16th LS-DYNA Forum 2022, Bamberg, Germany

GISSMO: Application to polymers

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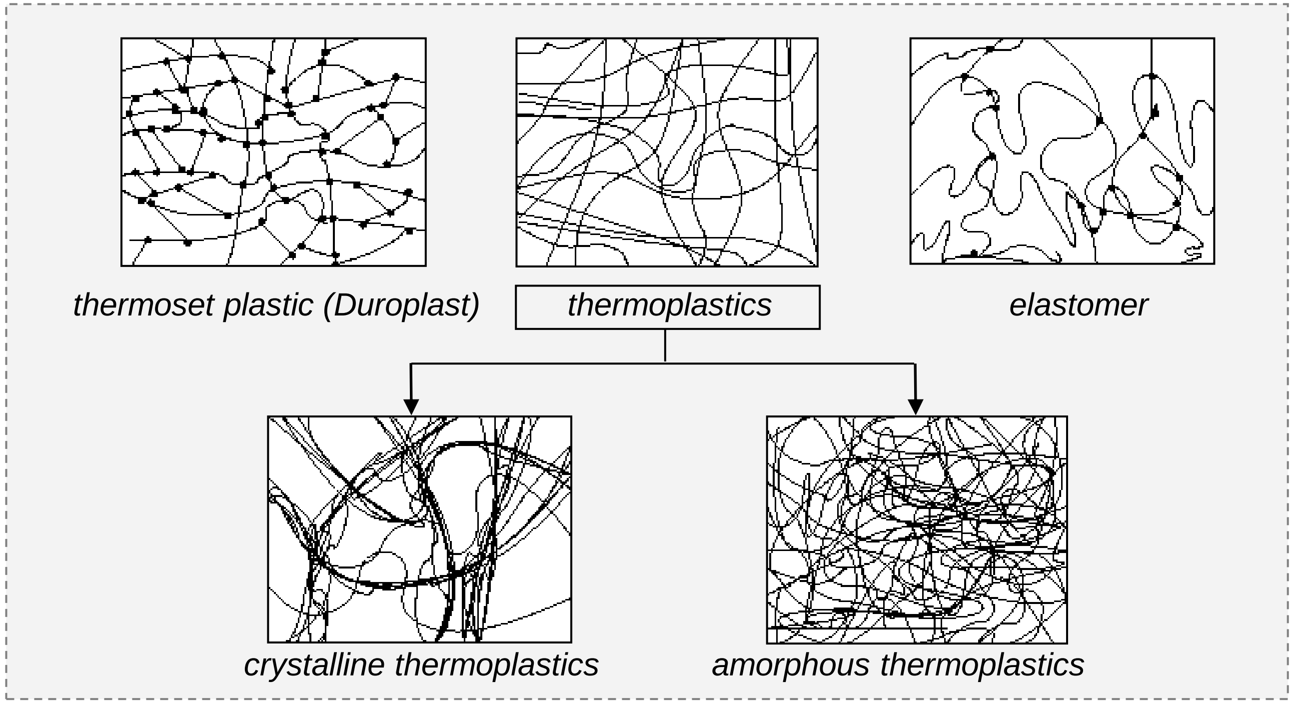
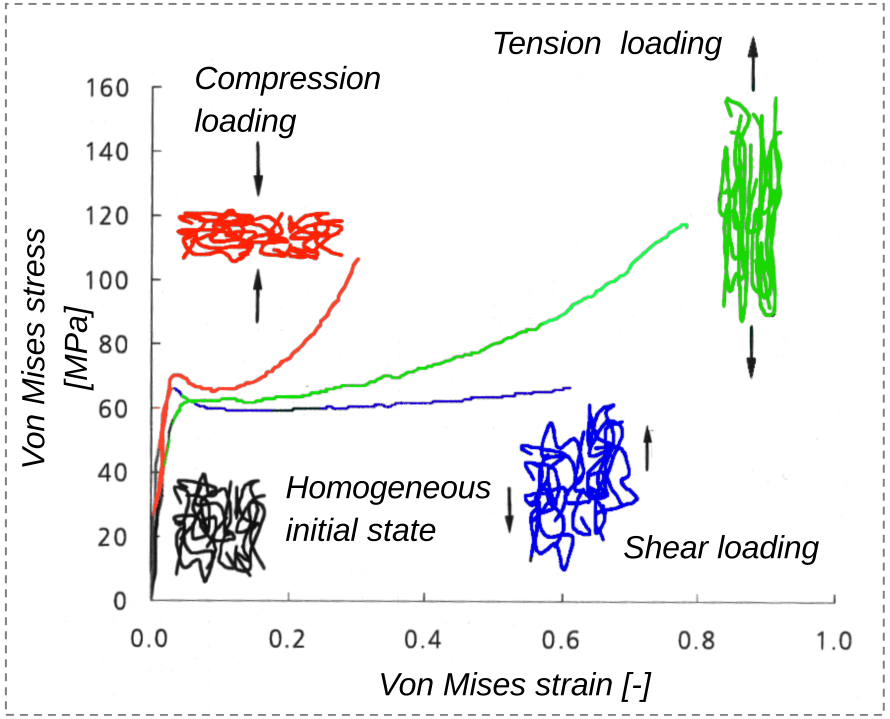
Mechanical behavior of polymers

Thermoplastics

- Polymers often exhibit anisotropic behavior
- Non-isochoric (i.e., compressible) behavior is also often observed at moderate and large deformations
- Damage evolution can be triggered by deviatoric and hydrostatic contributions

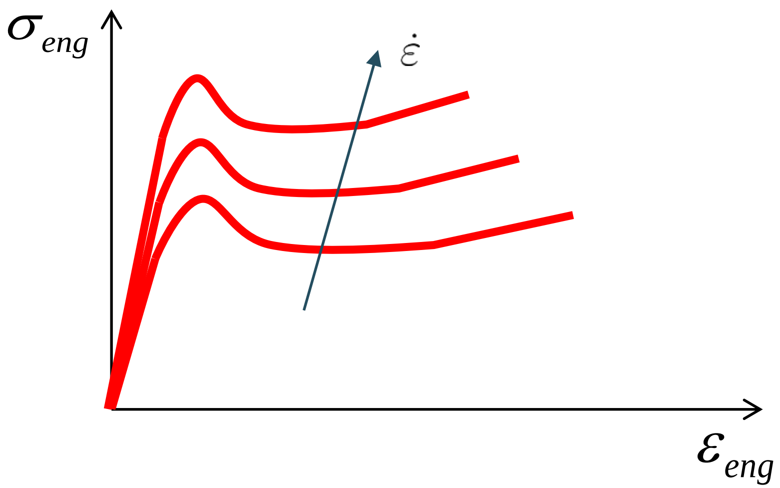




Thermoplastics

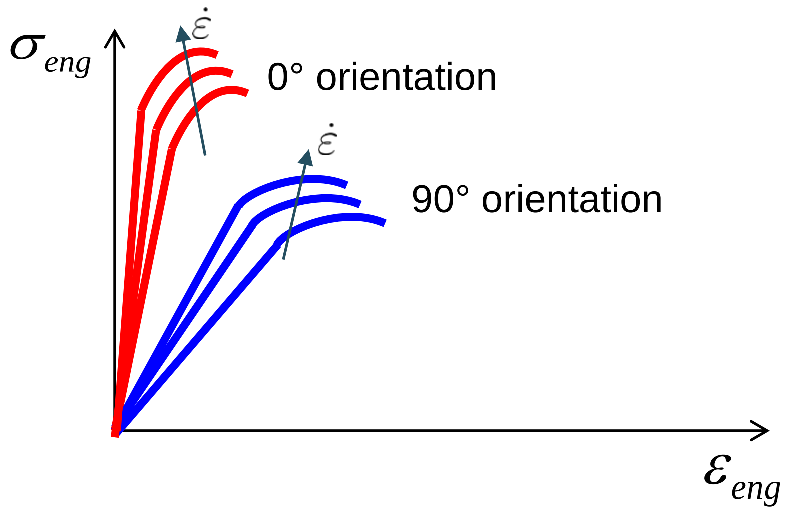
Typical behavior of thermoplastics used in structural applications

Unreinforced plastics



- **Ductile behavior → "telescope" effect**
- Nearly isotropic
- **Strain rate dependent (often viscoelastic)**
- Non-isochoric behavior

Reinforced plastics

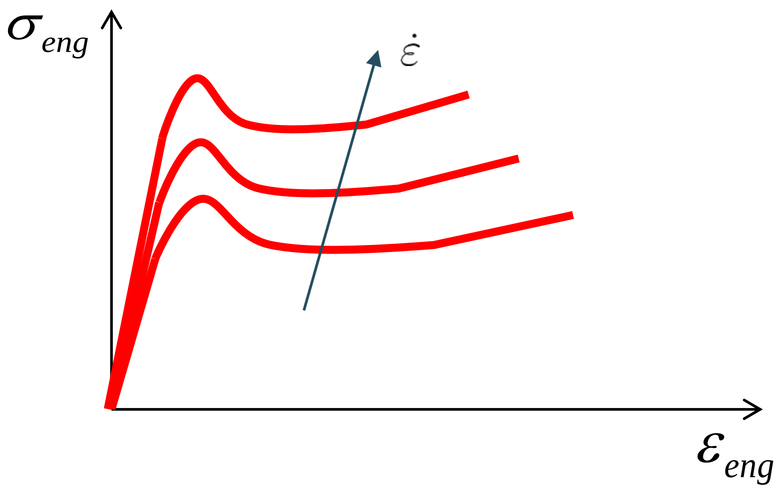


- Brittle behavior → no "telescope" effect
- **Highly anisotropic**
- **Strain rate dependent (often viscoelastic)**
- Non-isochoric behavior

Thermoplastics

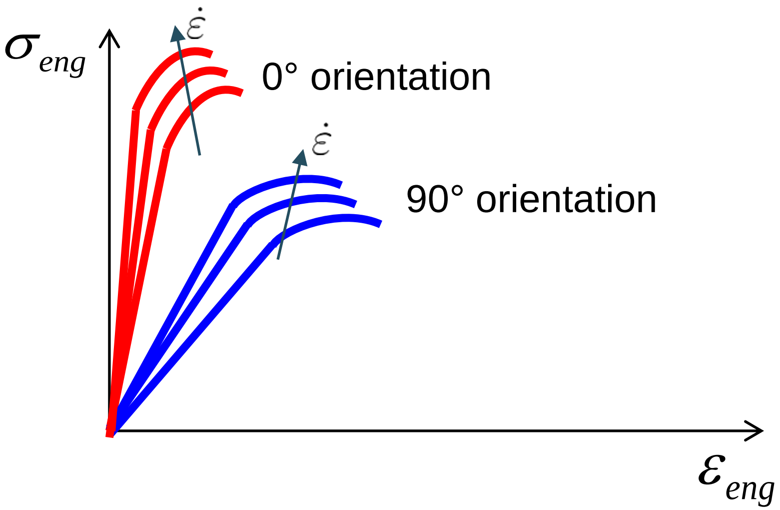
Challenges for the modeling and options in LS-DYNA

Unreinforced plastics



- **Ductile behavior + Strain-rate sensitivity**
- *MAT_024 + GISSMO
- *MAT_187/L + (e)GISSMO
  - With ν_p to capture the transversal behavior
  - With compression yield curve (tension / compression asymmetry)

