State of the art modelling of plastics in LS-DYNA.

André Haufe, Andrea Erhart & Tobias Erhart

DYNAmore GmbH

Introduction

DYNA*more* GmbH
Gesellschaft für
FEM-Ingenieurdienstleistungen

Stuttgart - Karlsruhe - Ingolstadt - Wolfsburg - Berlin - Dresden
Linköping - Gothenburg - Zürich - Turin - Paris - Columbus

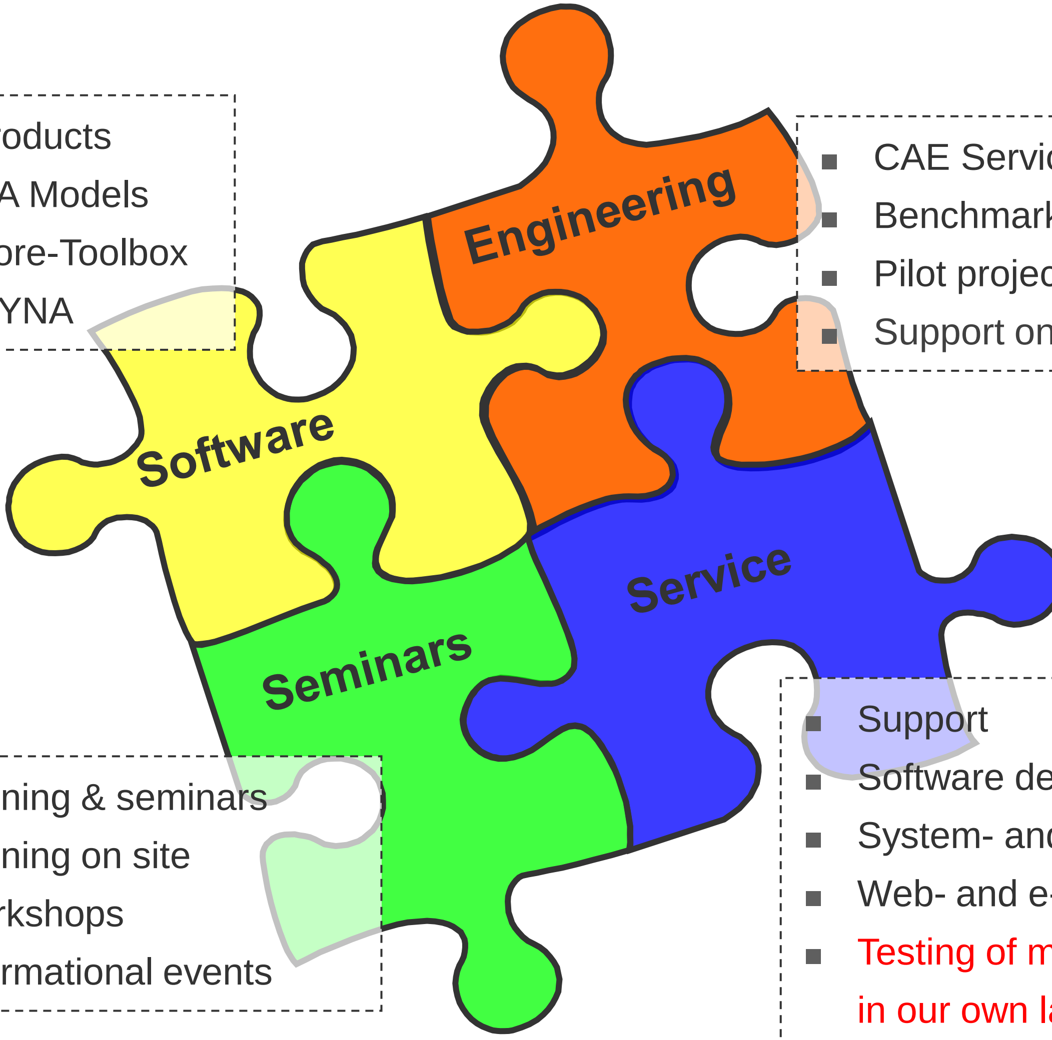
Industriestraße 2
D-70565 Stuttgart

Tel. 07 11 - 45 96 00 - 0
Fax 07 11 - 45 96 00 - 29
e-mail: info@dynamore.de
Internet: www.dynamore.de

DYNAmore – The Services

- LSTC Products
- LS-DYNA Models
- DYNAmore-Toolbox for LS-DYNA

- CAE Services
- Benchmarking
- Pilot projects
- Support on site

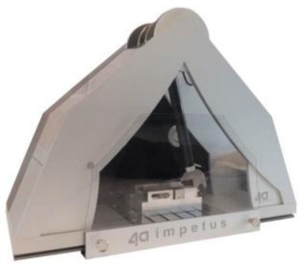


- Training & seminars
- Training on site
- Workshops
- Informational events

- Support
- Software development
- System- and process integration
- Web- and e-services
- Testing of material & calibration in our own lab

The DYNAmore Material Competence Center

Testing and calibration services for LS-DYNA constitutive models



4a Impetus pendulum

- Dynamic free bending
- Dynamic clampend bending

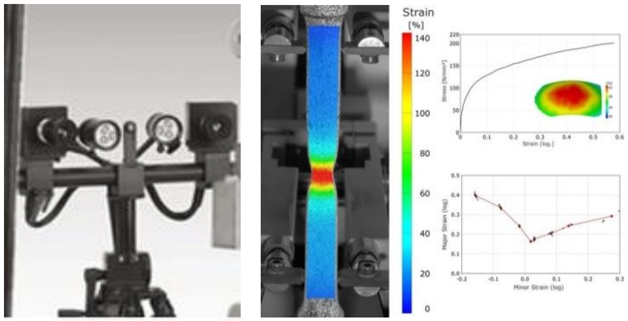
Climatic chamber

- Const. temperature
- Const. humidity

100kN tension test rig

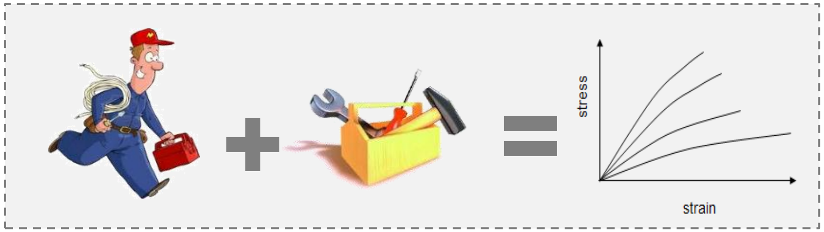
- Tension tests (QS)
- Bending tests (QS)
- Characterisation for damage and failure
- Shear tests
- Compression tests
- Notched tension tests

5M ARAMIS-System (GOM)



The DYNAmore Material Competence Center

Testing and calibration services for LS-DYNA constitutive models



Clients:

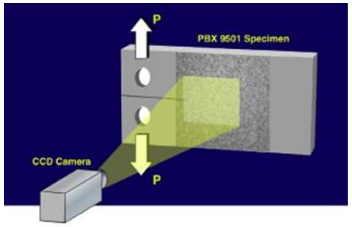
- Daimler AG [crashworthiness, sheet metal forming] (Polymers, steel, aluminium)
- Opel GmbH (polymers, steel)
- Porsche (polymers, steel, aluminium)
- VW AG(steel, aluminium)
- BMW AG (steel)
- Honda (polymers, glass)
- Siemens (aluminium extruded)
- DRL, Bosch , Novelis, BSH
- Britax, Croclin
- Constellium, ArcelorMittal, VoestAlpine
- Magna, Lord, Britax

Outsourcing:

- High speed dynamic testing to local labs
- Production of coupons (milling, laser oder high-speed water cutting)

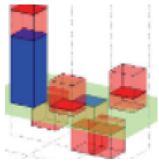
R&D within the material Competence Center:

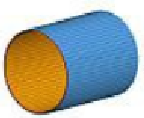
- Full Field Calibration
- Paramete ridentification with LS-OPT
- AI for constitutive modelling
- AI for faster parameter identification

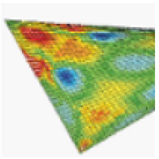


DYNAmore – Examples for Advanced Customer Support

- Participation in national research projects
  - WING (process modeling)
  - IMAUF (tool modeling in forming)
  - FOSTA working group (steel/adhesive bonding)
  - FAT (dummy models, foam and rubber, mapping)
  - IDDRG (international deep drawing group)
  - DLR (composites)
  - T-Pult (pultrusion process)
  - **ARENA 2036** (DigitPro, DigiBody, DigiFingerprint)
  - TISTRAQ (Magnesium hardening; aerospace structures)
- Participation in international research projects
  - IMVITER (virtual testing for homologation)
  - ROSETTA (human-robot-interaction)
  - ENFASS (material modeling, metals)
  - TWIP4EU (material modeling)
  - H2020 Extreme (impact on composites)
  - ITEA VMAP (process chain, data exchange format, …)







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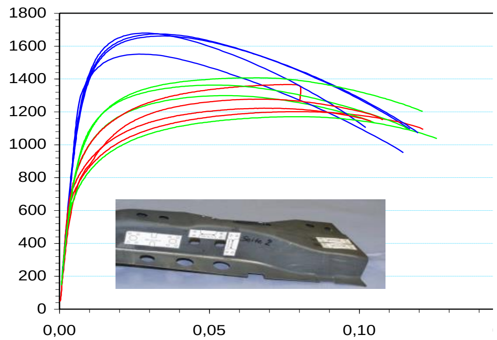
Identify industrial needs in crashworthiness simulation

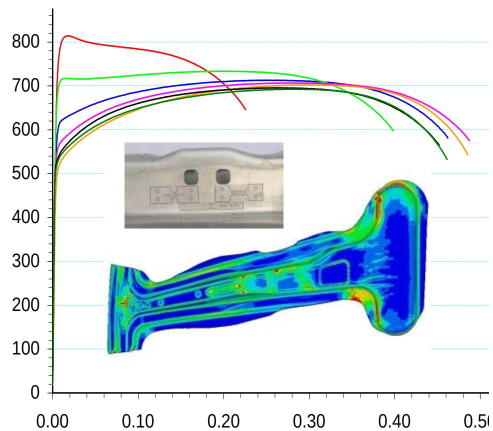
Effect of production process for steel sheets: Distribution of material properties (damage, pl. strains, thickness)

Taking process chain into account

Boron steel: 22MnB5



Micro alloyed ZStE340



Mapping of local properties like thickness, pl. strain, damage or stresses

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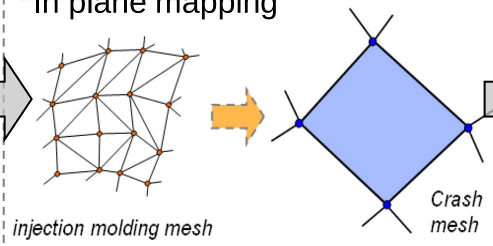
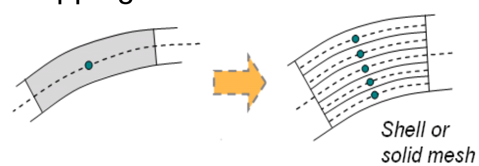
In plane mapping



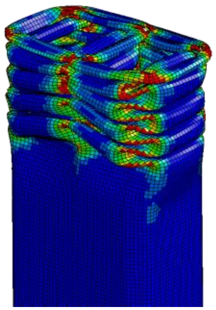
Mapping in thickness direction

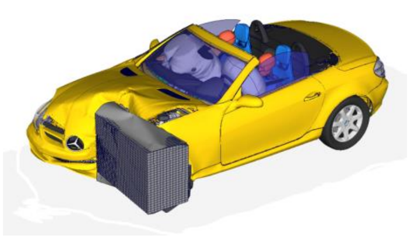


Correction of history variables when discretization or constitutive model will be altered !

Crash analysis

With calibrated anisotropic plasticity model including damage & failure

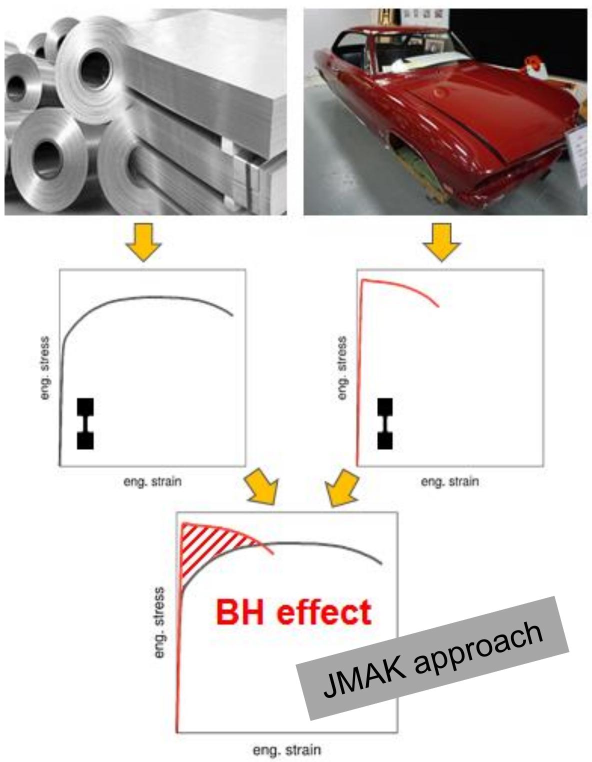




Effect of production process for BH sensitive materials: Local distribution of material properties due to pre-straining

Taking process chain into account

Bake or precipitation hardening effect or dependent on temperature treatment and pre-straining!



Mapping of local proper-ties like thickness, pl. pre-strain and temp. treatment

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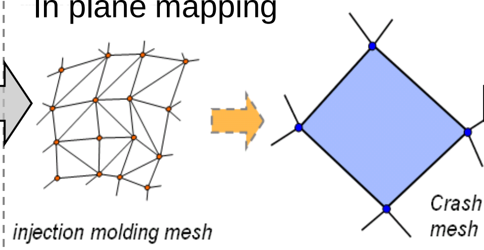
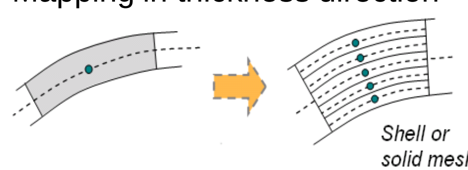
In plane mapping



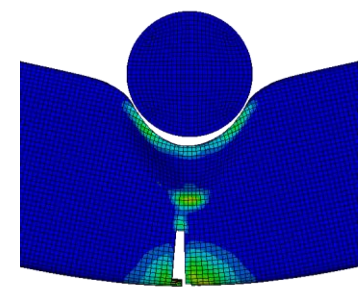
Mapping in thickness direction



Correction of history variables, yield curves when discretization or constitutive model is changed!

Crash analysis

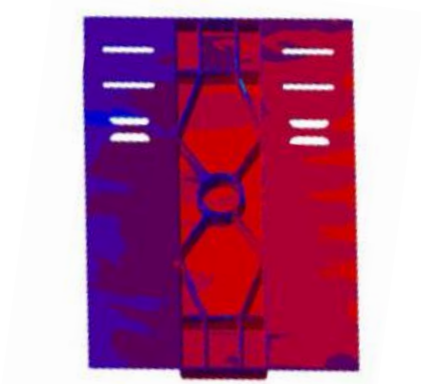
With calibrated plasticity model dependent on locally varying pre-strain and temperature effects (plus damage & failure parameters)



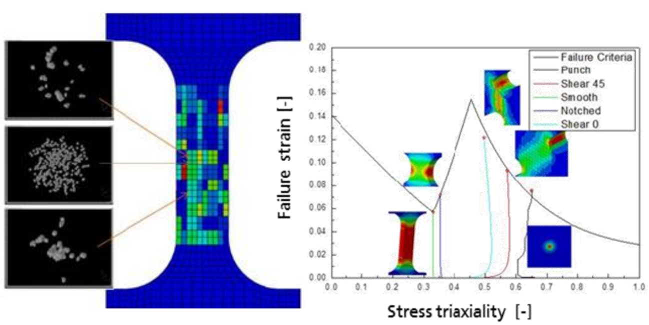
Effect of production process for cast materials: Local distribution of material properties (voids etc.)

Taking process chain into account

Aluminium cast part

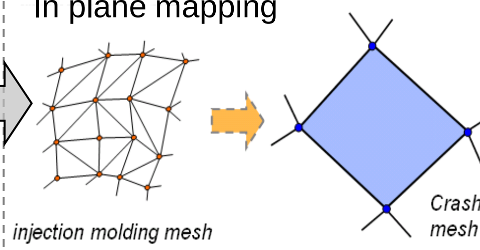


Locally varying constitutive Properties due to porosity etc.

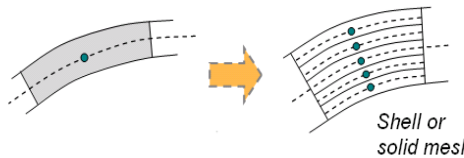


Mapping of local thickness, voids, derived damage from flow path length & Temp. or residual stresses

In plane mapping



Mapping in thickness direction



Correction of history variables, & estimated damage, when discretization or constitutive model is changed!

Crash analysis

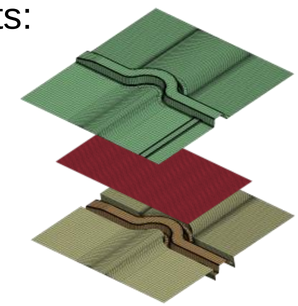
With calibrated anisotropic plasticity model including adjusted damage & failure.

