WORKSHOP
Introduction to material characterization

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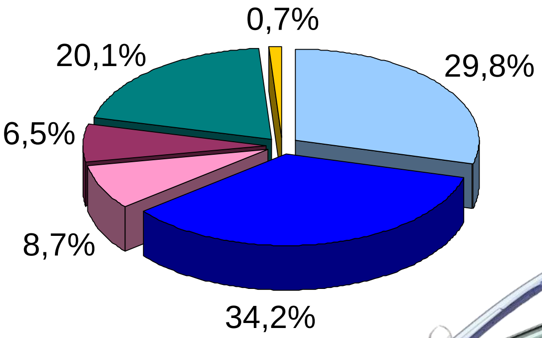
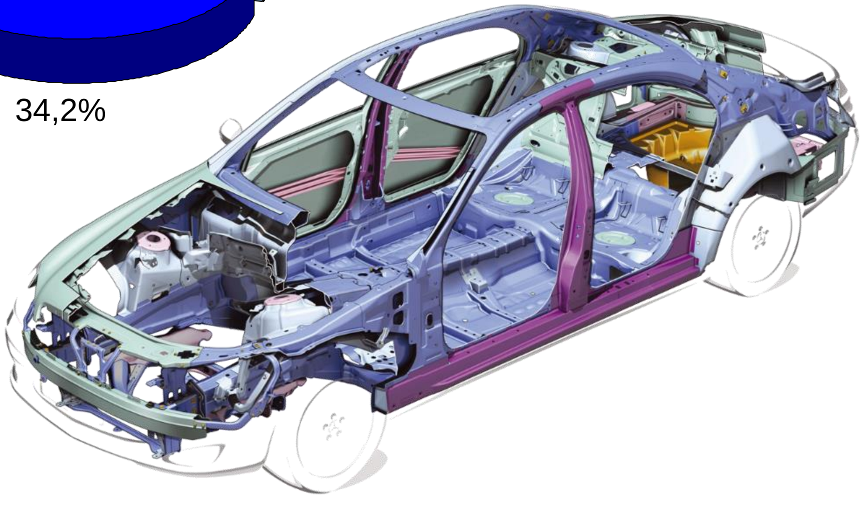
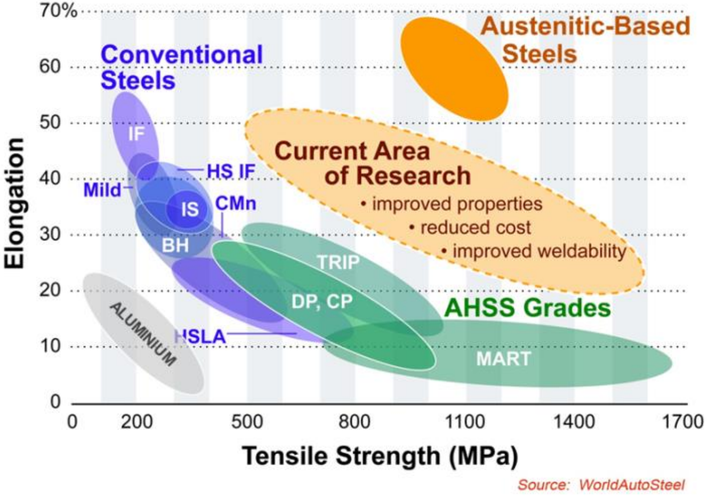
Motivation

Example of material usage in a modern car



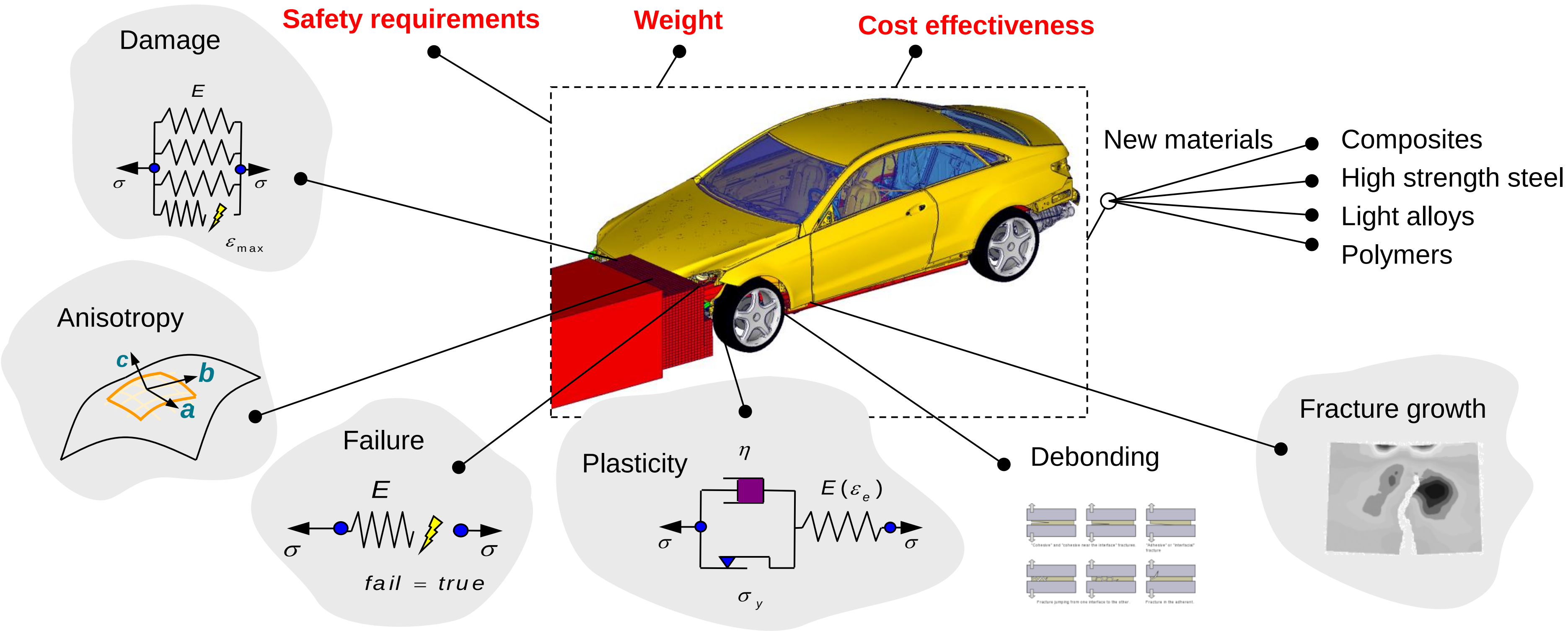




- Deep drawing steels
- High strength steels
- Very high strength steels
- Ultra high strength steels
- Aluminum
- Polymers

Motivation

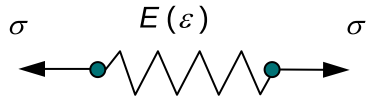
Challenges in the automotive industry for efficient lightweight structures

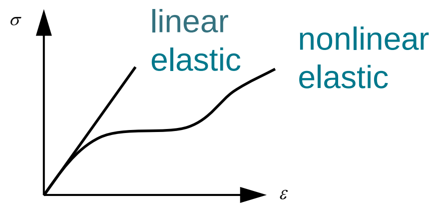


	Rheological models	Stress-strain relationship

Elasticity

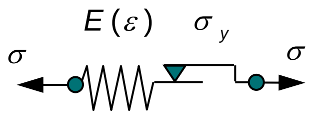
- Linear / nonlinear stress-strain relationship
- Loading and unloading paths identical
- Stress is a function of the strain
- Reversible deformations
- Elastic straining is non-isochoric for metals

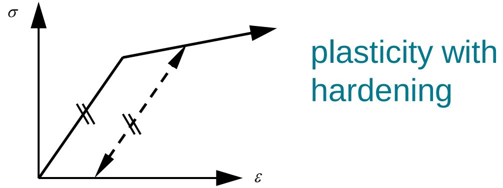




Plasticity

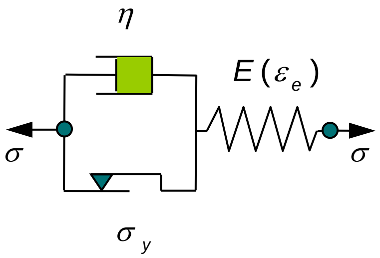
- Elastic behavior until yielding
- Irreversible deformations
- Hardening/softening behavior possible
- Isochoric for metals

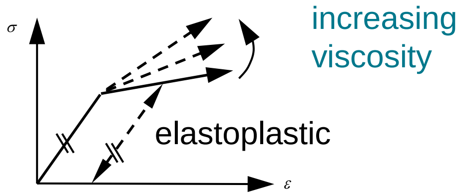




Viscoplasticity

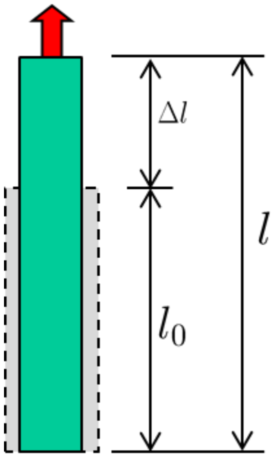
- Stress states outside the yield surface activate viscoplastic response
- Relaxation of overstress over time
- Limiting cases are elasticity and plasticity

