15th German LS-DYNA Forum, Bamberg, 2018

A Hosford-based orthotropic plasticity model in LS-DYNA

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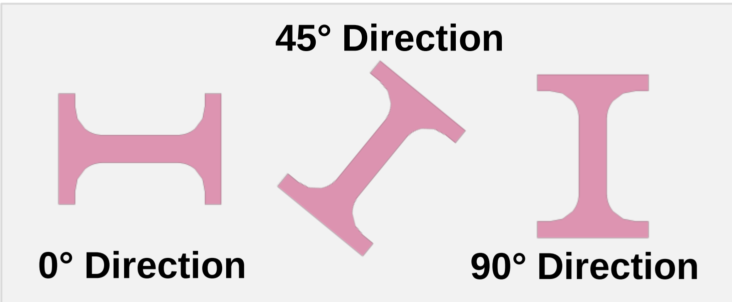
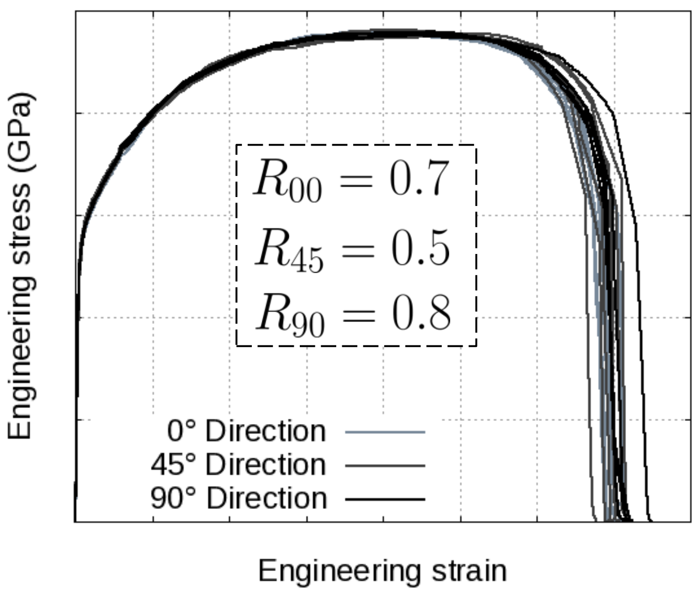
October 17th 2018

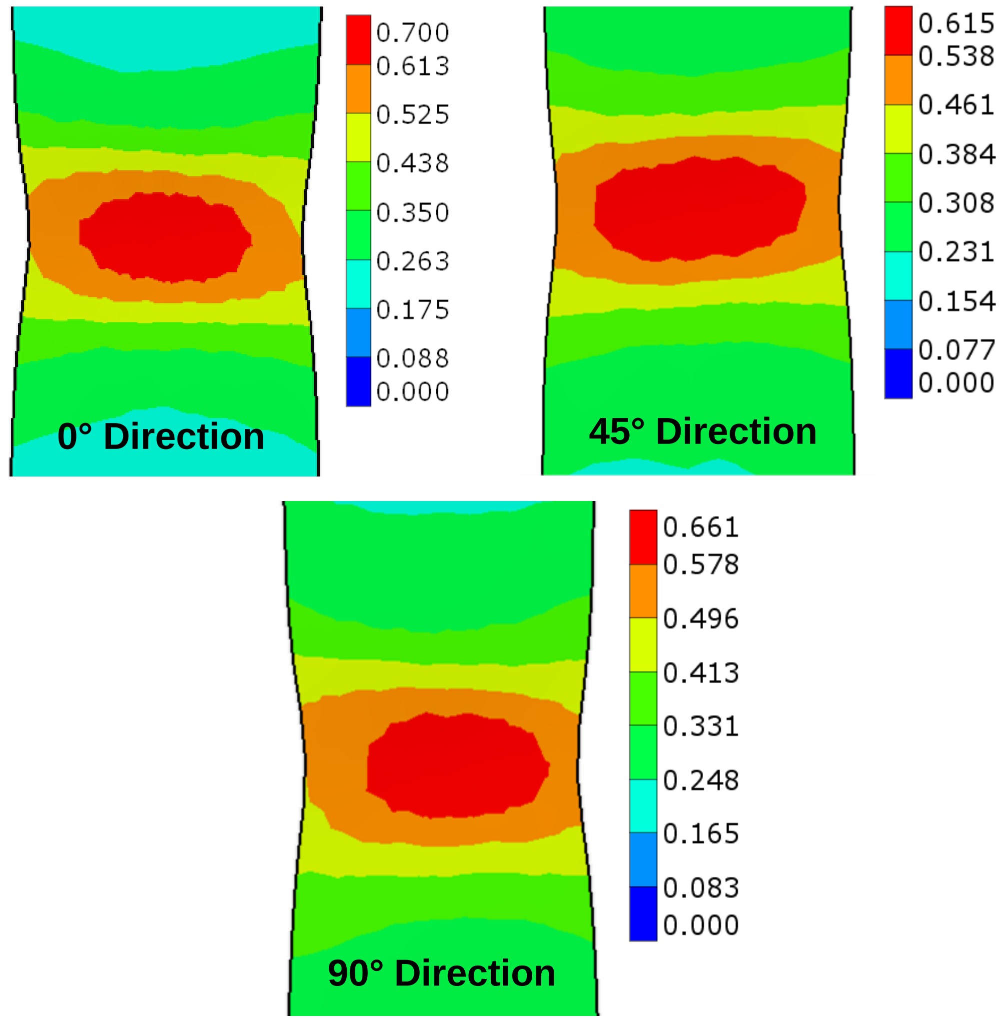
Orthotropic behavior

Example: aluminum sheet





Strain fields prior to failure (DIC measurement)

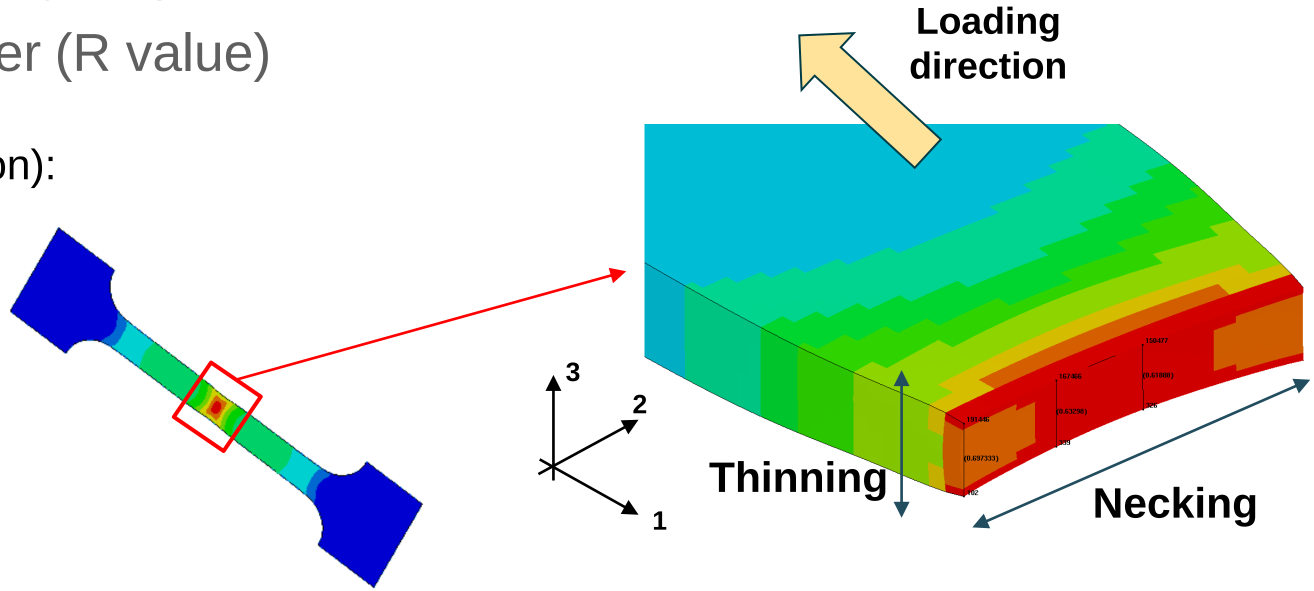


Orthotropic behavior

The Lankford parameter (R value)

- Definition (uniaxial tension):