Effect of production process for endless FRP: Local fiber angles (fiber orientation)

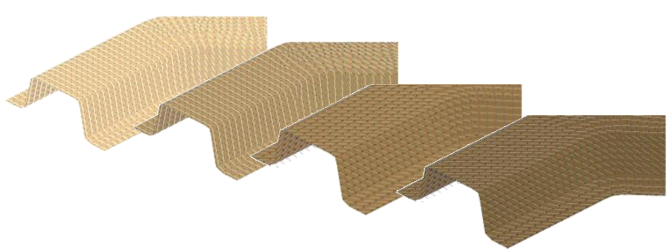
Taking process chain into account

Draping of endless fiber reinforced polymers

Dry or impregnated layups; also organo-sheets:



Prediction of fiber angles of woven fabrics or of stacked UD systems:



Mapping of local properties like orientation, strains, damage or stresses

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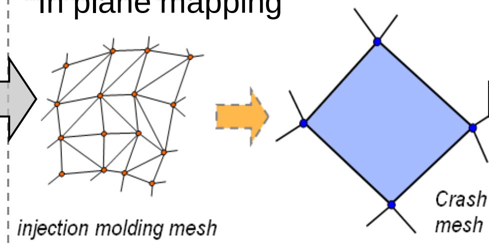
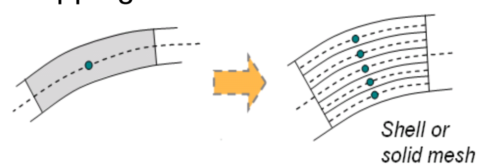
In plane mapping



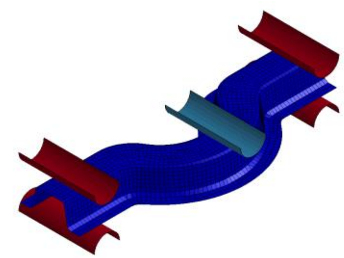
Mapping in thickness direction

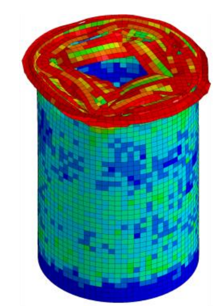


Correction of history variables when discretization or constitutive model will be altered !

Crash analysis

With calibrated anisotropic elastic & plastic model including damage & failure

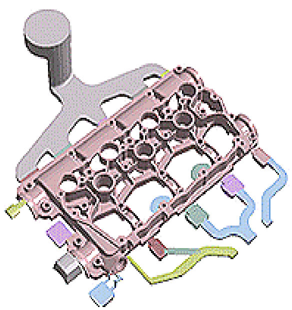


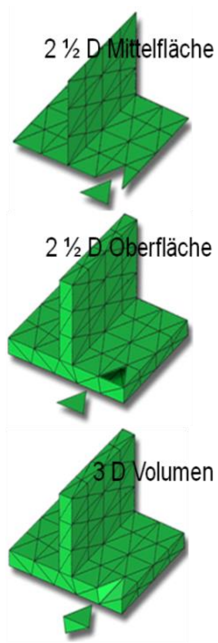


Effect of production process for short FRP: Distribution of material properties (fiber orientation & concentration)

Taking process chain into account

Injection molding





SIGMASOFT, Moldflow, Moldex, CADmold etc.

Fiber content & orientation

Mapping of local properties like thickness, fiber orientation tensor, stresses

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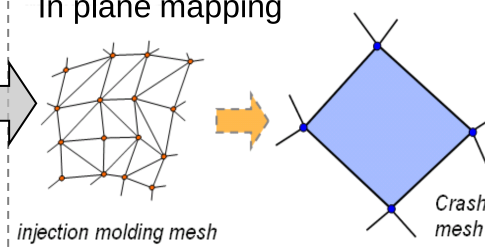
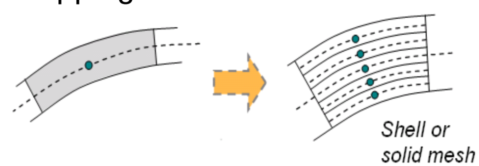
In plane mapping



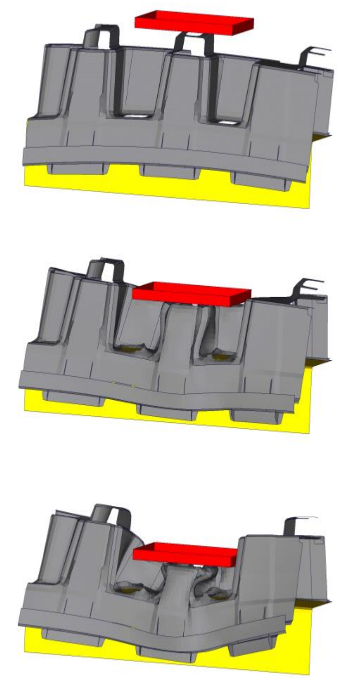
Mapping in thickness direction

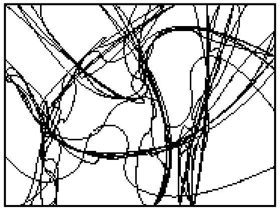


Transfer of fiber orientation tensor, fiber concentration, thicknesses, stresses & strains.

Crash analysis

With calibrated anisotropic plasticity model including damage & failure or **MAT_215**



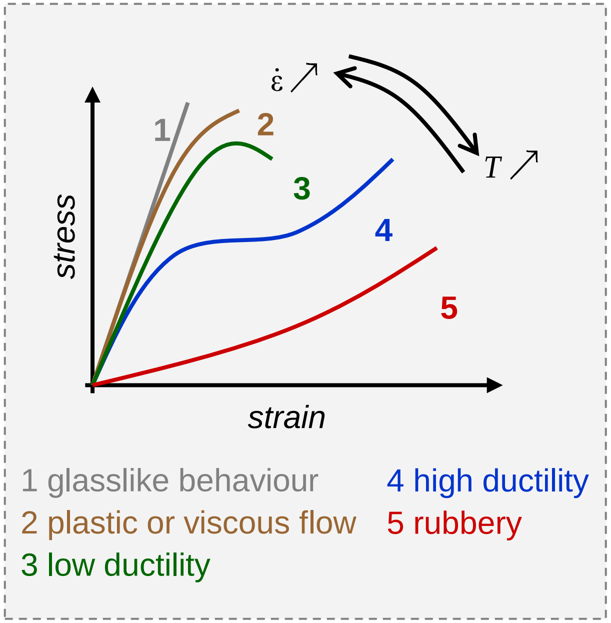


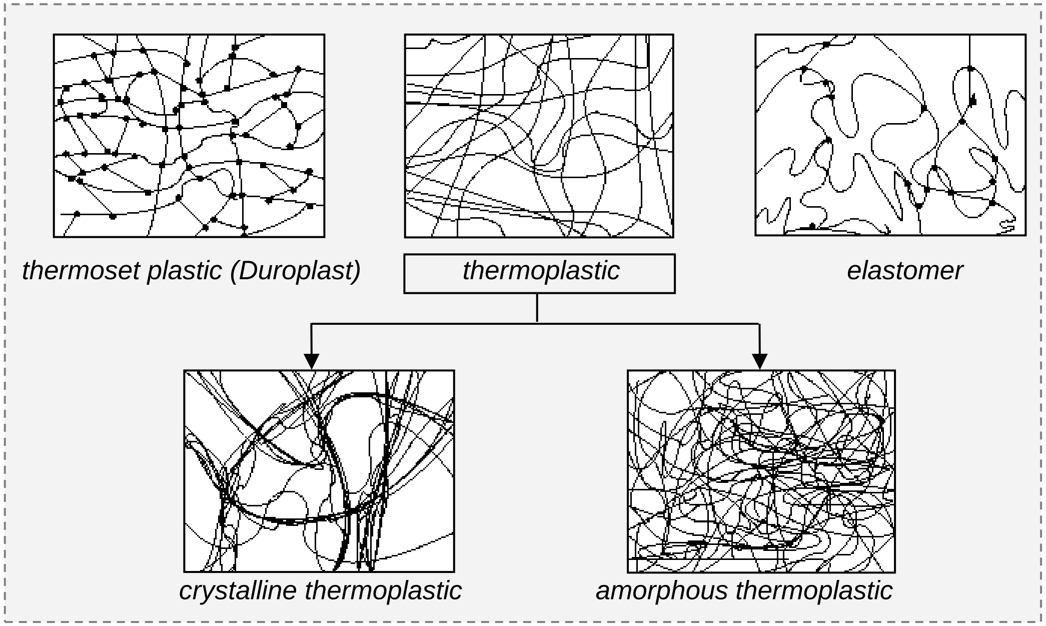
Unreinforced polymers: SAMP-1

- development finished in 2009 -

Industrial problem addressed 2004 onwards: Structures made of plastics

- Plastics is a group name comprising many different materials
- Mechanical response at room temperature may be glassy or rubbery, brittle or viscous

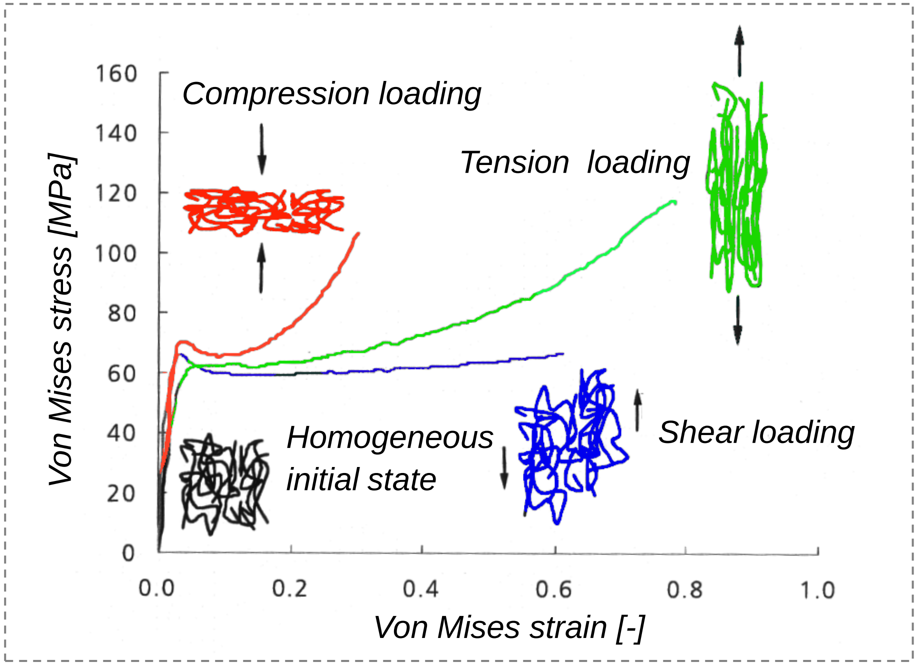




- Fiber reinforcement may cause anisotropic response
- Rib reinforcements represent an important modeling effort

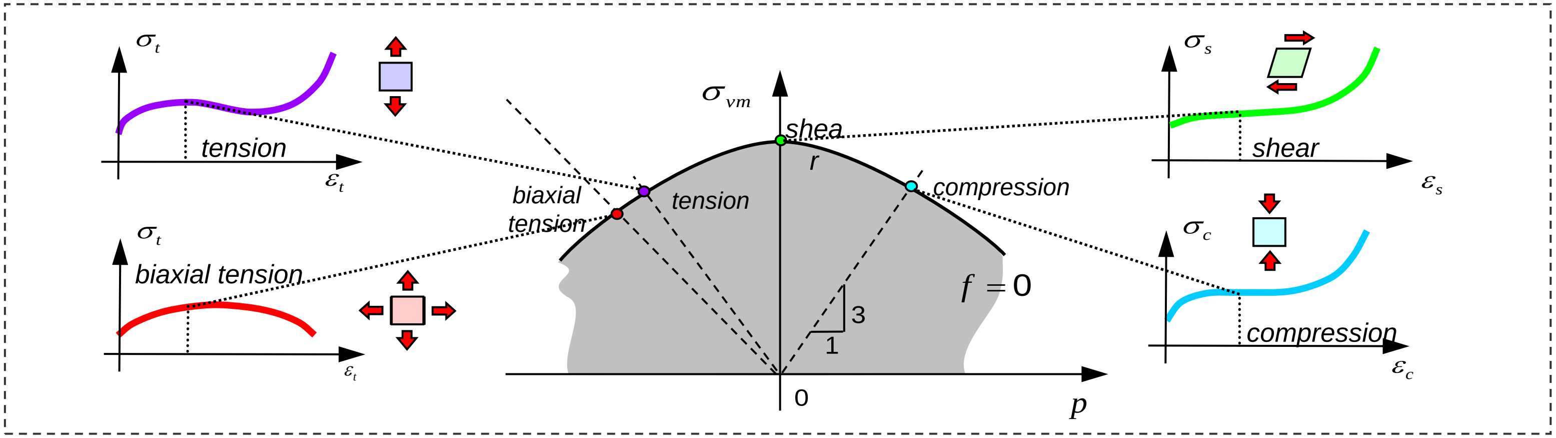
Identification:
Requirements for a model targeting polymers

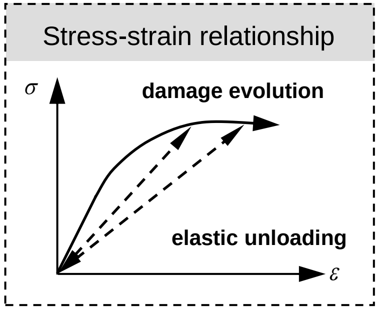
- Plastic incompressibility is not a realistic assumption for the most polymers
- Hence a pressure dependency must be considered in the yield surface and the plastic potential i. e. the plastic flow
- Initial isotropy – on a macroscopic level - will be disturbed eventually by straining:
  - *Molecule chains will be stretched* ➡ *leading to induced anisotropic behaviour*
  - *Different behaviour in tension, compression and shear direction*

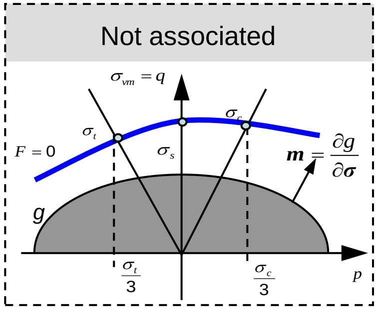


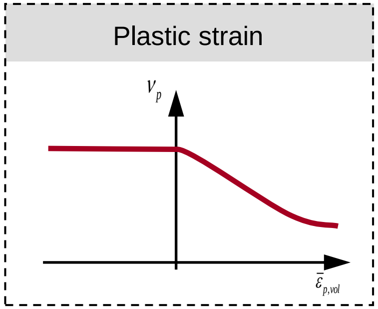
Unreinforced Polymers

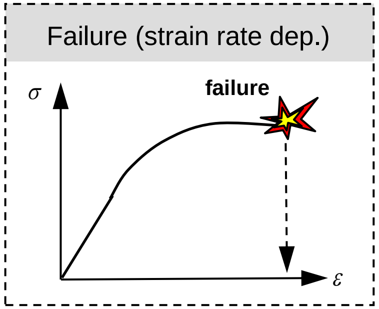
Detailed approach with new SAMP-1 (#187) model

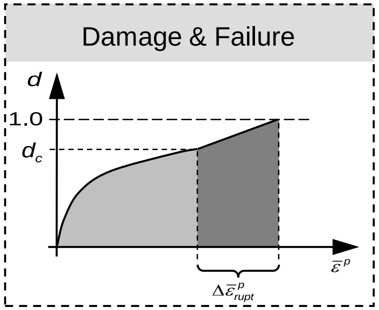


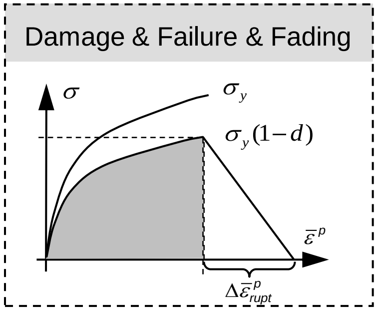


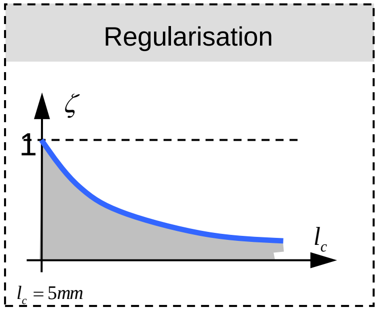


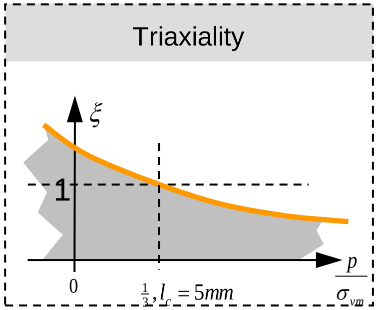






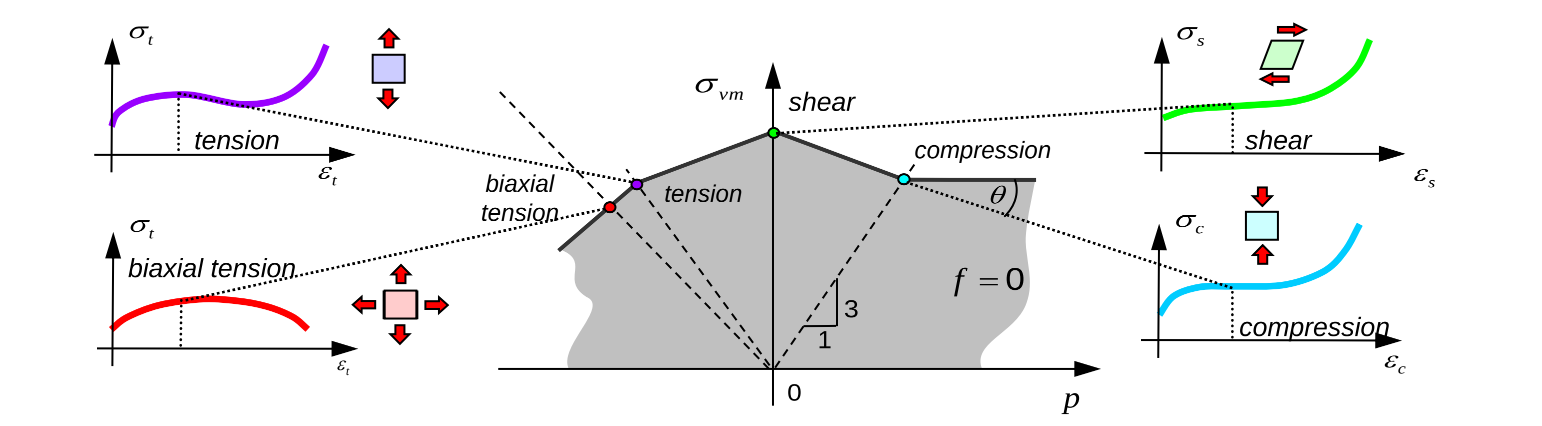


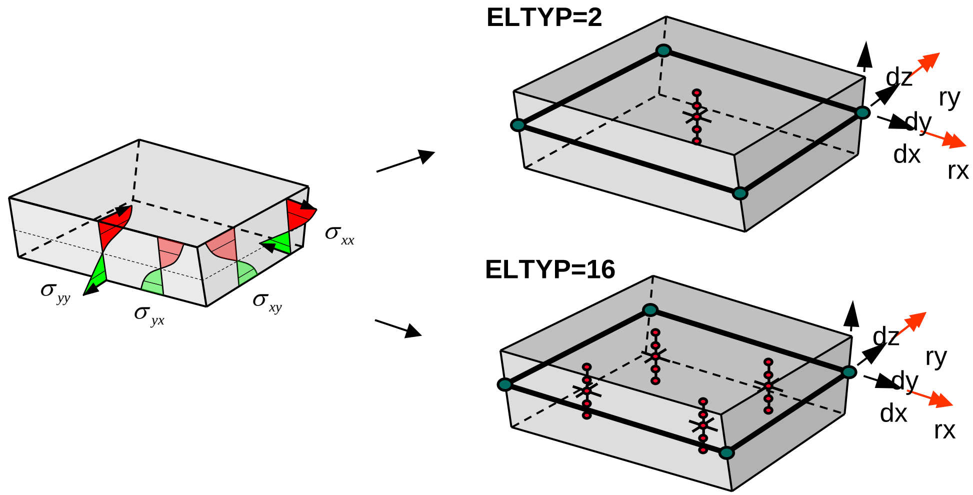


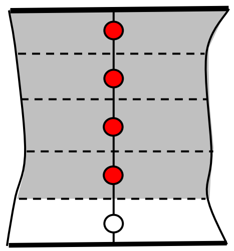


Unreinforced Polymers: Maturity of the model

Detailed approach with new SAMP-1 (#187) model







20% Failure

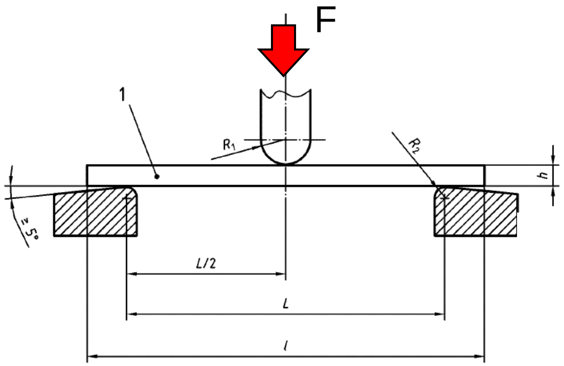
Element deletion is defined via a section percentage value of integration points that is flagged as failed