Reinforced plastics

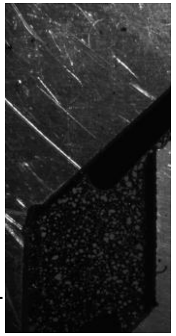


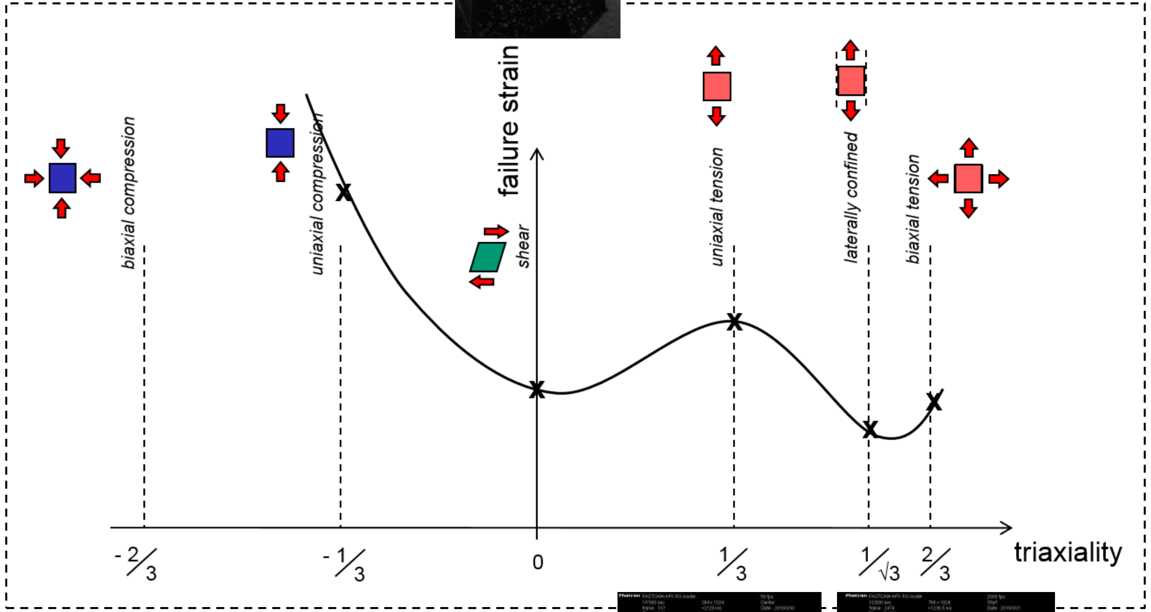
- **Highly anisotropic response**
- At a fixed direction: *MAT_024 + GISSMO
- Every direction: *MAT_157 + (e)GISSMO

Failure modeling with GISSMO

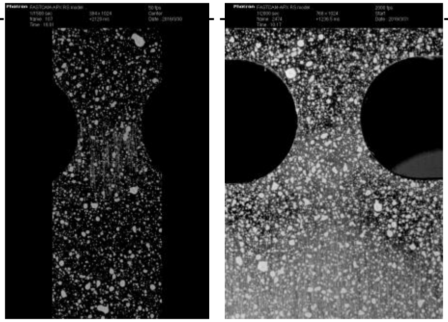
Failure of plastic materials is dependent on the stress triaxiality ratio

Shear specimen





Notched specimen

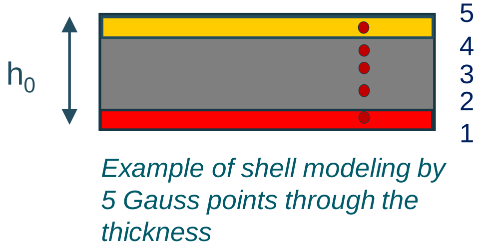


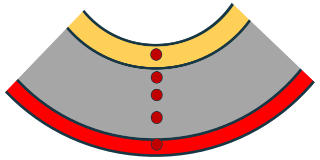
Current situation:

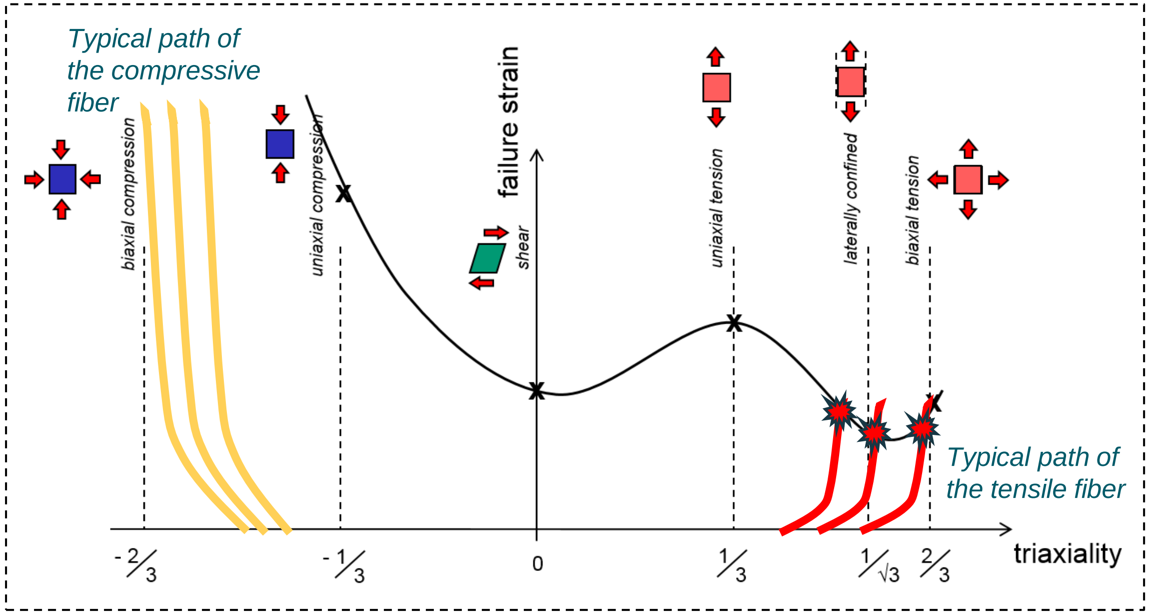
- Standard experiments for triaxiality ratios other than 1/3 do not typically deliver the expected results.
- Either the deformation process (high ductility) or the failure mechanism leads the stress-state of the shear or notched specimen out of the desired stress-state.
- Compression tests are always tricky to be performed due to the likely buckling of slender specimens: Injection mold technology ought to work with small thicknesses.
- Bending tests are then usually considered. They are easy to perform but convey a non-constant triaxiality ratio across the specimen thickness.

Failure modeling with GISSMO

Can we use bending tests to characterize the failure curve?







Current situation:

- Bending tests provide at least a qualitative information for the failure mechanism at tensile and at compressive stress-state.
- As expected they suggest a weaker failure strain at tensile as at compression, since the specimen starts yielding by the outer fiber subjected to tensile stress.
- Every failure curve that is able to provide this behavior is a good candidate.
- Bending tests can therefore be useful for the calibration of the GISSMO modeling.

How can one reach a triaxiality dependent failure curve?

Defining a failure curve

Cockcroft & Latham criterion

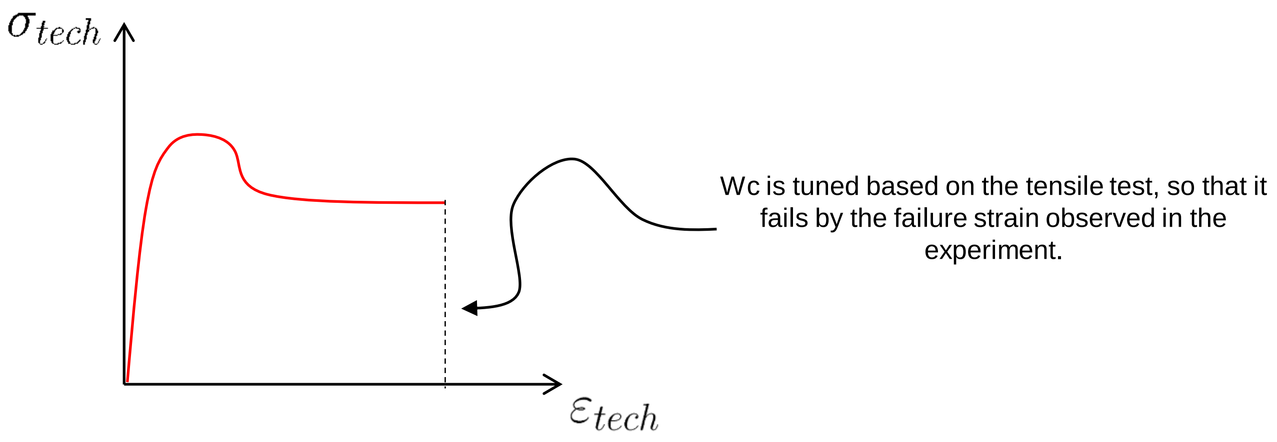
Failure curve for GISSMO

Proposal: Cockcroft & Latham (1968) Criterion

- Cockcroft & Latham proposed an energy criterion which is based on the first principal stress as a trigger for the failure:

$$W = \int_0^{\varepsilon_f} \max(\sigma_1, 0)\, d\varepsilon^p \leq W_c$$

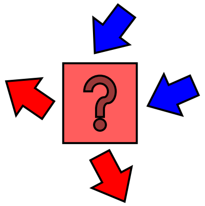
- The failure takes place if W reaches a critical value W_c. For the GISSMO failure curve to be generated the critical value W_c can be estimated from the failure strain of the tensile test.



Failure curve for GISSMO

*MAT_024: Von Mises or J2-Plasticity

- A general plane stress state is represented in principal directions by the following stress tensor:



$$\boldsymbol{\sigma} = \begin{pmatrix} \sigma_1 & 0 \\ 0 & k\sigma_1 \end{pmatrix}$$

$$p = -\frac{1}{3}\sigma_1(1+k)$$

$$\sigma_{eq} = \sigma_1\sqrt{1+(k-1)k}$$

$$\eta = \frac{-p}{\sigma_{eq}} = \frac{\frac{1}{3}(k+1)}{\sqrt{1+(k-1)k}}\mathrm{sign}(\sigma_1)$$

- The yield function defines the plastic stress state by imposing:

$$\sigma_{eq} - \sigma_y^t(\varepsilon^p) = 0$$

- From which the first principal stress results in:

$$\sigma_1 = \frac{\sigma_y^t(\varepsilon^p)}{\sqrt{1+(k-1)k}}$$

In the case of uniaxial tensile the first principal stress collapses to:

$$k = 0 \Rightarrow \sigma_1 = \sigma_y^t$$

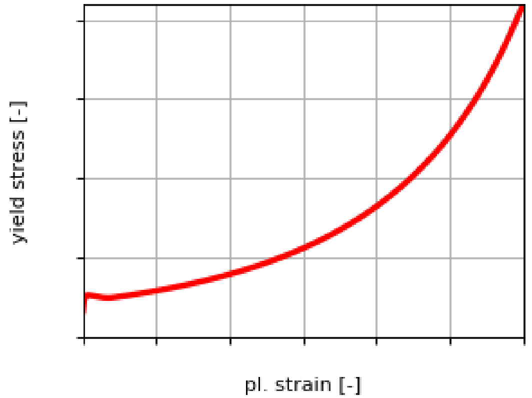
Failure curve for GISSMO

*MAT_024: Von Mises or J2-Plasticity

- The failure curve comes from solving the energy criterion at fixed triaxiality ratios or stress ratios *k*

$$W = \int_0^{\varepsilon_f} \frac{\sigma_y^t(\varepsilon^p)}{\sqrt{1+(k-1)k}} d\varepsilon^p \leq W_c^*$$

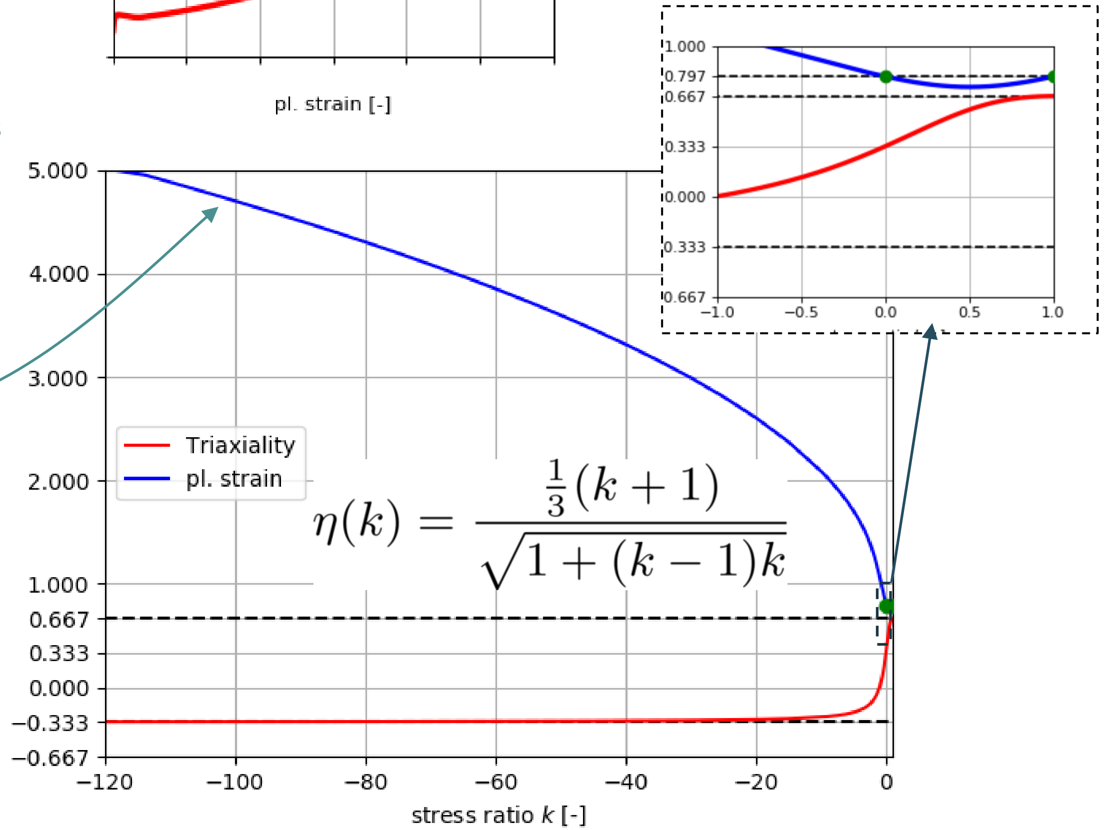
Typical flow curve for non-reinforced polymers