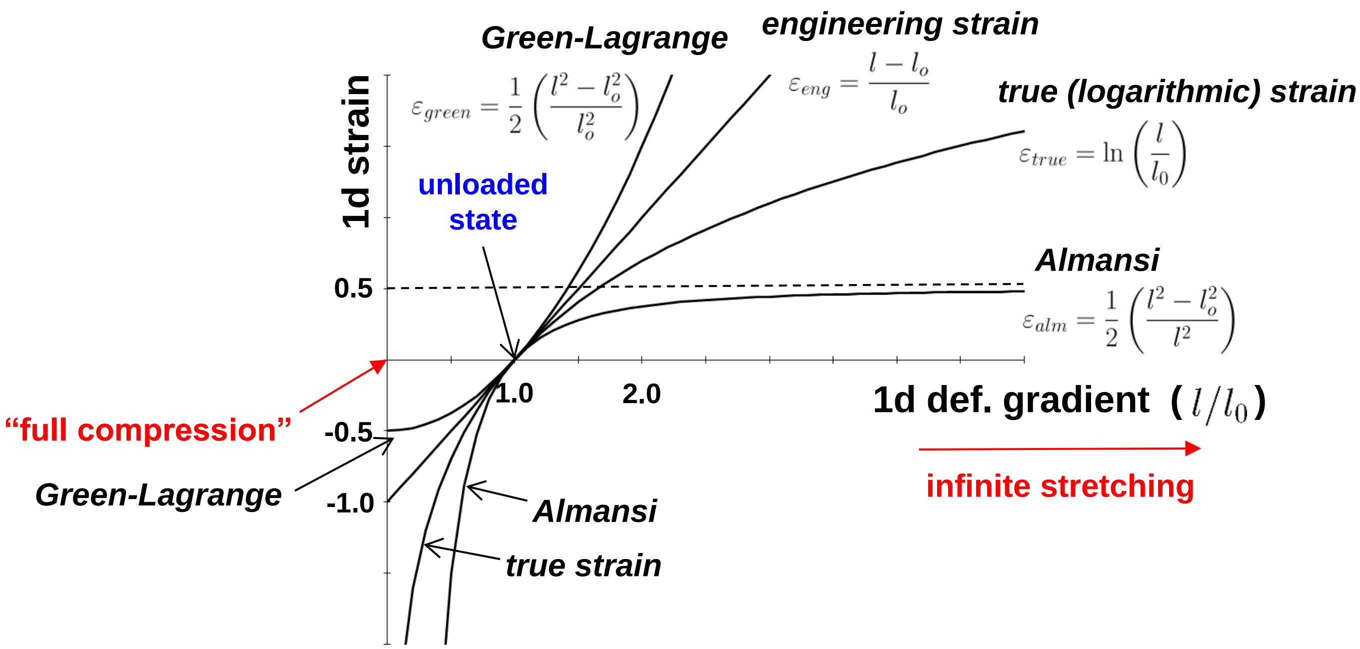




Strain measures

- For small deformations the strain measures is indifferent, all deliver the same result
- For large or finite deformations the strain measure depends on the type of problem, mathematical convenience, etc.



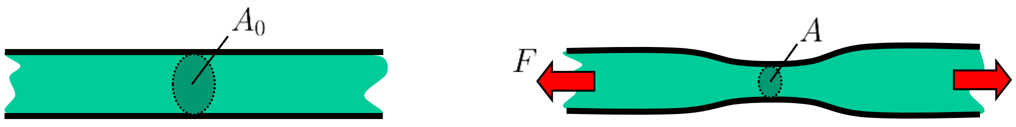


Stress measures

One-dimensional case

- in one dimension, the engineering and true stress measures are the most commonly used in practical engineering:

$$\sigma_{eng} = \frac{F}{A_o} \qquad \sigma_{true} = \frac{F}{A}$$



- assuming an isochoric deformation (i.e., constant volume), the true stress may be expressed as:

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

- in the three dimensional case, the above stress measures are generalized to tensorial quantities of second order, where other stress tensors are also relevant, e.g., the second Piola-Kirchhoff , the Kirchhoff stress tensor, etc.

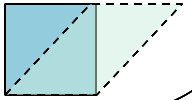
Stress measures

Some useful relations regarding the stress tensor

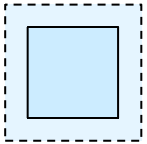
- The true stress tensor is symmetric and can be split in two parts

$$\boldsymbol{\sigma} = \begin{bmatrix} \sigma_{11} & \sigma_{12} & \sigma_{13} \\ & \sigma_{22} & \sigma_{23} \\ & & \sigma_{33} \end{bmatrix} = \mathbf{s} + \underbrace{\frac{1}{3}\mathrm{tr}(\boldsymbol{\sigma})}_{\text{mean stress}}\,\mathbf{I} = \underbrace{\begin{bmatrix} s_{11} & s_{12} & s_{13} \\ & s_{22} & s_{23} \\ & & s_{33} \end{bmatrix}}_{\text{stress deviator}} - \underbrace{p}_{\text{hydrostatic pressure}} \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Change in shape, but not in volume



Change in volume, but not in shape



- The principal stress tensor and its invariants

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

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

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

- The equivalent or von Mises stress is defined as

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

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

$$\underbrace{\boldsymbol{\sigma} = \mathbb{D} : \boldsymbol{\varepsilon}}_{}$$

$\mathbb{D}$: *Constitutive operator*

where

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

- 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

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

Simple plasticity model

*MAT_PLASTIC_KINEMATIC (*MAT_003)

*MAT_003

*MAT_PLASTIC_KINEMATIC

This is a bilinear elasto-plastic model which accounts for kinematic, isotropic or mixed hardening. Strain rate dependence can be considered and element deletion can be activated. It is a very simple and very fast material model that can be used to model plasticity in a simplified way.

```
*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 for *Cowper Symonds* strain rate model
- FS: Failure strain for eroding elements
- VP: Formulation for rate effects

Isotropic plasticity model

*MAT_PIECEWISE_LINEAR_PLASTICITY (*MAT_024)

*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

```

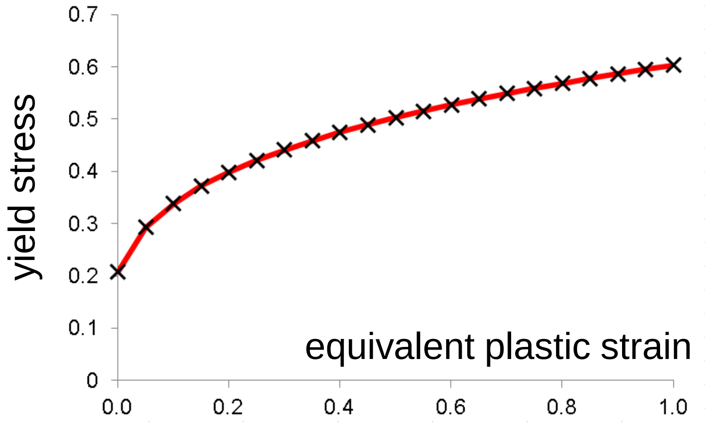
- FAIL: Failure flag
- TDEL: Minimum time step size for automatic element deletion
- C, P: Strain rate parameters C and P for Cowper-Symonds strain rate model
- LCSS: Load curve or table ID (yield curve, supersedes SIGY and ETAN)
- LCSR: Load curve ID defining strain rate effects on yield stress
- VP: 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
  (*MAT_225 is similar to *MAT_024, but allows the definition of kinematic hardening)
- Unless viscoplasticity (i.e., VP=1) is activated, the plasticity routine **does not iterate** (works very well in explicit, possibly problematic for large steps in implicit analysis)

NEW!

Recommended for **implicit**:
Set IACC=1 in *CONTROL_ACCURACY
to make *MAT_024 always iterate

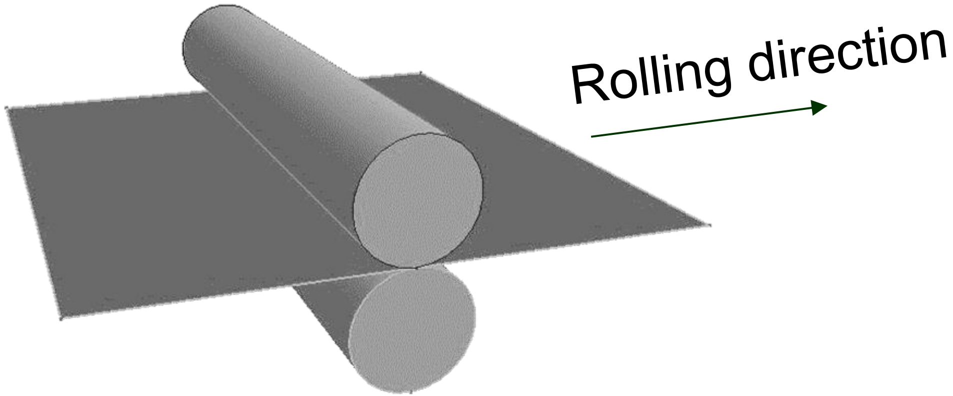
- The points between the rate-dependent curves are interpolated, either linearly or logarithmically
- The load curves are extrapolated in the direction of plastic strain by using the last slope of the curve
- No extrapolation is done in the direction of strain rate, i.e., the lowest (highest) curve defined 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*

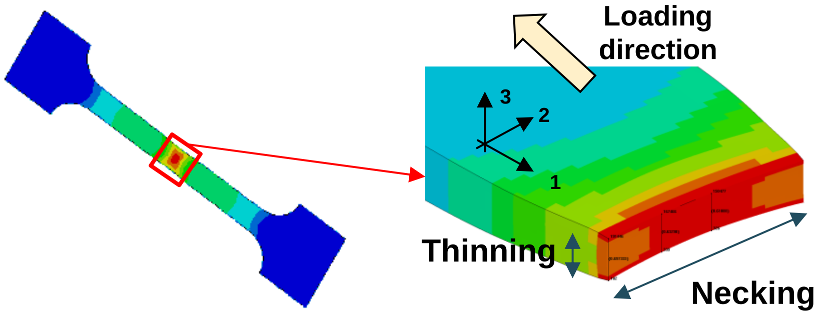


Anisotropy of metal sheets

The Lankford parameter (R-value)

- Definition

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



- Interpretation

$R = 1.0 \quad \rightarrow \quad \dot{\varepsilon}^p_{22} = \dot{\varepsilon}^p_{33} \quad \longrightarrow$ Necking and thinning are comparable

$R < 1.0 \quad \rightarrow \quad \dot{\varepsilon}^p_{22} < \dot{\varepsilon}^p_{33} \quad \longrightarrow$ Less necking, **More thinning**

$R > 1.0 \quad \rightarrow \quad \dot{\varepsilon}^p_{22} > \dot{\varepsilon}^p_{33} \quad \longrightarrow$ **More necking**, Less thinning

$R_{00} = R_{45} = R_{90} = 1 \quad \longrightarrow$ Isotropic material

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

$R_{00} \neq R_{45} \neq R_{90} \quad \longrightarrow$ *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