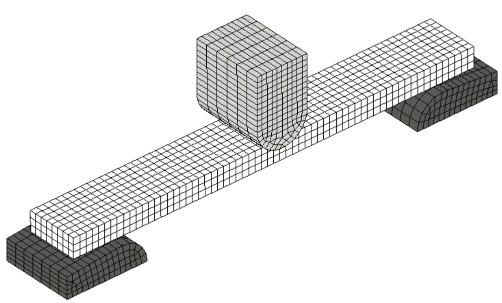
Validation PP_EPDM (a really old slide….)

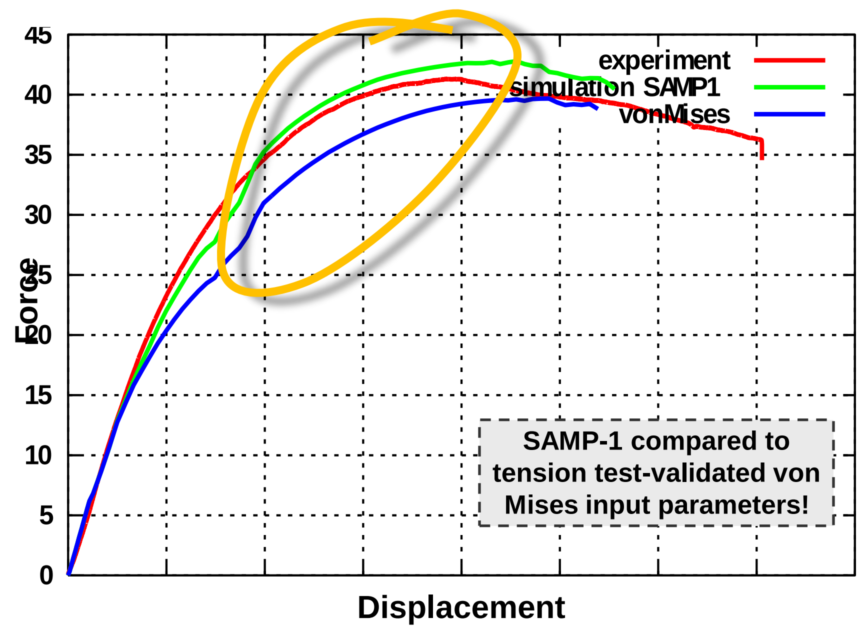
Three point bending test

- Specimen size 10 x 133 x 3.8 mm
- Downward prescribed displacement (quasi static)
- Solid elements, 1mm mesh size

- Overall we see good agreement with the results of small bending validation tests so far.
- SAMP has proven to be valuable but it is complicated and sometimes prohibitively slow.



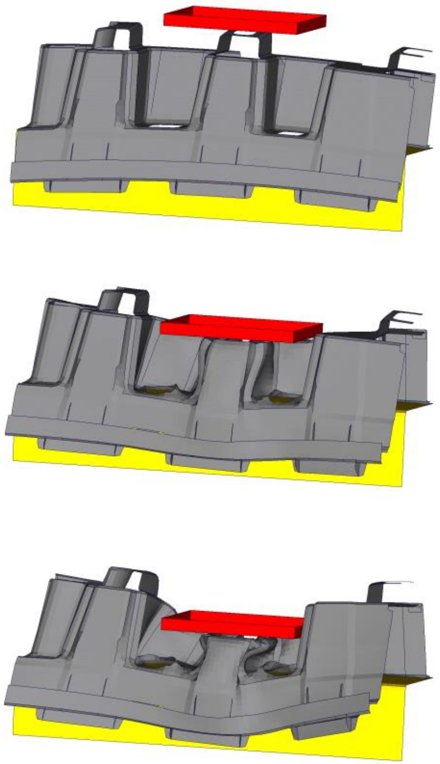


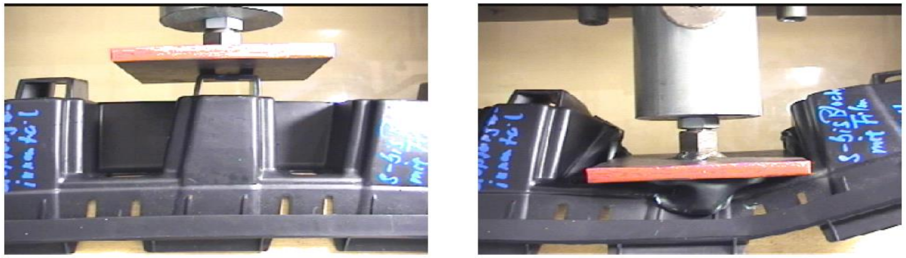


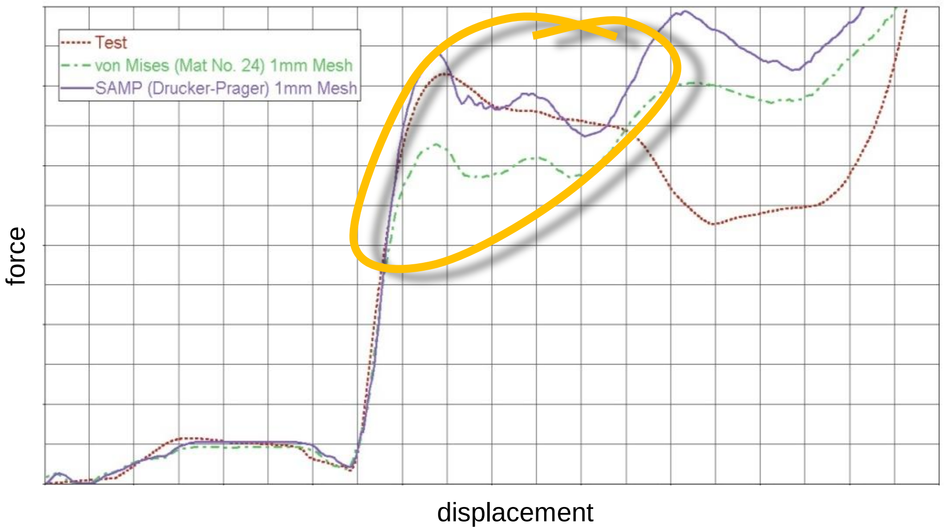
Unreinforced Polymers: Application

Detailed approach with SAMP-1 (#187)

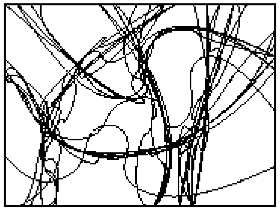
Typical behaviour for thermoplastics: material cards that are fitted for uniaxial tension yield a too soft response under bending and compression. Hence different yield curves under compression and tension are necessary!!







[Kolling, Feucht, DuBois, Haufe, 2006-2009, Courtesy Daimler AG]

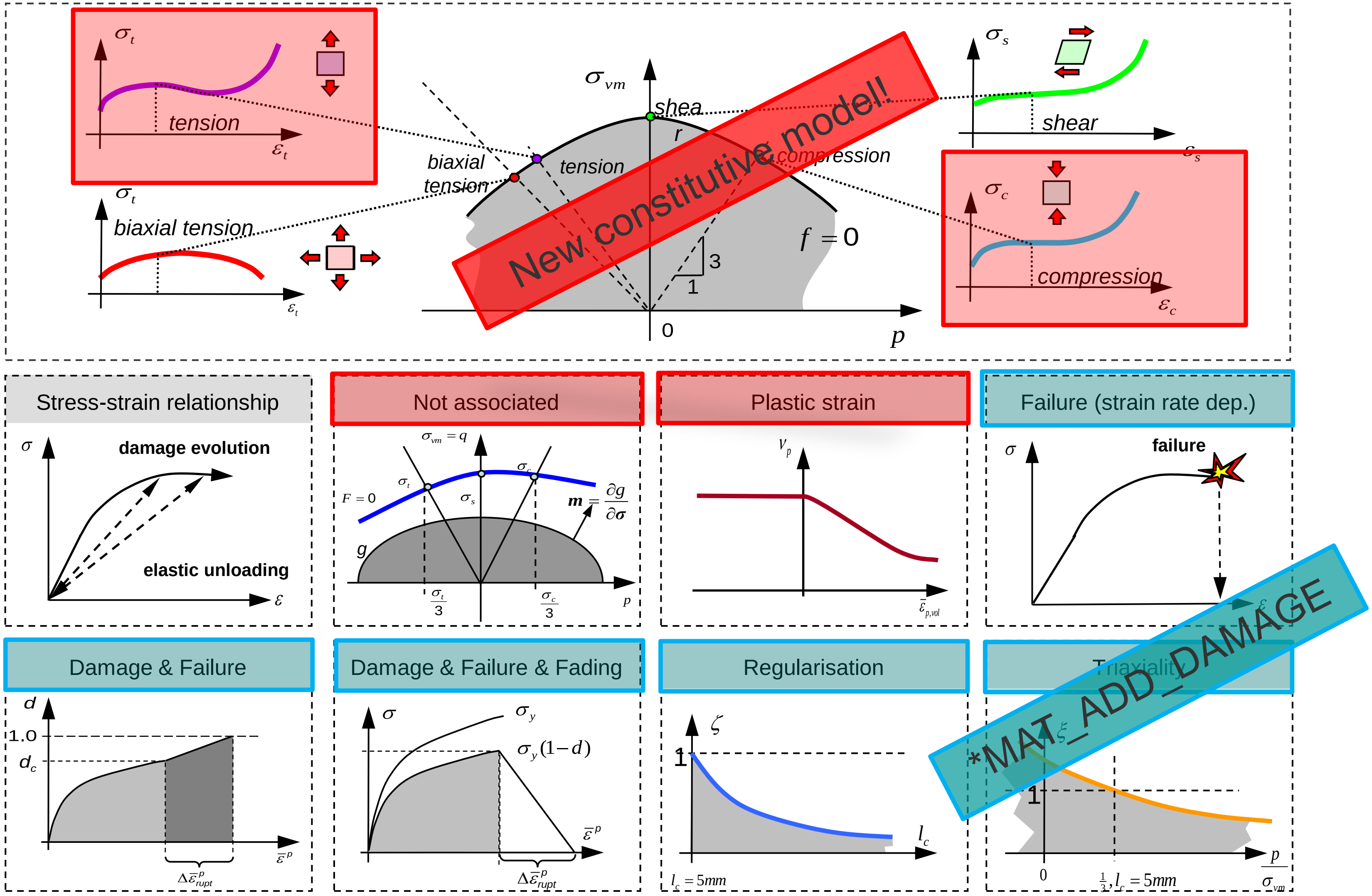


Unreinforced polymers: SAMP_Light

- actual ongoing development -

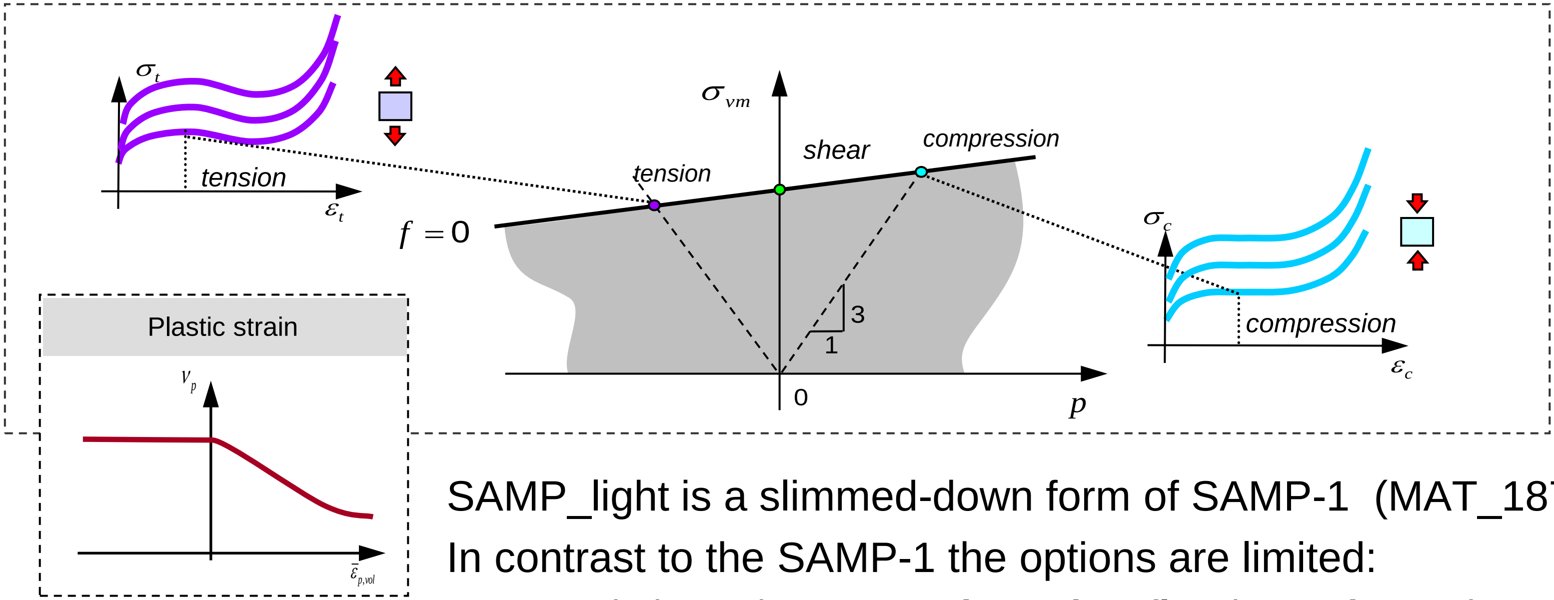
Unreinforced Polymers

What one really needs…



Unreinforced Polymers

What one really needs…



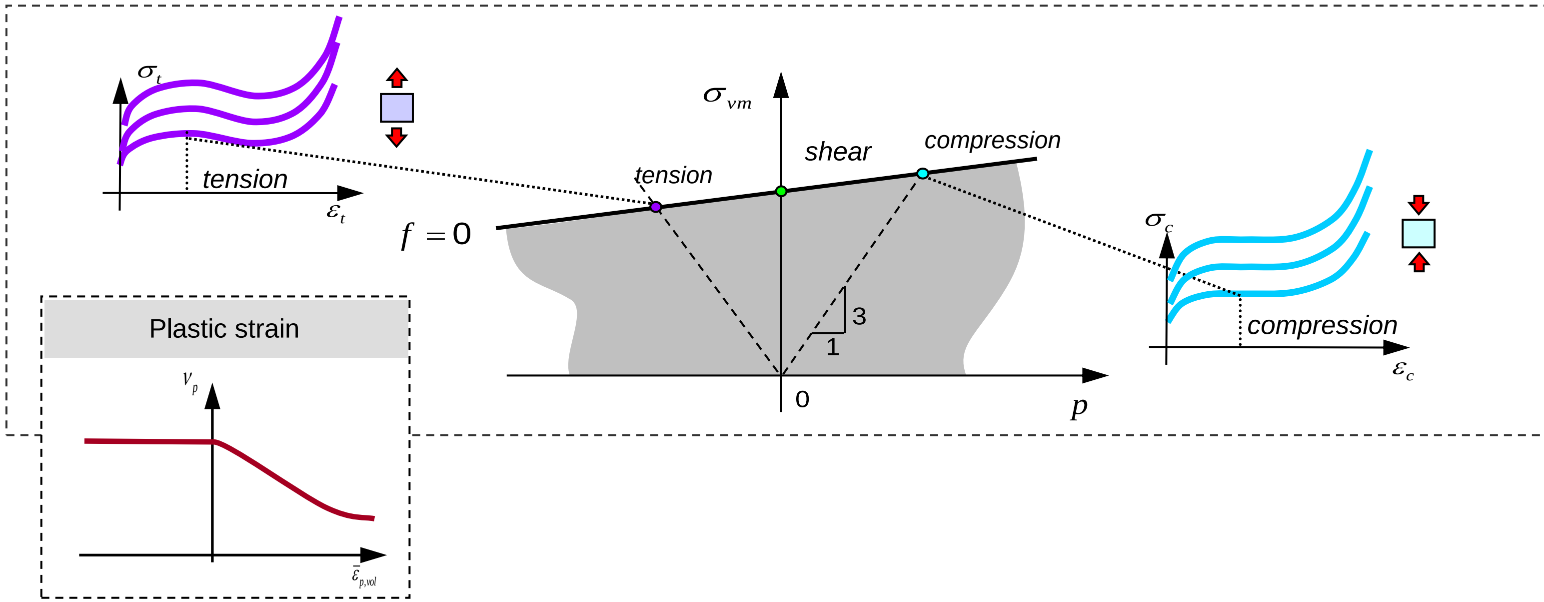
SAMP_light is a slimmed-down form of SAMP-1 (MAT_187)

In contrast to the SAMP-1 the options are limited:

- Rate independent or **rate dependent flow** in **tension** and **compression**
- Filtered strain rate instead of viscoplastic approach
- Constant or **variable plastic Poisson's ratio**
- **Shear** and **biaxial test data** are not incorporated
- **Damage** and **failure** is not available here. Instead use ***MAT_ADD_EROSION** or ***MAT_ADD_DAMAGE**
- This model is based on a complete re-coding of the plasticity algorithm.
- The **efficiency** was **improved. Computing times** will be much **shorter.**
- Only explicit at present.