- The solution gives the failure pl. strain ε_f at which failure takes place:

$$\varepsilon_f(k) = f(k)$$

Solution of the energy criterion in terms of the stress ratio



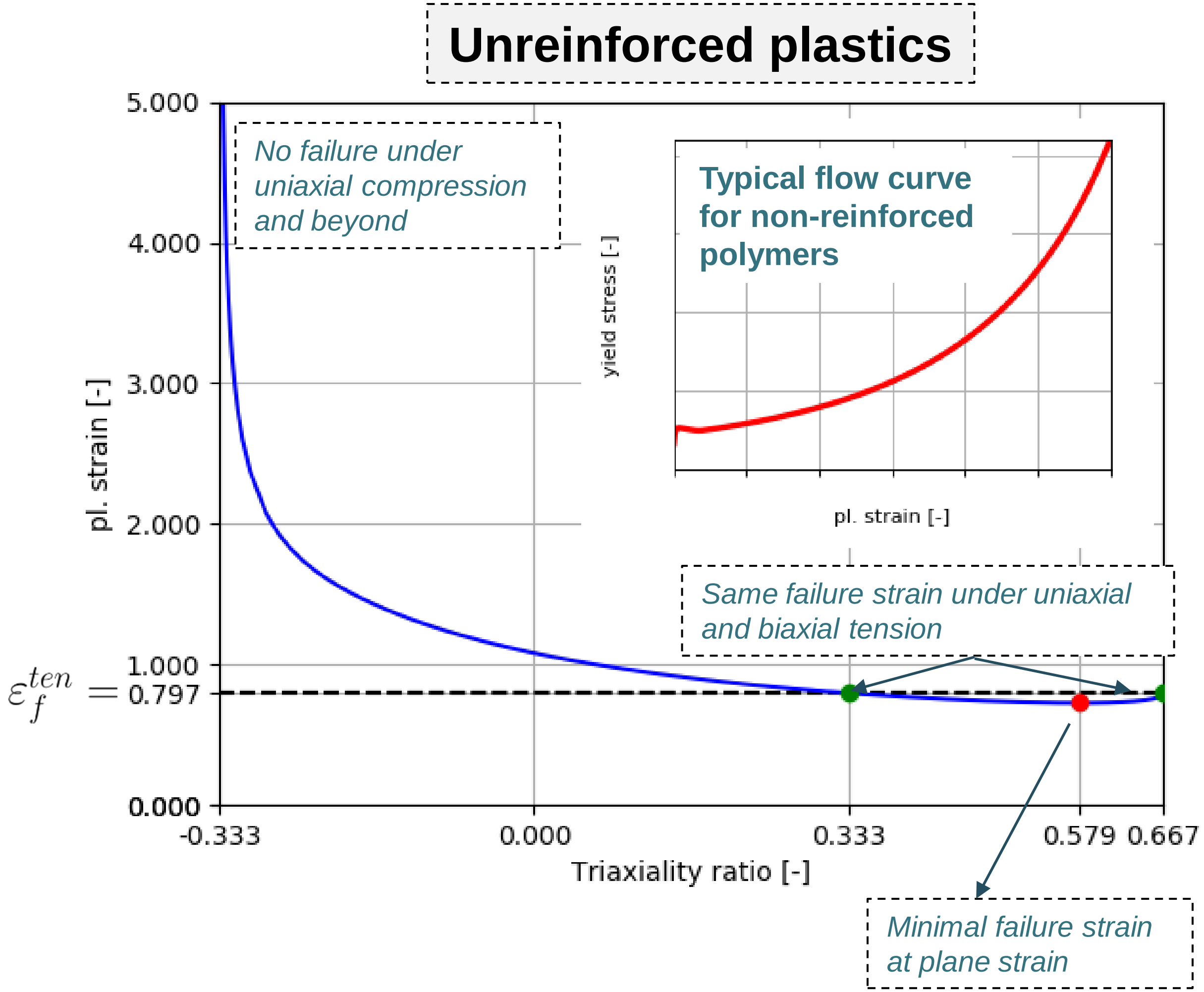
$$\eta(k) = \frac{\frac{1}{3}(k+1)}{\sqrt{1+(k-1)k}}$$

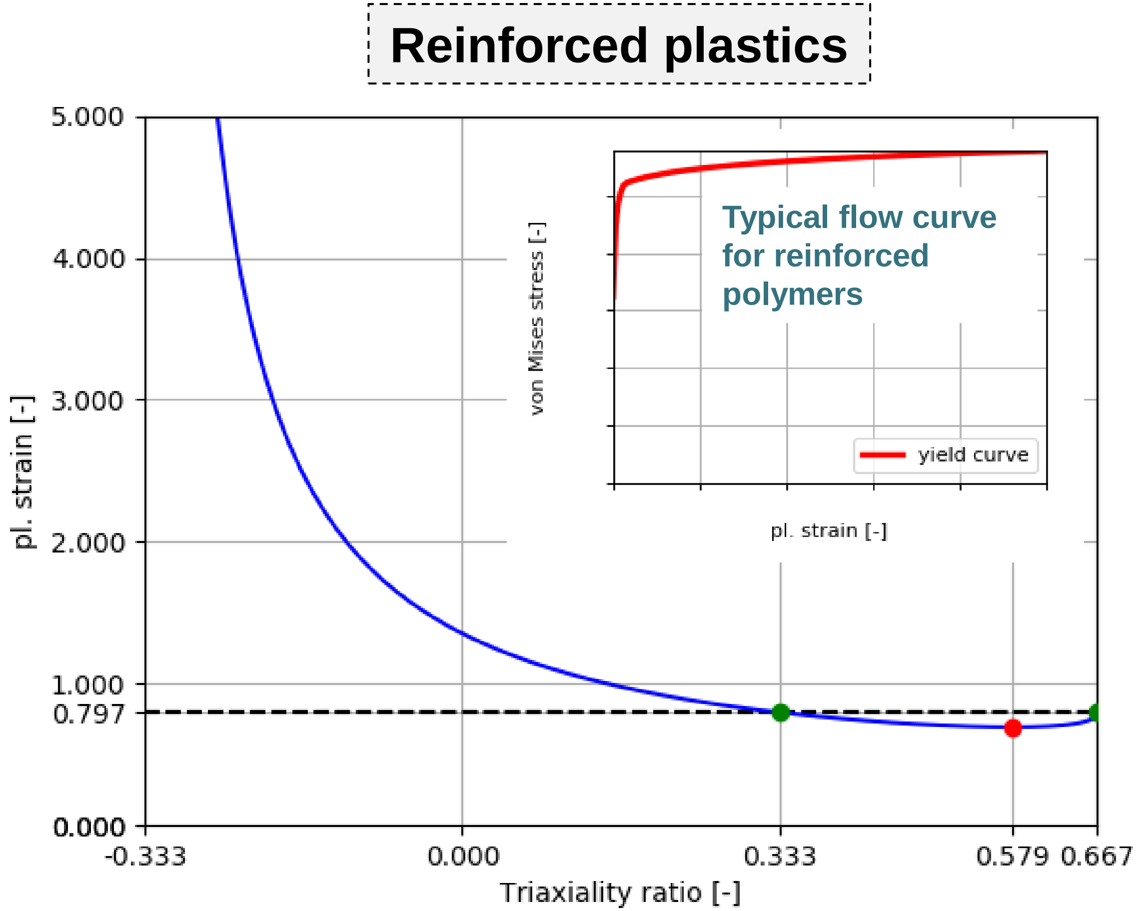
- A first estimation for the W_c^* can be extracted from the failure strain of the tensile test, assuming *k*= 0 or η=1/3:

$$W = \int_0^{\varepsilon_f^{ten}} \sigma_y^t(\varepsilon^p) d\varepsilon^p \leq W_c^*$$

Failure curve for GISSMO

Qualitative analysis of the failure curve provided by the Cockcroft-Latham
Influence of the yield curve on the shape of the failure curve