Anisotropic plasticity model

*MAT_3-PARAMETER_BARLAT (*MAT_036)

*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
$...
```

???

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

$R_{00} = 0.8$

$R_{45} = 1.0$

$R_{90} = 0.9$

σ_y, m

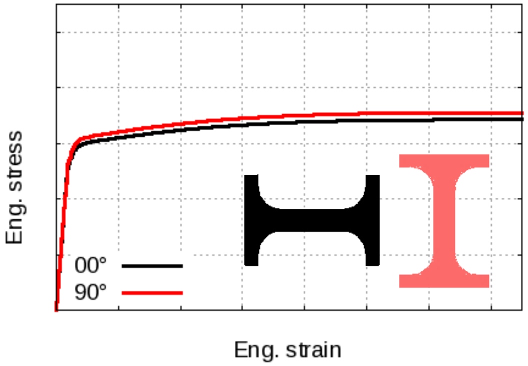
internal fitting

$a = \ldots$

$c = \ldots$

$h = \ldots$

$p = \ldots$



*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

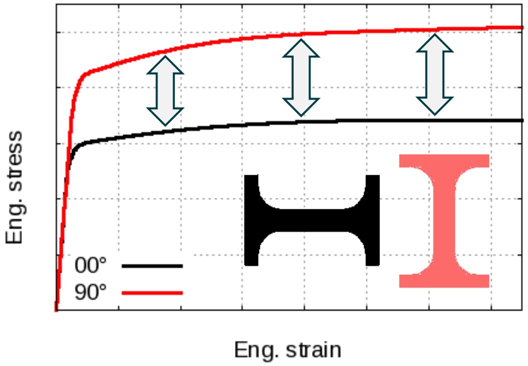
internal fitting

$a = \ldots$

$c = \ldots$

$h = \ldots$

$p = \ldots$



*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

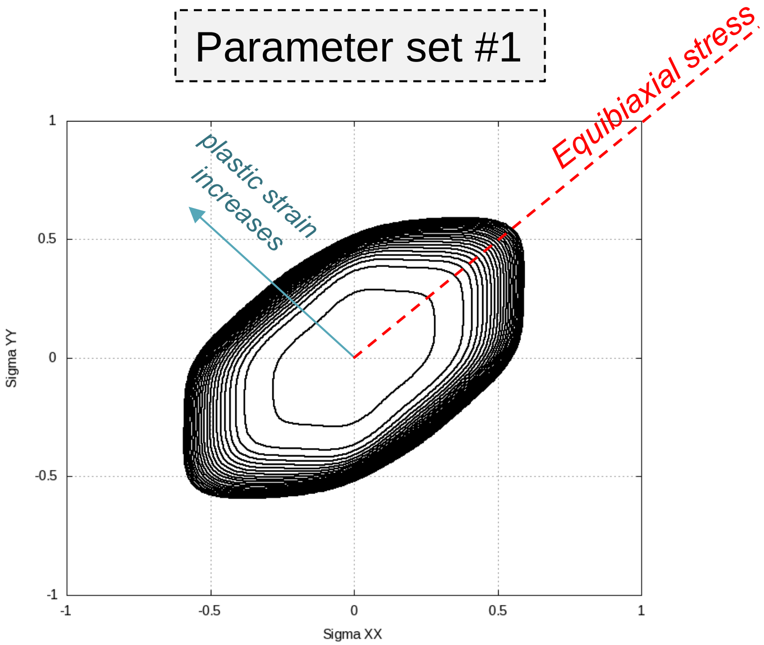
Hardening curve in the 0° direction

*MAT_036 + HR=7

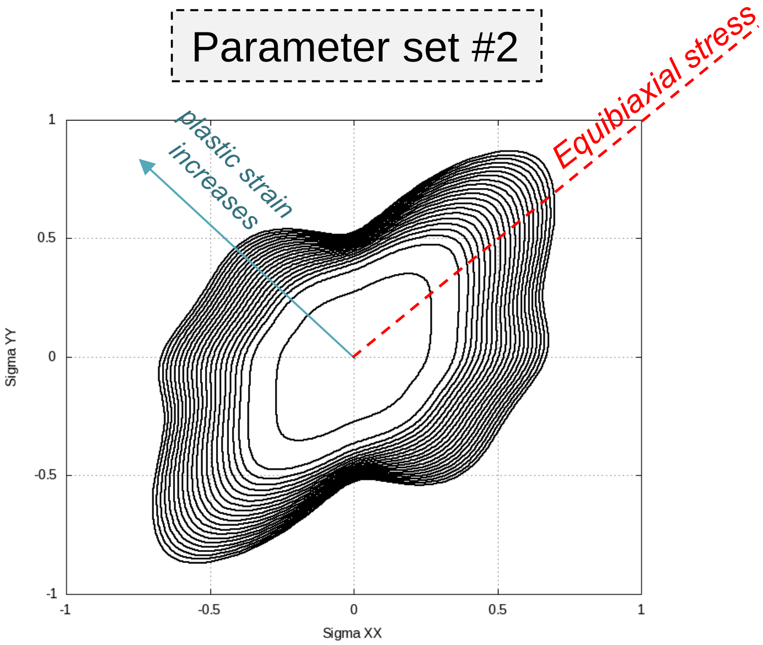
Yield surface

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

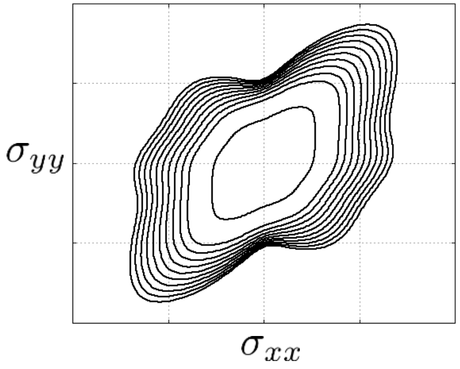
R-values in 0°, 45° and 90° directions:
- Negative values mean constant R-values
- Positive values correspond to the load curve IDs of variable R-values

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

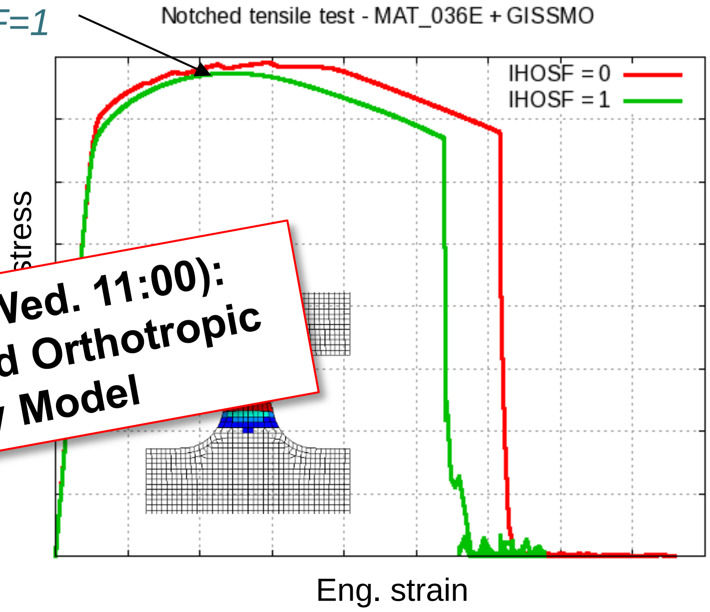
*MAT_036E

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

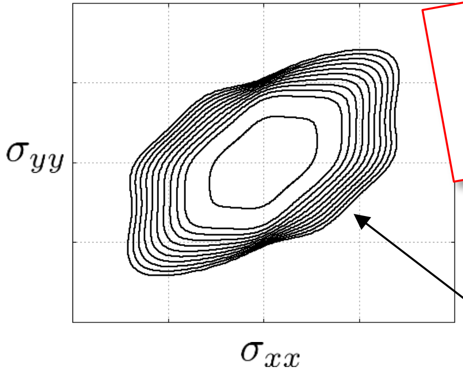
HOSF=0



No oscillations with HOSF=1



HOSF=1



