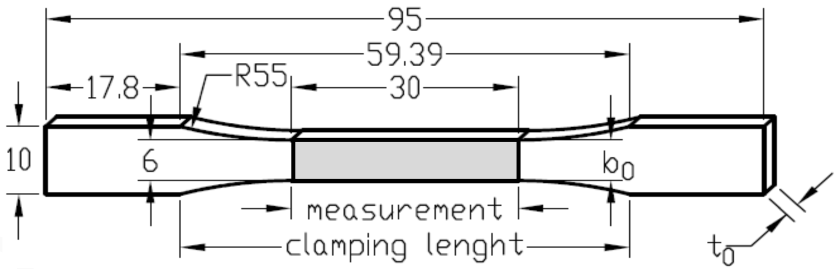
NEW!

```
$---+----1----+----2----+----3----+----4----+----5----+----6--
*KEYWORD
$---+----1----+----2----+----3----+----4----+----5----+----6--
*MAT_SAMP_LIGHT
$      mid        ro      BULK      GMOD      EMOD       nue
       100  1.00e-06                          2.50        .3
$   LCID_T    LCID_C                          NUEP    LCID-P    RFILTF
       100       200                            .3       500
$---+----1----+----2----+----3----+----4----+----5----+----6----+----7----+----8
*MAT_ADD_DAMAGE_GISSMO
$      MID                DTYP     REFSZ    NUMFIP
       100                   1       2.0     -67.0
$    LCSDG     ECRIT    DMGEXP     DCRIT    FADEXP    LCREGD
       110                   2       1.0
$    LCSRS      SHRF     BIAXF    LCDLIM   MIDFAIL     HISVN      SOFT     LP2BI
                   2       2.0
$---+----1----+----2----+----3----+----4----+----5----+----6----+----7----+----8
*DEFINE_TABLE
$#    tbid
       100
$#               value      lcid
           -1.6118E01       101
               1.0e-5       102
               1.0e-3       103
               1.0e00       104
$---+----1----+----2----+----3----+----4----+----5----+----6----+----7----+----8
*DEFINE_CURVE
$#    lcid      sidr       sfa       sfo      offa      offo    dattyp
       101
$#                  a1                  o1
                   0.0               0.200
```