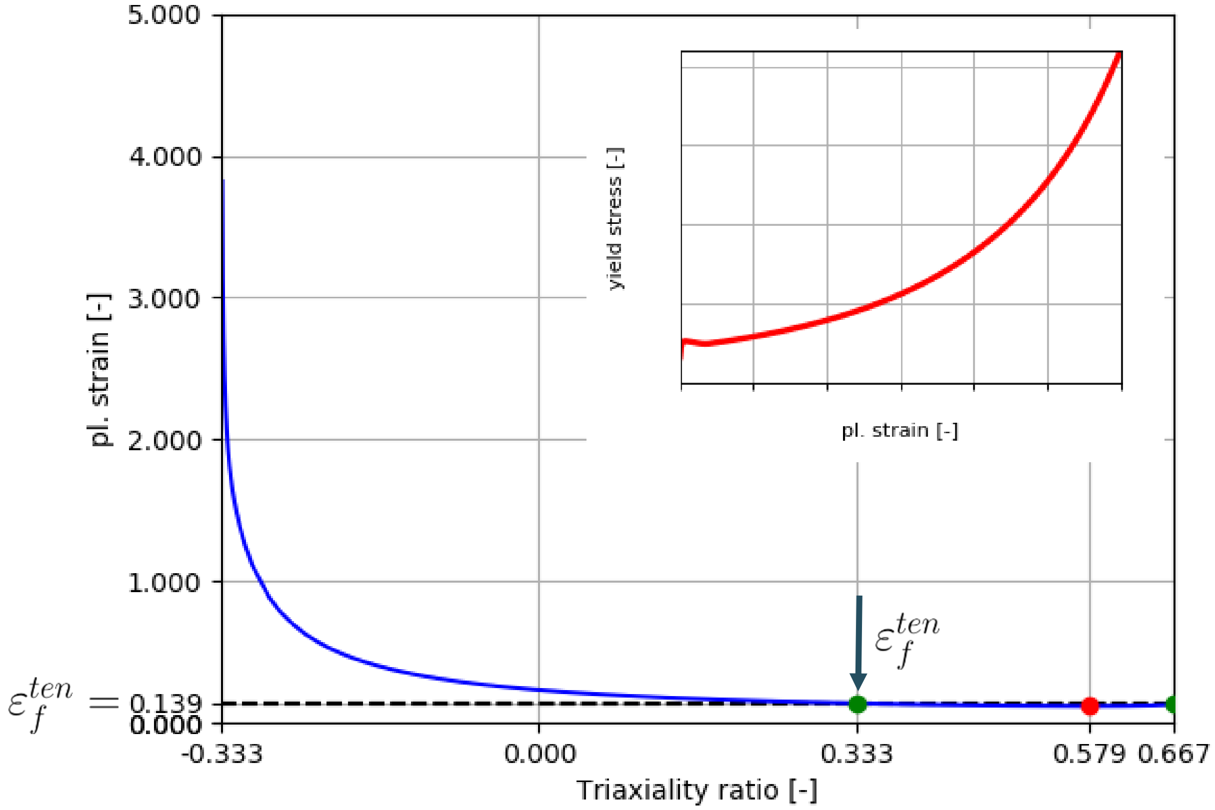




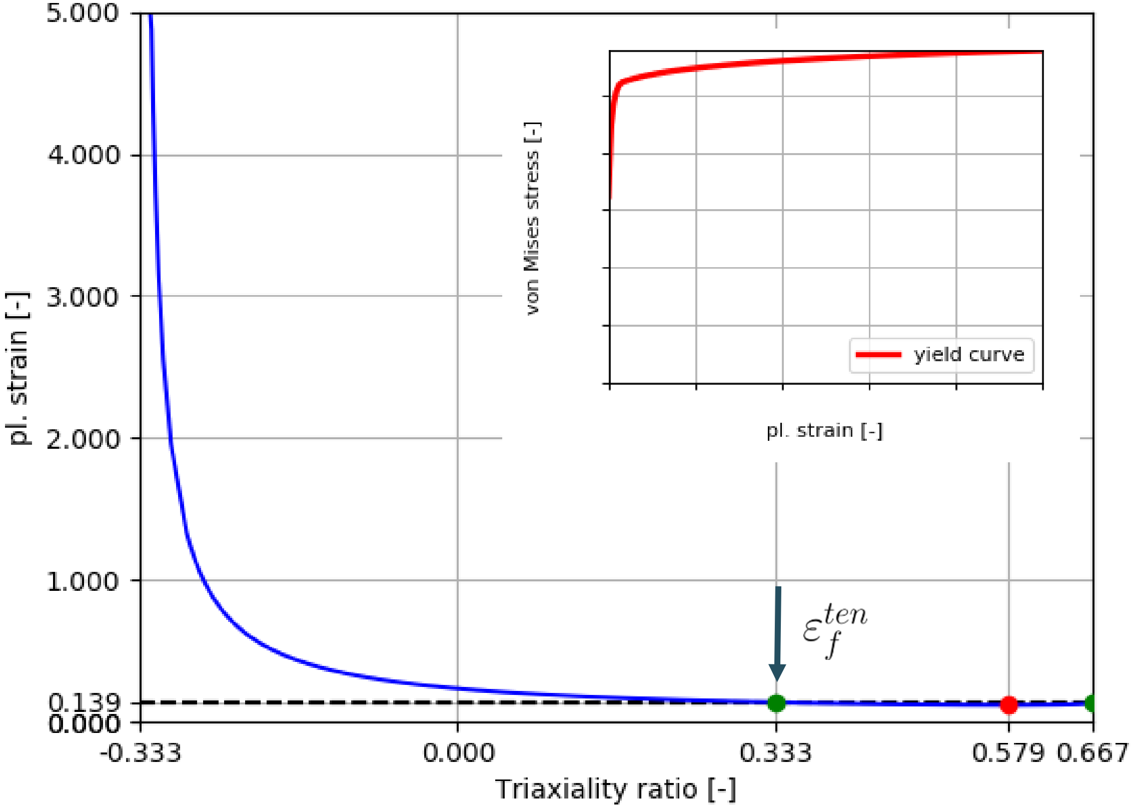
Failure curve for GISSMO

Qualitative analysis of the failure curve provided by the Cockcroft-Latham
Influence of the strain at failure on the shape of the failure curve

Unreinforced plastics



Reinforced plastics



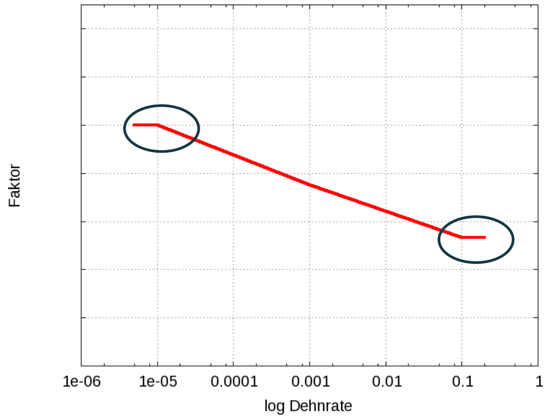
Failure curve for GISSMO

Definition of the strain-rate sensitivity

- GISSMO allows for the definition of scaling factors on the failure curve to consider the strain-rate dependence of the failure (LCSRS).

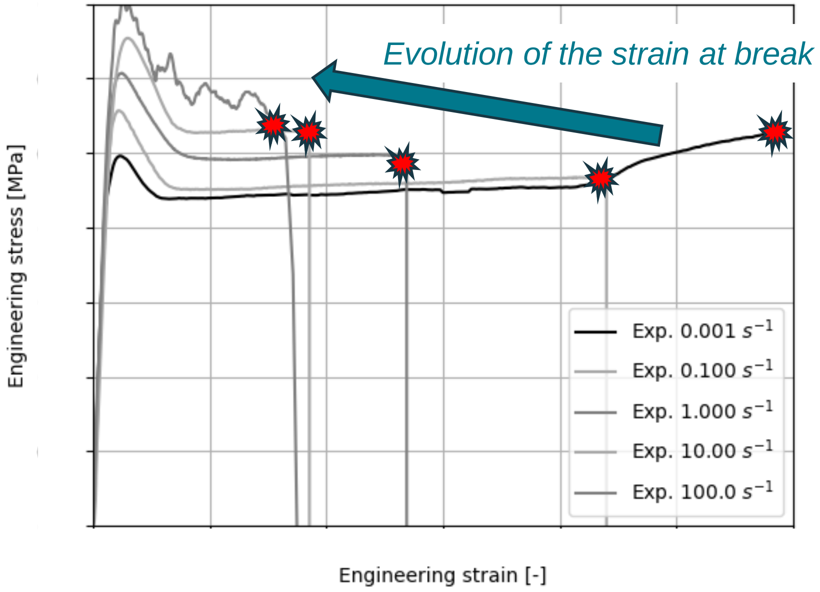
```
*DEFINE_CURVE
$      LCID
        300
$                STRRATE                   FACTOR
                 0.5E-05                   1.0000
                 1.0E-05                   1.0000
                 1.0E-03                   0.7000
                 1.0E-01                   0.5000
                 2.0E-01                   0.5000
```

- Due to its expected decreasing evolution, it is strongly recommended that this curve be capped at least for high strain-rates. Otherwise, negative factors can show up.



Dynamic tensile tests on polymers usually show that the strain at failure is getting shorter as the specimen is pulled faster.

Real dynamic tensile tests on a PC/ABS



Extension to Drucker-Prager modeling

Can the Cockcroft & Latham criterion be still used?

Failure curve for GISSMO

*MAT_SAMP-1/*MAT_SAMP_LIGHT with LCID-T and LCID-C

- *MAT_SAMP-1 or *MAT_SAMP_LIGHT offers the option of building a Drucker-Prager model, when an additional yield curve for the plastic behavior under compression is entered. In this case, the yield functions results in:

$$\Phi(\boldsymbol{\sigma}, \varepsilon^p) = \sigma_{eq} - 3\frac{\sigma_y^c(\varepsilon_{ct}^p) - \sigma_y^t(\varepsilon_{ct}^p)}{\sigma_y^t(\varepsilon_{ct}^p) + \sigma_y^c(\varepsilon_{ct}^p)}p - 2\frac{\sigma_y^t(\varepsilon_{ct}^p)\sigma_y^c(\varepsilon_{ct}^p)}{\sigma_y^t(\varepsilon_{ct}^p) + \sigma_y^c(\varepsilon_{ct}^p)} = 0$$

- And the non-associated flow rule is given by $\dot{\boldsymbol{\varepsilon}}^p = \dot{\gamma}\frac{\partial \Psi}{\partial \boldsymbol{\sigma}}$ where $\Psi(\boldsymbol{\sigma}, \alpha) = \sigma_g = \sqrt{\sigma_{eq}^2 + \alpha p^2}$

Example of a *MAT_SAMP-1 card

```
*MAT_SAMP-1
 $#     MID        RO      BULK     SHEAR      EMOD       NUE    RBCFAC
          1    1.1E-6                           1.3       0.4
 $#  LCID-T    LCID-C    LCID-S    LCID-B      NUEP    LCID-P              INCDAM
        100       200                           0.5
 $#  LCID-D    EPFAIL    DEPRPT  LCID-TRI   LCID-LC

 $#   MITER      MIPS             INCFAIL     ICONV      ASAF
```

Example of a *MAT_SAMP_LIGHT card

```
*MAT_SAMP_LIGHT
 $      MID        RO                                EMOD       NUE
          1    1.1E-6                                 1.3       0.4
 $   LCID_T    LCID_C                      RATEOP   RNUEP    LCID-P    RFILTF
        100       500                           0     0.5                0.95
```

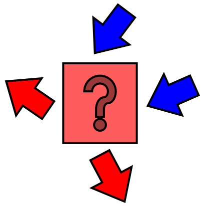
Flag for the plastic Poisson coefficient. Either a constant (NUEP) or as function of the pl. strain given by the load curve (LCID-P)

$$\nu_p = 0.5 \Leftrightarrow \alpha = 0$$

Failure curve for GISSMO

*MAT_187/L: Non-associated Drucker-Prager

- Again, making use of the plane stress state relations for the pressure and von Mises stress



$$\boldsymbol{\sigma} = \begin{pmatrix} \sigma_1 & 0 \\ 0 & k\sigma_1 \end{pmatrix} \quad \rightarrow \quad p = -\frac{1}{3}\sigma_1(1+k), \qquad \sigma_{eq} = \sigma_1\sqrt{1+(k-1)k}$$

- The first principal stress can be written in terms of the given hardening curves and the stress ratio *k* as follows:

$$\sigma_1 = \frac{2\sigma_y^t\sigma_y^c}{(\sigma_y^t+\sigma_y^c)\sqrt{1+(k-1)k}+(\sigma_y^c-\sigma_y^t)(1+k)}$$

- Then, the energy criterion proposed by Cockcroft & Latham takes the form:

$$W = \int_0^{\varepsilon_f} \frac{2\sigma_y^t(\varepsilon_{ct}^p)\sigma_y^c(\varepsilon_{ct}^p)}{[\sigma_y^t(\varepsilon_{ct}^p)+\sigma_y^c(\varepsilon_{ct}^p)]\sqrt{1+(k-1)k}+[\sigma_y^c(\varepsilon_{ct}^p)-\sigma_y^t(\varepsilon_{ct}^p)](1+k)}d\varepsilon_{ct}^p \le W_c^*$$

In the case of uniaxial tensile the first principal stress collapses to:

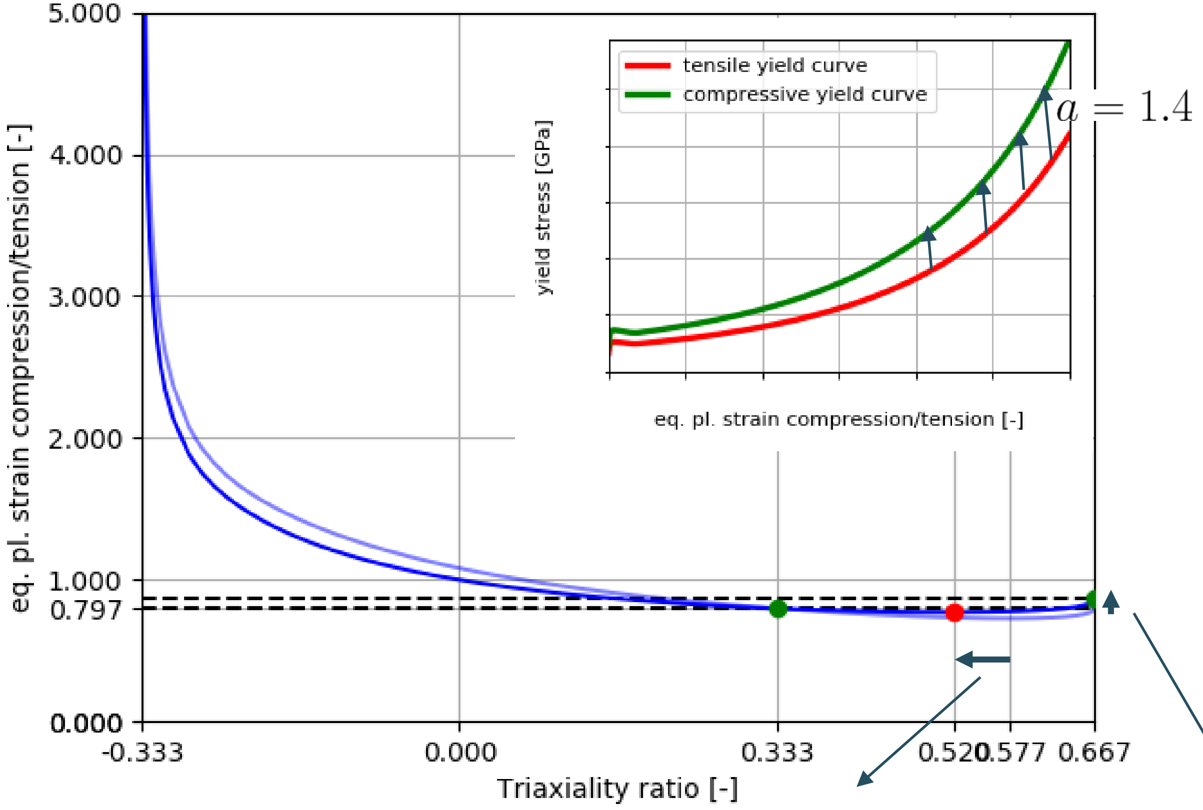
$k = 0 \Rightarrow \sigma_1 = \sigma_y^t$