Presentation (Wed. 11:00): A Hosford-based Orthotropic Plasticity Model

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

Material calibration

Material calibration

Overview of material models an the required tests

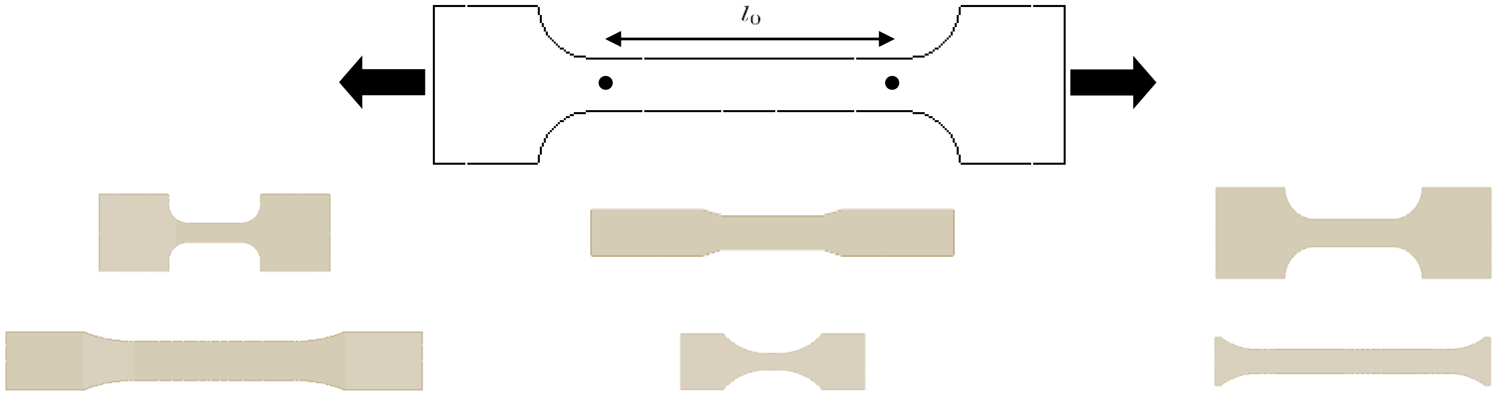
Material behavior \ Test	Quasi-static tensile	Quasi-static compression	Quasi-static Shear/biax	Dynamic tensile/bending	Cyclic tensile/bending/ compression
Elasticity	✓	(✓)	(✓)		
Visco-elasticity	✓	(✓)	(✓)	✓	✓
Plasticity	✓	(✓)	(✓)		
Visco-plasticity	✓	(✓)	(✓)	✓	
Damage	✓		✓	(✓)	

Workshop (Wed. 9:00): Failure prediction with GISSMO

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)

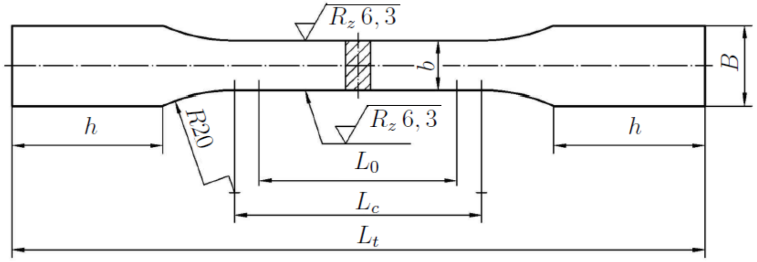


- different standards, e.g., for metallic materials DIN EN 10002

Calibration of yield curves

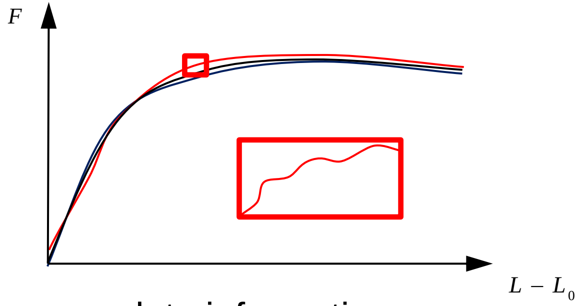
From test data to material input

- 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

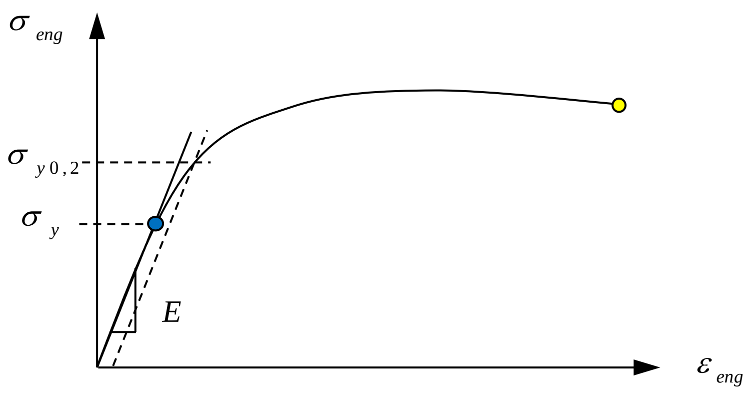
- smoothing, filtering and averaging
- start at (0, 0)

averaging of all test curves

Calibration of yield curves

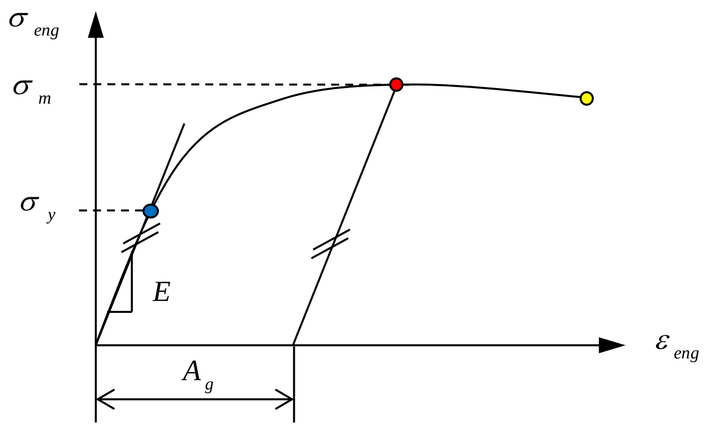
From test data to material input

- 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:

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

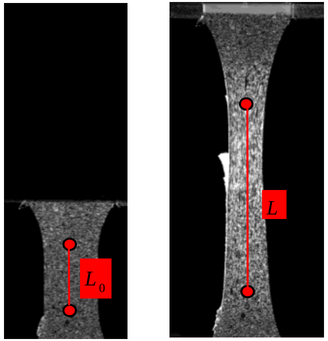