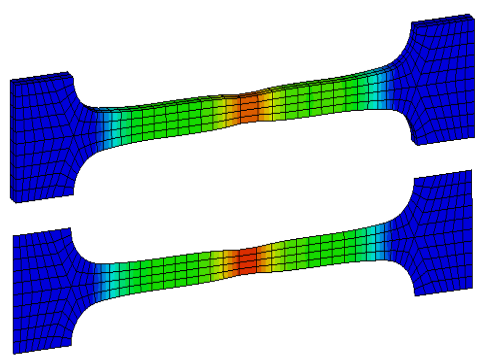
Unreinforced Polymers

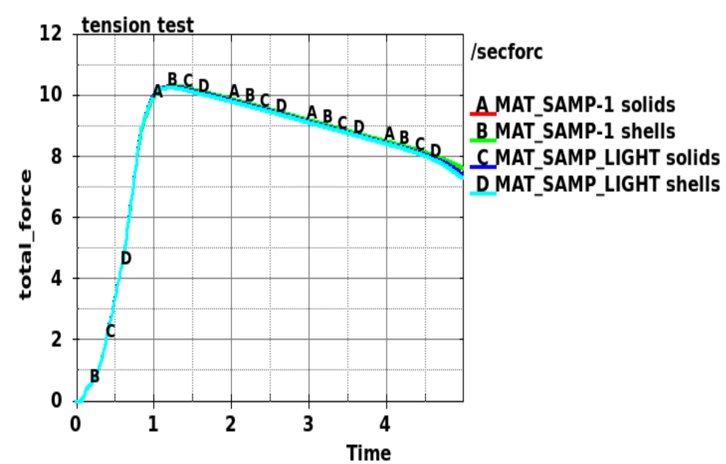
What one really needs…



First example:

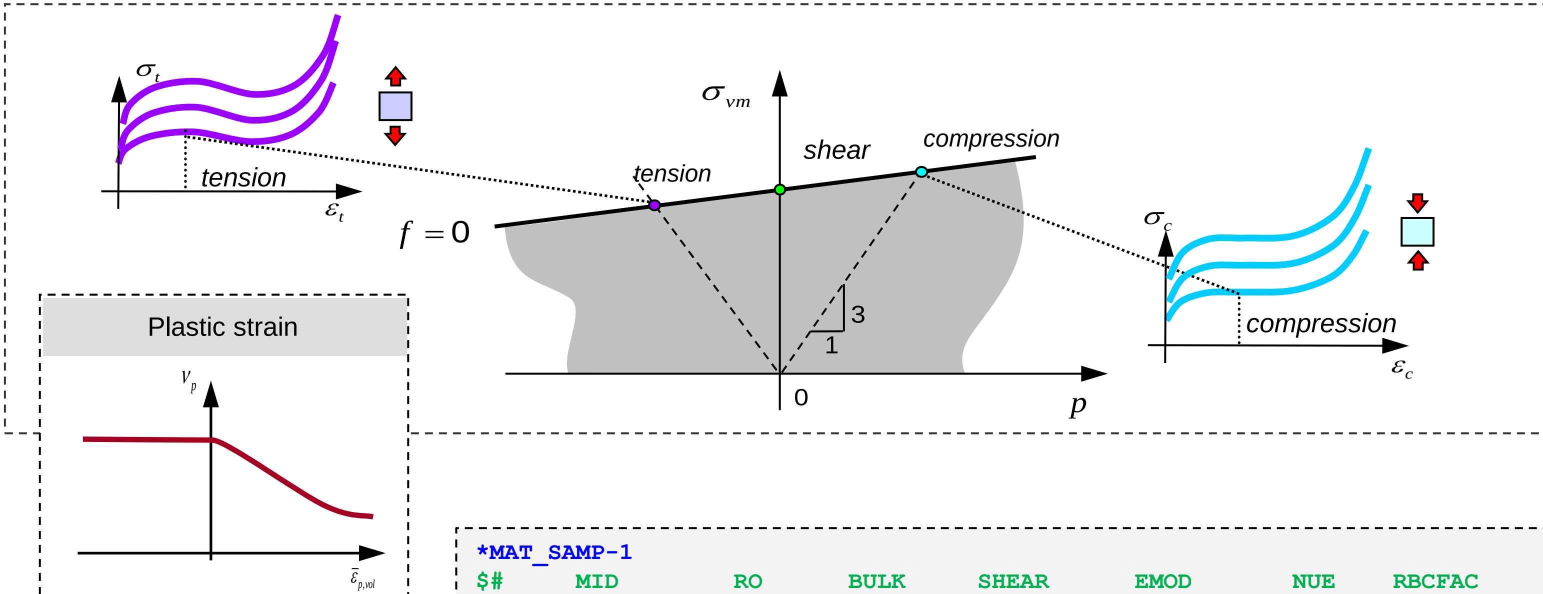
Tension test w/ solid and shell elements is seven times faster with the new model showing comparable results.





Unreinforced Polymers

What one really needs…



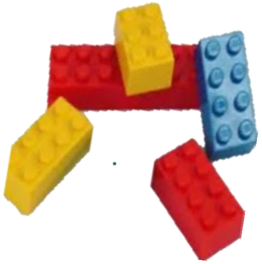

```
*MAT_SAMP-1
$#     MID        RO      BULK     SHEAR      EMOD       NUE    RBCFAC
         1    1.1E-6                           1.3       0.4
$#  LCID-T    LCID-C    LCID-S    LCID-B      NUEP    LCID-P              INCDAM
       100                                     0.5
$#  LCID-D    EPFAIL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

$#   MITER      MIPS             INCFAIL     ICONV      ASAF
                                       1
```

```
*MAT_SAMP_LIGHT
$#     MID        RO                          EMOD       NUE
         1    1.1E-6                           1.3       0.4
$#  LCID-T    LCID-C                          NUEP    LCID-P    RFILTF
       100                                     0.5                0.95
```

Starting R11.1

Calibration example: Rubber- toughened polymer

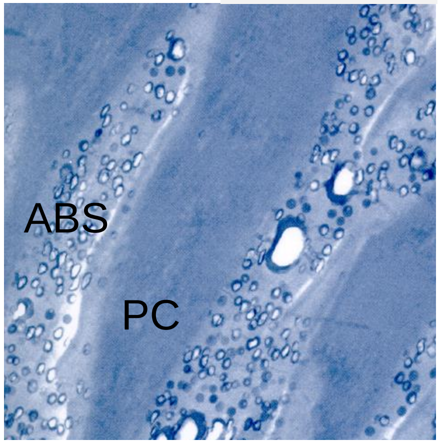
- Products with rubber-toughened polymers



- Glassy polymer matrix
- Fine dispersed rubber particles
  - Acrylonitrile butadiene styrene (ABS)
  - High-impact polystyrene (HIPS)
  - Polymerblends (PC/ABS)

(Grellmann, 1998)

(Inberg, 2001)



Calibration example: Rubber- toughened polymer

- Products with rubber-toughened polymers

Ultimate goal:

→ Easy test geometries and conditions
→ Easy, fast and robust material models
→ Easy identification of material parameters
→ Easy description of important material behavior

SAMP Light

Daily issues:

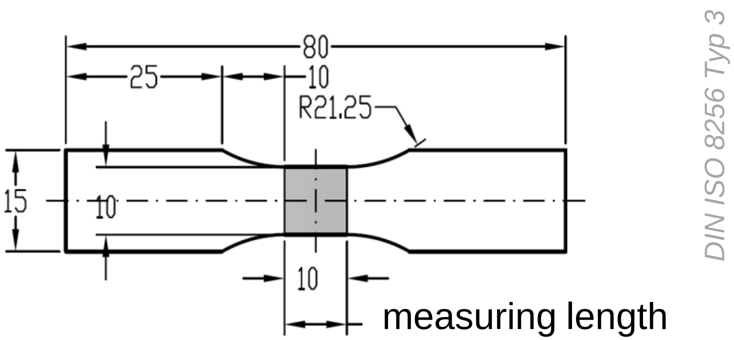
- **Microstructure is unknown** (rubber content and size, ..)
- Influence of process parameters
- Generally anisotrop

Material card:

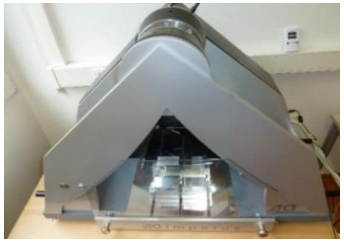
- Calibration as simple and fast as possible
- Calculation time is critical

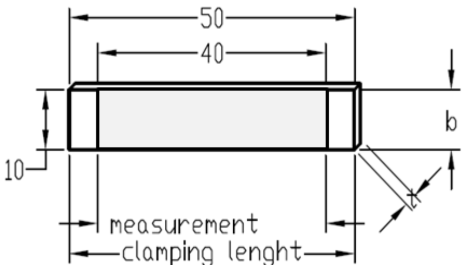
Testing: Specimen geometry used

- Tensile specimen
  - Static and dynamic tests
  - Strain via DIC
  - Engineering strain with l_0=10 mm
  - Target mesh size: 2 mm
  - Milled specimen

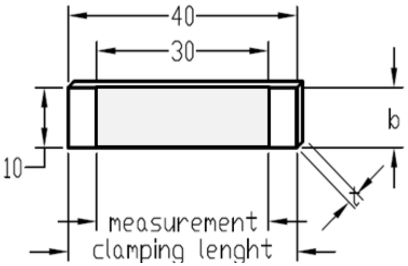


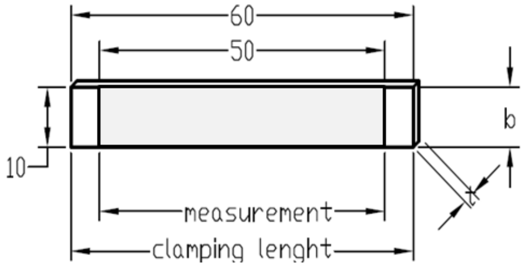
- 3 point Bending:
  - Static and dynamic tests
  - Milled specimen
  - Large of strain rates possible





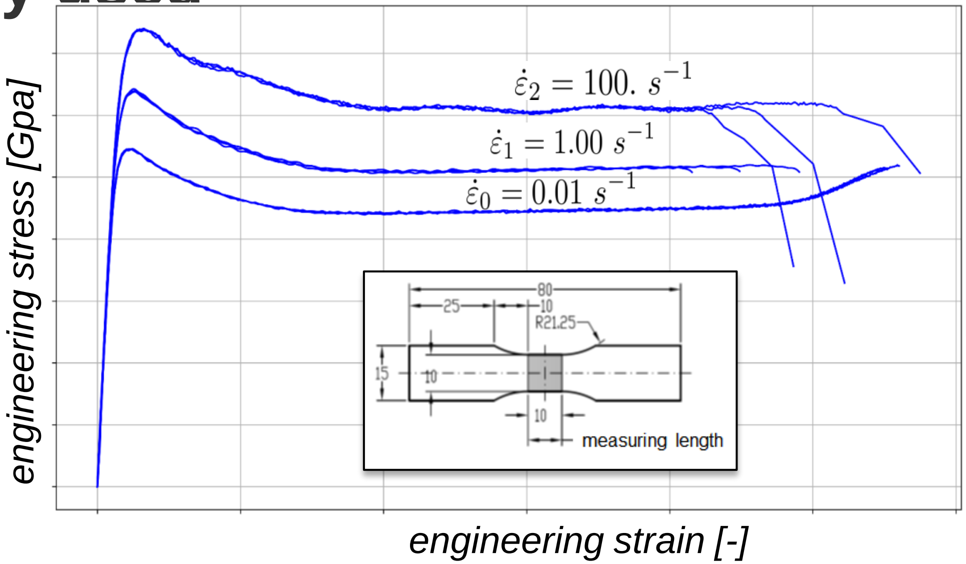
- Simple compression test
  - Complicated boundary conditions



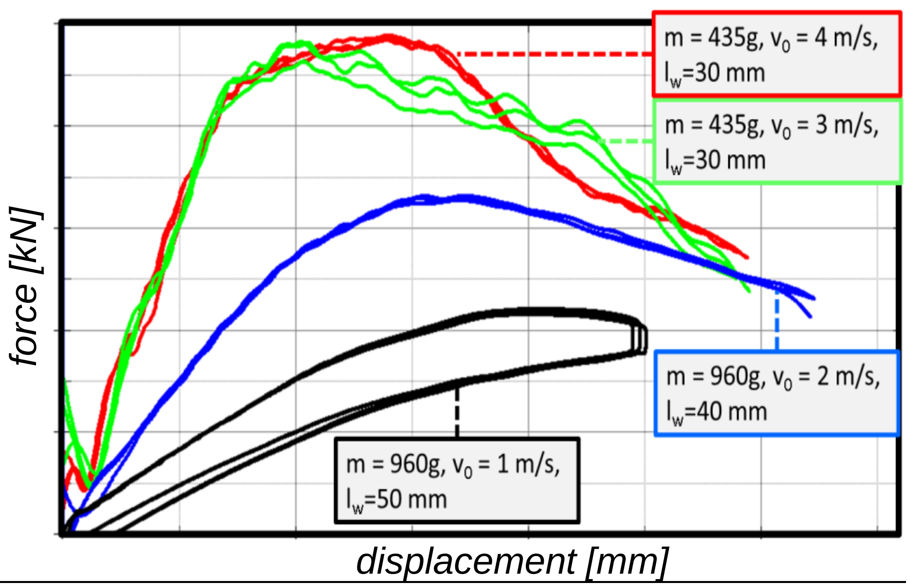


Testing: Specimen geometry used

- Tensile specimen
  - Static and dynamic tests
  - Strain via DIC
  - Engineering strain with l_0=10 mm
  - Target mesh size: 2 mm
  - Milled specimen

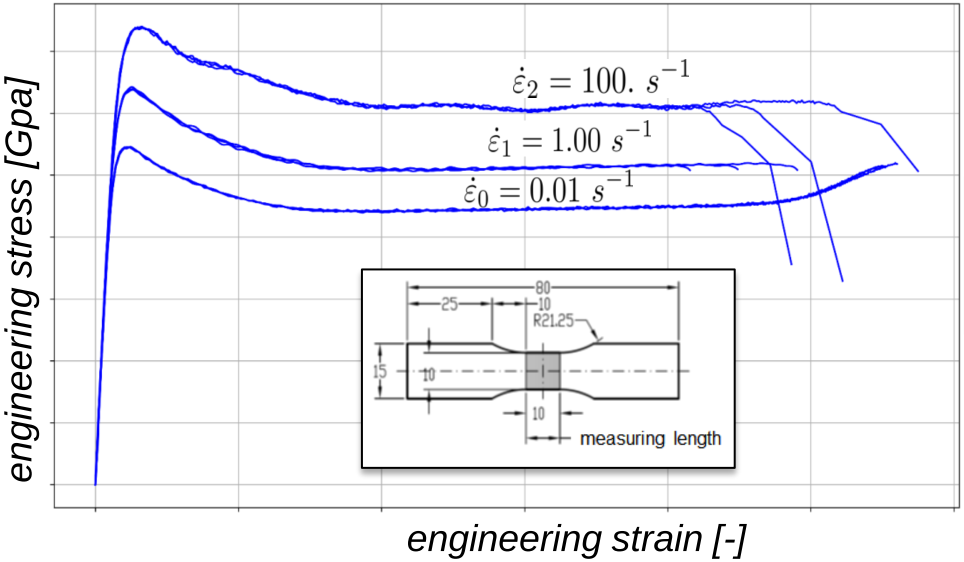


- 3 point Bending:
  - Static and dynamic tests
  - Milled specimen
  - Large of strain rates possible

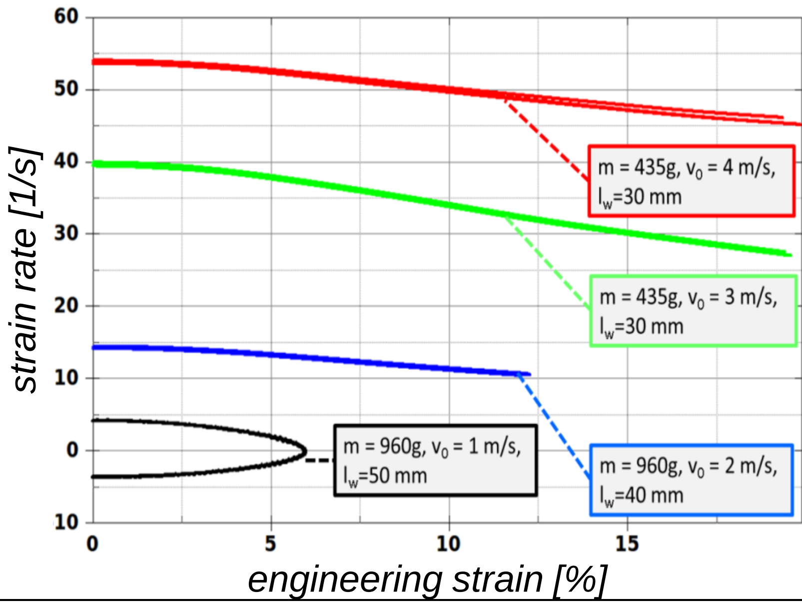


Testing: Specimen needed

- Tensile specimen
  - Static and dynamic tests
  - Strain via DIC
  - Engineering strain with l_0=10 mm
  - Target mesh size: 2 mm
  - Milled specimen