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



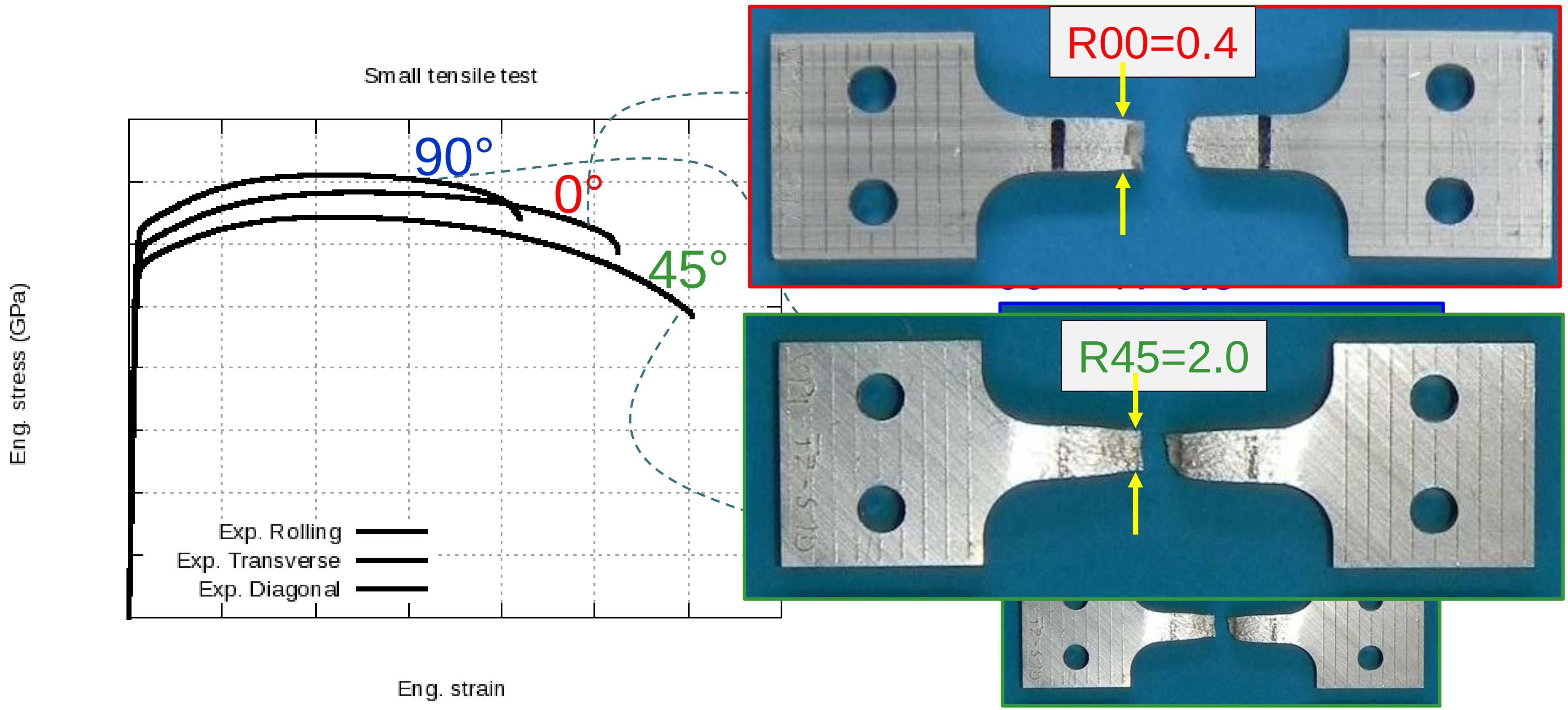
$$R = \frac{\dot{\varepsilon}_{22}^{p}}{\dot{\varepsilon}_{33}^{p}} = 1.0 \longrightarrow \dot{\varepsilon}_{22}^{p} = \dot{\varepsilon}_{33}^{p} \longrightarrow$$ **Thinning and necking are comparable**

$$R = \frac{\dot{\varepsilon}_{22}^{p}}{\dot{\varepsilon}_{33}^{p}} < 1.0 \longrightarrow \dot{\varepsilon}_{22}^{p} < \dot{\varepsilon}_{33}^{p} \longrightarrow$$ **More thinning** **Less necking**

$$R = \frac{\dot{\varepsilon}_{22}^{p}}{\dot{\varepsilon}_{33}^{p}} > 1.0 \longrightarrow \dot{\varepsilon}_{22}^{p} > \dot{\varepsilon}_{33}^{p} \longrightarrow$$ **Less thinning** **More necking**

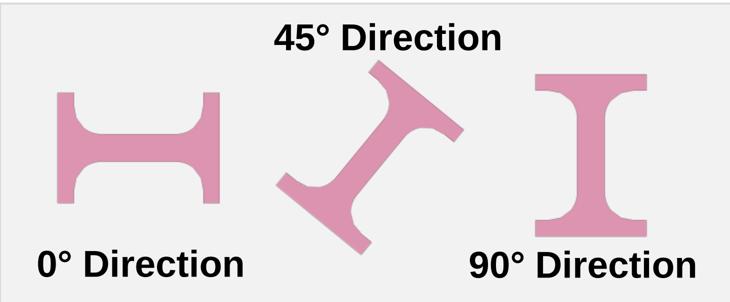
Orthotropic behavior

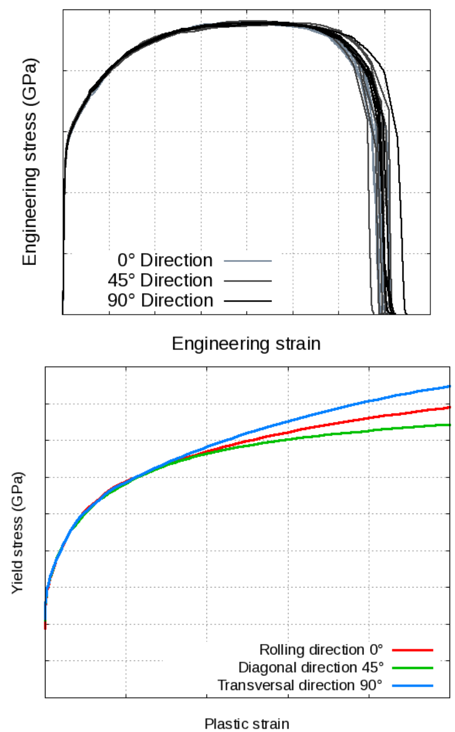
Example: aluminum extrusion



Orthotropic modeling

From experimental data to simulation parameters





$$R_{00} = 0.7$$
$$R_{45} = 0.5$$
$$R_{90} = 0.8$$
$$R_B = \ldots$$
$$R_S = \ldots$$

LS-DYNA

MATERIAL MODELING IN LS-DYNA

*MAT_036 + HR=3

Barlat & Lian (1989)

R values are similar

```
*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

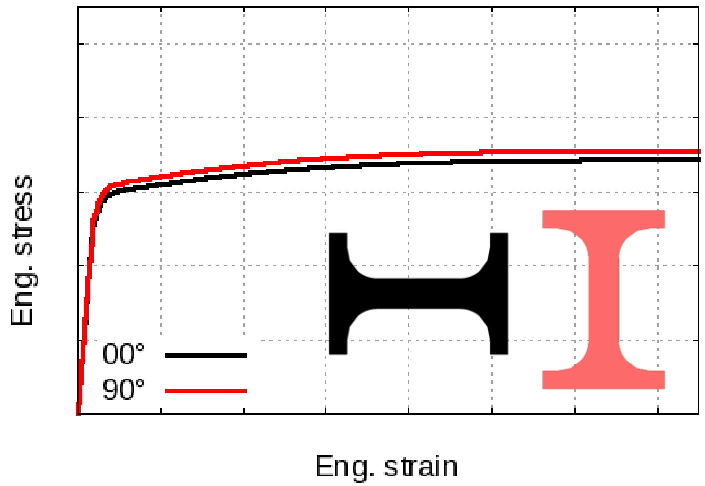
internal fitting

$a = \dots$

$c = \dots$

$h = \dots$

$p = \dots$



*MAT_036 + HR=3

Barlat & Lian (1989)

R values <u>differ significantly</u> 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

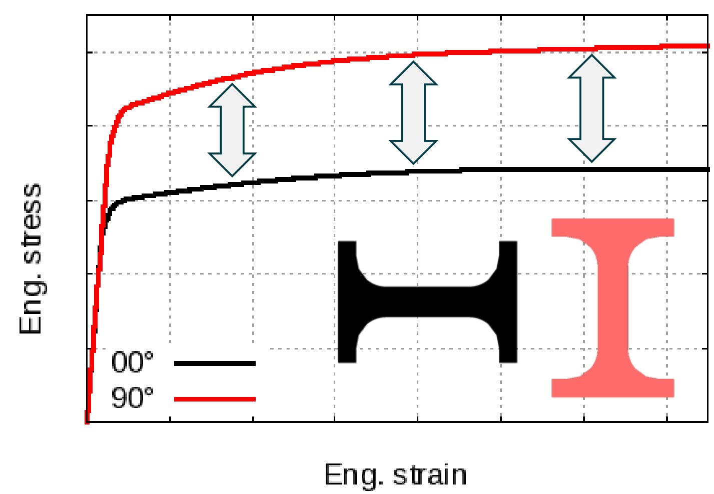
internal fitting

$a = \ldots$

$c = \ldots$

$h = \ldots$

$p = \ldots$



*MAT_036 + HR=7

Fleischer & Borrvall (2007): modified Barlat & Lian

R values differ significantly from each other

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

```
*MAT_3-PARAMETER_BARLAT
$       MID        RO         E        PR        HR        P1        P2      ITER
          1  2.70E-06      70.0       0.3         7       145       190
$         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

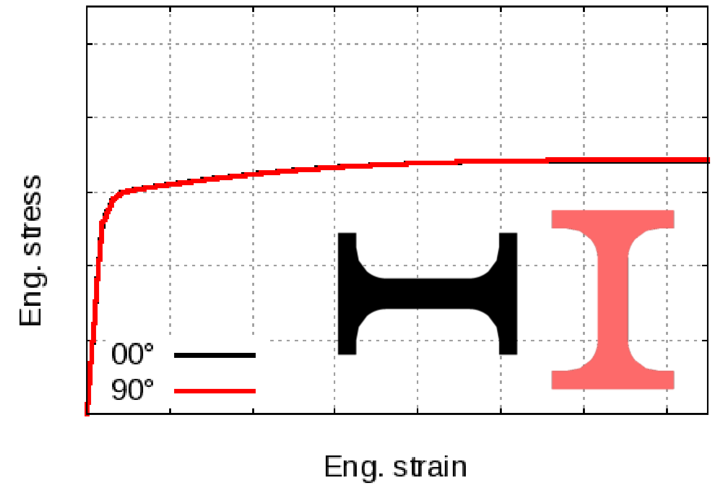
internal fitting

$a = \ldots$

$c = \ldots$

$h = \ldots$

$p = \ldots$



*MAT_036 + HR=7

Fleischer & Borrvall (2007): modified Barlat & Lian

Yield function

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

$$\sigma_y(\boldsymbol{\sigma}, \varepsilon^p) = \alpha_{00}\sigma_y^{00}(\varepsilon^p) + \alpha_{45}\sigma_y^{45}(\varepsilon^p) + \alpha_{90}\sigma_y^{90}(\varepsilon^p) + \alpha_B\sigma_y^{B}(\varepsilon^p) + \alpha_{shear}\sigma_y^{shear}(\varepsilon^p)$$