Calibration of yield curves

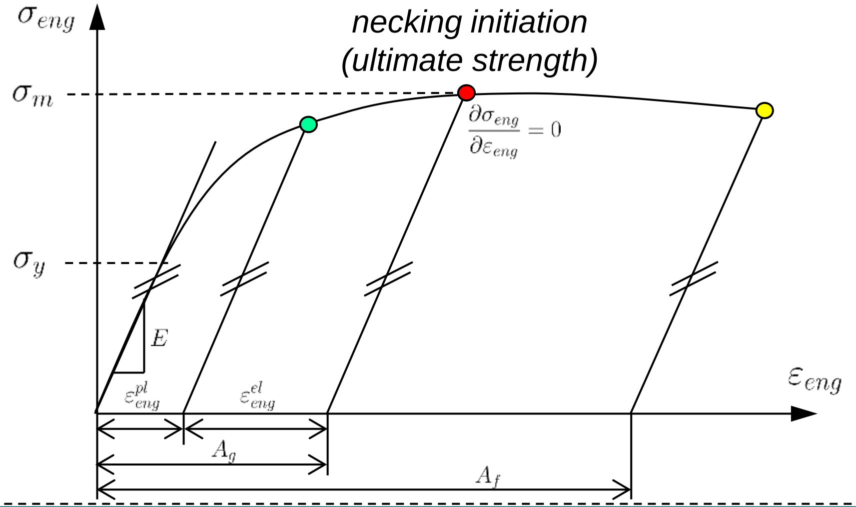
From test data to material input

- 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

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

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



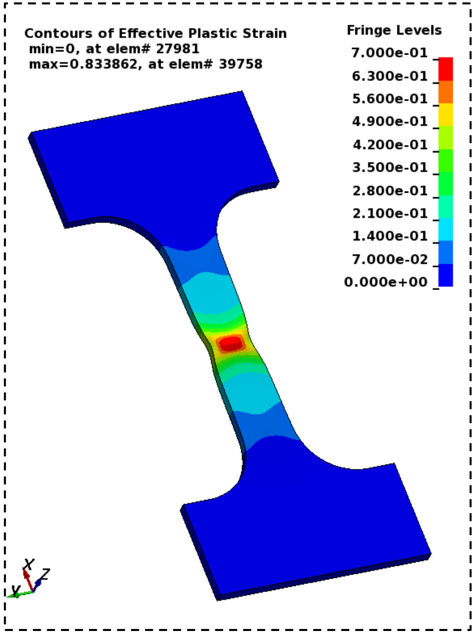


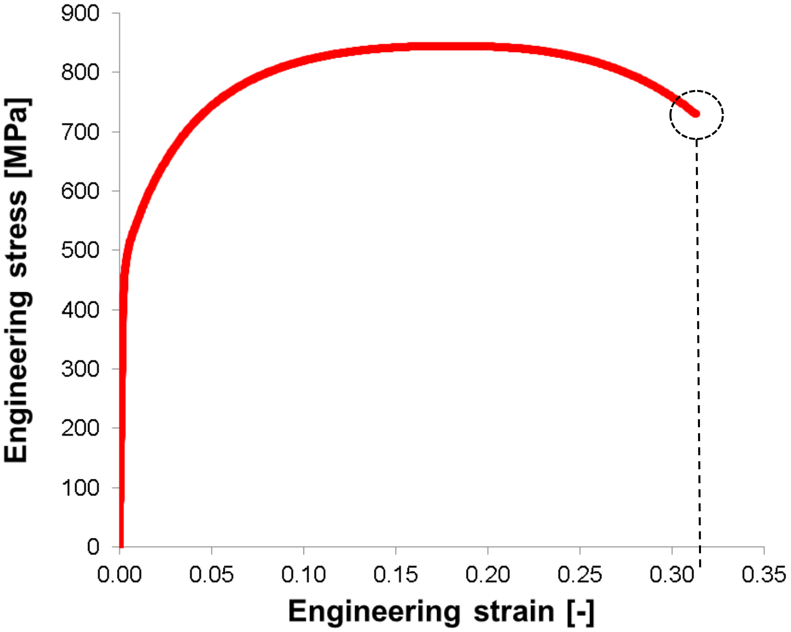
Behavior after necking initiation is unstable:

- 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

Difference between engineering and true strain





Max. true plastic strain: 70%

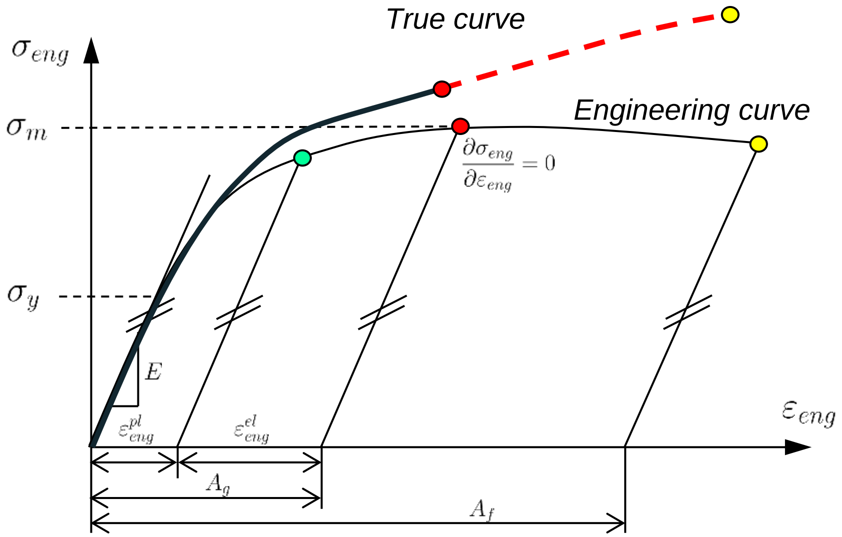
Max. engineering strain: 32%

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

Calibration of yield curves

Parametrization of the yield curve

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

$$\sigma_y = \sigma_{eng}(1+\varepsilon_{eng})$$

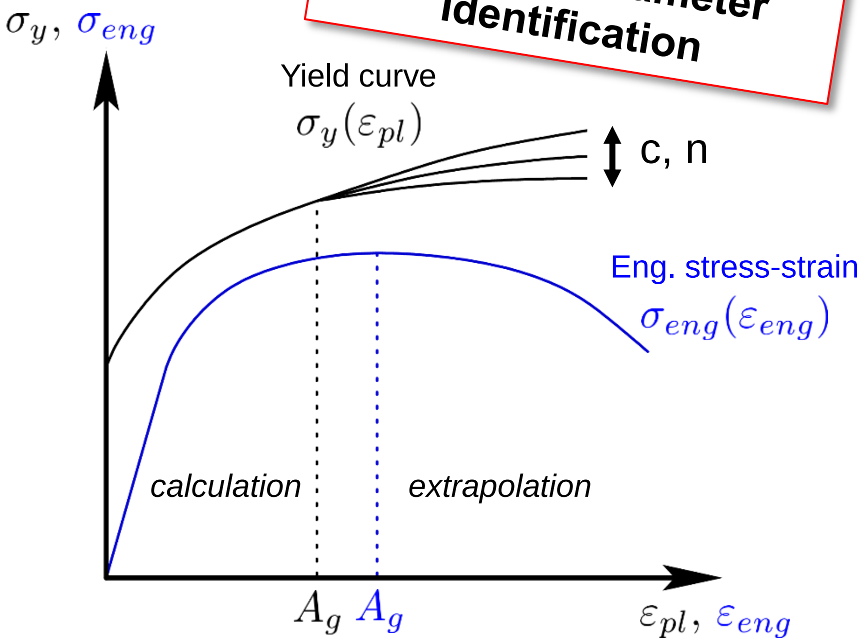
$$\varepsilon_{pl} = \ln(1+\varepsilon_{eng}) - \frac{\sigma_{eng}}{E}$$

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



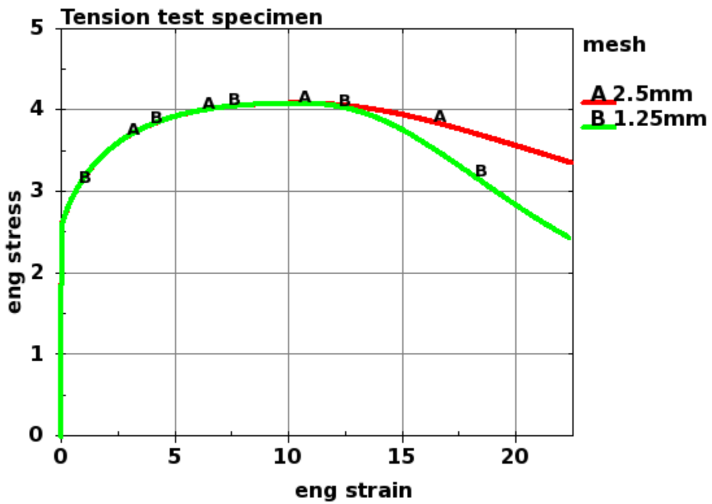
➢ Remaining variables c and n are the remaining free parameters

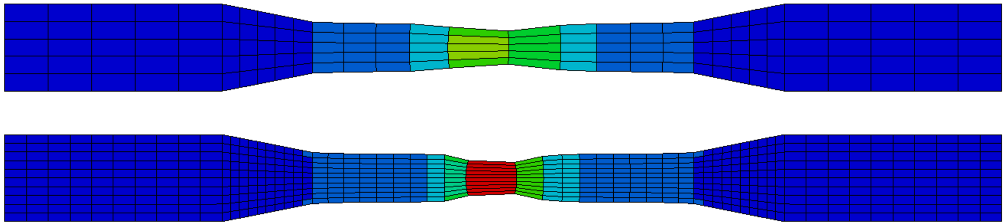
Calibration of yield curves

Element size dependence

Workshop (Wed. 9:00): Failure prediction with GISSMO