Failure curve for GISSMO

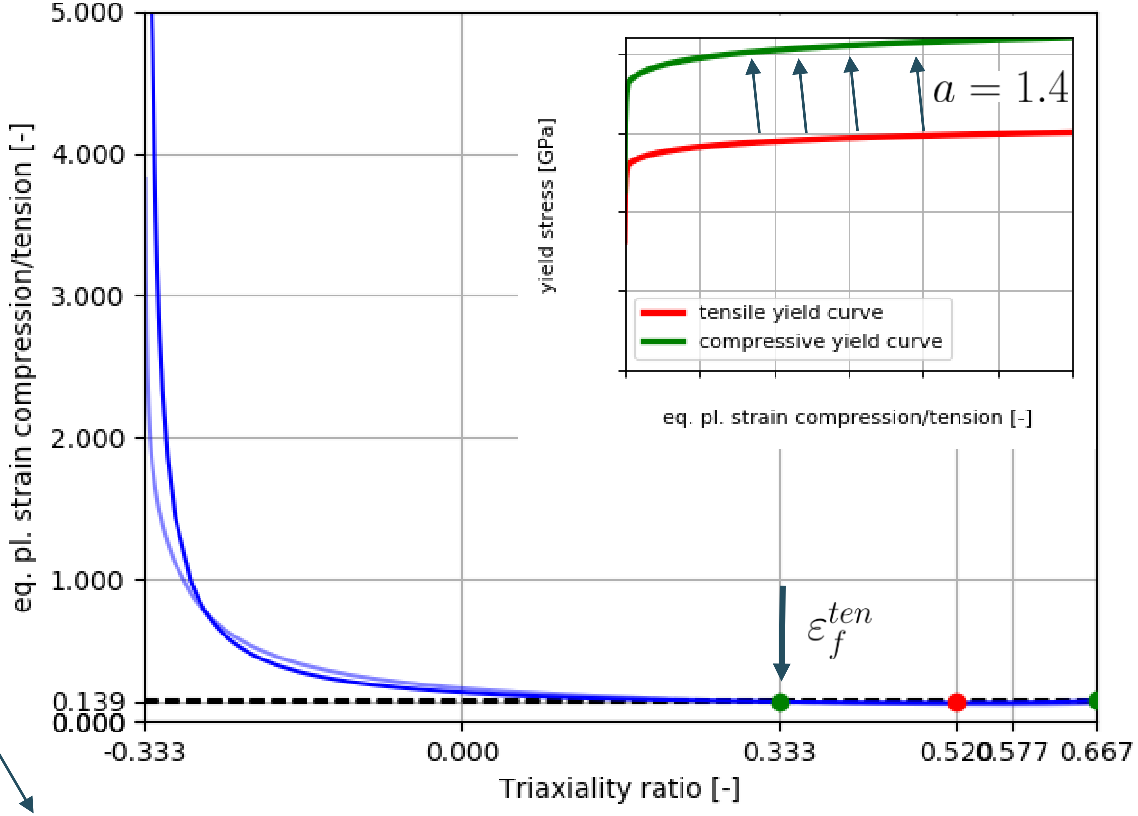
*MAT_187/L: Non-associated Drucker-Prager

Compression yield curve as a scaled tensile yield curve: $\sigma_y^c(\varepsilon_{ct}^p) = a\sigma_y^t(\varepsilon_{ct}^p)$

Unreinforced plastics



Reinforced plastics



The minimum does not show up at plane strain anymore

Now the predicted failure for the pure biaxial tensile is slightly higher than for uniaxial tensile

Example: PC/ABS

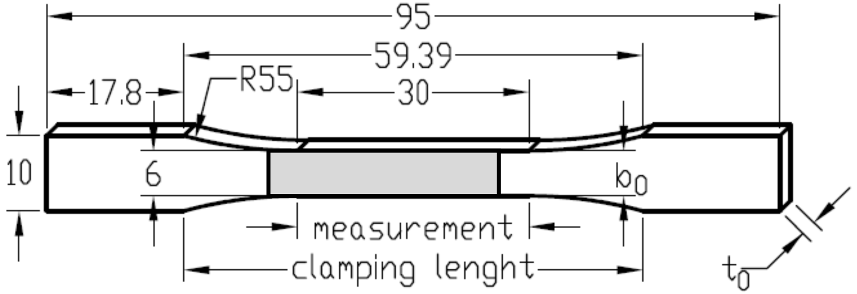
Based on:

M. Helbig, A. Haufe. “Modeling of crazing in rubber toughened polymers with LS-DYNA”.
15th International LS-DYNA Conference and Users Meeting, 2018.

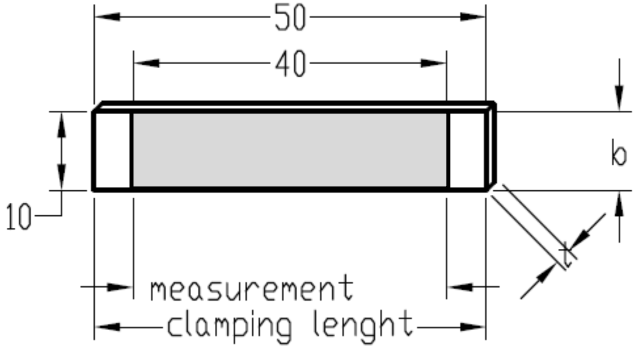
PC/ABS

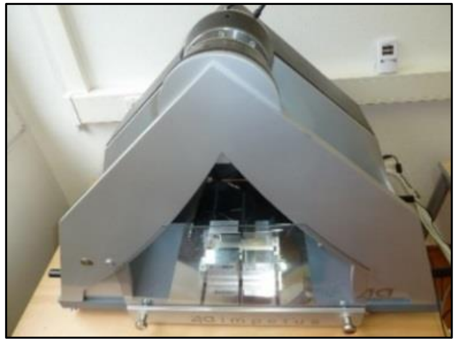
Specimens used

- Tensile specimen:
  - static and dynamic tests
  - Strain via digital image correlation (DIC), only for the quasi-static test.
  - Strain gauge for engineering strain l_0=30 mm
  - Target mesh size: 2mm
  - Injection molded specimen (target thickness 2mm)



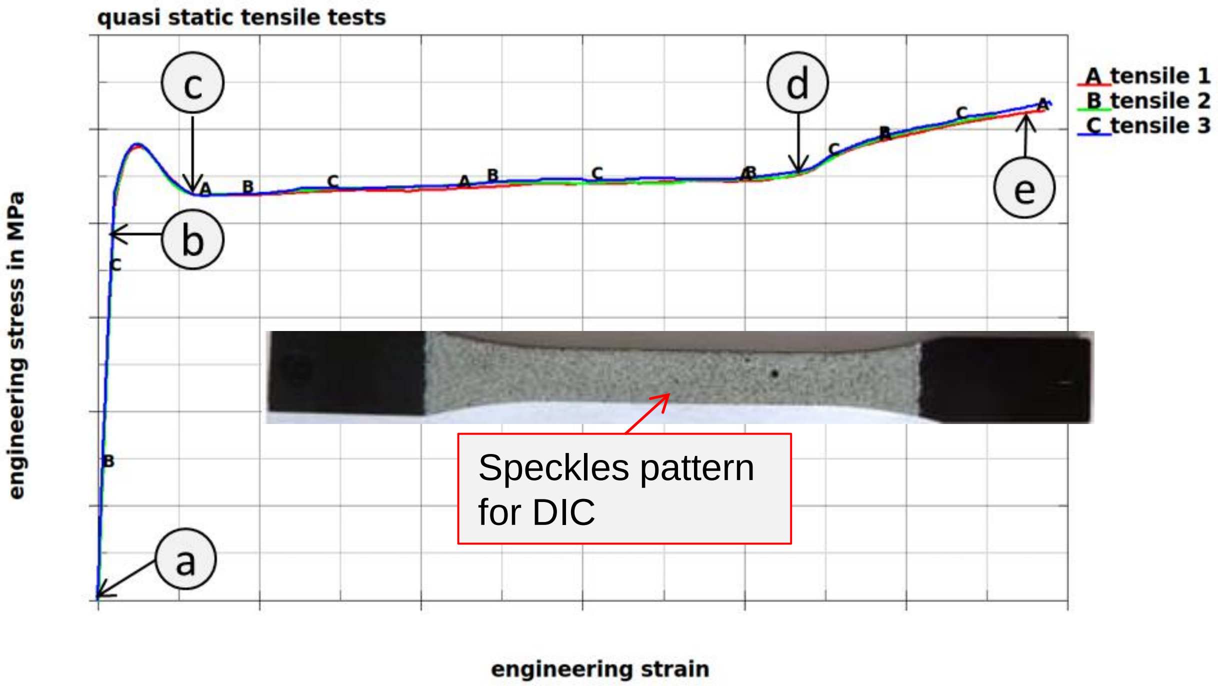
- 3-point Bending:
  - Static and dynamic tests
  - Specimen milled out from sheet



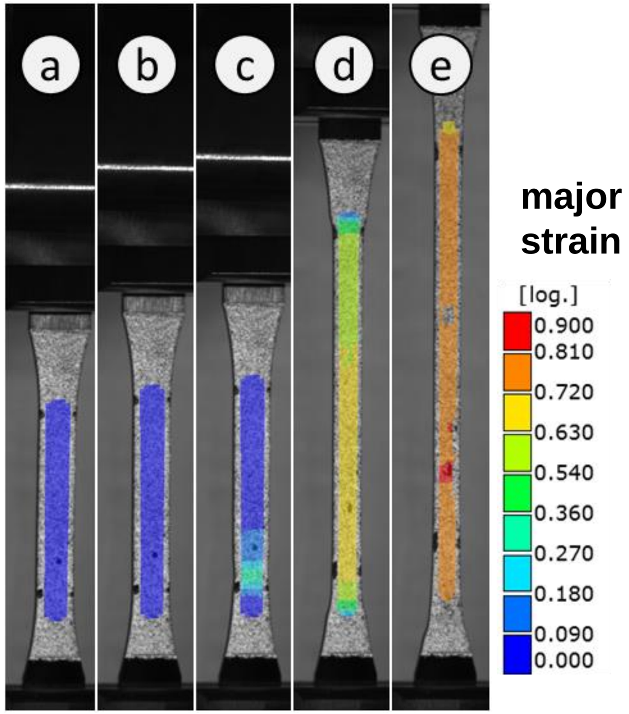


PC/ABS

Deformation under tension at very low velocity (quasi-static)