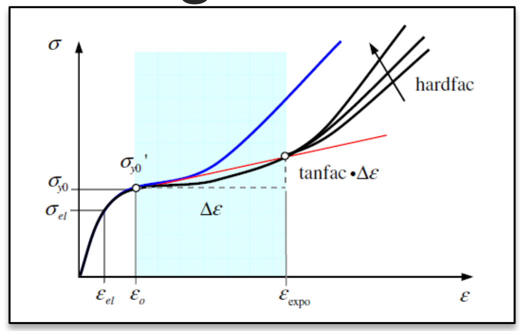


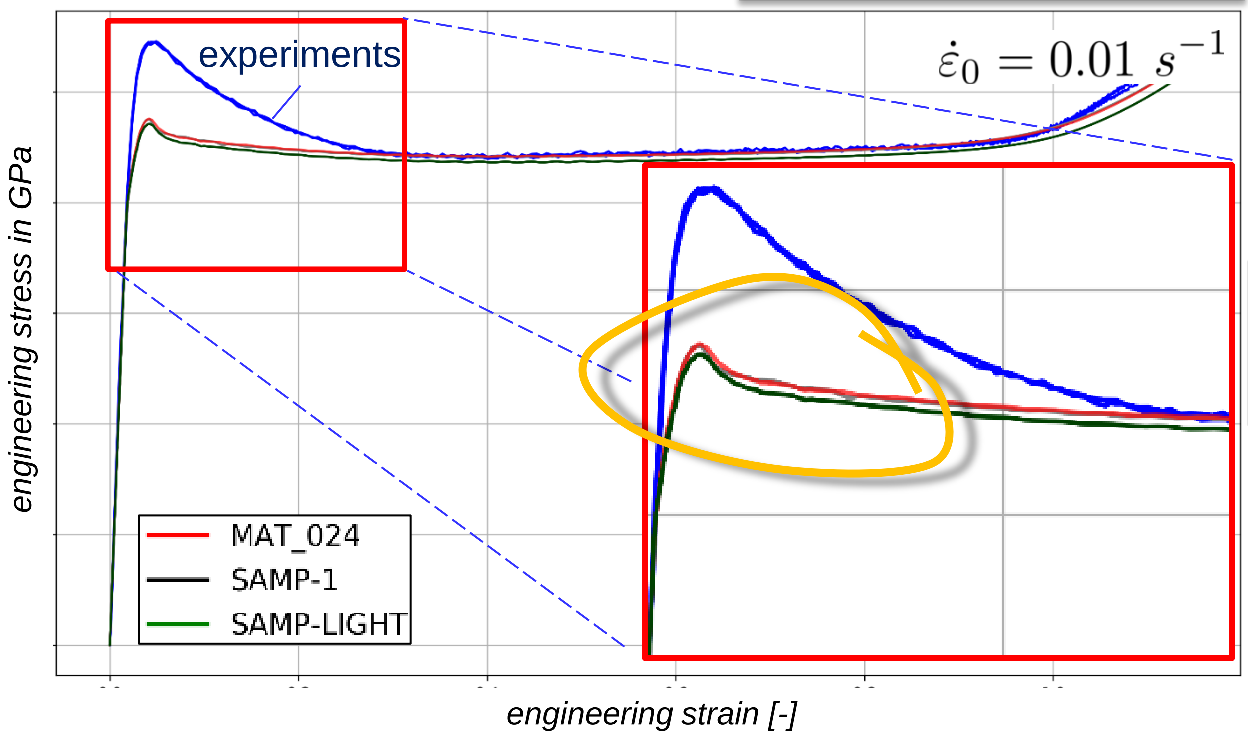
- 3 point Bending:
  - Static and dynamic tests
  - Milled specimen
  - Large of strain rates possible

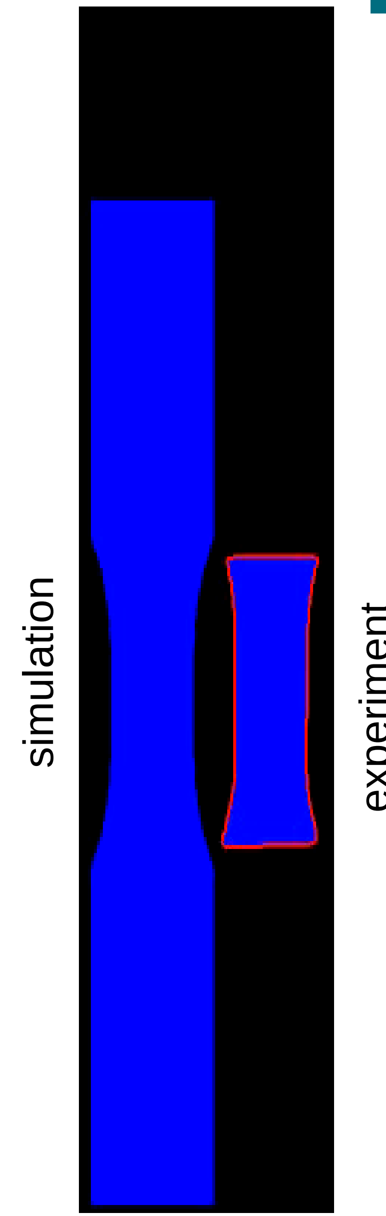


Comparison of quasi-static strain-field obtained via inverse modelling

The objective of the yield curve calibration was to achieve the **best possible** agreement of **the strain field versus time** in the quasi static load case with “PDB-C1” ansatz.

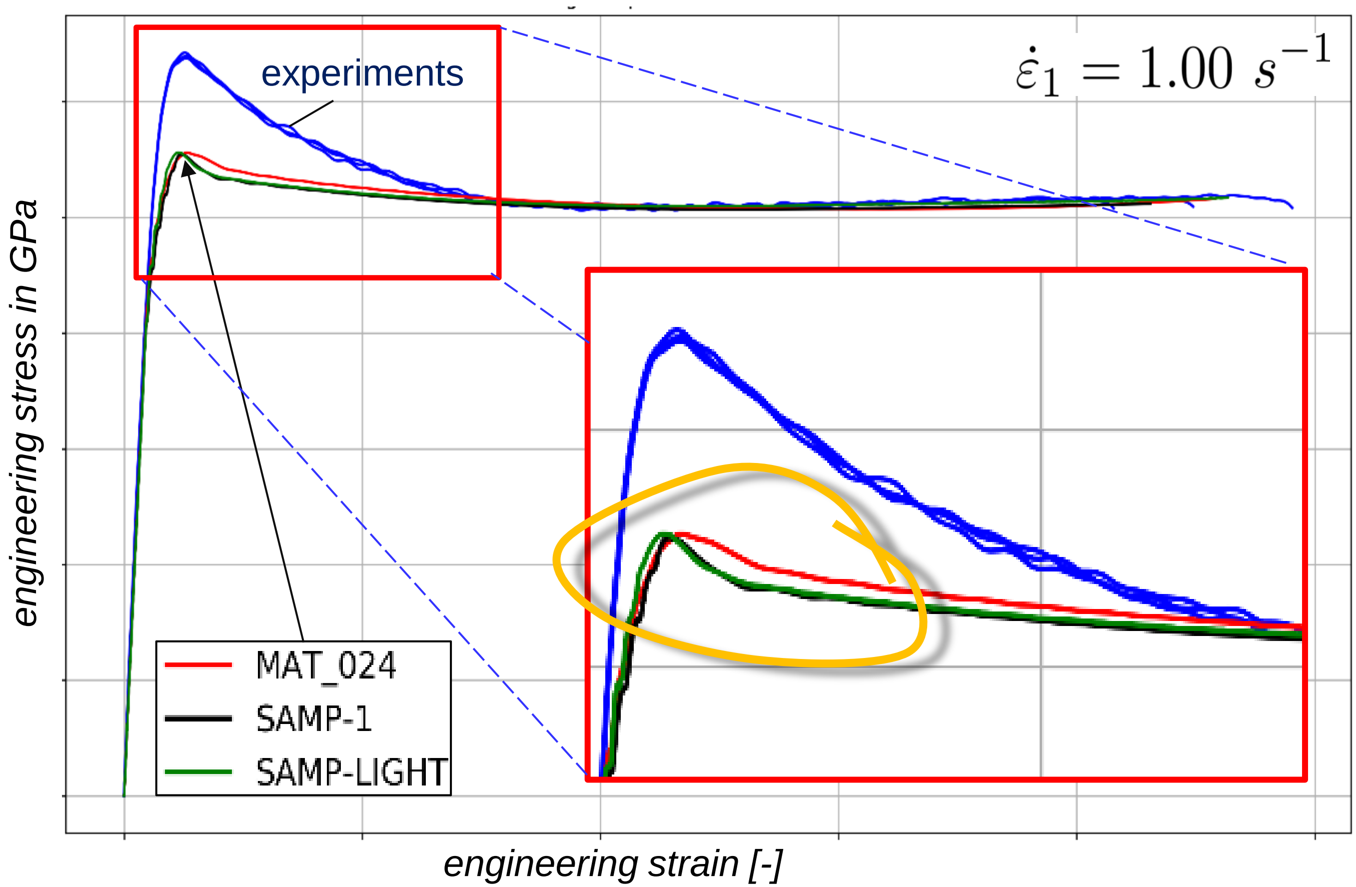






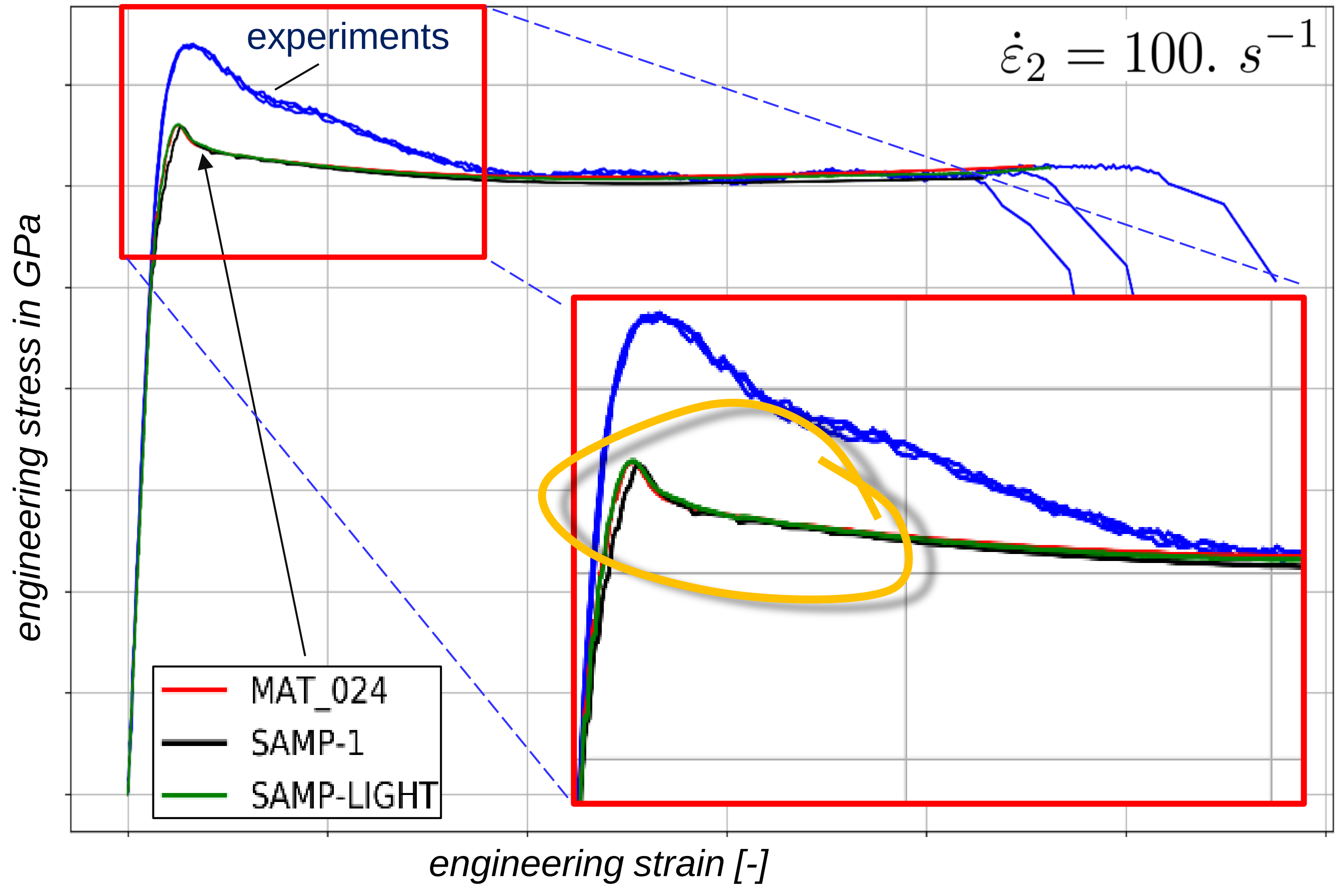
Modelling visco-plastic behavior: Elevated strain rate $\dot{\varepsilon}_1$

- Strain rate dependency by **scaling** of the quasi-static yield curve
- Same scaling factor was used in both constitutive models



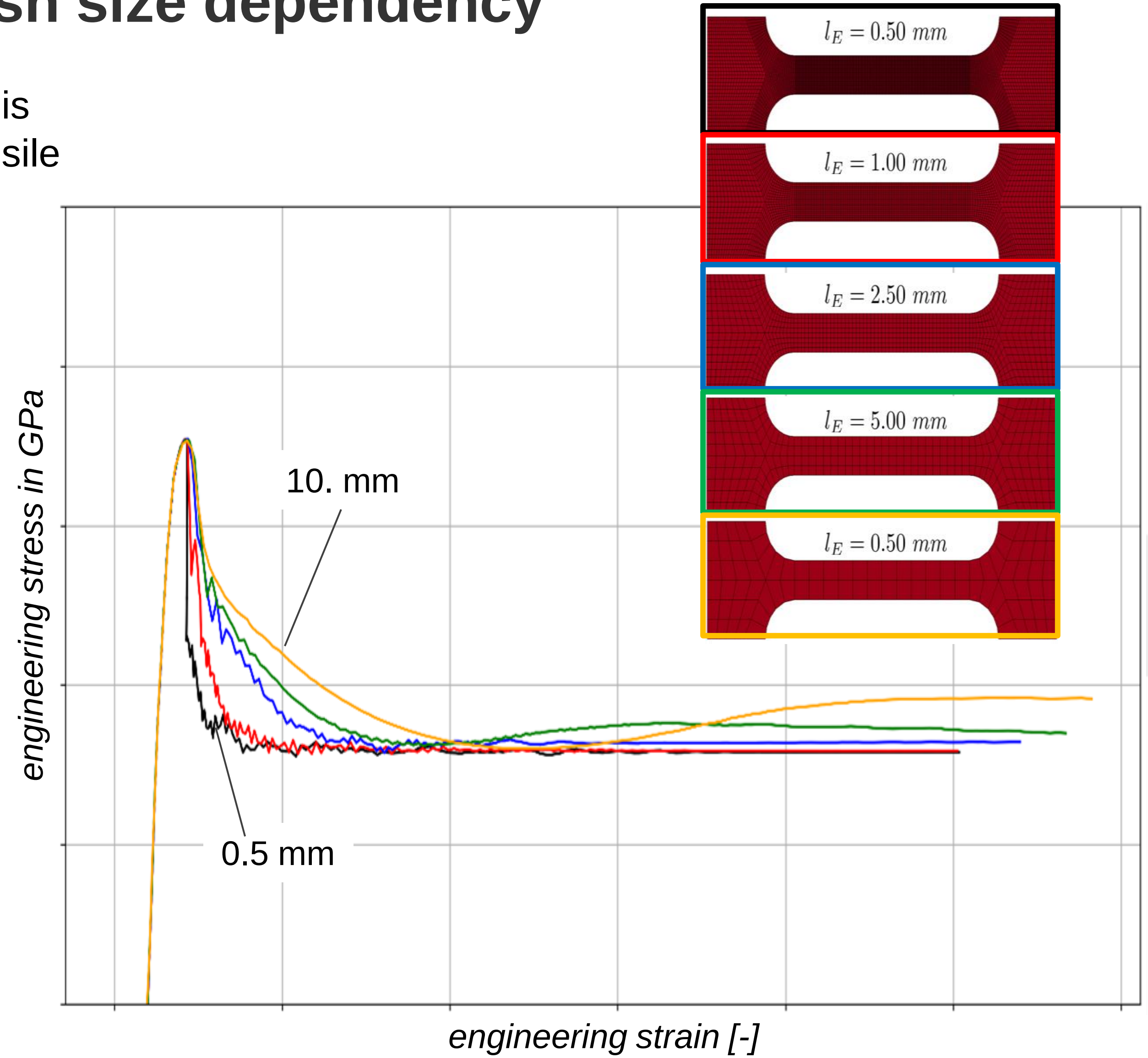
Modelling visco-plastic behavior: Elevated strain rate $\dot{\varepsilon}_2$

- Strain rate dependency by **scaling** of the quasi-static yield curve
- Same scaling factor was used in both constitutive models