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!

The lab @ DYNAmore

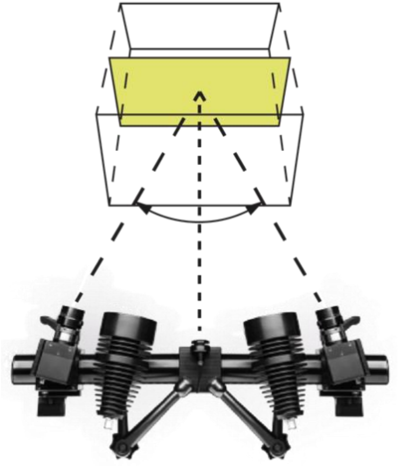
On site material testing

Testing equipment

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

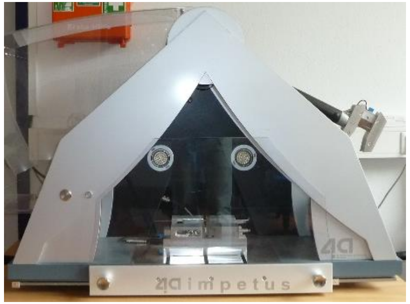
- Tension
- Compression
- Shear
- Biaxial
- Bending
- Cyclic

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)



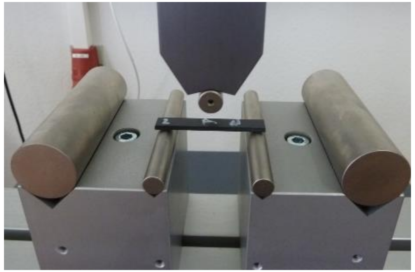
- Bending (plastics, composites)
- Compression (foam)

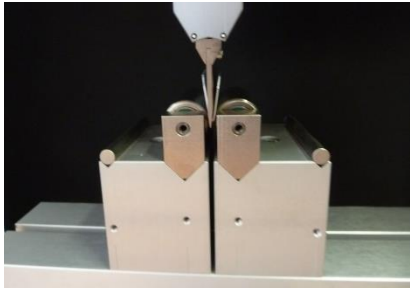
Workshop (Tue. 11:00): VALIMAT

On site material testing
Testing equipment

Quasi-static tension

Quasi-static bending





Quasi-static compression

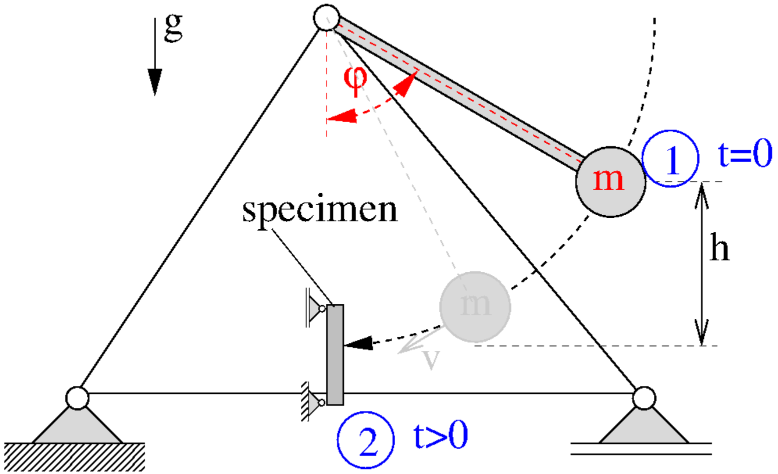
Quasi-static biax

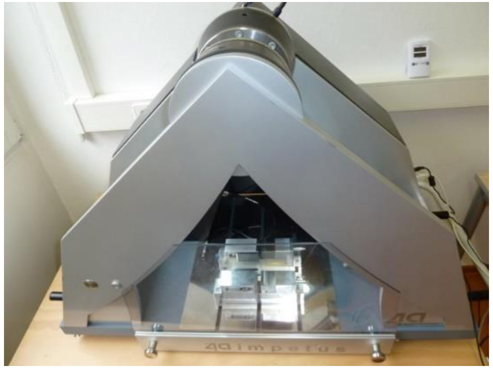
Testing and modelling of foams using

*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 $W_{pot} = mgh$

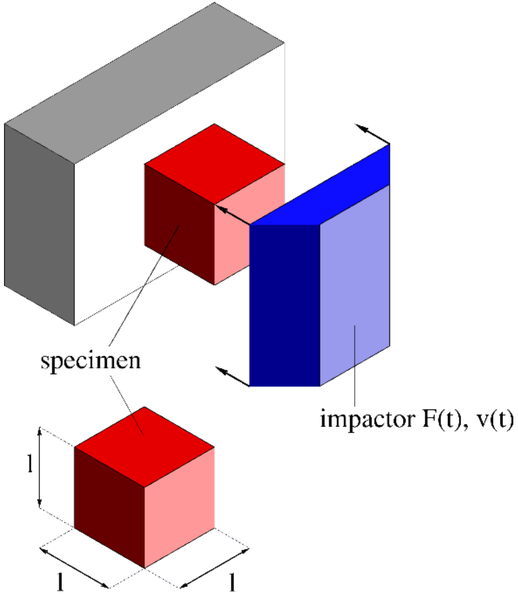
t>0: m moves from 1 to 2
W_{pot} changes to $W_{kin} = \frac{1}{2}mv^2$

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 adhevive tape
- variation of nominal strainrate $\dot{\varepsilon}$ due to
  - different specimen size l
  - different initial velocities v

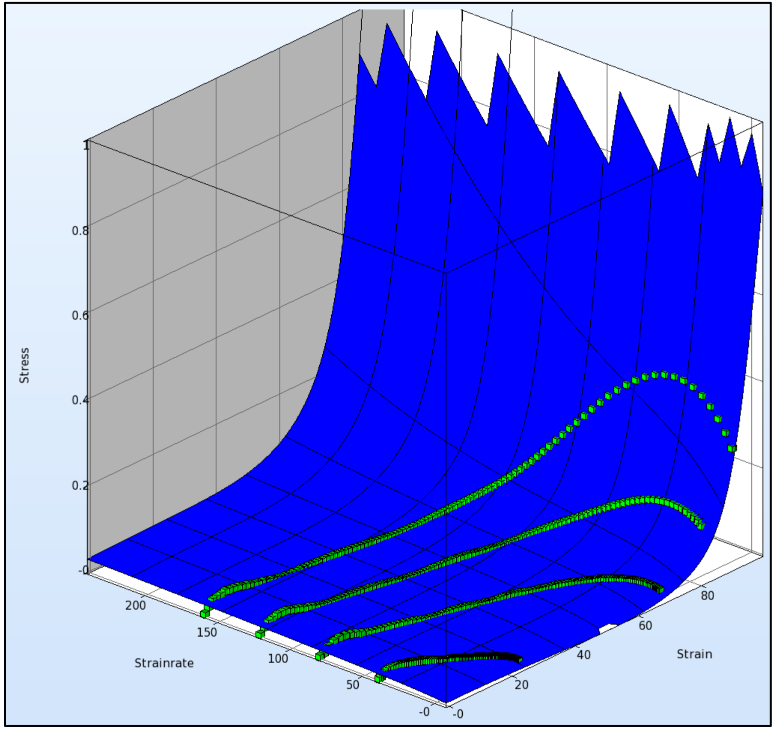
strain rate in 1/s	l in mm	v in m/s
