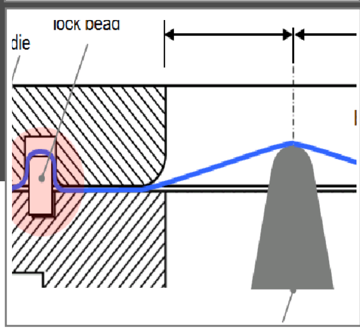
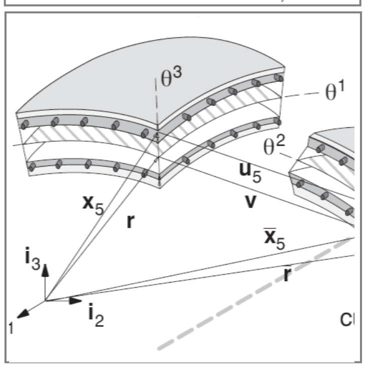




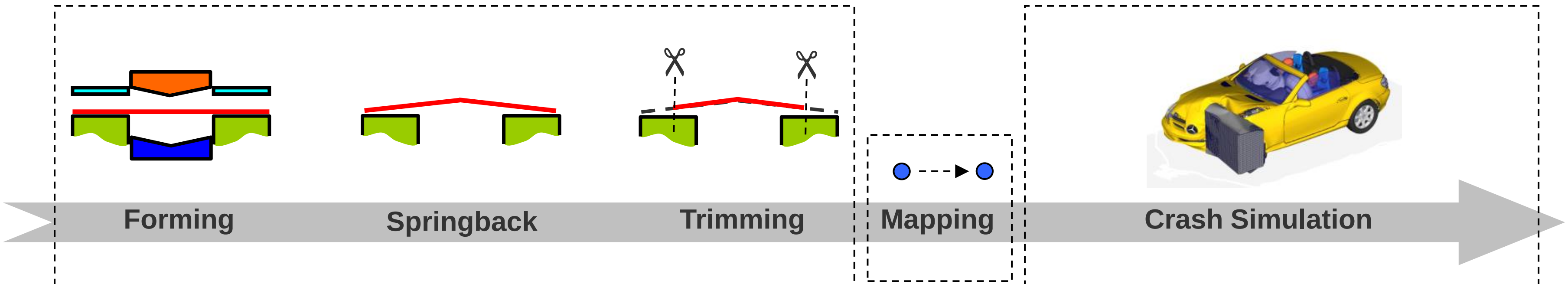
13. LS-DYNA Anwenderforum 2014

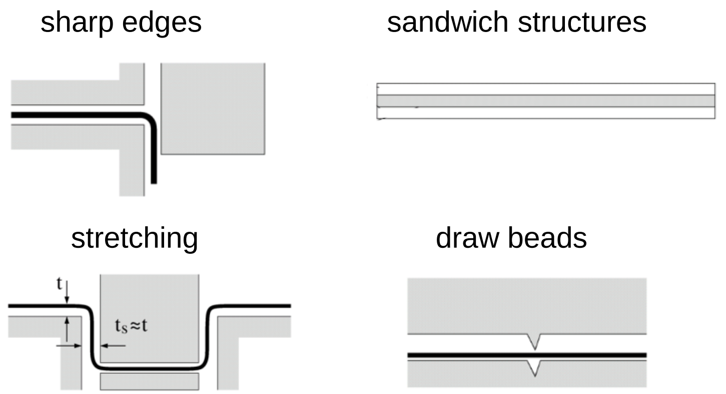
The Effect of full 3-dimenisonal Stress States on the Prediction of Damage and Failure in Sheet Metal Forming Simulation

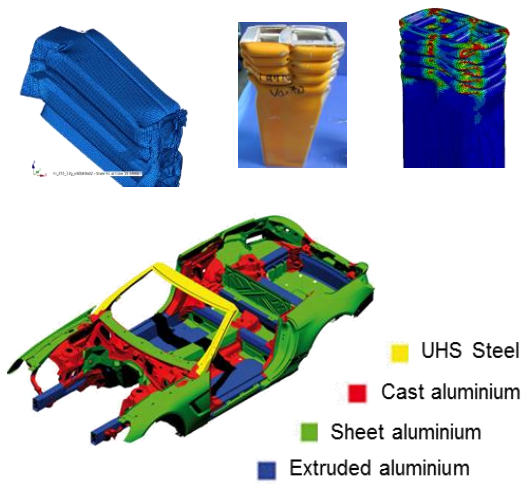
A. Haufe, A. Erhart
DYNAmore GmbH, Stuttgart