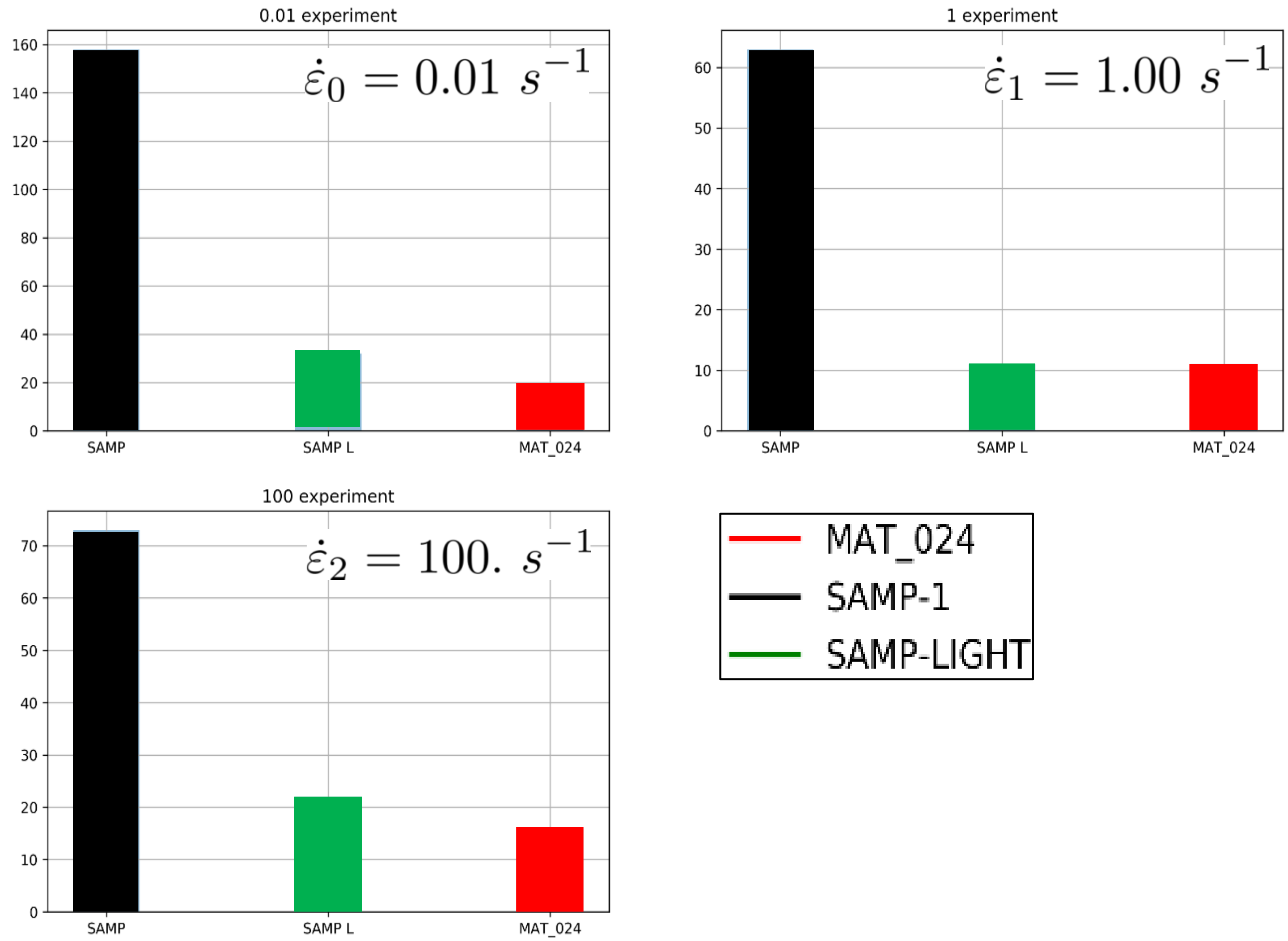
Investigating mesh size dependency

- Mesh size dependency is investigated on A80-tensile specimen geometry
- Element edge length chosen from 0.5 up to 10 mm
- Typical approach for metallic materials to calibrate parameter w.r.t. element size when using GISSMO



Comparison of computation time

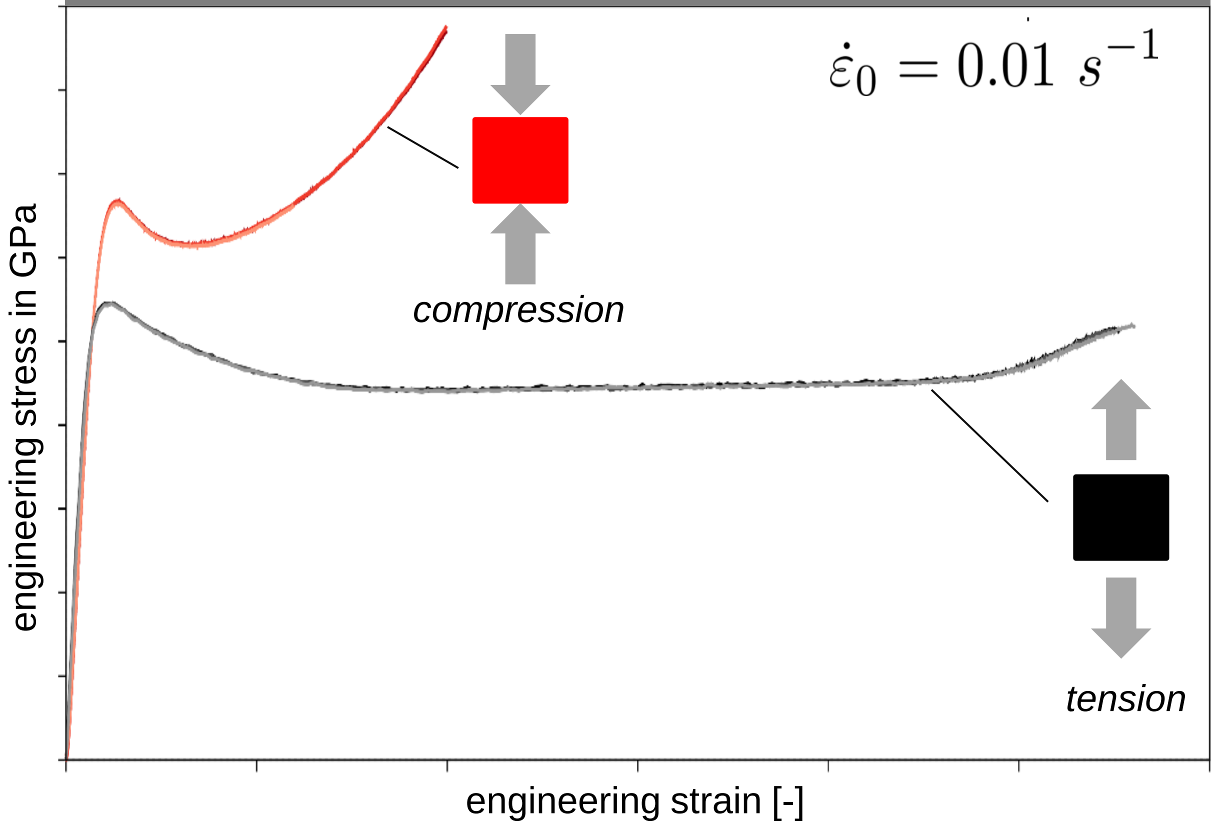
Here: von Mises yield locus



Investigating Tension - Compression behavior

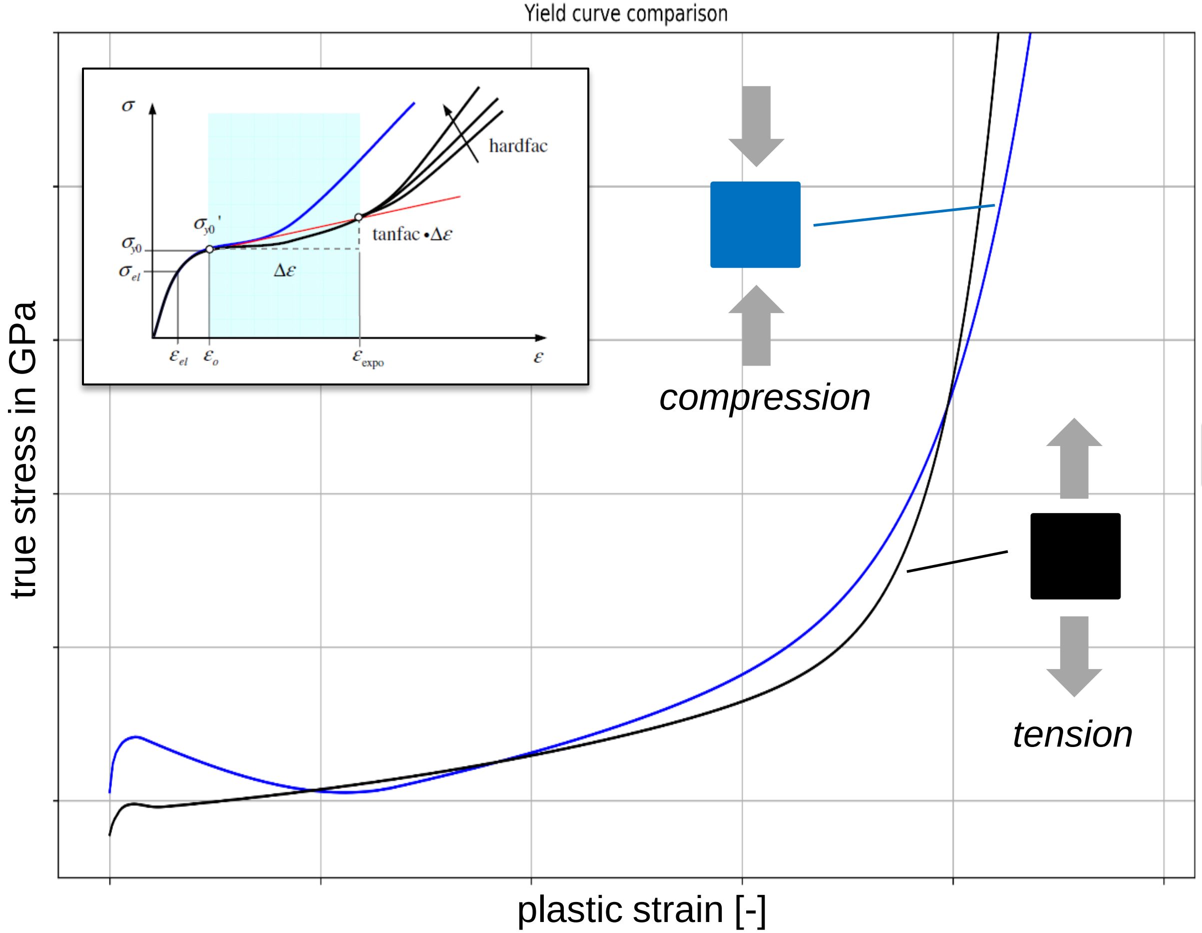
- **MAT_SAMP-1** and **MAT_SAMP_LIGHT** allow different yield behavior in tensile and compression loading
- An additional yield curve is used to define compressive behavior

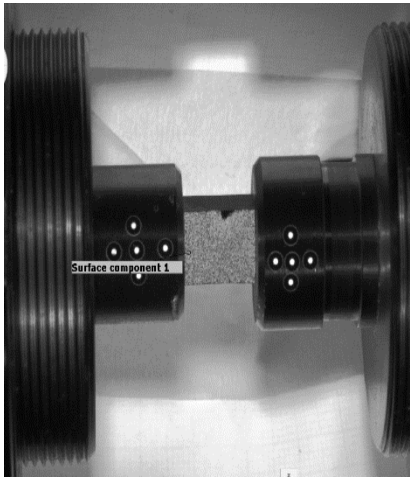
Test data (quasi static)

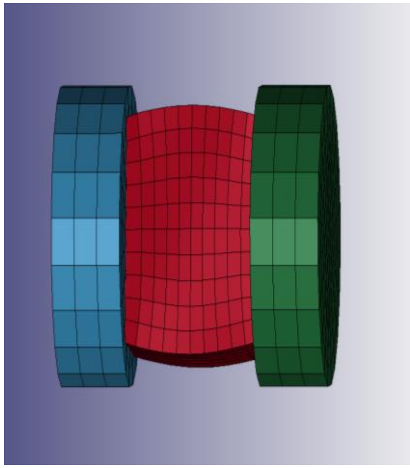


Two yield curves in tension and compression

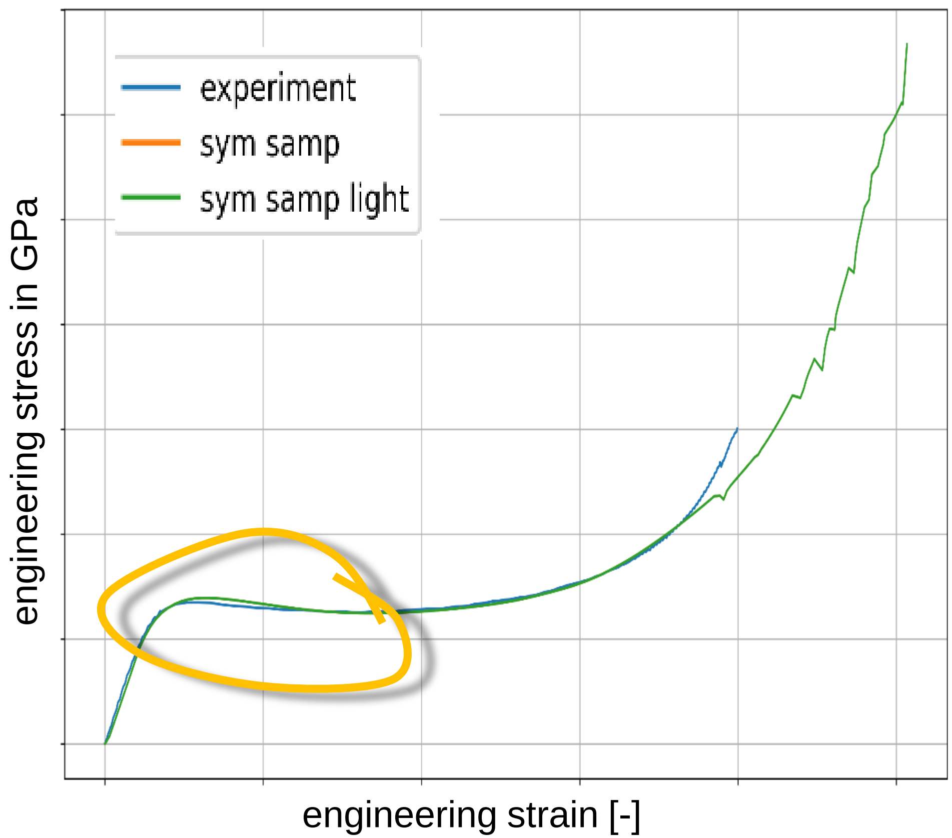
- Identification from inverse modelling
- SAMP-1 and SAMP_Light use same definiton

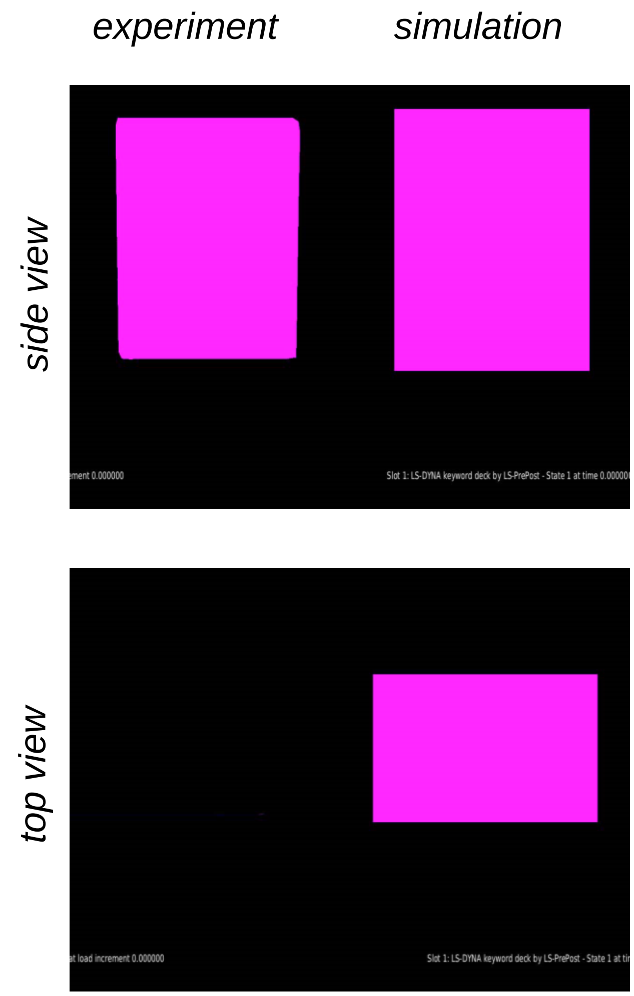






Calibrating compression test: Results quasi static

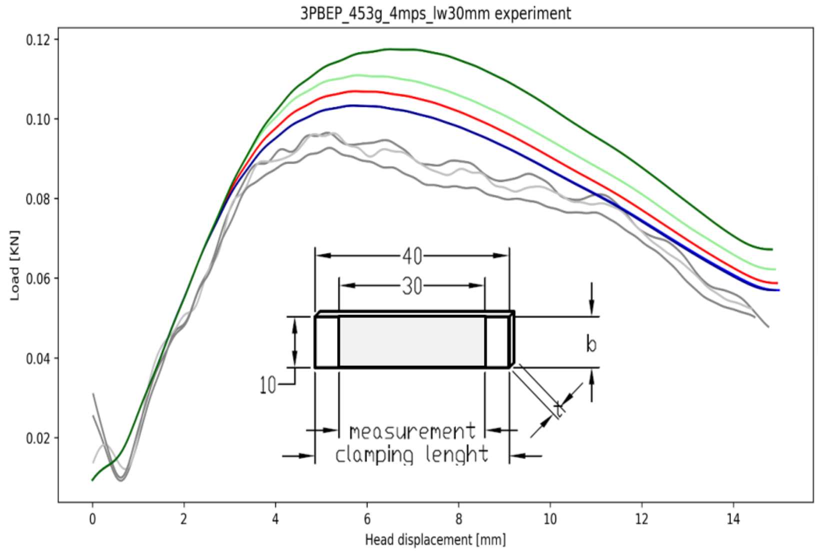


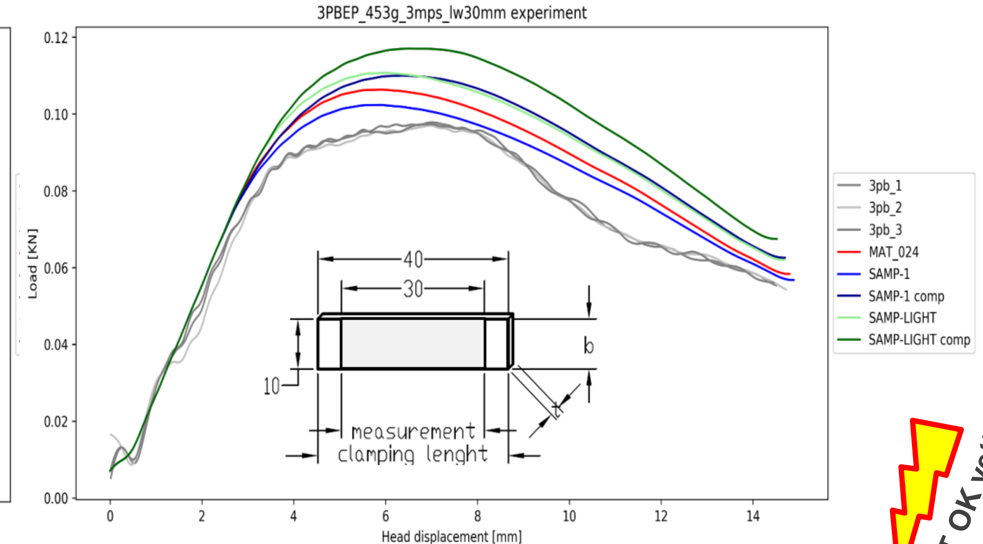


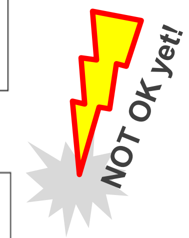
Does that approach do the „trick“?