0.001	20	0.00002
0.01	20	0.0002
0.1	15	0.0015
0.3	15	0.0045
40	20	0.8
100	15	1.5
200	20	4.0



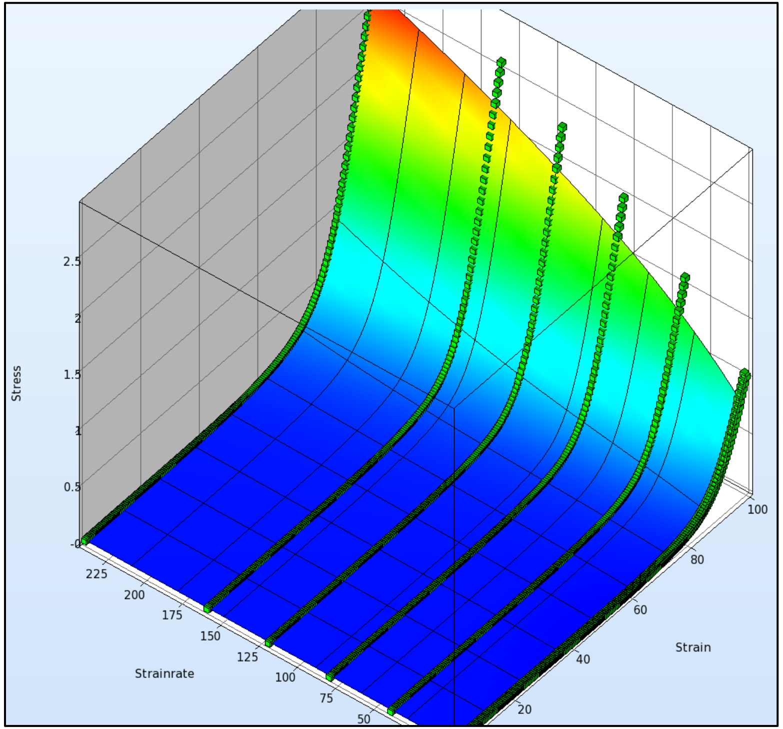
nominal strain rate: $\dot{\varepsilon} = \frac{v}{l}$

Example: LS-OPT meta model

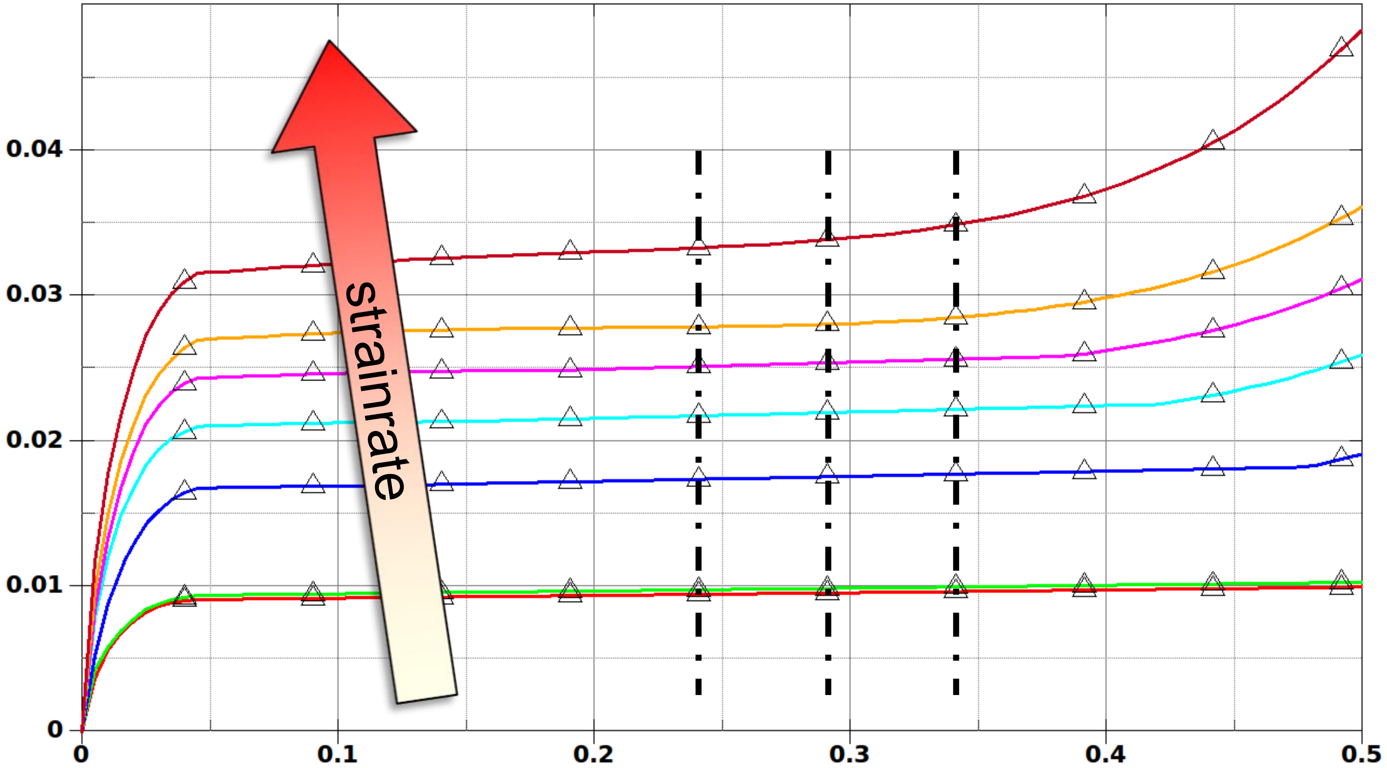
Stress strain cuves from Experiment

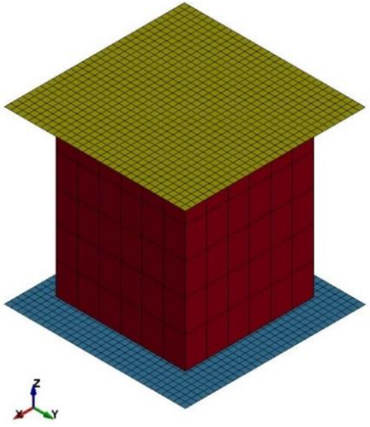


Stress Strain curves with constant strain rates



Example: Fu-Chang-Foam



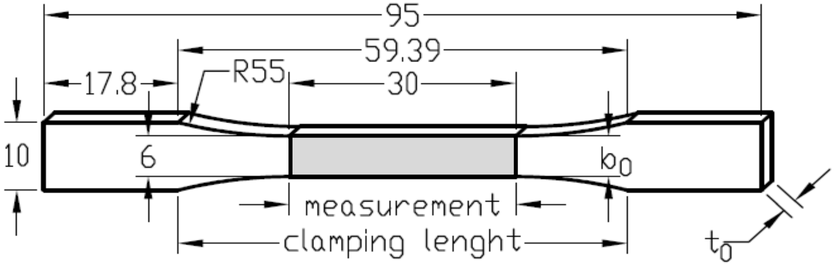


Testing and modelling of Polymers using

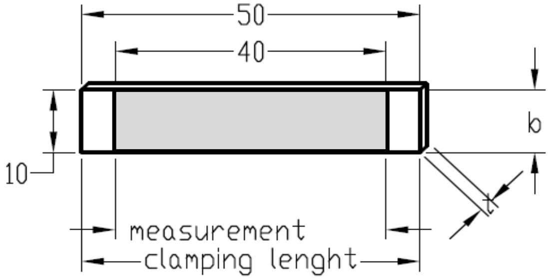
*MAT_SAMP (*MAT_187)

Specimen

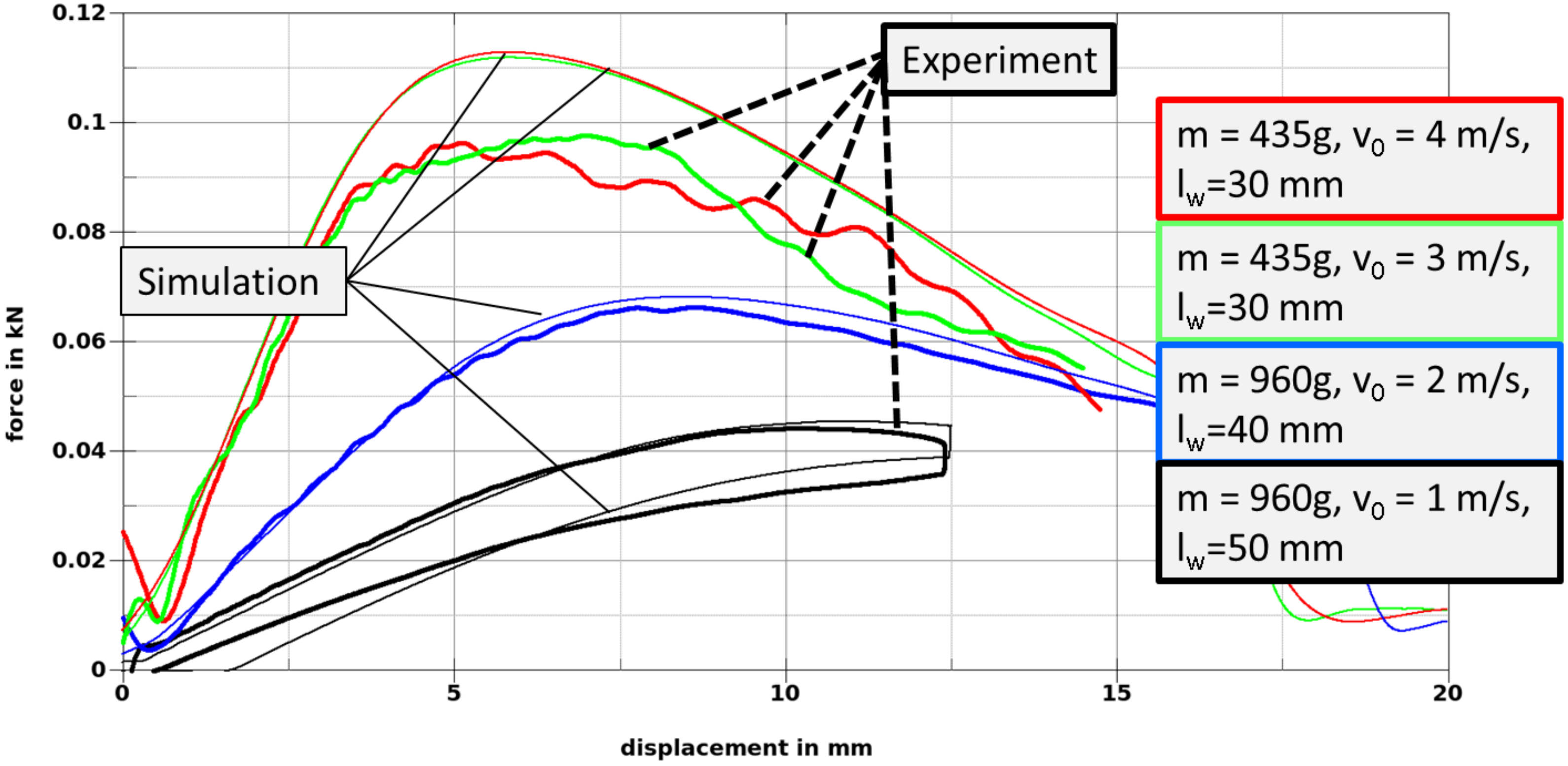
- Tensile specimen
  - static and dynamic tests
  - Strain via DIC
  - Engineering strain with l_0=30 mm
  - Target mesh size: 2mm
  - Milled specimen



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

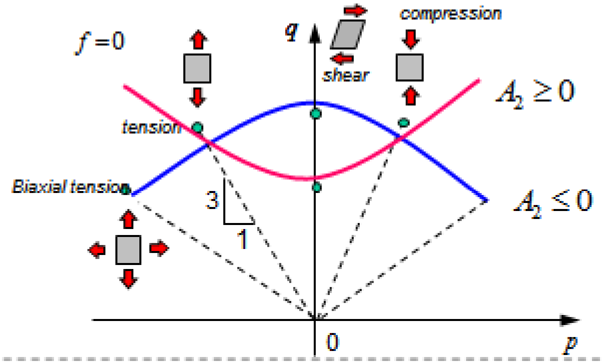


Results of MAT_024 + GISSMO card: bending tests



Material modelling of polymers in LS-DYNA

Isotropic plasticity with SAMP-1 (*MAT_187)

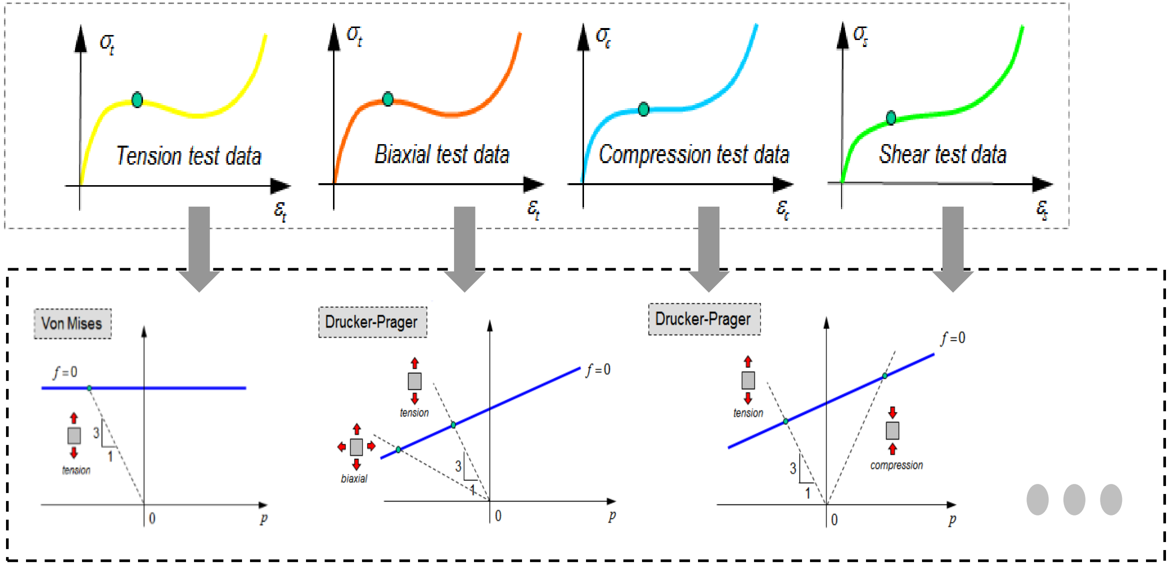


Yield surface:

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

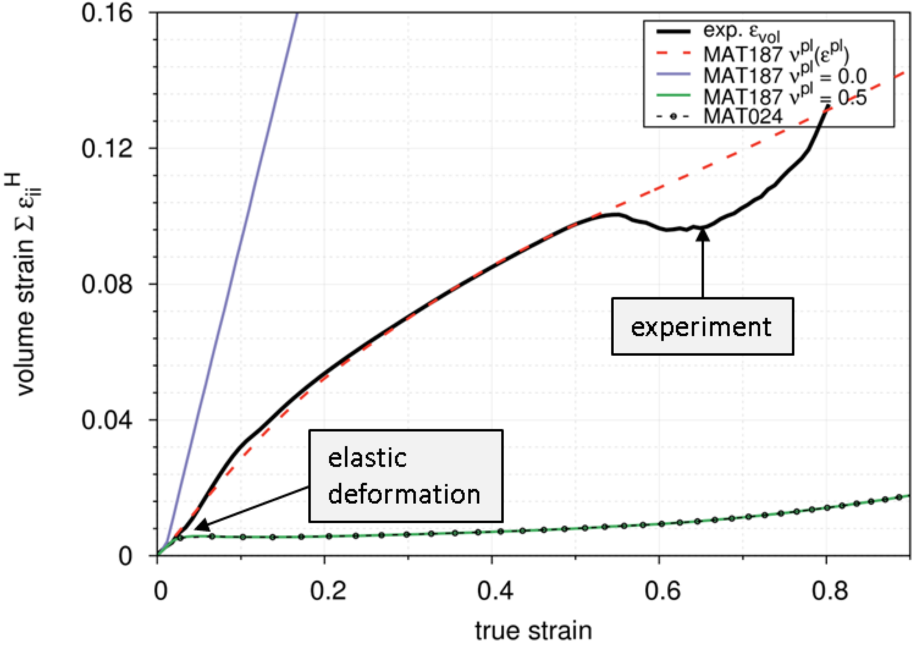
Condition for convexity :

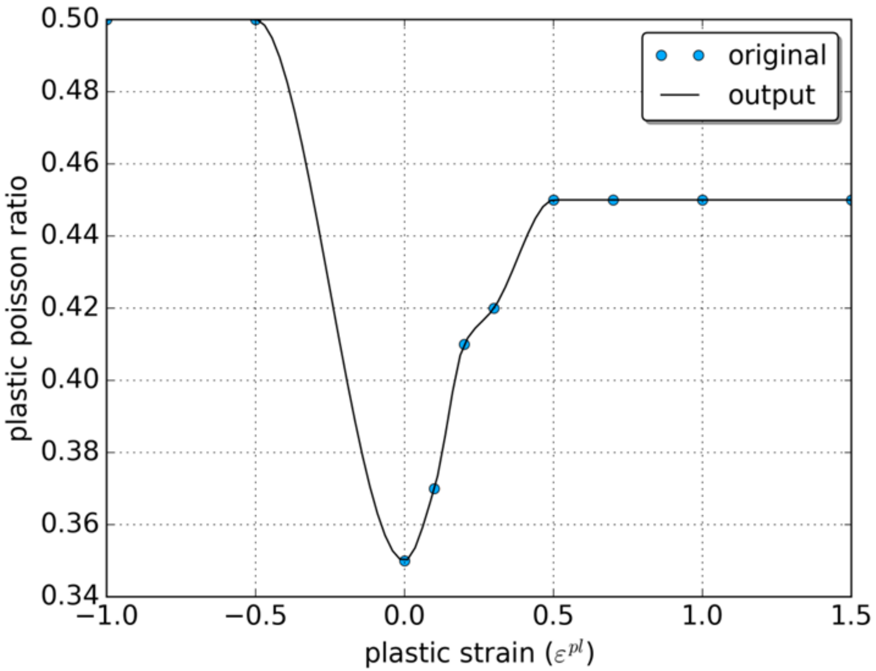