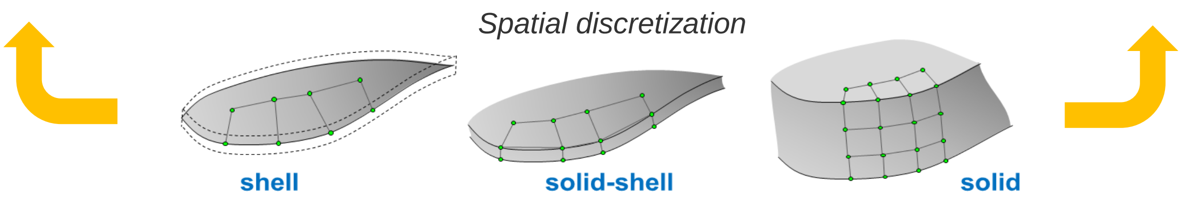
Th. Borvall
DYNAmore Nordic, Sweden

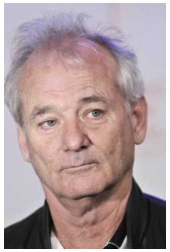
Motivation: Process chain in sheet metal applications









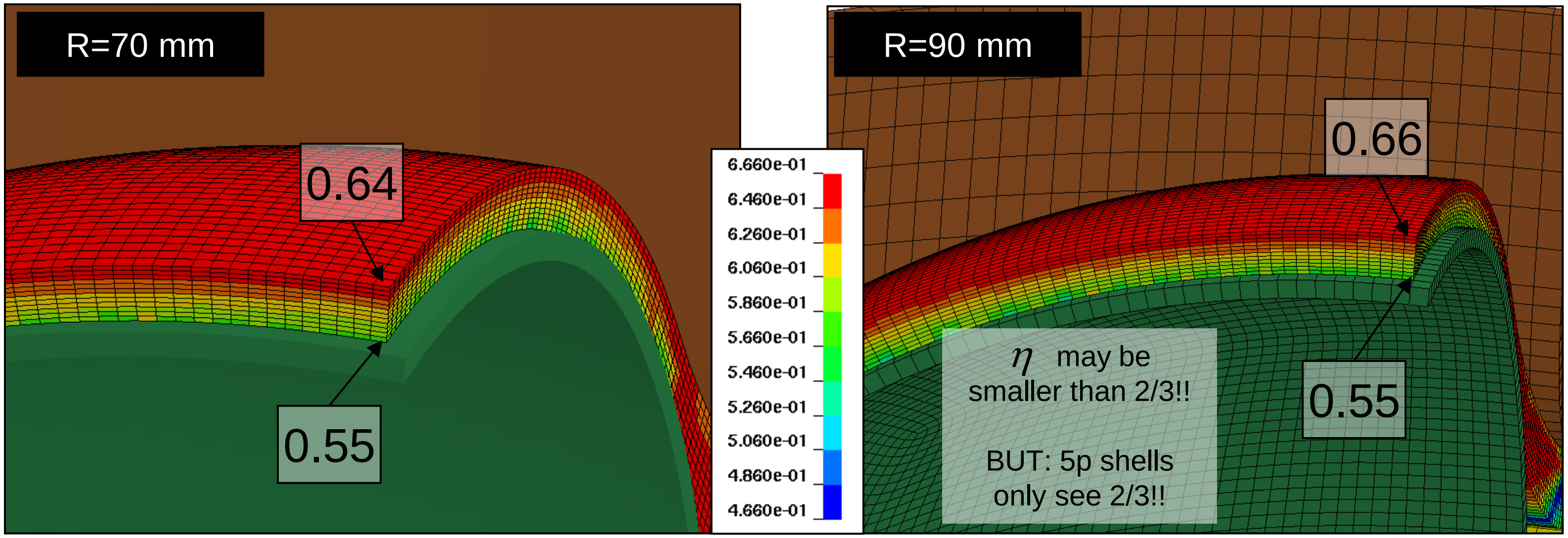


What the heck is so complicated with this?