Flow rule

$$\dot{\boldsymbol{\varepsilon}}^p = \begin{bmatrix} \dot{\varepsilon}_{11}^p & \dot{\varepsilon}_{12}^p & \dot{\varepsilon}_{13}^p \\ \dot{\varepsilon}_{21}^p & \dot{\varepsilon}_{22}^p & \dot{\varepsilon}_{23}^p \\ \dot{\varepsilon}_{31}^p & \dot{\varepsilon}_{32}^p & \dot{\varepsilon}_{33}^p \end{bmatrix} = \dot{\gamma}\left(\frac{\partial \Phi}{\partial \boldsymbol{\sigma}} + \Delta \mathbf{N}\right)$$

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

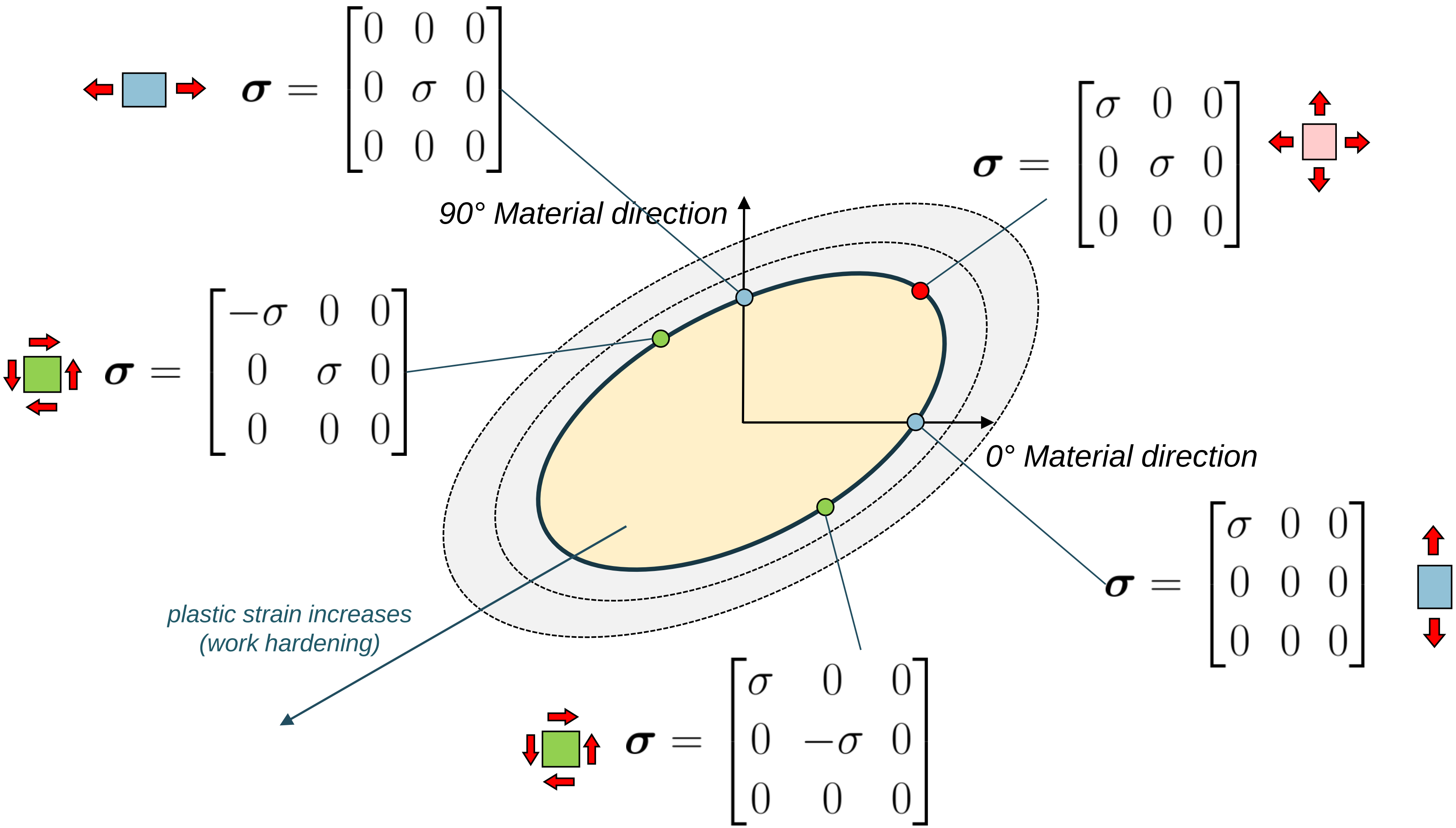
associated plasticity

smallest necessary increment to match experimental R values

non-associated plasticity

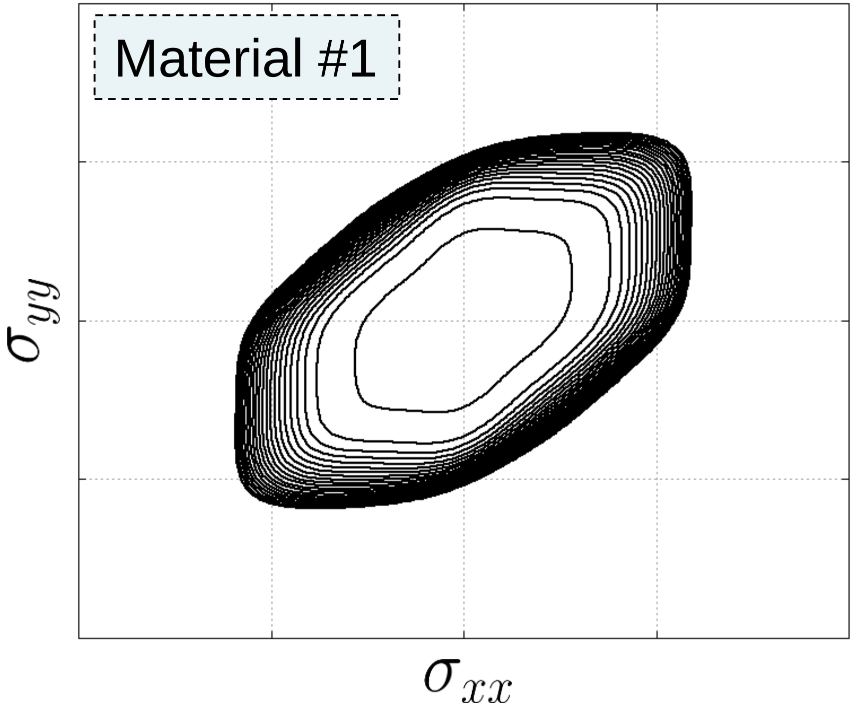
Yield surface (von Mises)