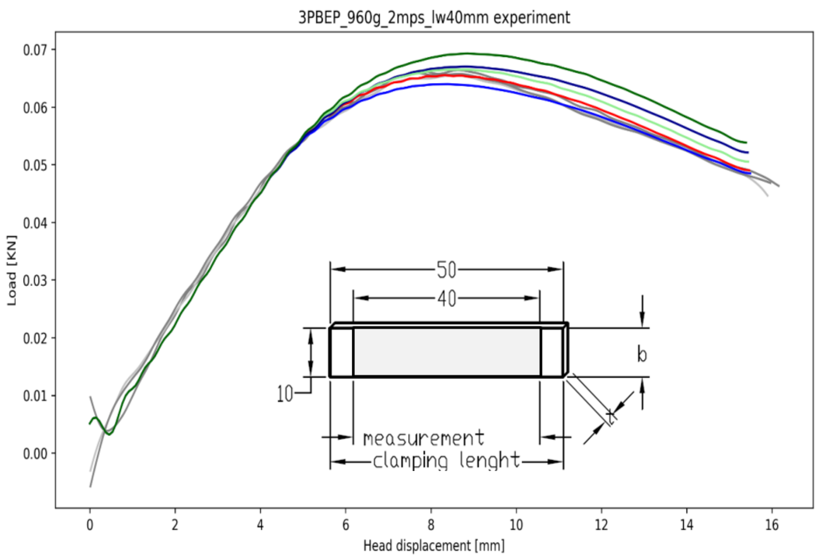
Bending, bending, bending…

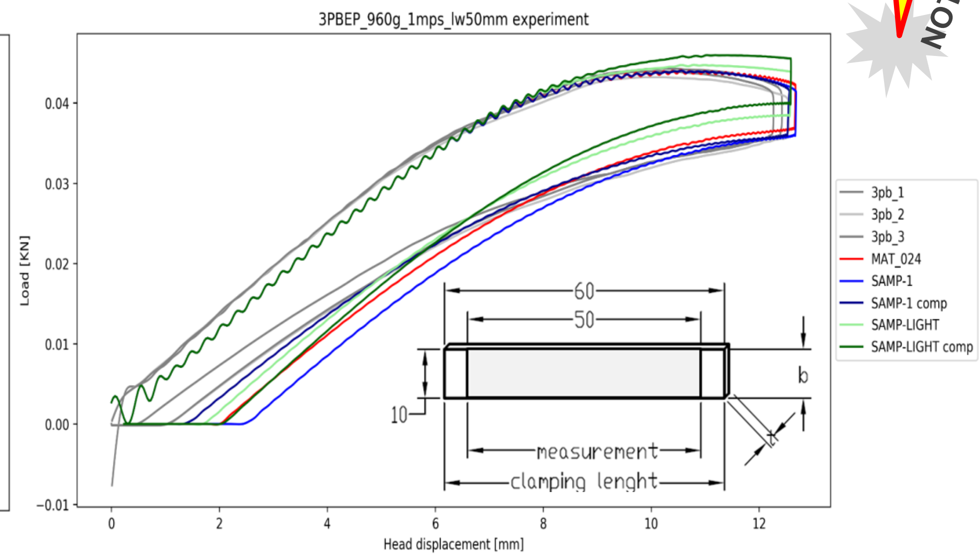
Three point bending results with this two yield curves











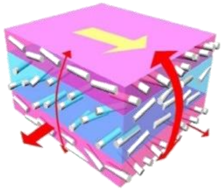
Remember

- Compression tests – as seen in the previous slides – are not very “reliable”: They very often produce stress states that may be far away from “pure” compression (i.e. the triaxiality is typically not -1/3).

- Strain rate evaluation is different in SAMP-1 and SAMP_light.
  So recalibration might be necessary.

- Do not expect identical results from viscous
  plastic strain rate vs. filtered total strain rate:

  For instance: If you compare MAT_24 with SAMP_LIGHT remember to use VP=0 and RFILTF=0.001. Also use the same number of curves and the same value for LCINT.



Crushable foams

- active development -

MAT_CRUSHABLE_FOAM, MODEL=1:

- **Lateral straining:**

  Individual elastic and plastic Poisson's ratio available: $\nu^{el}, \ \nu^{pl}$

- **Yield condition: Elliptic in the pressure – stress deviator space**

$$F = \sqrt{q^2 + \alpha^2 p^2} - B(\sigma^y) = 0$$

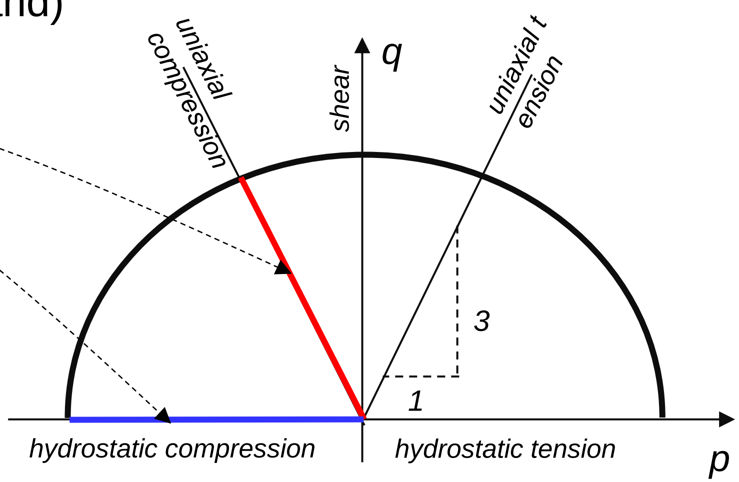
Tension-compression symmetry (easy to expand)

Ratio $k = \frac{\sigma^{y,uniaxial\ compression}}{\sigma^{y,hydrostatic\ compression}}$

describes shape of yield ellipse.

$0 \leq k < 3$

$k = 0$: von Mises



MAT_CRUSHABLE_FOAM, MODEL=1:

Yield condition:

$$F = \sqrt{q^2 + \alpha^2 p^2} - B(\sigma^y) = 0$$

$$p = \frac{1}{3} tr\, \boldsymbol{\sigma}$$

$$q = \sqrt{\frac{3}{2} dev\boldsymbol{\sigma} : dev\boldsymbol{\sigma}}$$

$$\alpha = \frac{3k}{\sqrt{9 - k^2}}$$

$$k = \frac{\sigma^{y,initial,uniax}}{\sigma^{y,initial,hydrostatic}}$$

$$B = \sigma^{y,uniax} \sqrt{1 + \left(\frac{\alpha}{3}\right)^2}$$

Flow potential:

$$G = \sqrt{q^2 + \beta^2 p^2} - B(\sigma^y) = 0$$

$$\beta = \frac{3}{\sqrt{2}} \sqrt{\frac{1 - 2\nu^{pl}}{1 + \nu^{pl}}}$$

Hardening:

Rate independent (curve):

$$\sigma^{y,uniaxial} = \sigma^y(\varepsilon^{pl})$$

Rate dependent (table):

$$\sigma^{y,uniaxial} = \sigma^y(\varepsilon^{pl}, \dot{\varepsilon}^{pl})$$

Rate dependent approximation (table):

$$\sigma^{y,uniaxial} = \sigma^y(\varepsilon^{pl}, \dot{\varepsilon}^{equiv,filtered})$$

Keyword:

```
*MAT_CRUSHABLE_FOAM
$       mid       rho         e        pr      lcid       tsc      damp     model
        ...   3.0e-11       6.0       0.0     12345                0.05         1
$       prp         k    rfiltf    bvflag     srcrt     escal
        0.2       1.3         0         0       0.1       5.0
```

- Parameters in *MAT_CRUSHABLE_FOAM, Model=1

  - MID: material ID
  - RHO: density
  - E: E-Modulus
  - PR: elastic Poisson's ratio
  - LCID: if MODEL.eq.1.:
    Load curve or table ID for rate independent or rate dependent hardening respectively (uniaxial yield stress vs. equivalent plastic strain for rate independent hardening, for rate dependent hardening see below)
  - TSC: only available for MODEL.eq.0.0
  - DAMP: only available for MODEL.eq.0.0

Keyword:

```
*MAT_CRUSHABLE_FOAM
$       mid       rho         e        pr      lcid       tsc      damp     model
        ...   3.0e-11       6.0       0.0     12345                0.05         1
$       prp         k    rfiltf    bvflag     srcrt     escal
        0.2       1.3         0         0       0.1       5.0
```

- Parameters in *MAT_CRUSHABLE_FOAM

  - MODEL:
    MODEL.eq.0.: Von Mises yield condition,
    hardening curve: yield stress vs. volumetric strain,
    only rate independent hardening (*MAT_163 for rate dependence)

    MODEL.eq.1: Elliptic yield surface in the p-q space with
    tension-compression symmetry, see slides above,
    independent elastic and plastic Poisson's ratio can be defined
  - PRP: only available for MODEL.eq.1.: plastic Poisson's ratio.
    $-1 < PRP \leq 0.5$. PRP determines the yield potential, i.e. the direction of plastic flow.
    For associated flow choose: $PRP = \frac{3-k^2}{6}$
  - K:only available if MODEL.eq.1.: ratio $k = \frac{\sigma^{y,uniaxial\ compression}}{\sigma^{y,hydrostatic\ compression}}$, determines the shape of the yield ellipse

Keyword:

```
*MAT_CRUSHABLE_FOAM
$       mid       rho         e        pr      lcid       tsc      damp     model
        ...   3.0e-11       6.0       0.0     12345               0.05         1
$       prp         k    rfiltf    bvflag     srcrt     escal
        0.2       1.3         0         0       0.1       5.0
```

- Parameters in *MAT_CRUSHABLE_FOAM

  - RFILTF: only available if MODEL.eq.1. Only of interest for rate dependent hardening (if LCID refers to a table).

    If RFILTF=0. (default) and MODEL.eq.1. and LCID refers to a table:
    yield stress $\sigma^{y,uniaxial} = \sigma^{y}(\varepsilon^{pl}, \dot{\varepsilon}^{pl})$ i.e. the table values are the yield stress vs. equivalent plastic strain for different plastic strain rates.

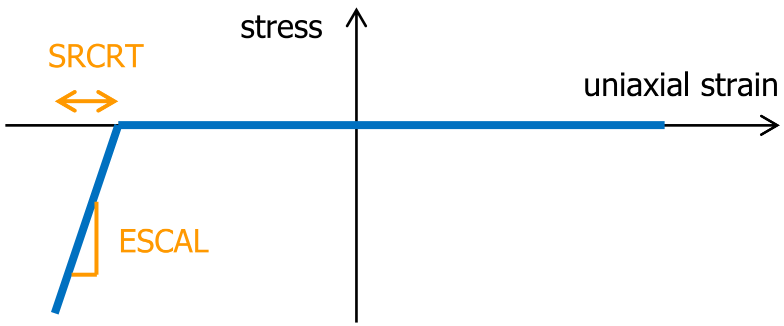
    If 0<RFILTF<1. and MODEL.eq.1. and LCID refers to a table:
    yield stress $\sigma^{y,uniaxial} = \sigma^{y}(\varepsilon^{pl}, \dot{\varepsilon}^{equiv})$ i.e. the table values are the yield stress vs. equivalent plastic strain for different filtered equivalent *total* strain rates, with

$$\dot{\varepsilon}^{equiv} = RFILTF * \dot{\varepsilon}^{total,\,equiv,\,n} + (1 - RFILTF) * \dot{\varepsilon}^{total,\,equiv,n+1}$$

Keyword:

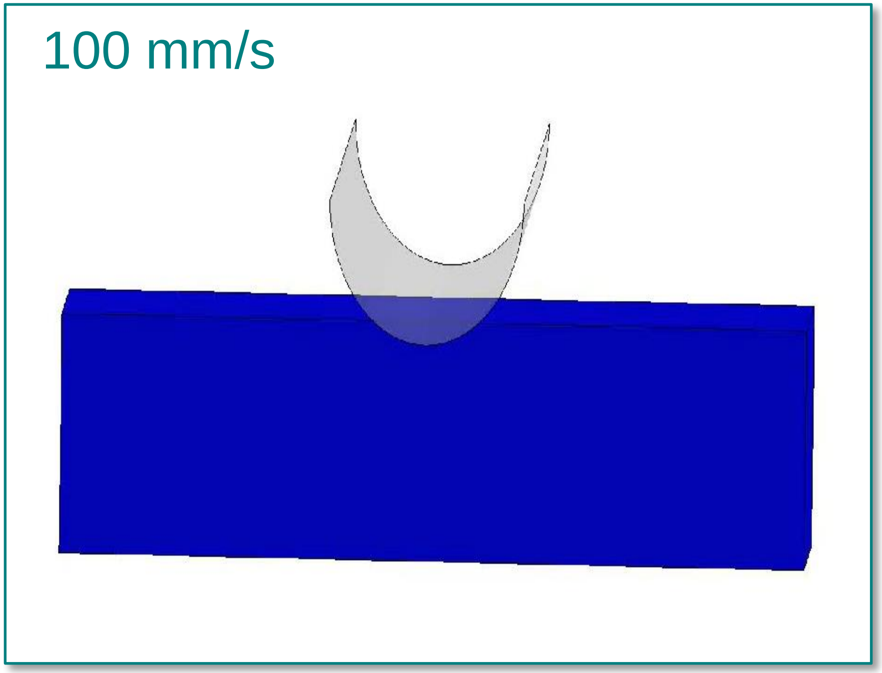
```
*MAT_CRUSHABLE_FOAM
$       mid       rho         e        pr      lcid       tsc      damp     model
        ...   3.0e-11       6.0       0.0     12345                0.05         1
$       prp         k    rfiltf    bvflag     srcrt     escal
        0.2       1.3         0         0       0.1       5.0
```

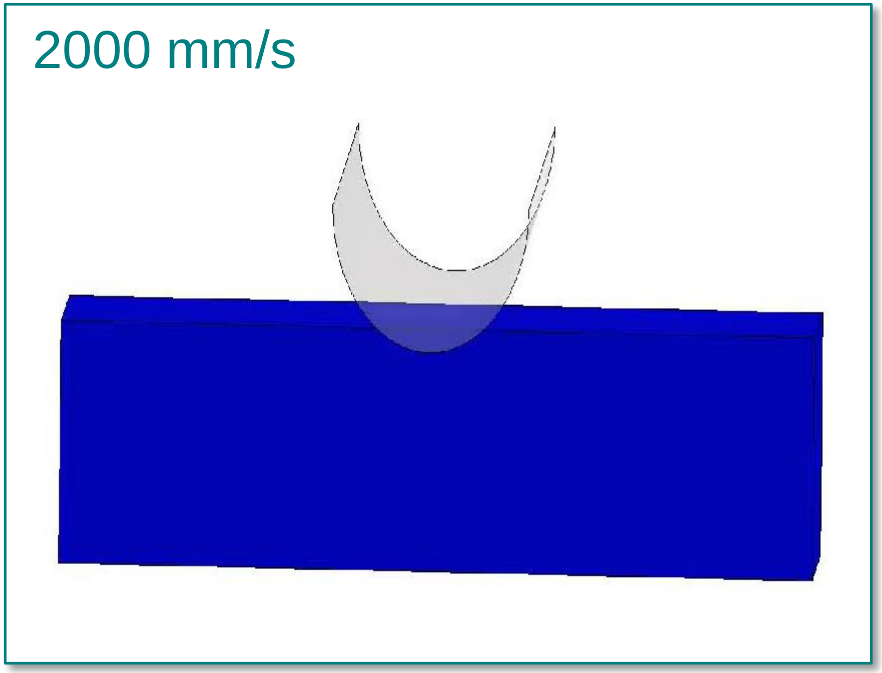
- Parameters in *MAT_CRUSHABLE_FOAM
  - SRCRT: critical stretch ratio
    (SRCRT=0.1 means 10% residual length)
  - ESCAL: scale factor for stiffness
    (ESCAL=5.0 means 5 x Young's modulus)



History variables (post processing) for MODEL.eq.1.:

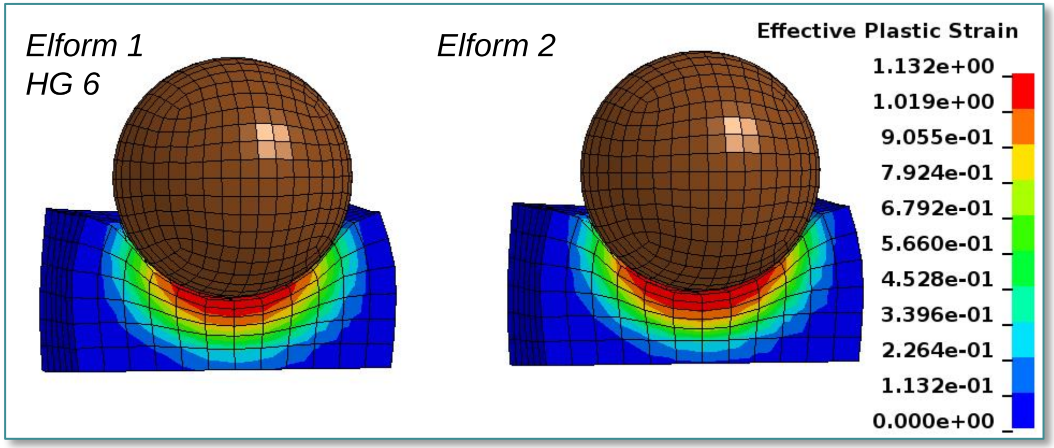
- History variable 1: Strain rate
  - For RFILTF.eq.0.: Plastic strain rate
  - For 0<RFILTF<1:   Equivalent filtered total strain rate
- History variable 3: Number of iterations of plasticity algorithm





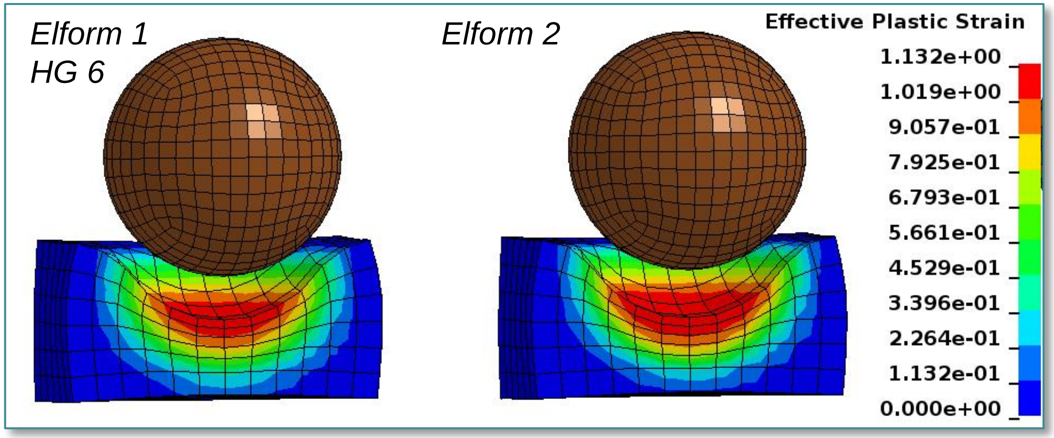
Impact on crushable foam, rate dependent

Plastic strain, moment of maximum intrusion



Plastic strain, moment when springback starts

Non-reversible plastic deformations



Conclusions!