Limitation of shell discretization

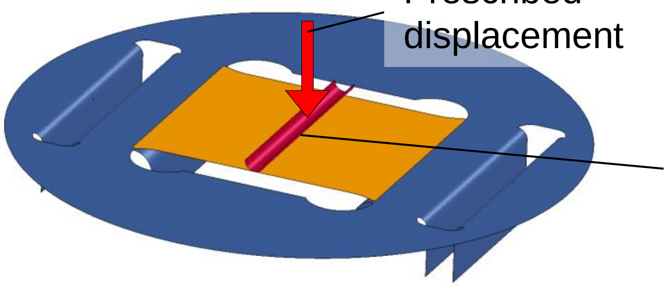
Influence of lateral compression

Older study of Nakazima-specimen: Triaxiality variation across thickness in solid discretization



[Basaran 2010]

Stretch-bending-setup (shells and solids)



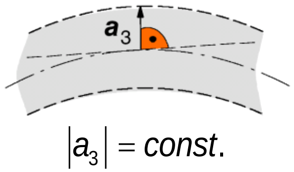
$$\eta \approx \pm\frac{1}{3}$$

Again: 5p shells only „see“ a triaxiality value of 1/3

Shell theories / Shell models

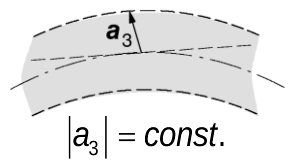
- **3-parameter shell model: Kirchhoff-Love**
  (cross section straight and unstreched,
  no shear deformations, i.e. normal to mid surface)

$$\sigma_{zz} = 0, (\varepsilon_{zz} = 0)$$
$$\gamma_{xz} = \gamma_{yz} = 0$$



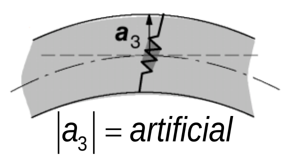
- **5-parameter shell model: Reissner-Mindlin**
  (cross section straight and unstreched,
  shear deformations possible)

$$\sigma_{zz} = 0, (\varepsilon_{zz} = 0)$$
$$\gamma_{xz} \neq 0; \ \gamma_{yz} \neq 0$$



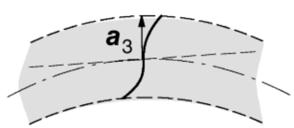
- **6- or 7-parameter shell model:**
  (cross section straight but stretchable)

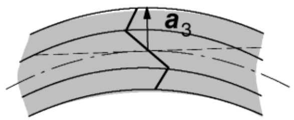
$$\sigma_{zz} \neq 0, \varepsilon_{zz} \neq 0$$
$$\gamma_{xz} \neq 0; \ \gamma_{yz} \neq 0$$



- **Higher order shell theory: multi-layer or -director:**
  (not straight and stretchable)

$$\sigma_{zz} \neq 0, \varepsilon_{zz} \neq 0$$
$$\gamma_{xz} \neq 0; \ \gamma_{yz} \neq 0$$





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  (cross section straight and unstreched,
  shear deformations possible)

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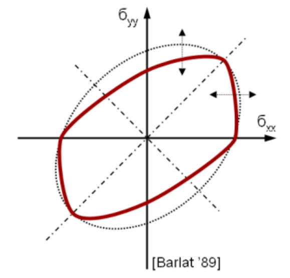
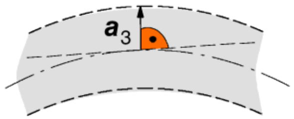
  (cross section straight but stretchable)

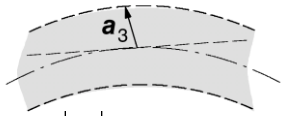
- **Higher order shell theory: multi-layer or -director:**
  (not straight and stretchable)



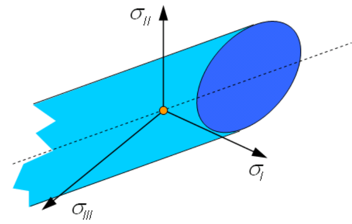


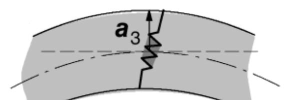
$|a_3| = const.$

Reduced constitutive models
(2D „*plane stress*“)



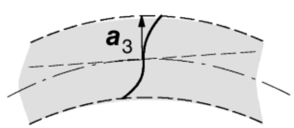
$|a_3| = const.$

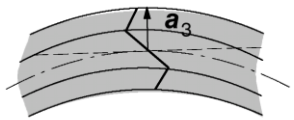




$|a_3| = artificial$

Full 3D constitutive models





Shell theories / Shell models

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  (cross section straight and unstreched,
  no shear deformations, i.e. normal to mid surface)