Example: Yielding at different stress states

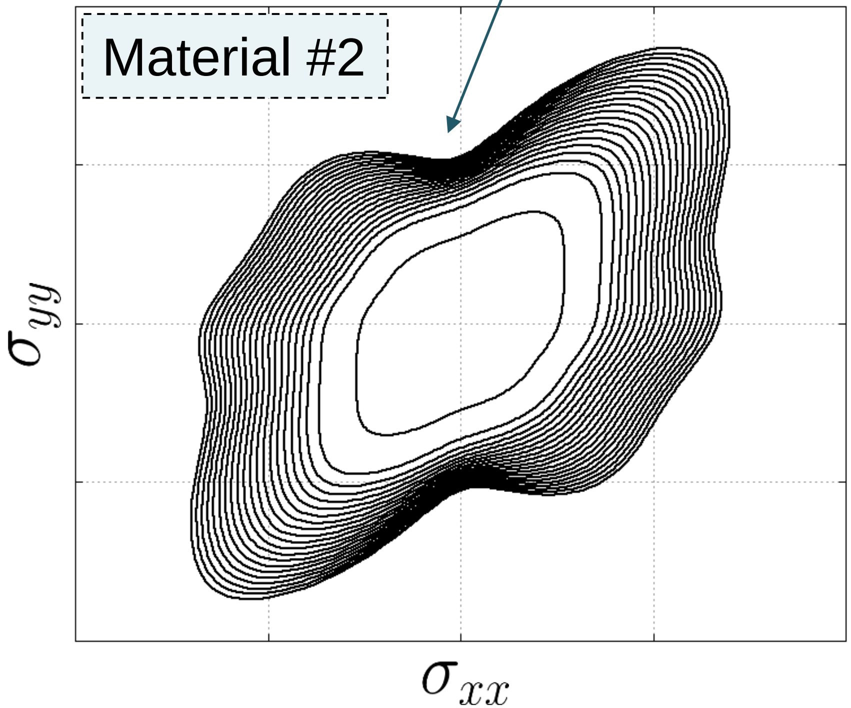


*MAT_036 + HR=7

Yield surface with increasing plastic strain

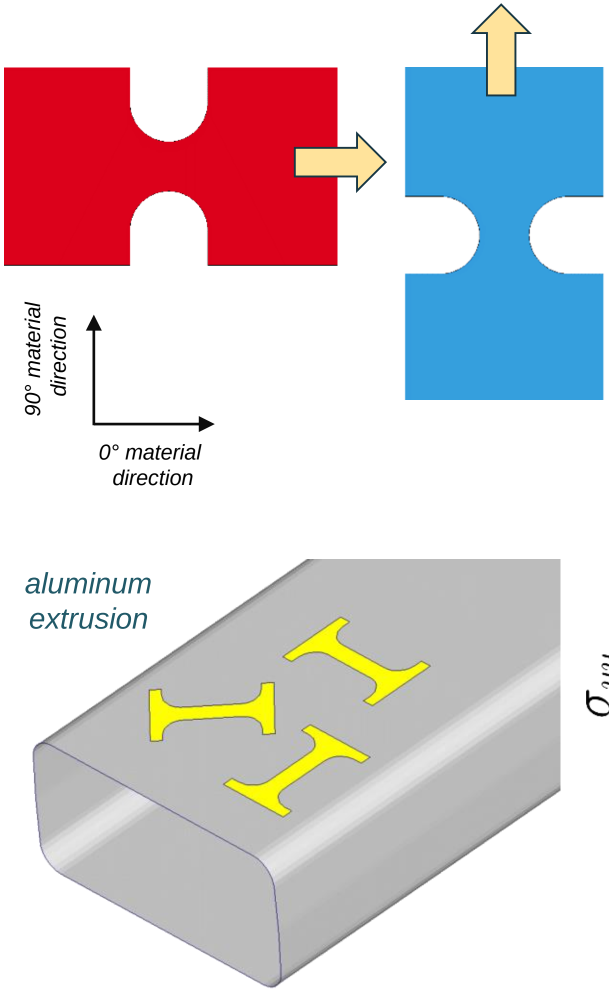


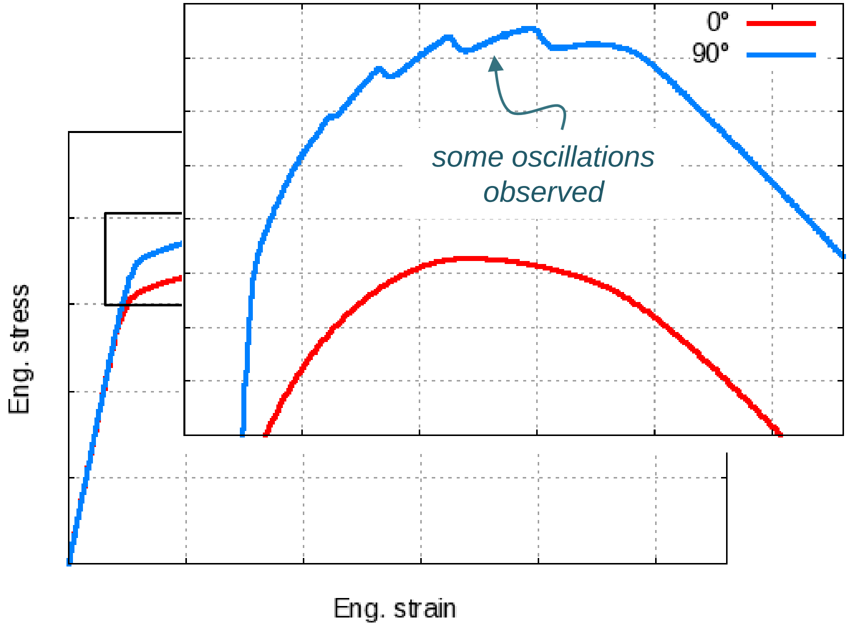
lack of convexity may cause instabilities and "generate energy"

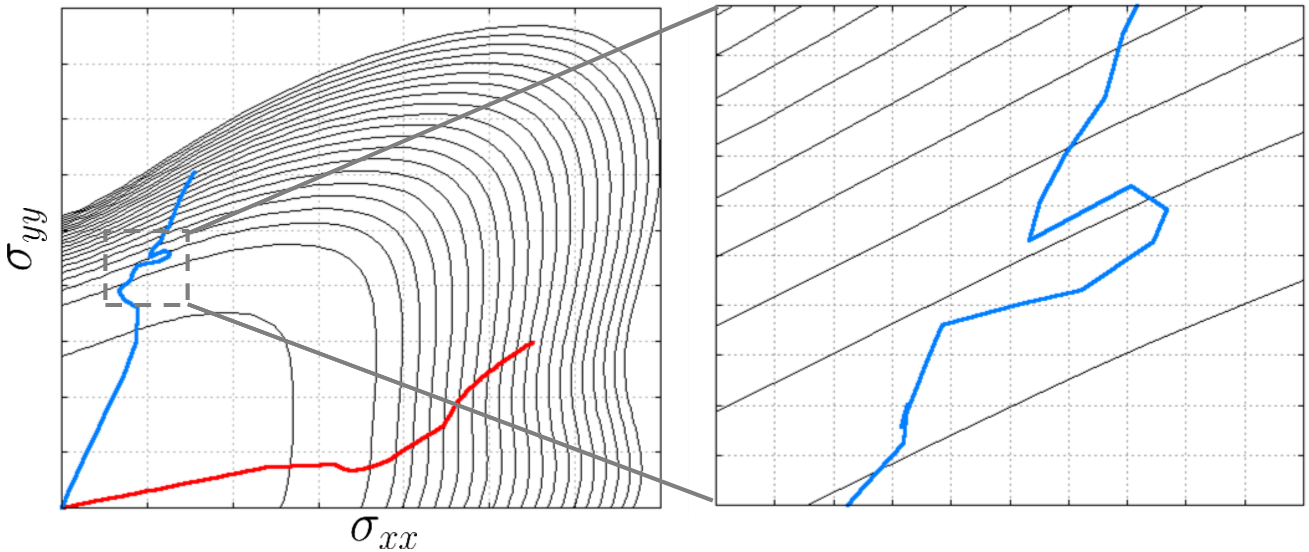


*MAT_036 + HR=7

Possible effect of a concave yield surface
Simulation of a notched tensile test







*MAT_036E + HOSF=0/1

Barlat- and Hosford-based orthotropic models

flow rule

$$\dot{\boldsymbol{\varepsilon}}^p = \dot{\gamma}\left(\frac{\partial \Phi}{\partial \boldsymbol{\sigma}} + \Delta \mathrm{N}\right)$$

```
*MAT_EXTENDED_3-PARAMETER_BARLAT / *MAT_036E
$      MID        RO         E        PR
         1   2.70E-6      70.0       0.3
$    LCH00     LCH45     LCH90     LCHBI     LCHSH      HOSF
       100       145       190                           0/1
$    LCR00     LCR45     LCR90     LCRBI     LCRSH         M
      -0.5      -1.0      -2.0                             8
$...
```

HOSF=0 **(*MAT_036+HR=7)** →

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

HOSF=1 →

$$\Phi(\boldsymbol{\sigma}) = \frac{1}{2}\left(\left|\sigma_1\right|^m + \left|\sigma_2\right|^m + \left|\sigma_1-\sigma_2\right|^m\right) - \sigma_y^m = 0$$

No use of a, c, p and h in the yield function
(i.e., no influence of the R values on the yield function)

*MAT_036E + HOSF=1

Hosford-based orthotropic model

Yielding (hardening curve) and plastic flow
(R values) are treated separately!

```
*MAT_EXTENDED_3-PARAMETER_BARLAT / *MAT_036E
$       MID        RO         E        PR
          1   2.70E-6      70.0       0.3
$     LCH00     LCH45     LCH90     LCHBI     LCHSH      HOSF
        100       145       190                             1
$     LCR00     LCR45     LCR90     LCRBI     LCRSH         M
       -0.5      -1.0      -2.0                             8
$...
```

Yield function

$$\Phi(\boldsymbol{\sigma}) = \sigma_{eff} - \sigma_y^m = 0$$

$$\sigma_{eff} = \frac{1}{2}\left(|\sigma_1|^m + |\sigma_2|^m + |\sigma_1 - \sigma_2|^m\right)$$

Flow rule

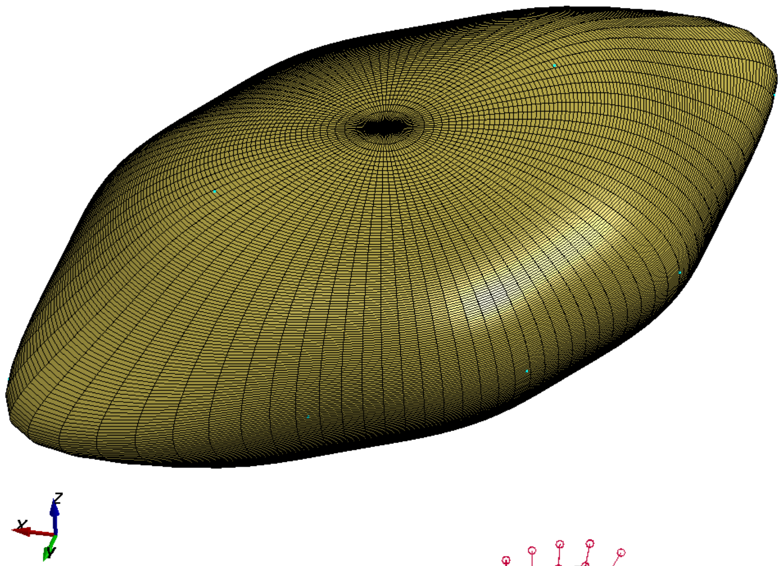
$$\dot{\boldsymbol{\varepsilon}}^p = \dot{\gamma}\left(\frac{\partial \Phi}{\partial \boldsymbol{\sigma}} + \Delta \mathrm{N}\right)$$

non-associated plasticity!