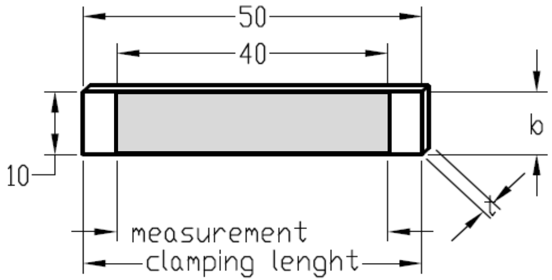
damage

Specimen

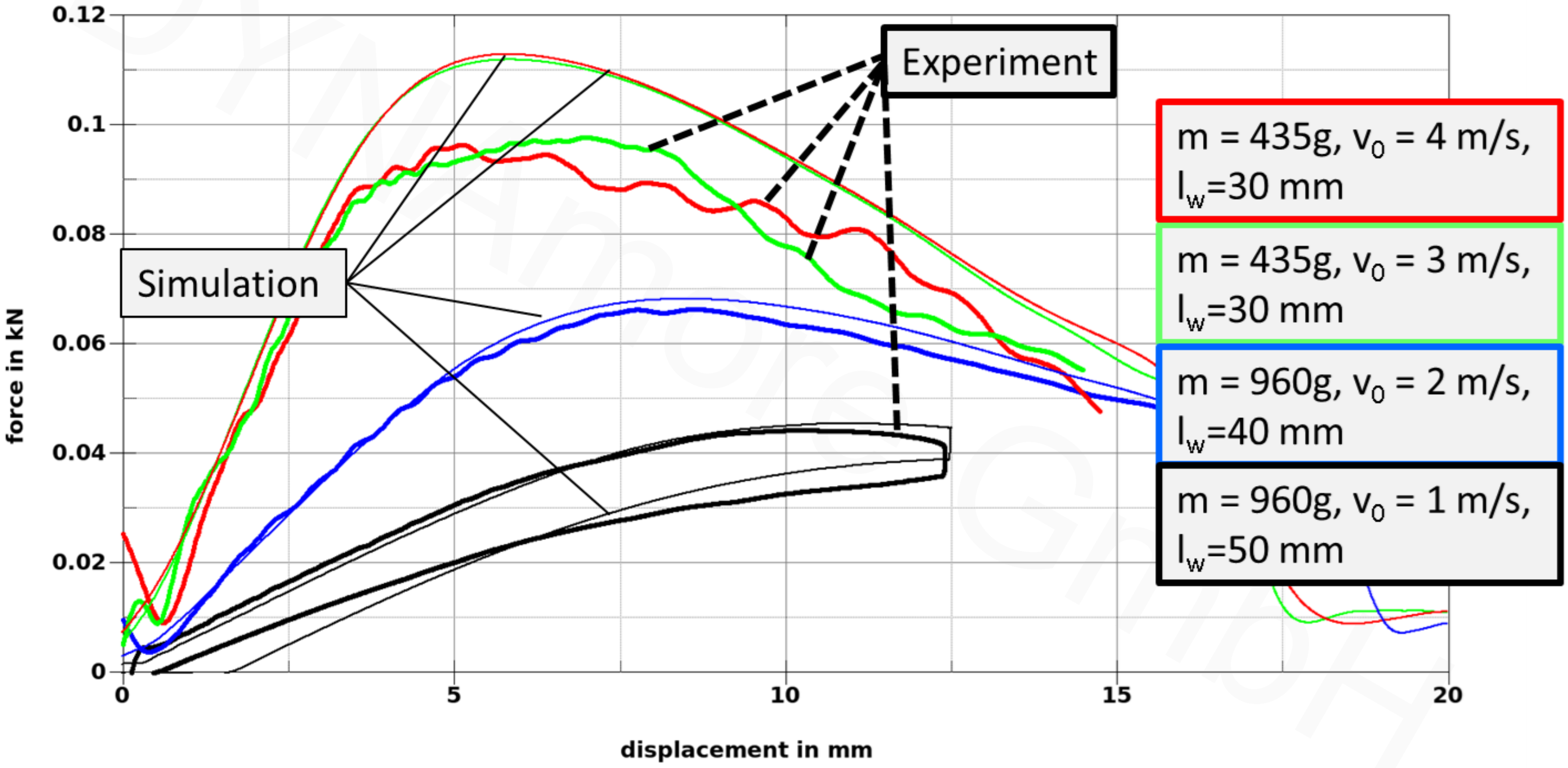
- Tensile specimen
  - static and dynamic tests
  - Strain via DIC
  - Engineering strain with l_0=30 mm
  - Target mesh size: 2mm
  - Milled specimen



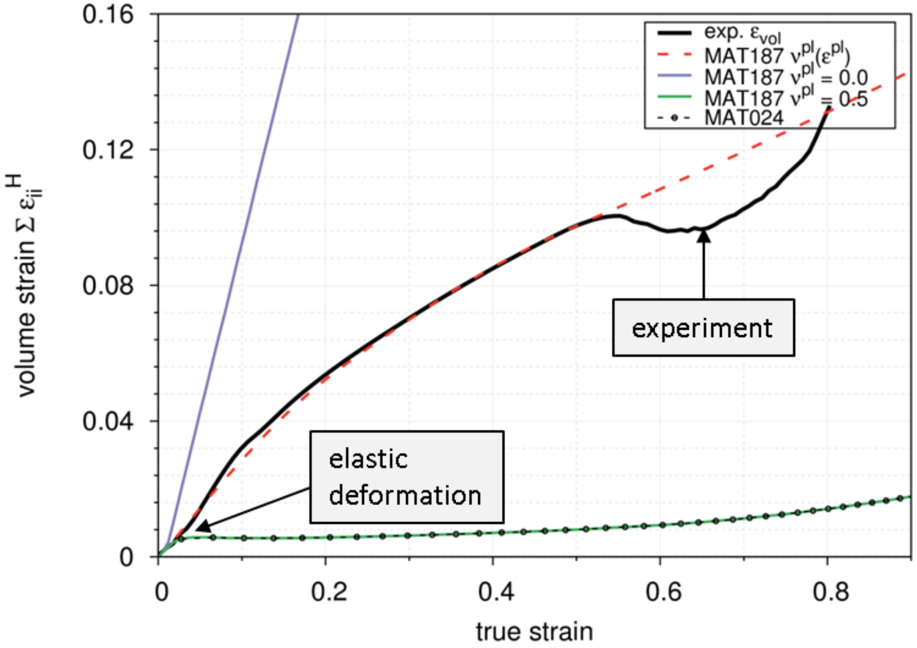
- 3 point Bending:
  - Static and dynamic tests
  - Milled specimen
  - Large range of strain rates possible