$$A_2 \le 0 \Leftrightarrow \sigma_s \ge \frac{\sqrt{\sigma_t \sigma_c}}{\sqrt{3}}$$



- ➢ Dependency of plastic poisson ratio

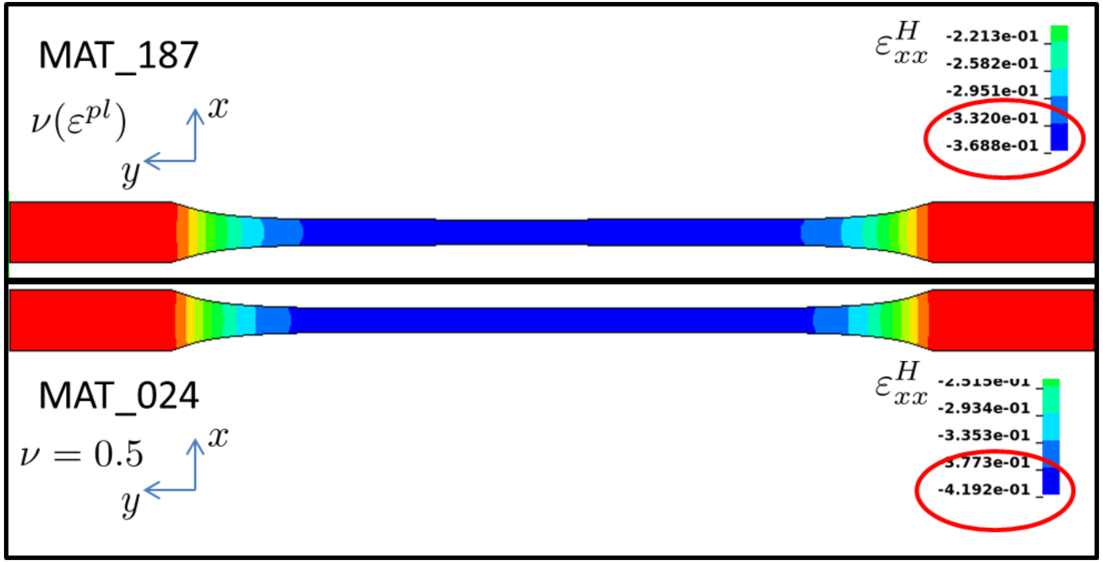
SAMP#1: plastic poisson‘s ratio





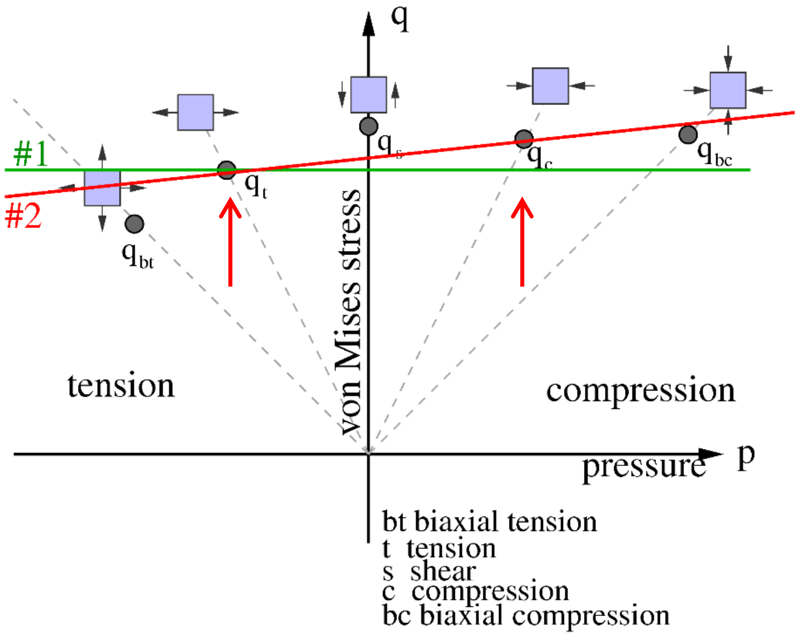
SAMP#1: plastic poisson‘s ratio

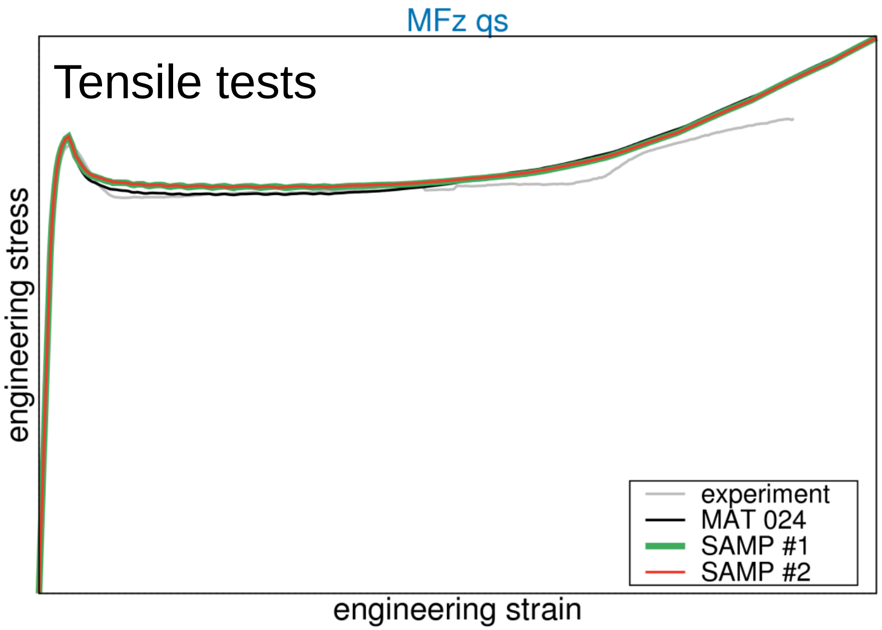
- Taking ratio into account:
  - influence on strain transversal to loading direction
  - influence plastic strain at notch tip
  - important for complex FE-models



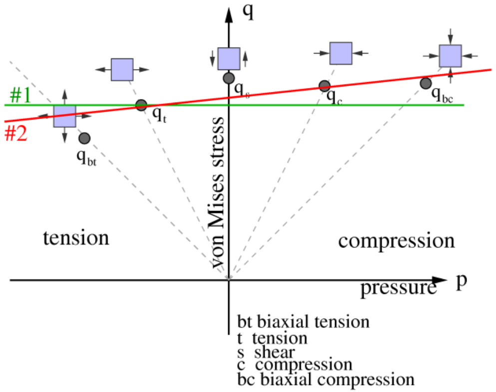
➢ Important for simulation of thermoplastics with increasing macroscopic volume (e.g. Crazing at ABS, HIPS, PC/ABS

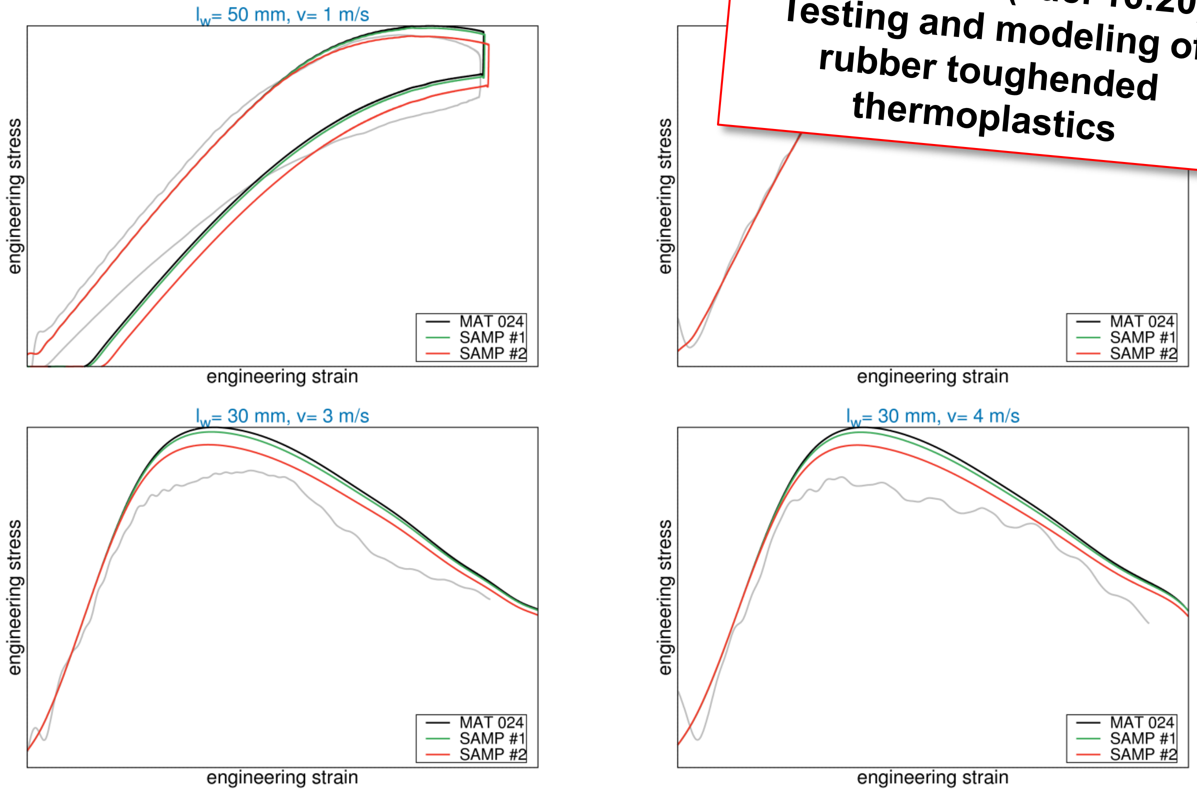
SAMP #2: taking compression into account





Bending results





Presentation (Tue. 16:20): Testing and modeling of rubber toughended thermoplastics

Experimental material characterization at DYNAmore Stuttgart

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- **Services**
  - Material deformation characterization and LS-DYNA material model calibration for: **Polymers, Foams, Metals**
  - Experiments
    - Tensile, bending, compression, punch test
    - Component testing
    - Local strain analysis with DIC
  - Damage and fracture characterization and calibration for GISSMO and eGISSMO models