*MAT_036E + HOSF=1

Hosford-based orthotropic model

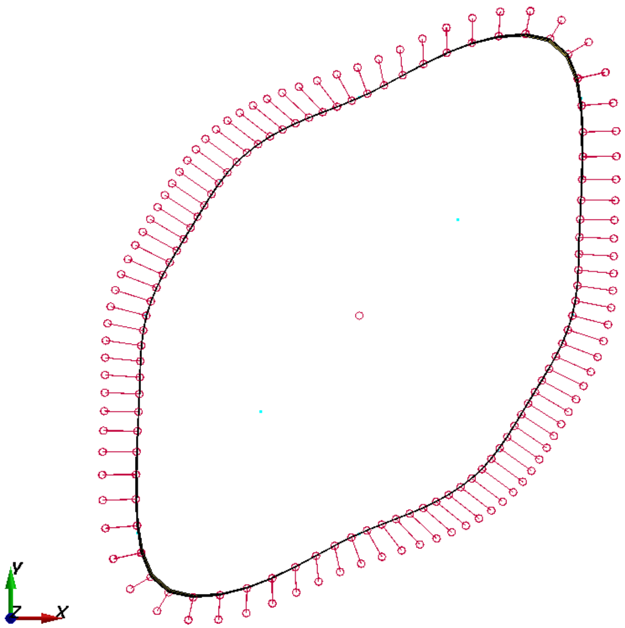
$$\boldsymbol{\sigma} = \begin{bmatrix} \sigma_{11} & \sigma_{12} & 0 \\ 0 & \sigma_{22} & 0 \\ 0 & 0 & 0 \end{bmatrix}$$



Flow rule

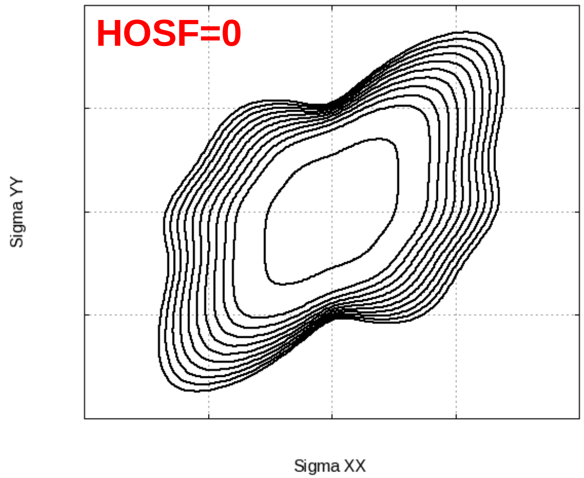
$$\dot{\boldsymbol{\varepsilon}}^p = \dot{\gamma}\left(\frac{\partial \Phi}{\partial \boldsymbol{\sigma}} + \Delta \mathbf{N}\right)$$

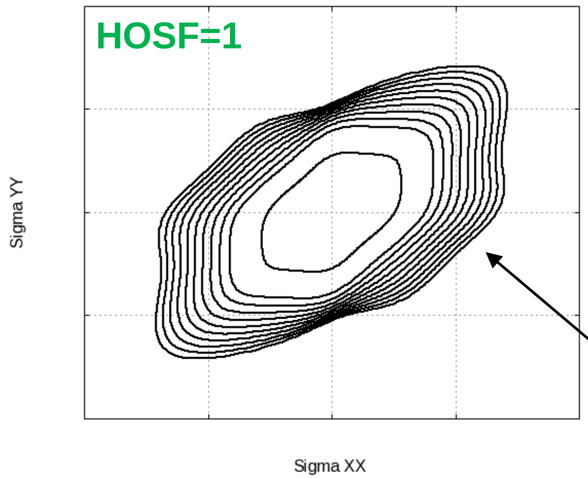
non-associated plasticity!



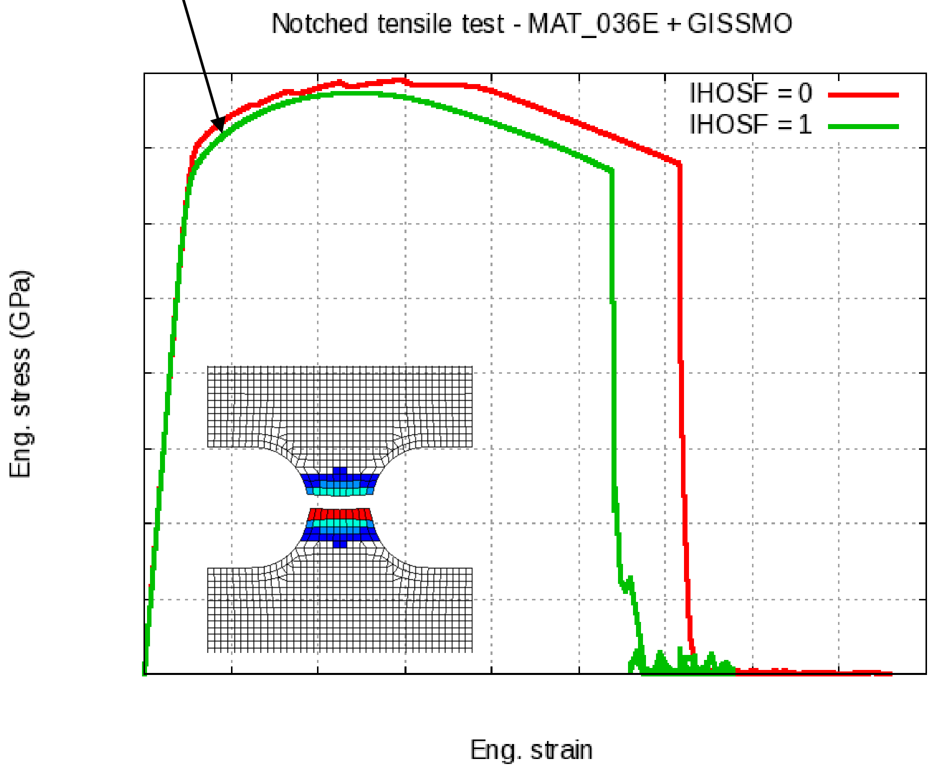
*MAT_036E + HOSF=0/1

Comparison between the formulations (aluminum extrusion)





No oscillations with HOSF=1



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

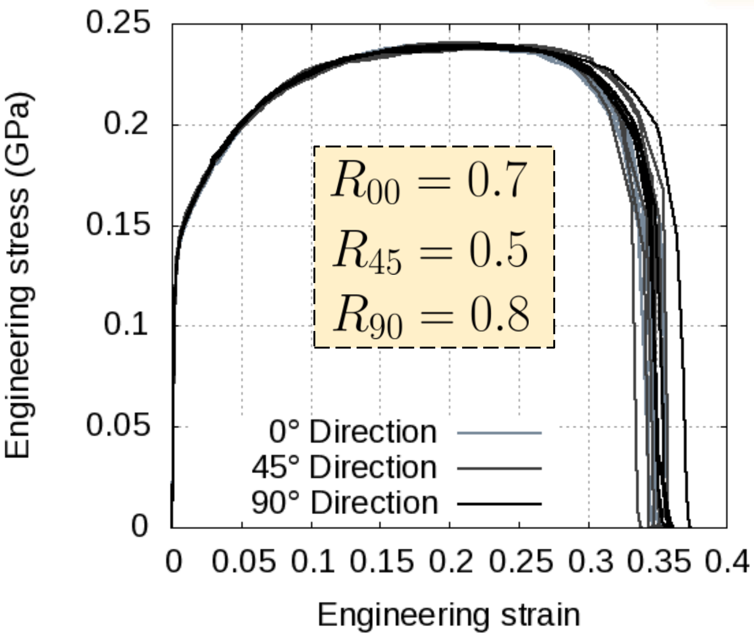
EXAMPLE:
ALUMINUM SHEET (t=1.5mm)

Aluminum sheet (t=1.5mm)

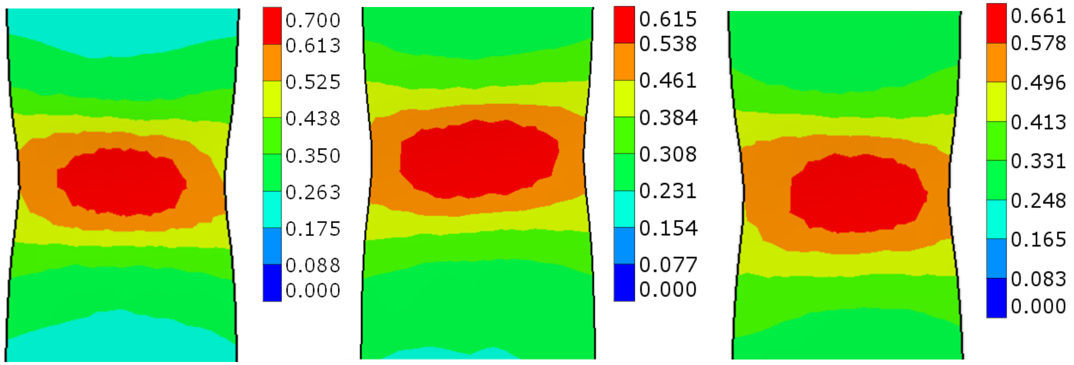
Experiments performed at DYNAmore in Stuttgart

Workshop:
"Material Characterization"
15th Oct 2018

DYNAmore GmbH
Industriestr. 2
70565 Stuttgart



Strain fields prior to failure (DIC measurement)