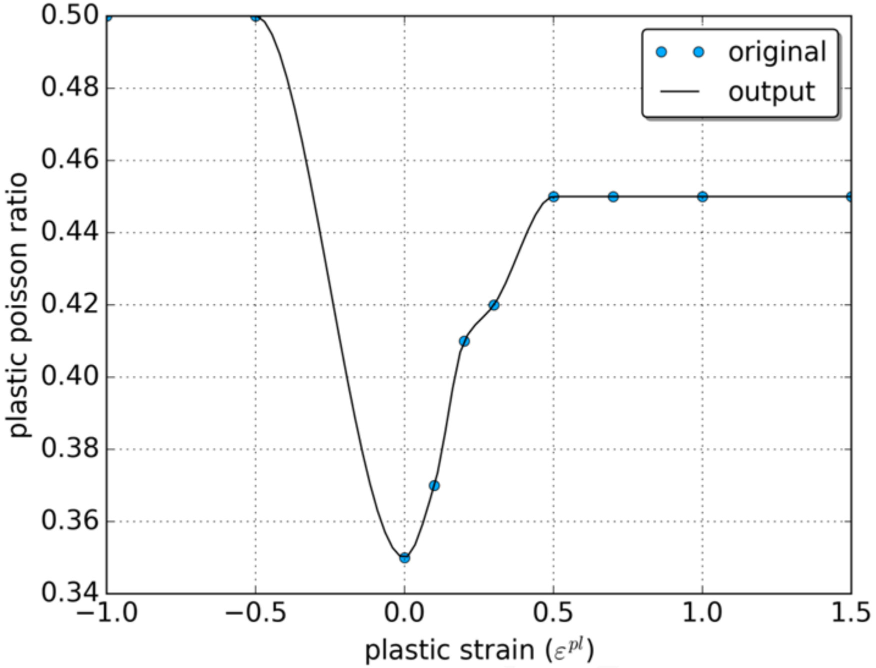


Results of MAT_024 + GISSMO card: bending tests



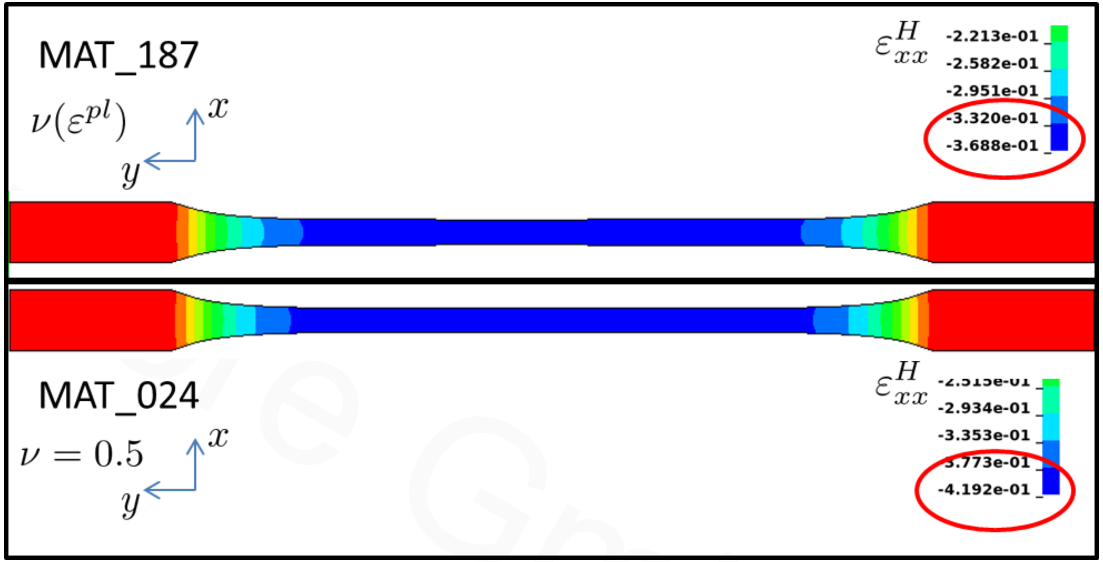
SAMP#1: plastic poisson‘s ratio





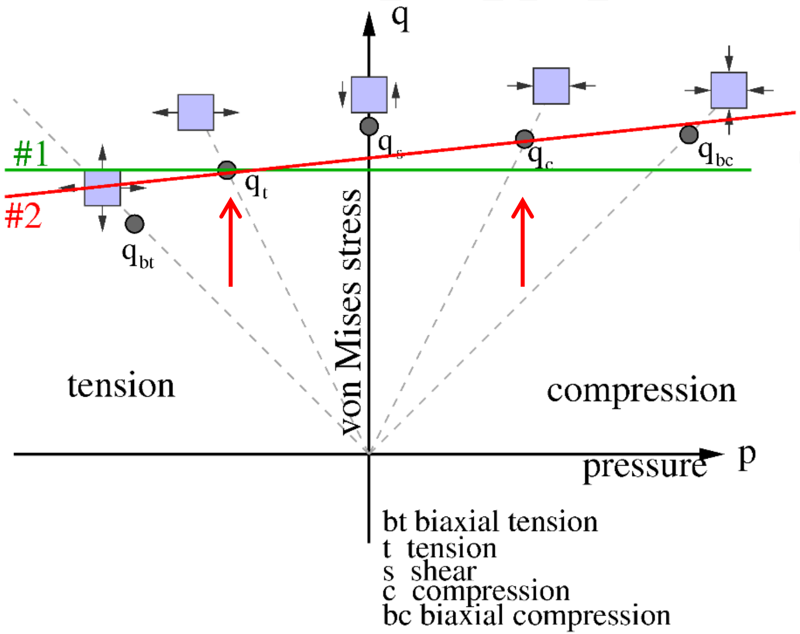
SAMP#1: plastic poisson‘s ratio

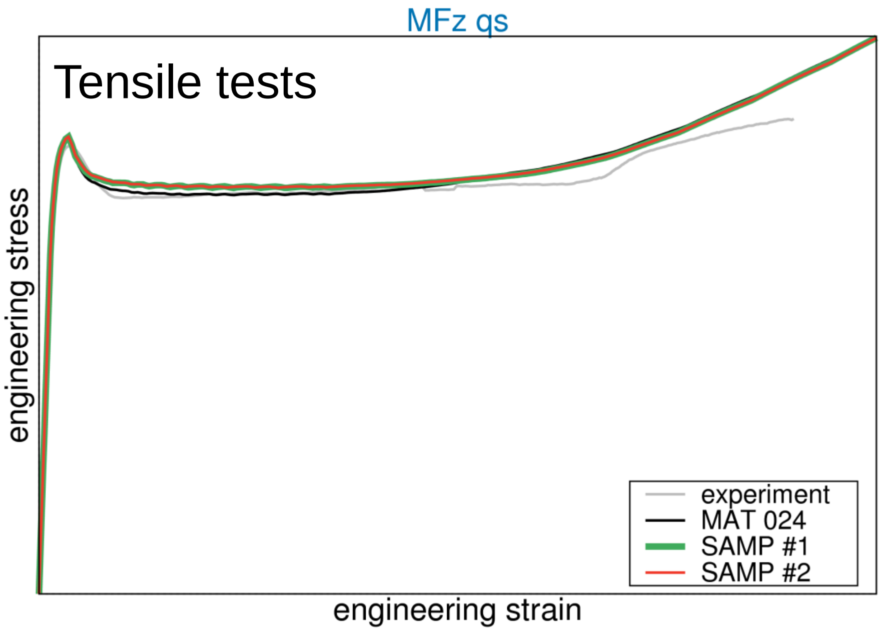
- Taking ratio into account:
  - influence on strain transversal to loading direction
  - influence plastic strain at notch tip
  - important for complex FE-models



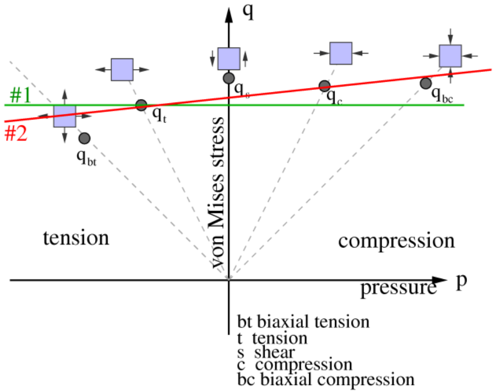
> ➢ Important for simulation of thermoplastics with increasing macroscopic volume (e.g. Crazing at ABS, HIPS, PC/ABS