Conclusions

- The process chain of material treatment and manufacturing will find its way into everyday engineering work. While many different tools to simulate the production process along that path may be available finding connective and versatile tools is key. However, big efforts are necessary to calibrate the constitutive models along that chain.

- A new simpler version of MAT_SAMP-1, called SAMP_light was shown. The model is supposedly much faster in execution and simpler in application. It lacks damage and fracture options and relies therefore on in the MAT_ADD_EROSION/DAMAGE-family. Calibration shall be easier as well. **But remember strain rate evaluation is different!**

- The new sub-model of MAT_CRUSHABLE_FOAM was presented as well. The model is a true plasticity model with variable plastic Poisson's ratio. It is still in its infancy but will quickly mature and become surely a work horse for crushable/plastic foams.

Thank you for your attention!

ARENA2036

Parts of this work was carried out in the frame of the ARENA2036 – DigitPro project which received funding from the national research and innovation programme of the BMBF under grant agreement No 02PQ5012.

Bundesministerium für Bildung und Forschung

VMAP

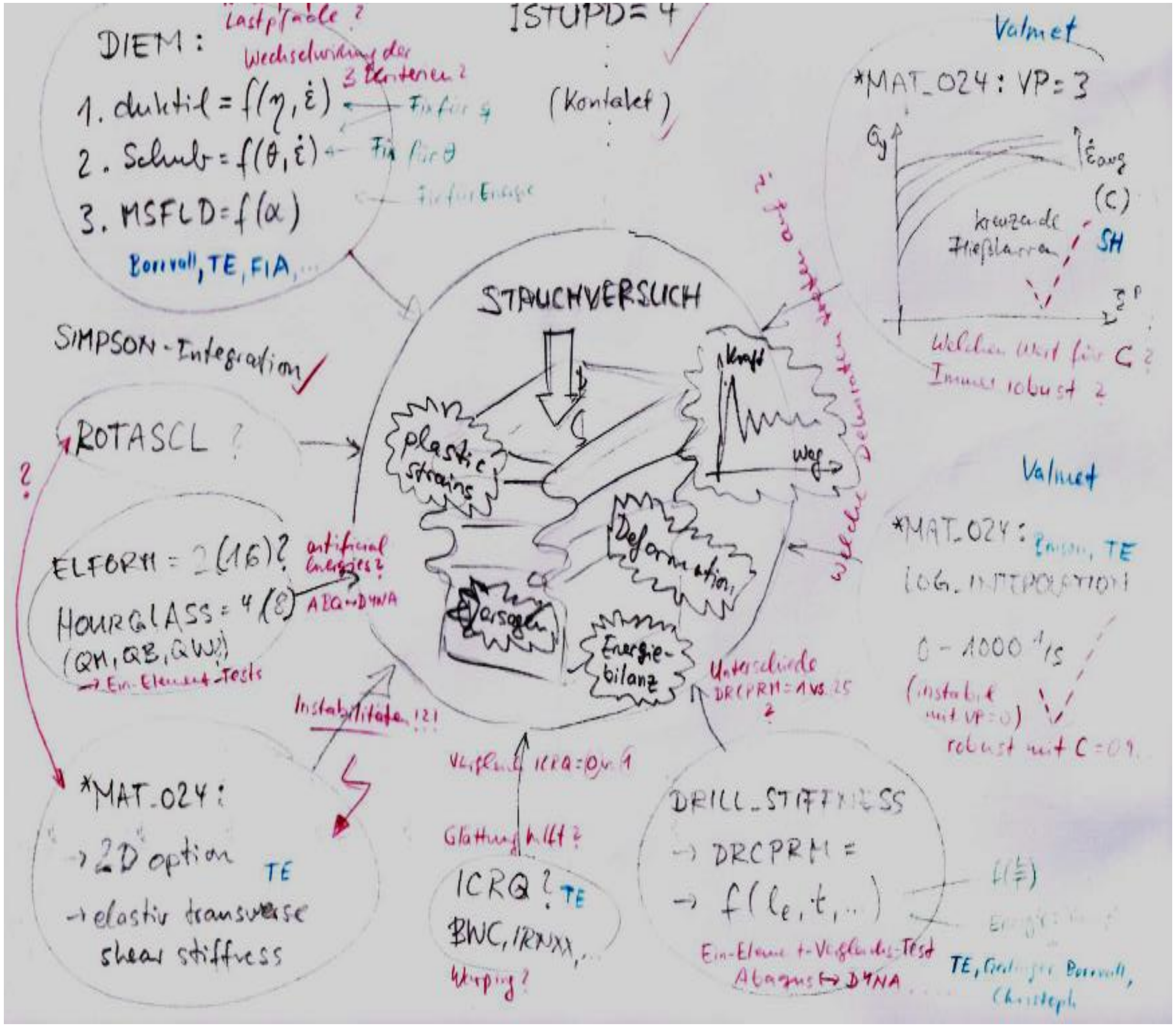
Parts of this work was carried out in the frame of the VMAP project which received funding from the national research and innovation programme of the BMBF under grant agreement No 01IS17025D.

Bundesministerium für Bildung und Forschung

Just if you wondered where we are going these days…

We have a plan…

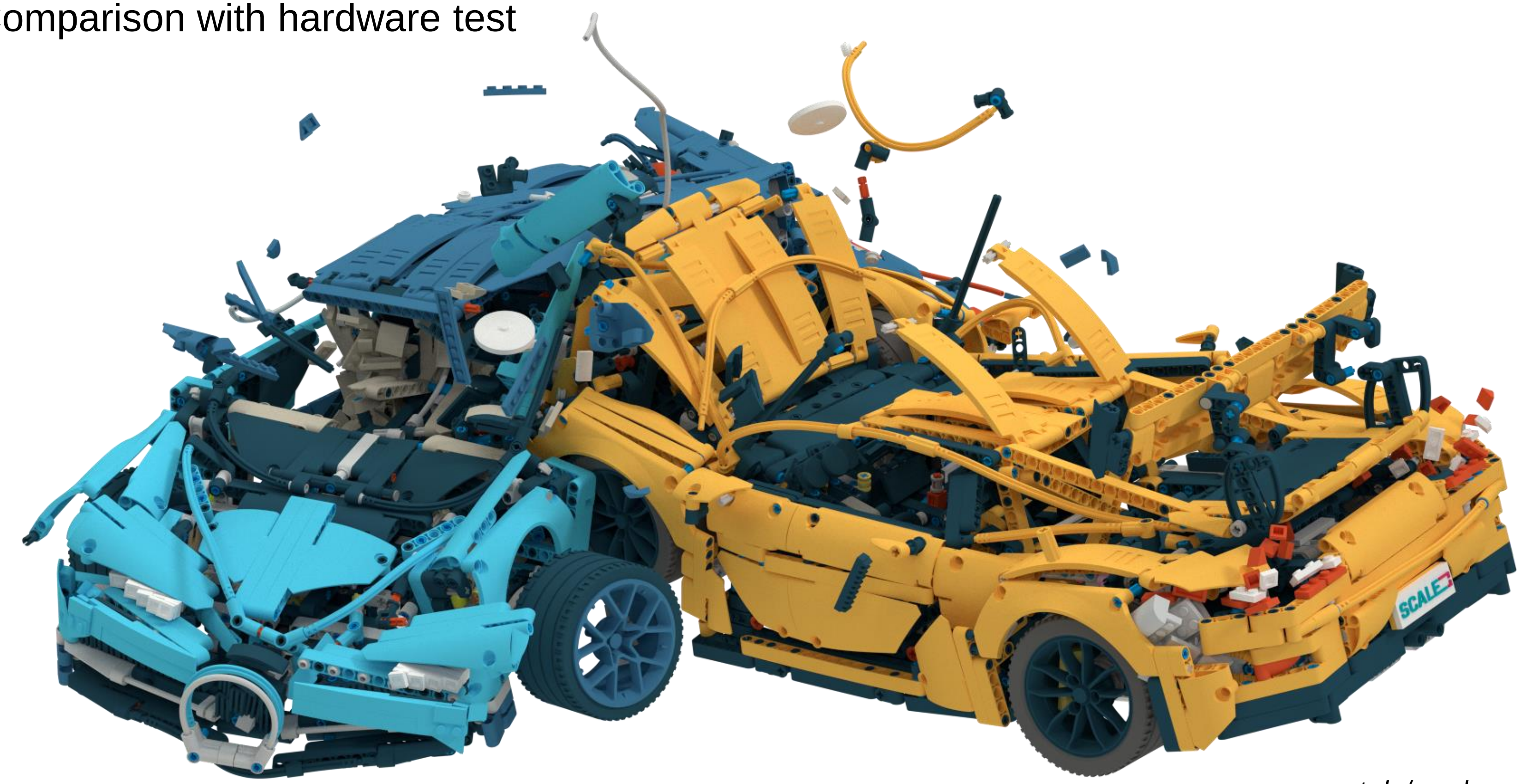
We have a plan…. and this is how it looks!



And we are serious.

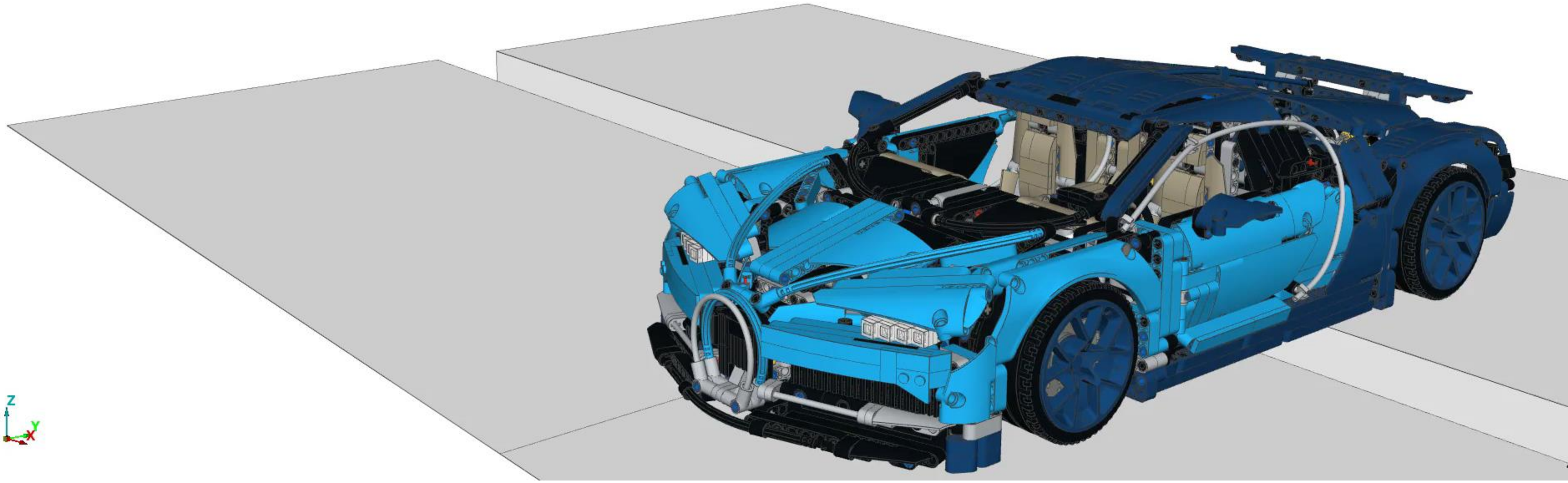
State of the art in crashworthiness with polymers… :o)

- THE 2018/2019 nerd project of DYNAmore colleagues
- 46Mio solid elements
- MAT_24 calibrated from tests in the DYNAmore MCC
- Impact at 60 m/s
- Comparison with hardware test

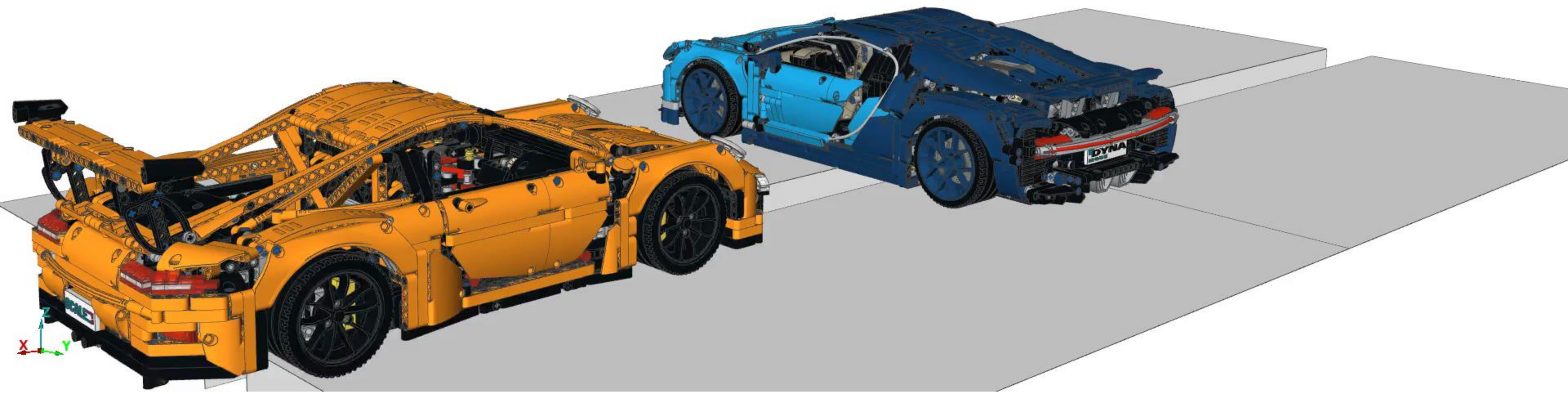


www.ct.de/crash

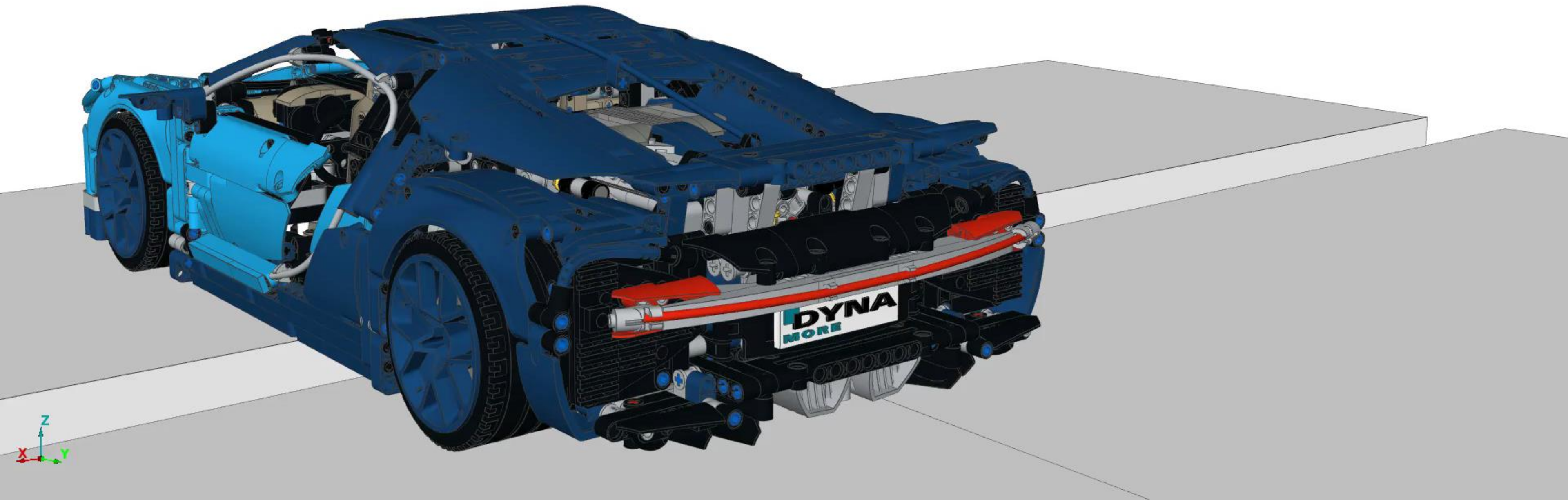
State of the art in crashworthiness with polymers… :o)



State of the art in crashworthiness with polymers… :o)



State of the art in crashworthiness with polymers… :o)



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