Deformation and strain at different stages

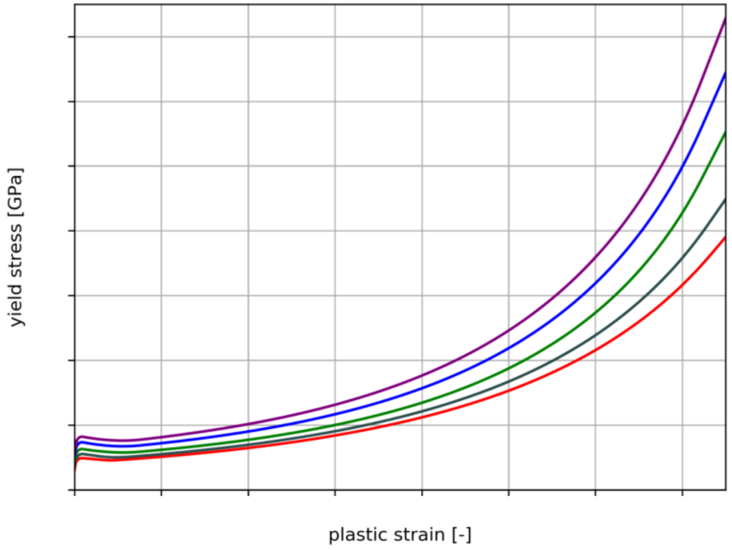


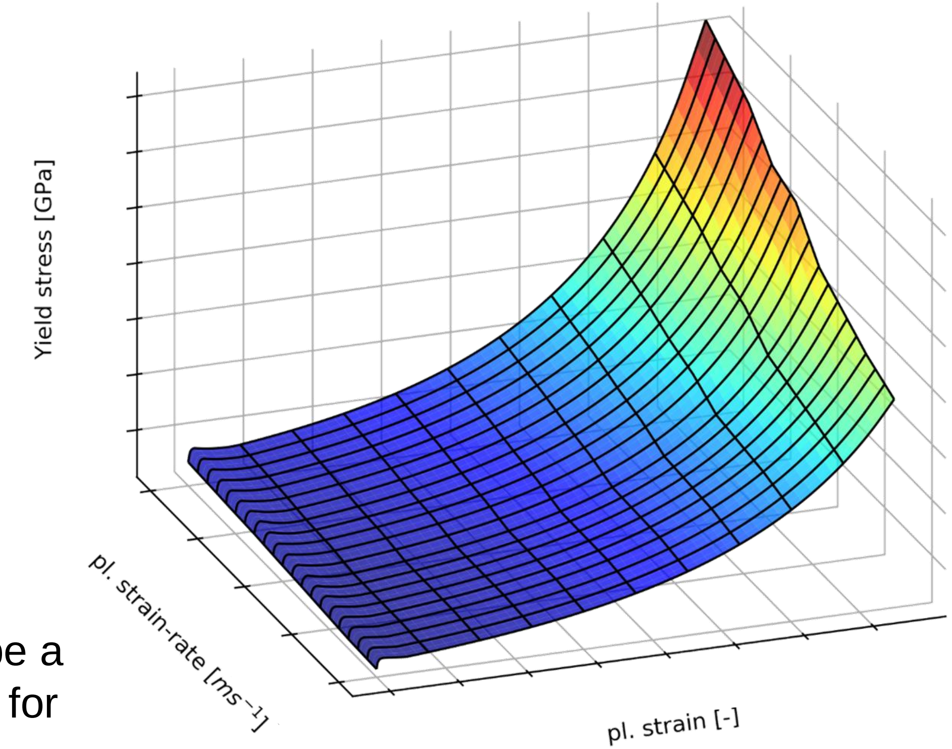
PC/ABS

Calibration of the strain-rate dependent plasticity: *MAT_024_LOG_INTERPOLATION

```
*MAT_PIECEWIESE_LINEAR_PLASTICITY_LOG_INTERPOLATION
$      MID        RO         E        PR      SIGY      ETAN      FAIL      TDEL
         1    1.1E-6       2.2       0.4
$        C         P      LCSS      LCSR        VP
                           100                   1
$ ...
```

Visualization of the strain-rate dependence

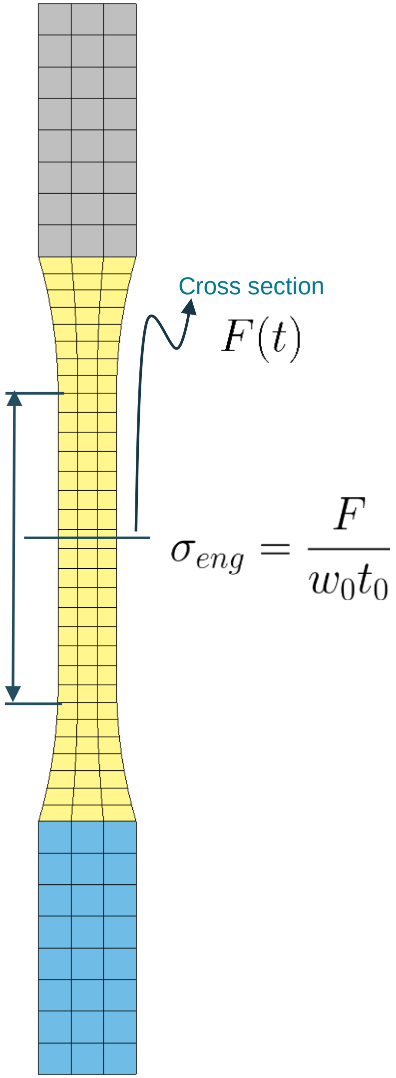




- The calibration based on *MAT_024 requires the yield curves to describe a softening after the maximum followed by a strong hardening to account for the development of the telescope effect

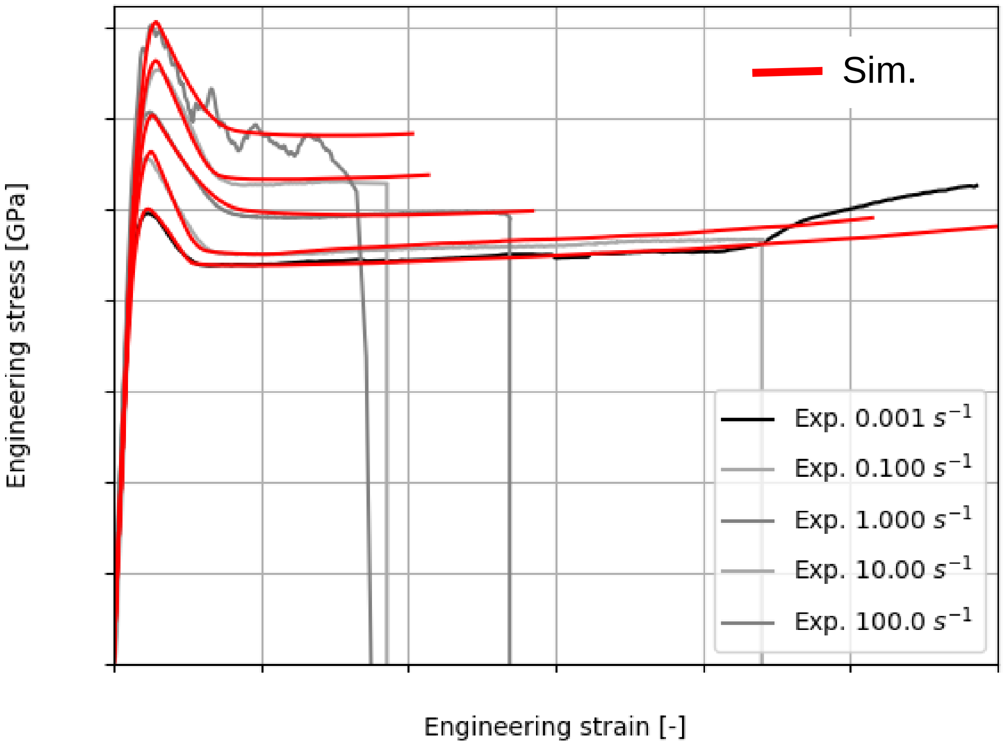
PC/ABS

Simulation of the quasi-static and dynamic tensile tests



$$\sigma_{eng} = \frac{F}{w_0 t_0}$$

Eng. stress vs. eng. strain



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

Remarks:

- The modeling of the plastic response of the material manages to capture the behavior of the tensile specimen at all tested strain-rates.
- This represents a good starting point to achieve the proper strain-rate dependent failure as we show in next slides.

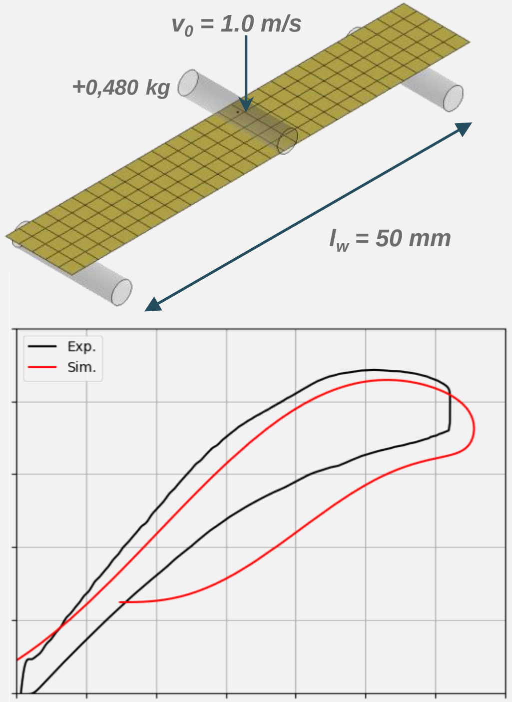
PC/ABS

Simulation of the dynamic bending tests performed with the pendulum machine

edot = 4.80 s^{-1}

*SECTION_SHELL
ELFORM=16, 5 IPs.
L_e= **2.0 mm x 2.0mm**
t = **2.0 mm**

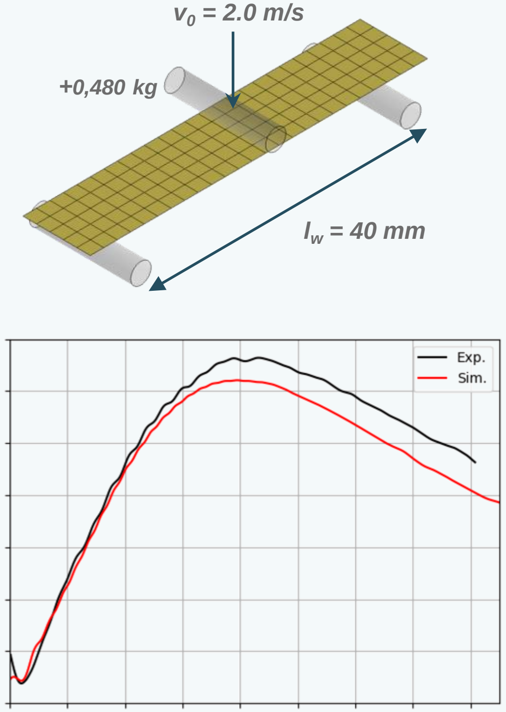
$$\dot{\varepsilon}_0 = \frac{6 v_0 t}{l_w^2}$$



Filter: CFC SAE 500 Hz

edot = 15.00 s^{-1}

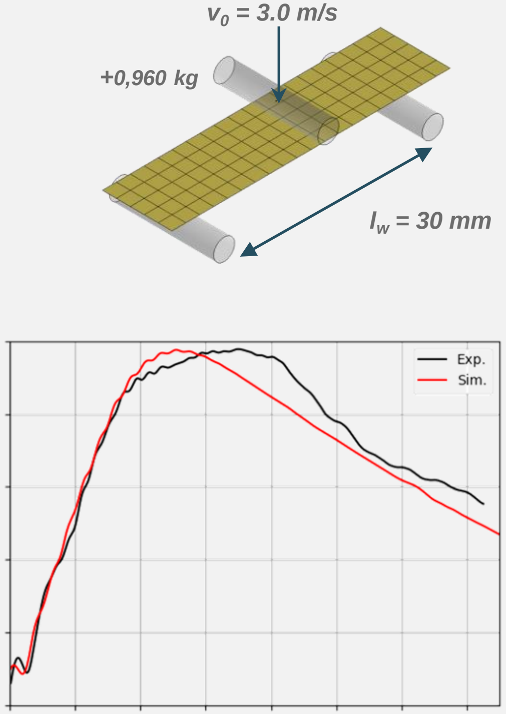
*SECTION_SHELL
ELFORM=16, 5 IPs.
L_e= **2.0 mm x 2.0mm**
t = **2.0 mm**