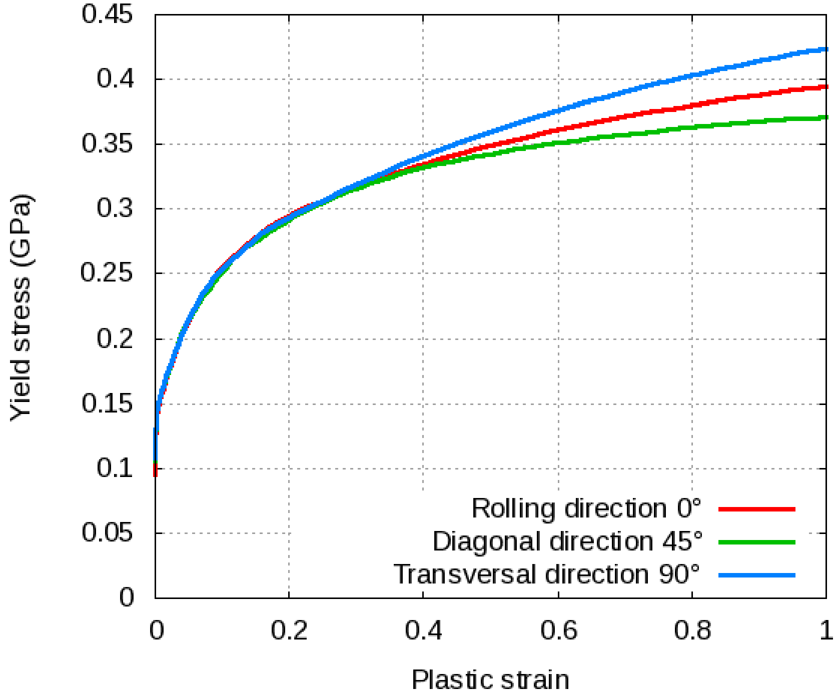


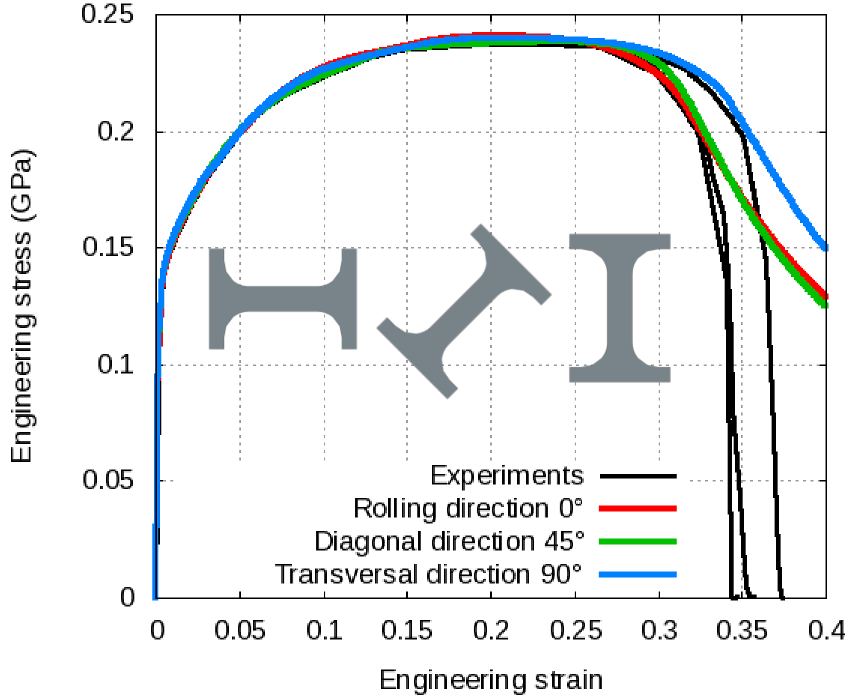
0° Direction **45° Direction** **90° Direction**

Hardening curves

Rolling (0°), diagonal (45°) and transversal (90°) directions

- Shell elements of formulation **ELFORM=16**
- Element size for the calibration: $\mathbf{L_e}$**=0.5mm**
- Material model: ***MAT_036E, HOSF=1**
- Constant R values assumed: $\mathbf{R_{00}=0.7, R_{45}=0.5, R_{90}=0.8}$
- Calibration through “reverse engineering”

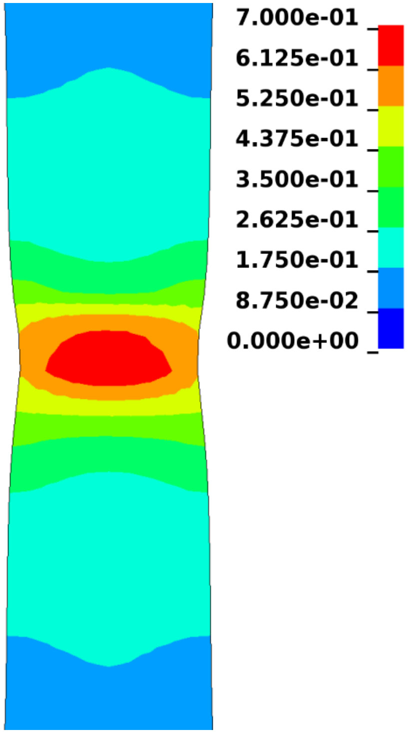




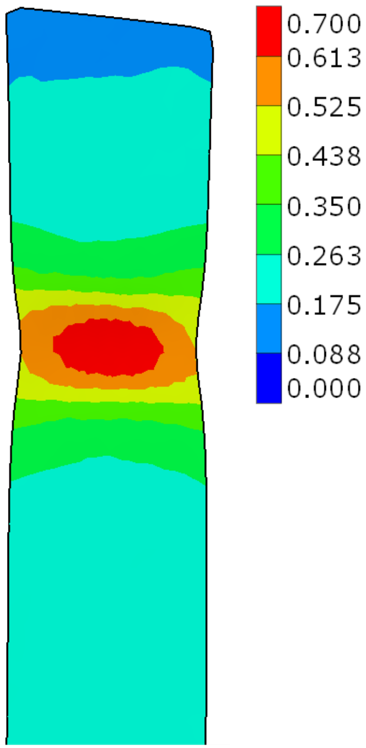
Small tensile test

Equivalent strain, rolling direction (0°)

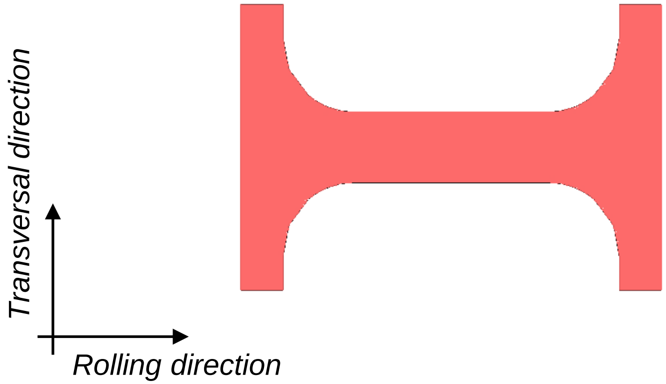
LS-DYNA (*MAT_036E)

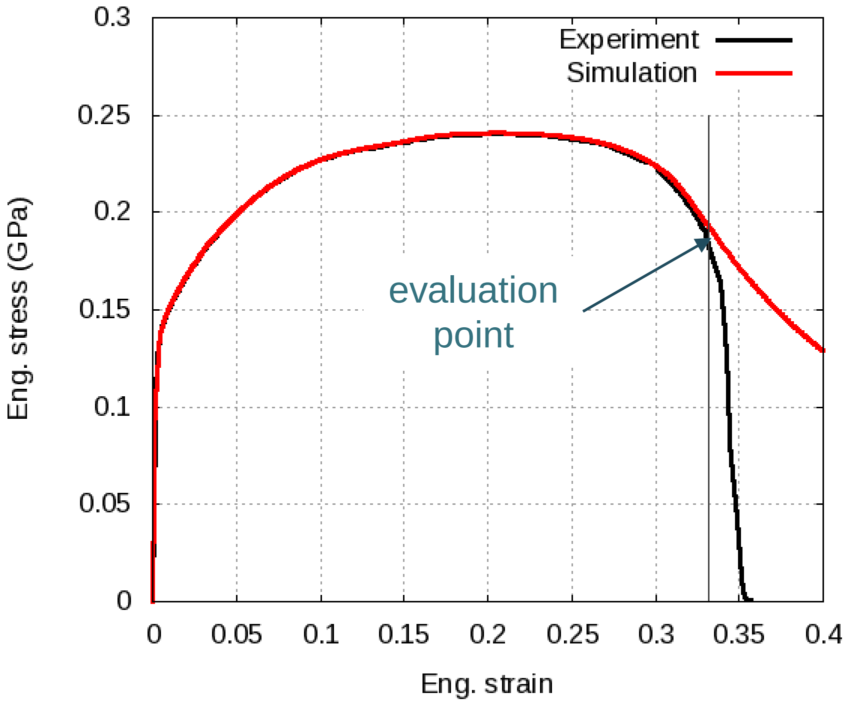


Experiment (DIC with ARAMIS)