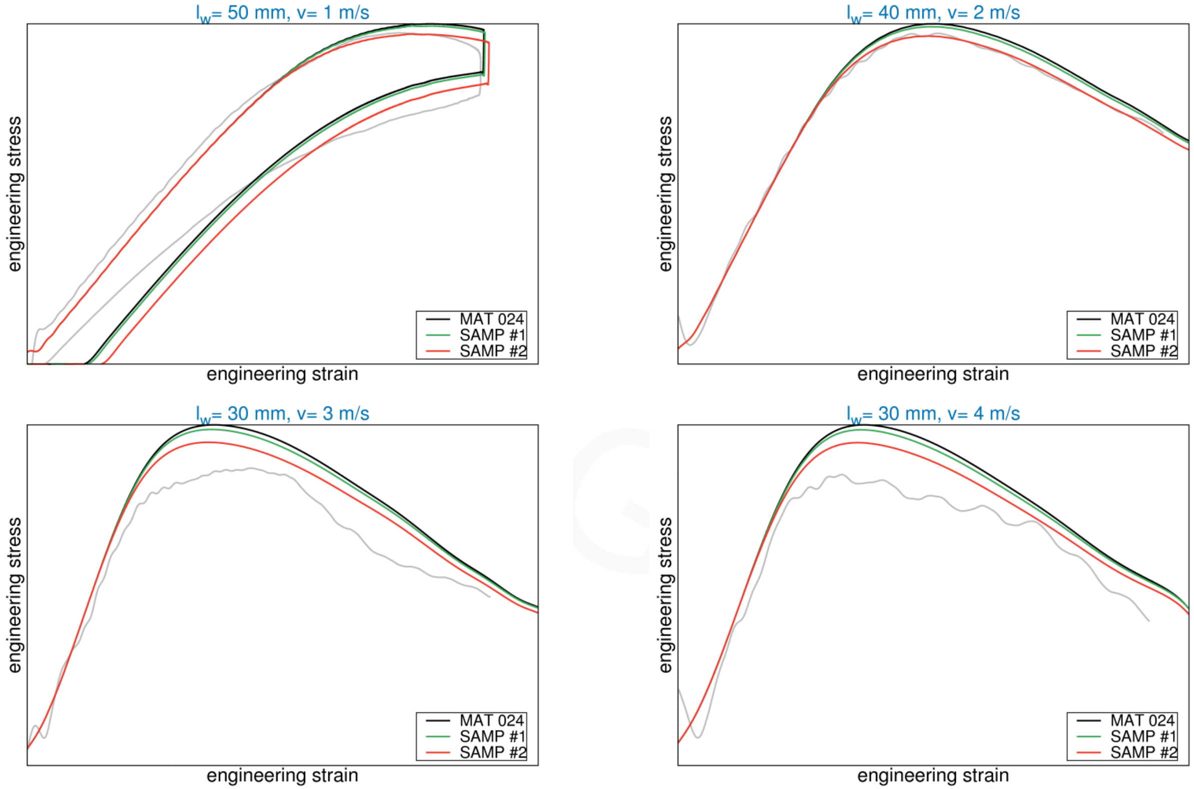
SAMP #2: taking compression into account





Bending results





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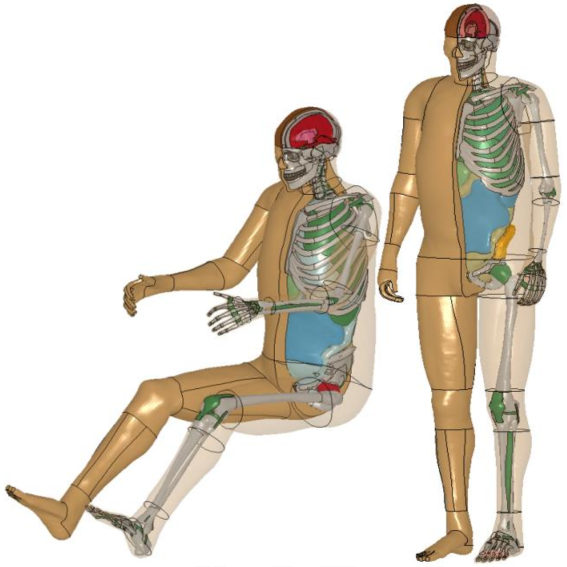

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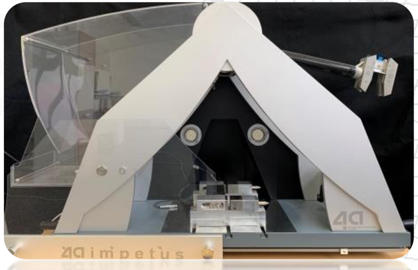
  - Experiments
    - Tensile, bending, compression, punch test
    - Component testing
    - Local strain analysis with DIC
  - Damage and fracture characterization and calibration for GISSMO and eGISSMO models



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