Filter: CFC SAE 500 Hz

edot = 40 s^{-1}

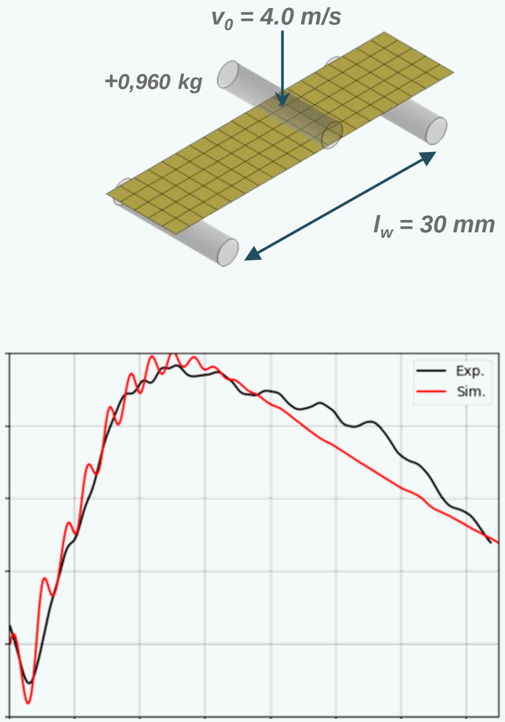
*SECTION_SHELL
ELFORM=16, 5 IPs.
L_e= **2.0 mm x 2.0mm**
t = **2.0 mm**



Filter: CFC SAE 600 Hz

edot = 53.33 s^{-1}

*SECTION_SHELL
ELFORM=16, 5 IPs.
L_e= **2.0 mm x 2.0mm**
t = **2.0 mm**



Filter: CFC SAE 600 Hz

PC/ABS

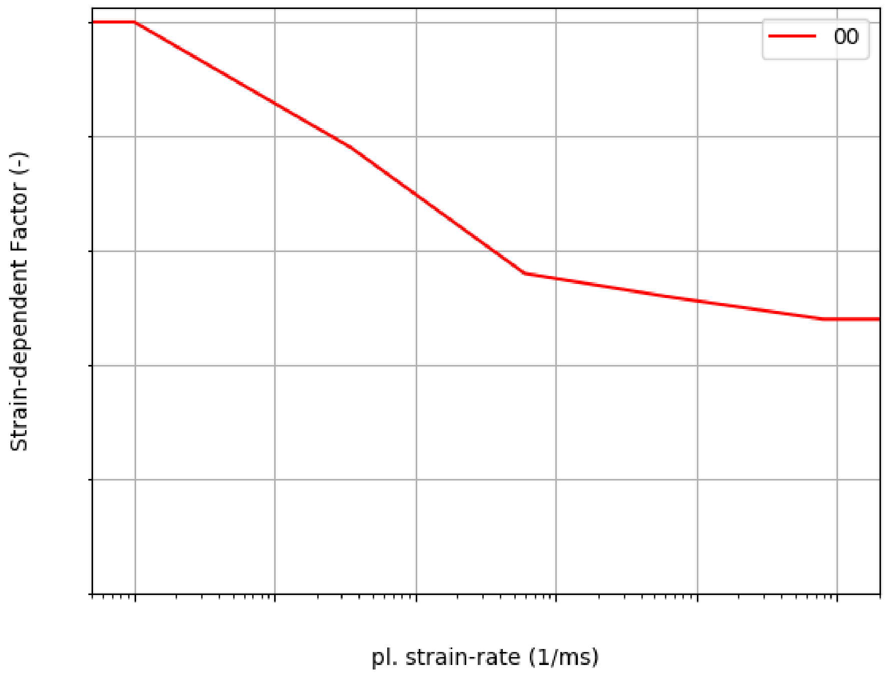
Calibration of the strain-rate dependent failure: *MAT_ADD_EROSION/*MAT_ADD_DAMAGE_GISSMO

*MAT_ADD_EROSION card:

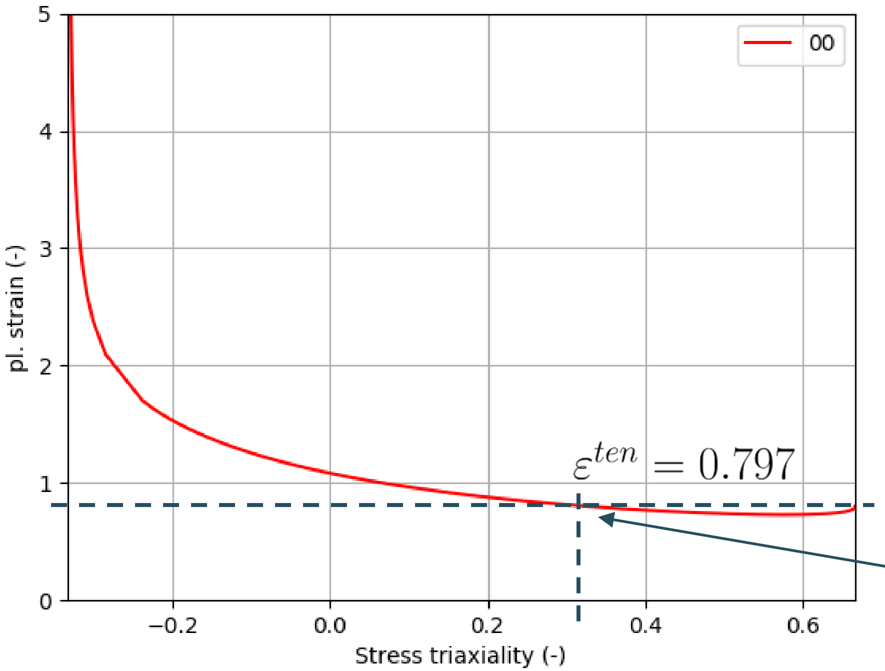
```
*MAT_ADD_EROSION
$      MID      EXCL    MXPRES     MNEPS    EFFEPS    VOLEPS    NUMFIP       NCS
         1
$   MNPRES     SIGP1     SIGVM     MXEPS     EPSSH     SIGTH   IMPULSE    FAILTM

$     IDAM    DMGTYP     LCSDG     ECRIT    DMGEXP     DCRIT    FADEXP    LCREGD
         1                 200                   2       1.0
$   SIZFLG     REFSZ     NAHSV     LCSRS      SHRF     BIAXF
                                     300
```

Factors on failure curve (LCSRS)



Failure curve (LCSDS)



The "local" strain at break observed in the DIC measurement is around 0.9. After few iterations, a value of 0.797 in combination with the introduced Cockcroft & Latham criterion provided a satisfactory correlation with the eng. stress-strain curve:

$$W = \int_0^{0.797} \sigma_y^t(\varepsilon^p)d\varepsilon^p \leq W_c^*$$

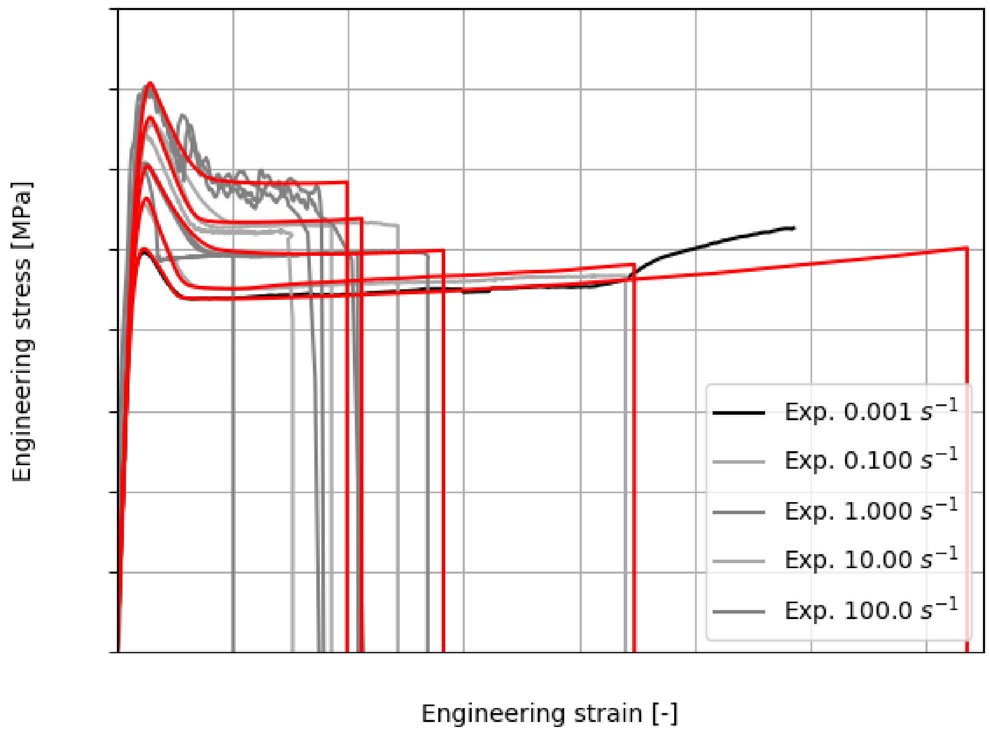
$$W_c^* = 0.0587$$

A proper calibration of the plasticity should lead to a monotonically decreasing form of the strain-rate factors as was the case in this calibration