Shell elements, EFORM=16, Le=0.5mm

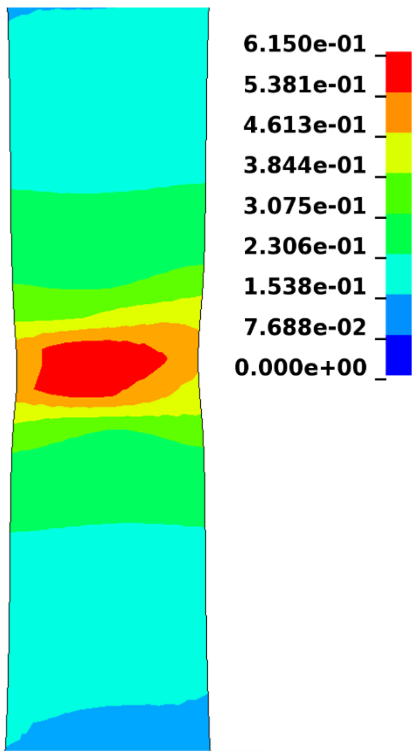




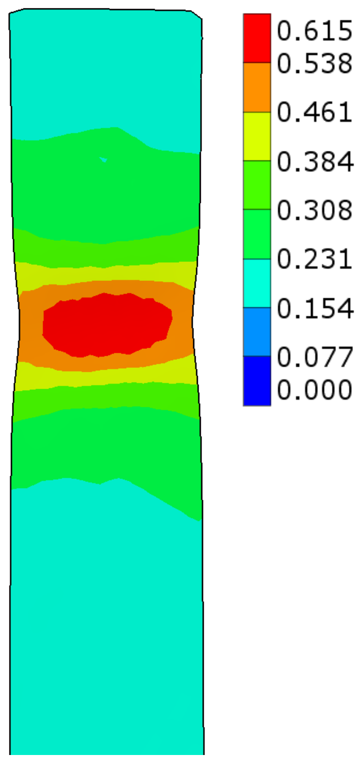
Small tensile test

Equivalent strain, diagonal direction (45°)

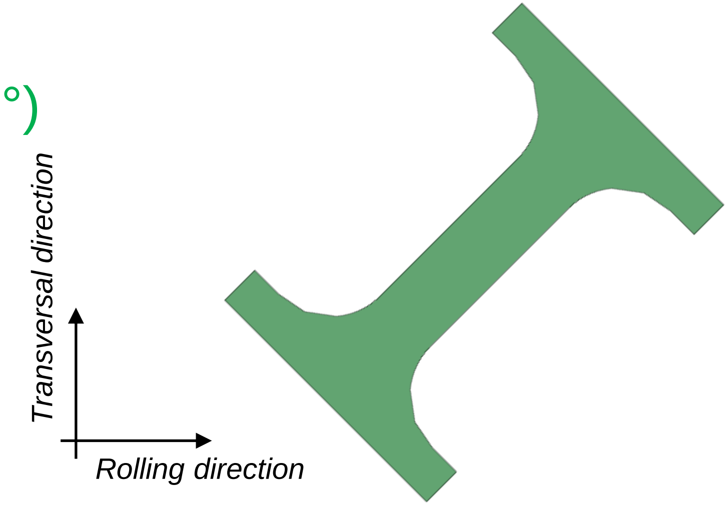
LS-DYNA
(*MAT_036E)

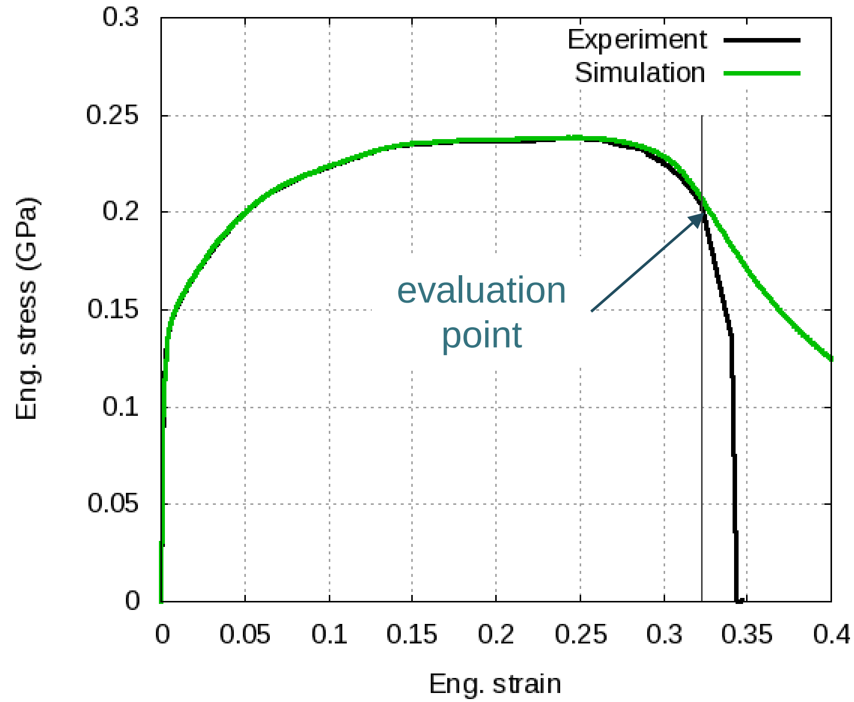


Experiment
(DIC with ARAMIS)



Shell elements, EFORM=16, Le=0.5mm

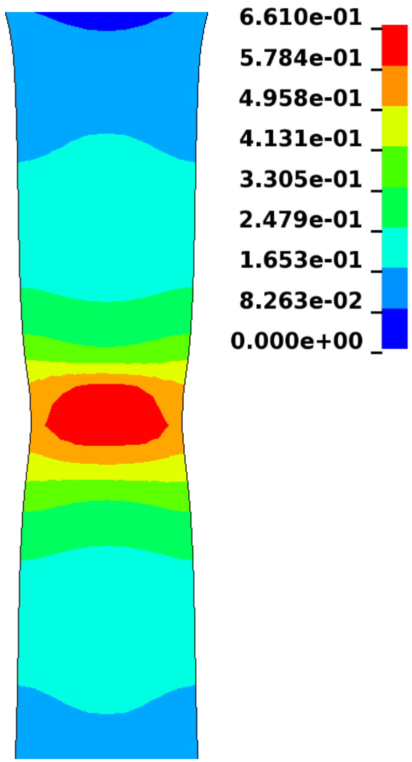




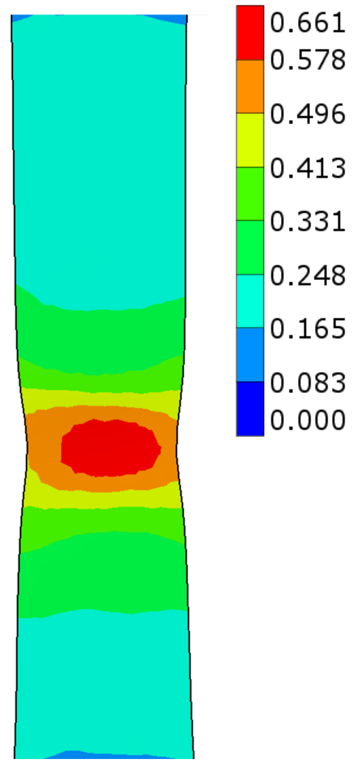
Small tensile test

Equivalent strain, transversal direction (90°)

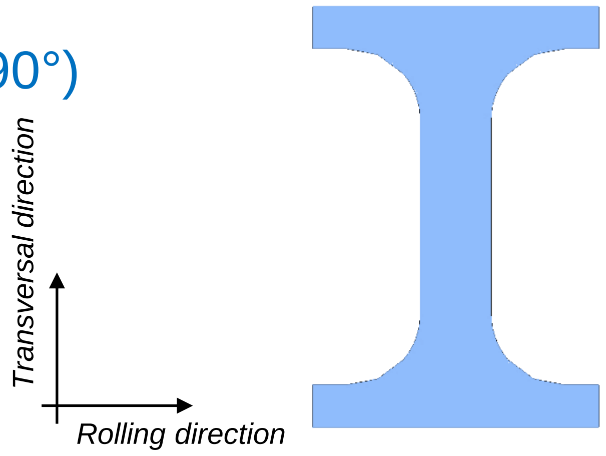
LS-DYNA (*MAT_036E)

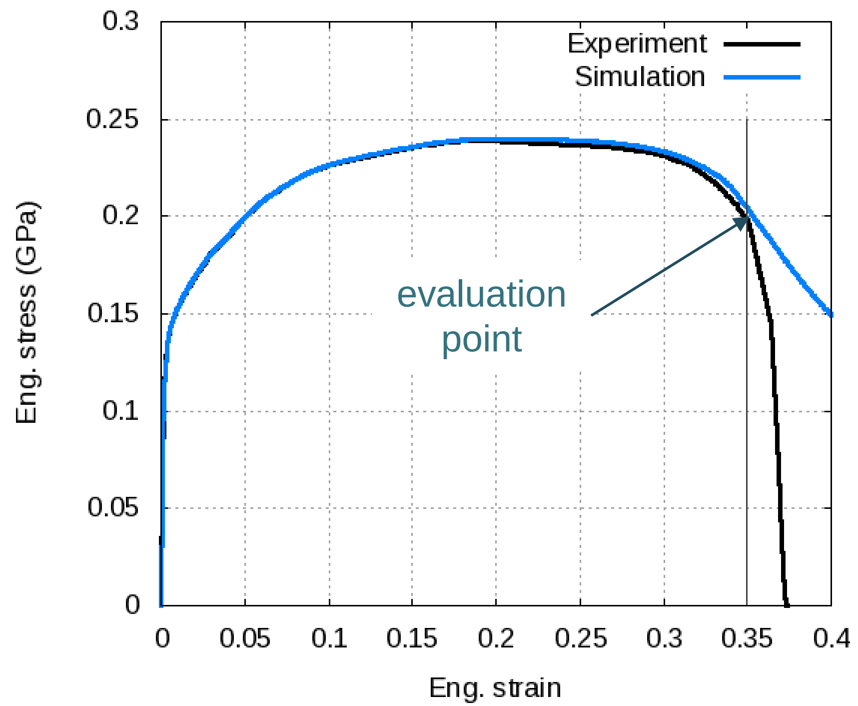


Experiment (DIC with ARAMIS)