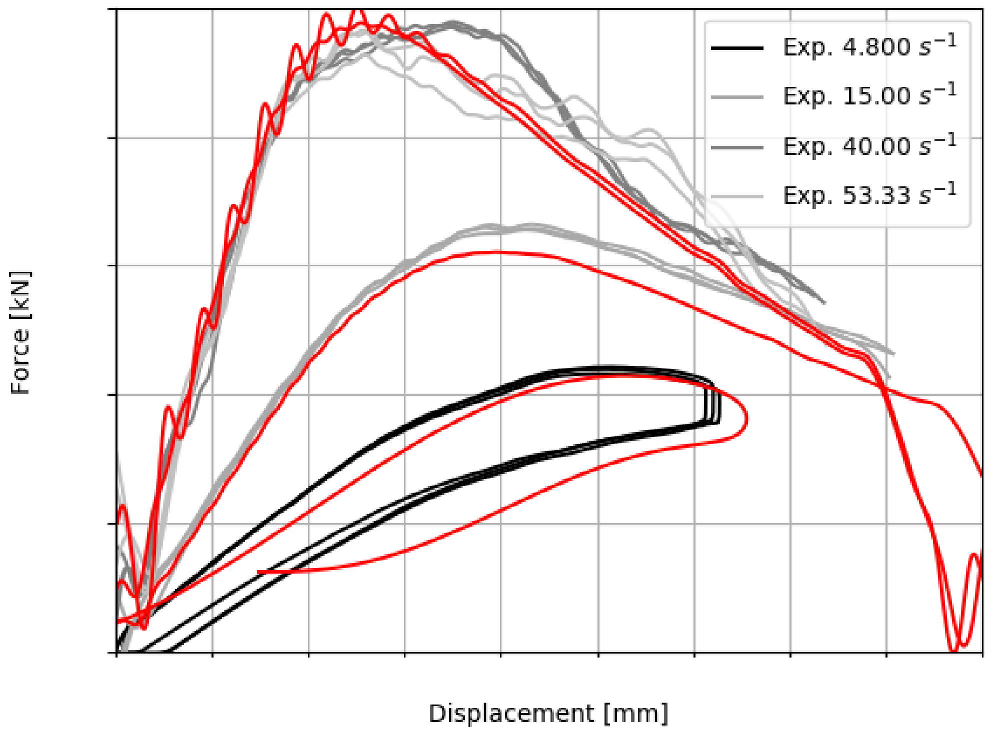
PC/ABS

Comparison every experiment vs. simulation

Tensile Tests



Bending tests

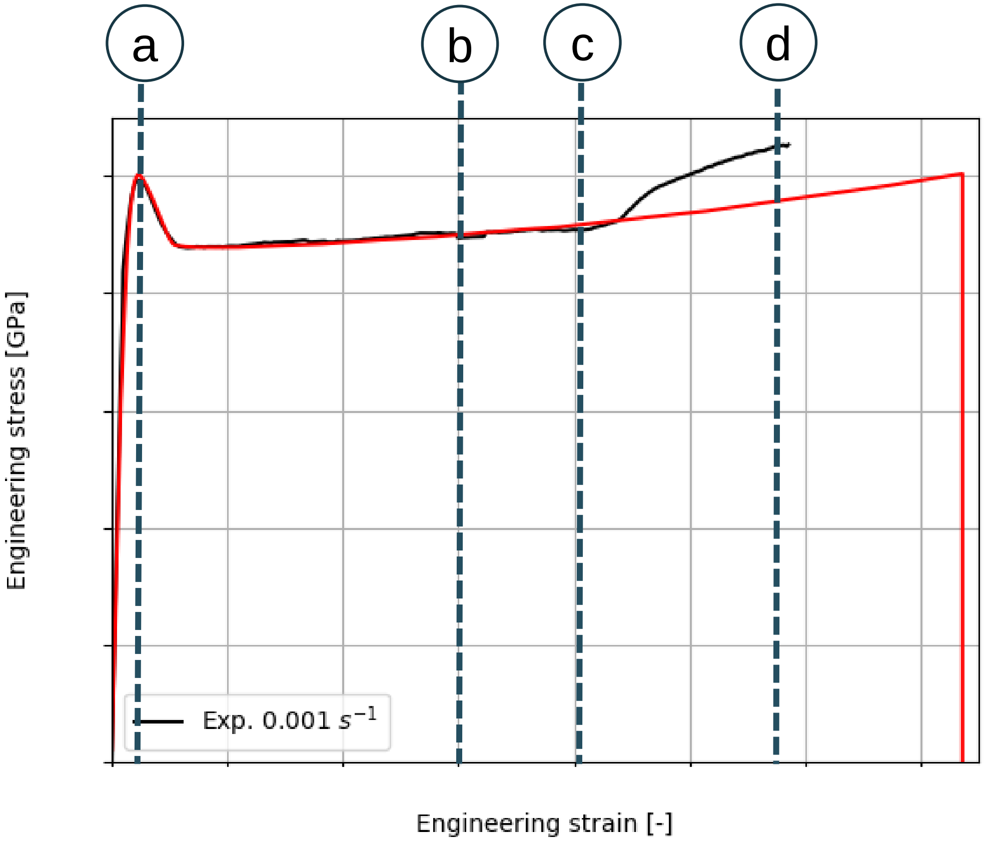


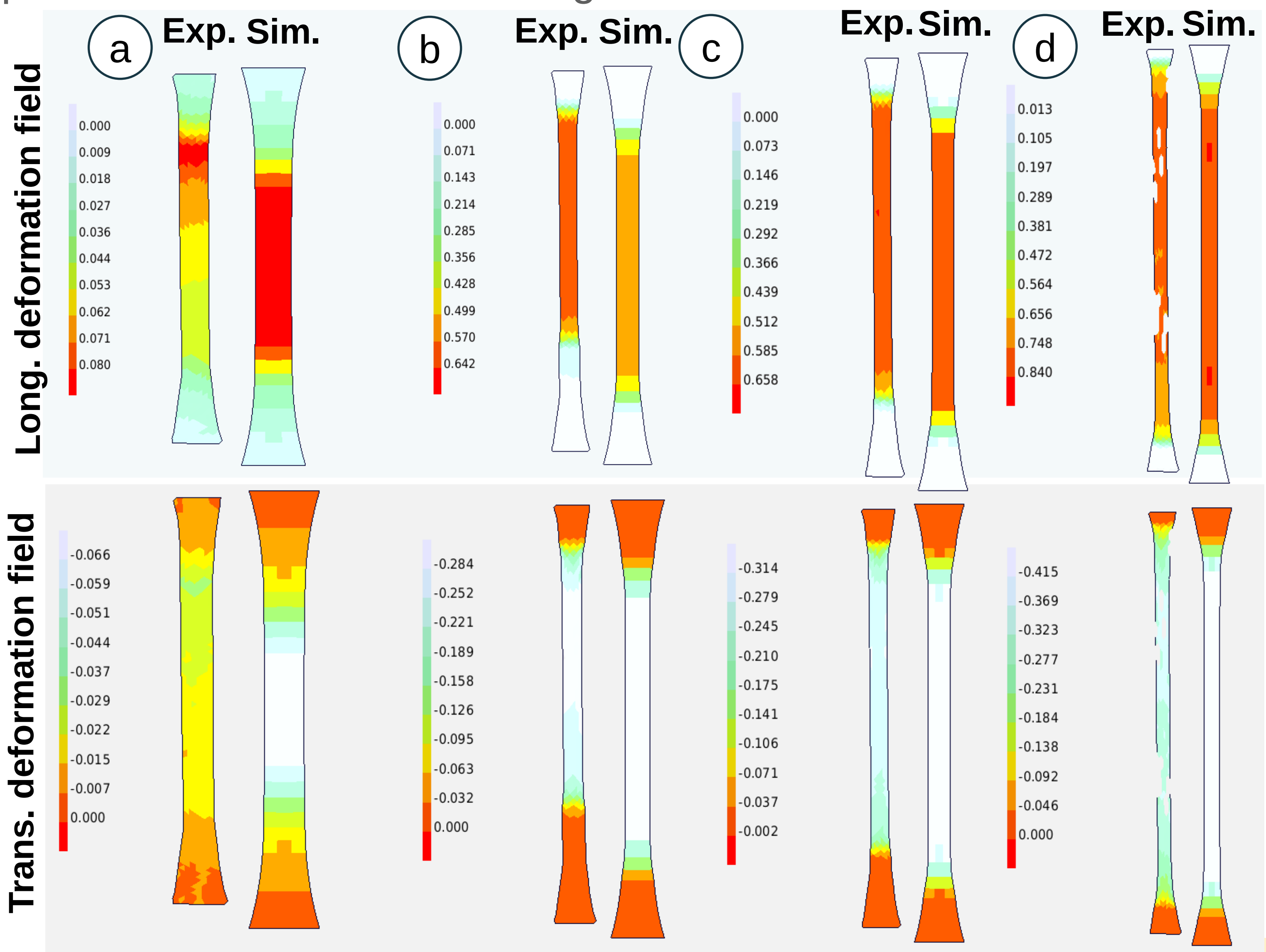
The failure modeling is able to predict the fading conduct of the strain at failure while causing no failure at bending tests as observed in the experiments performed with the pendulum.

PC/ABS

Evolution of the deformation fields in comparison with the DIC recording
strain-rate: 0.001 s^{-1}

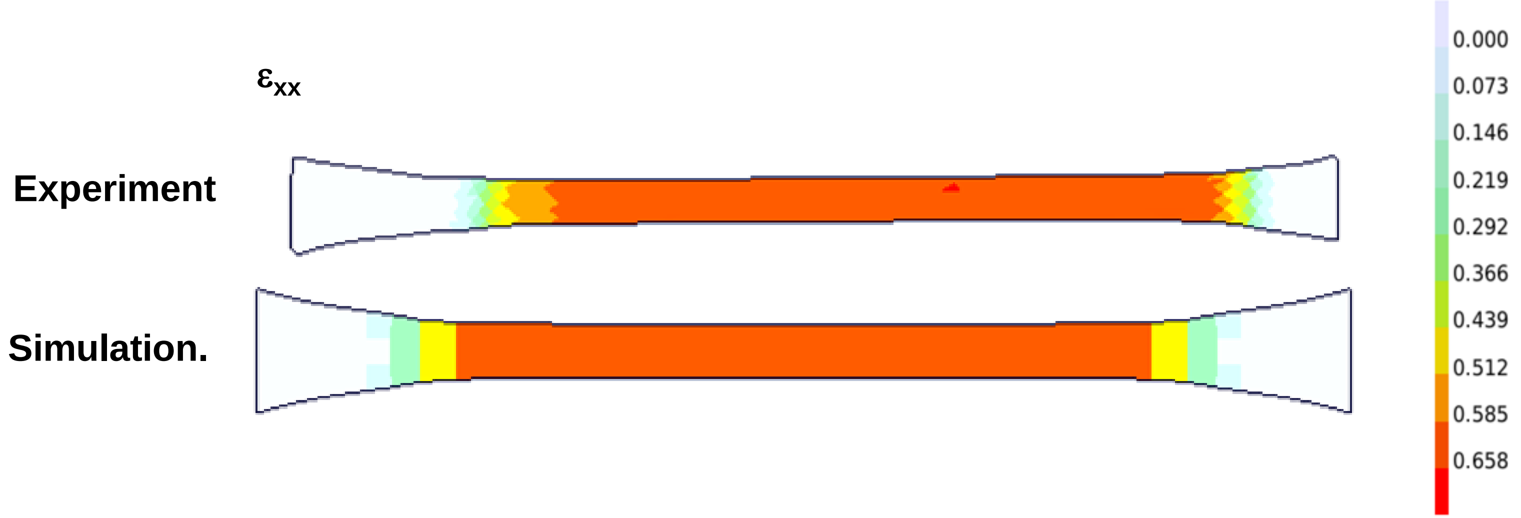
- Comparison: eng. stress vs. eng. strain



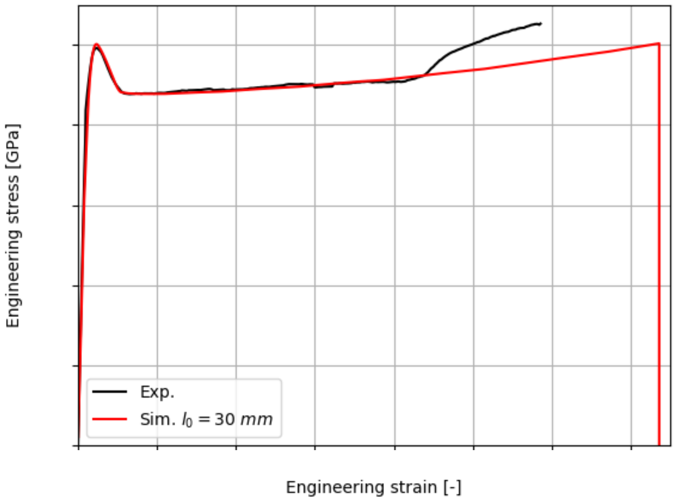


PC/ABS

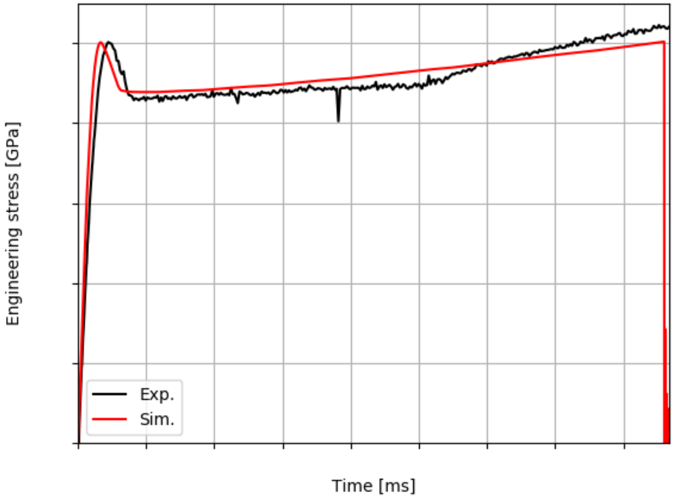
Detailed evaluation of the tensile test at strain-rate 0.001 s^{-1}



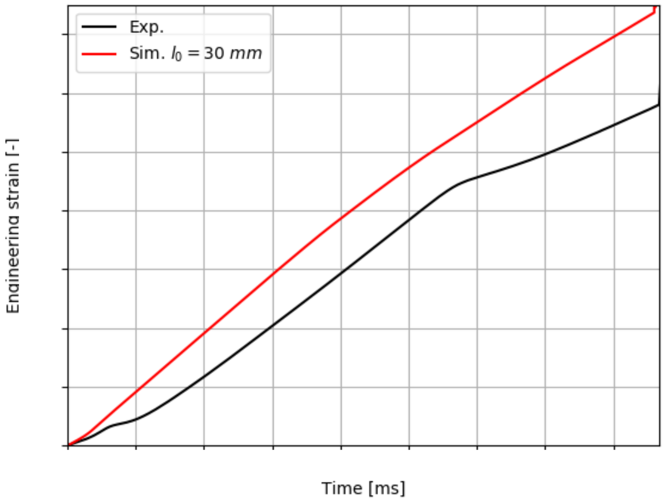
Stress vs. strain



Stress vs. time



Strain vs. time



Concluding remarks

- In absence of reliable tests on polymers for stress states other than tensile, we made use of the energy-criterion proposed by Cockcroft & Latham to define a proper failure curve for GISSMO that covers the stress states from uniaxial compression to biaxial tensile.
- This methods provides a continuous form of the failure curve in contrast to the so far widely used step form based on the failure strain for tensile applied to the whole positive range of the triaxiality.
- The resulting failure curve is able to predict the failure at tensile while showing a promising behavior at bending tests.
- The strain-rate dependence of the failure can be addressed by scaling decreasingly the failure curve, as long as the calibration of the plastic response is good enough.
- Further tests at component level are required to fully validate the proposed methodology.
- There is already in the literature promising attempts to achieve reliable shear tests on polymers that can be eventually used to validate the here proposed failure curve in the range closed to stress triaxiality ratio equal to 0.

Thank You

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