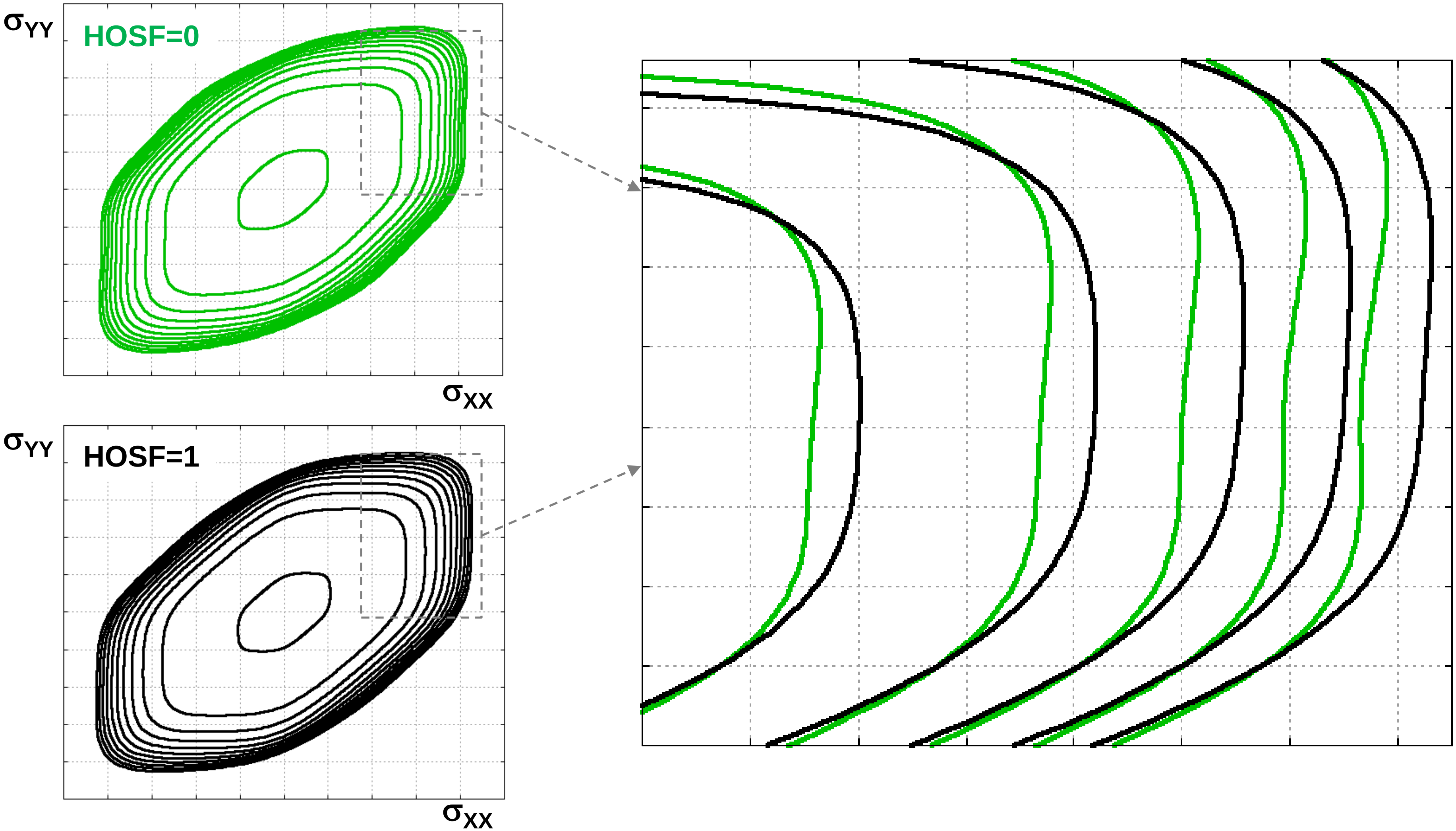
Shell elements, EFORM=16, Le=0.5mm





Yield Surface (*MAT_036E)

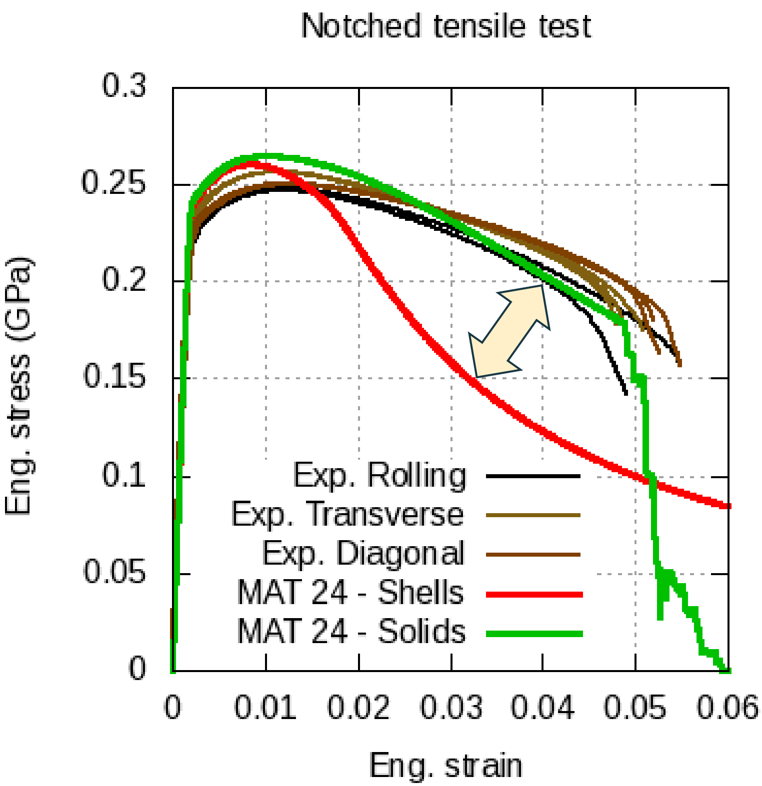
Comparison between Barlat-based (HOSF=0) and Hosford-based (HOSF=1)

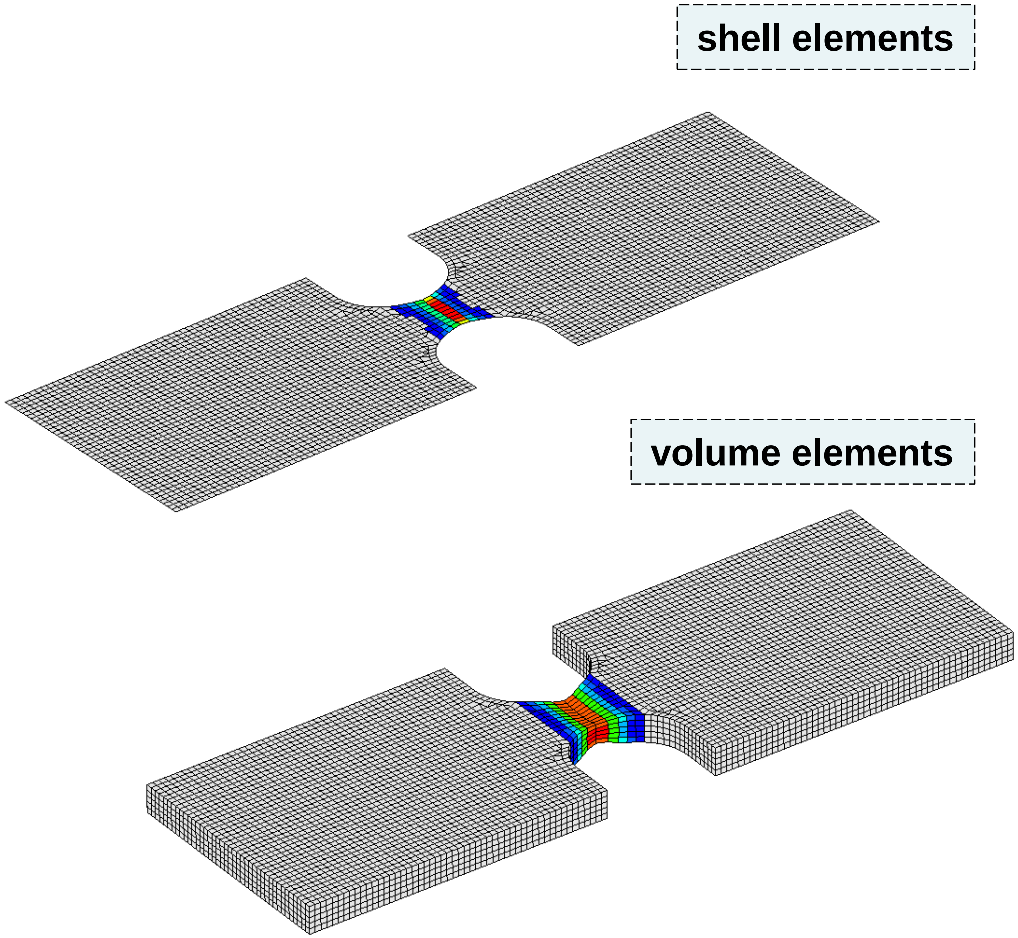


Modeling with standard shell elements

Limits of the modeling approach

Example: Aluminum extrusion with t=2.5mm





Conclusions

Final remarks and outlook

- Good plasticity is very important for accurate local strains
  (DIC measurements make validation possible)
- Plastic strain “not only coming from hardening curve”
- *MAT_036E is very flexible for matching experimental data
  (concave yield surfaces still possible, but generally only for “extreme” data)
- Modeling with standard shell elements still poses some barriers…
- Extension to volume elements not quite straightforward…
  … but we’re working on that too

Thank you!

Your LS-DYNA distributor and more