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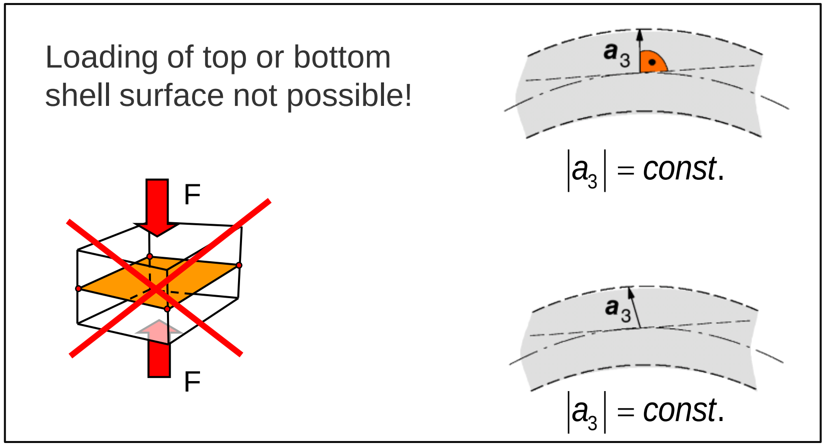
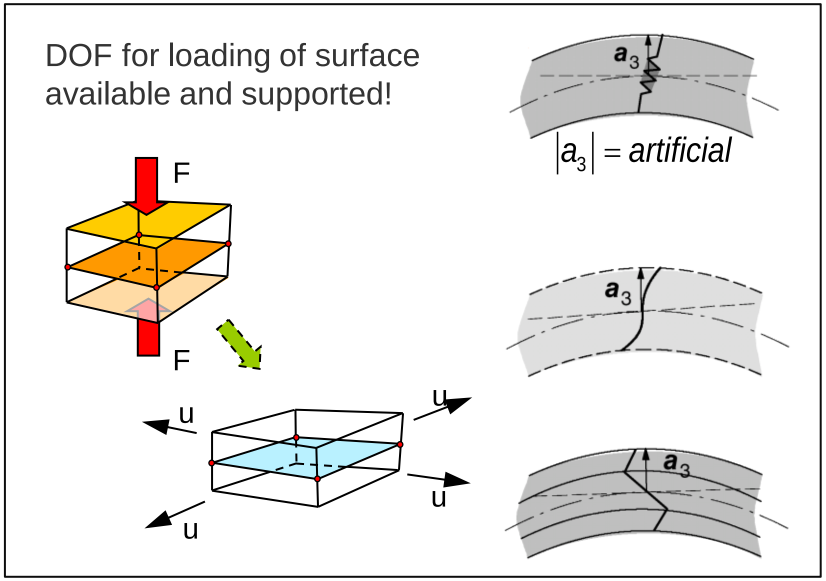
- **6- or 7-parameter shell model:**
  (cross section straight but stretchable)

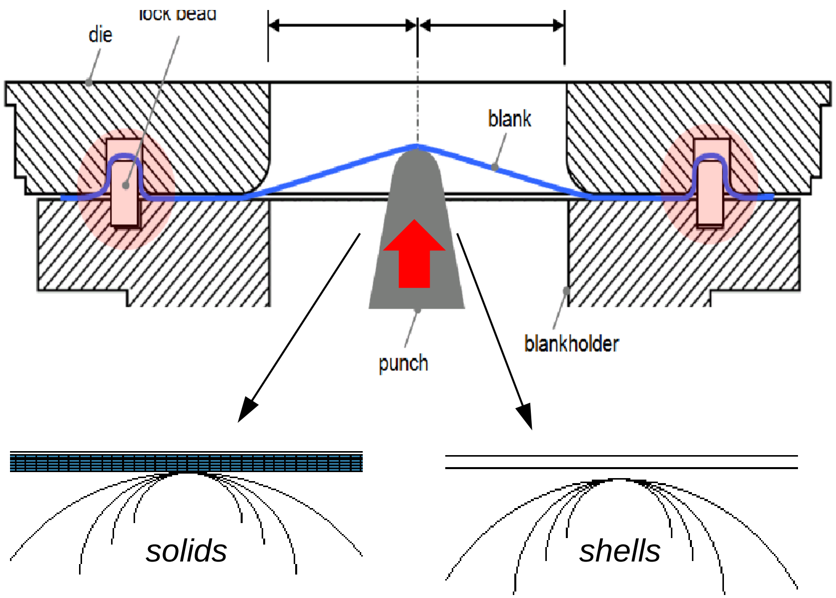
- **Higher order shell theory: multi-layer or -director:**
  (not straight and stretchable)



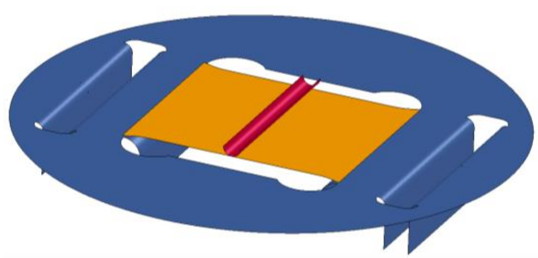


Stretch bending test: various materials and discretization

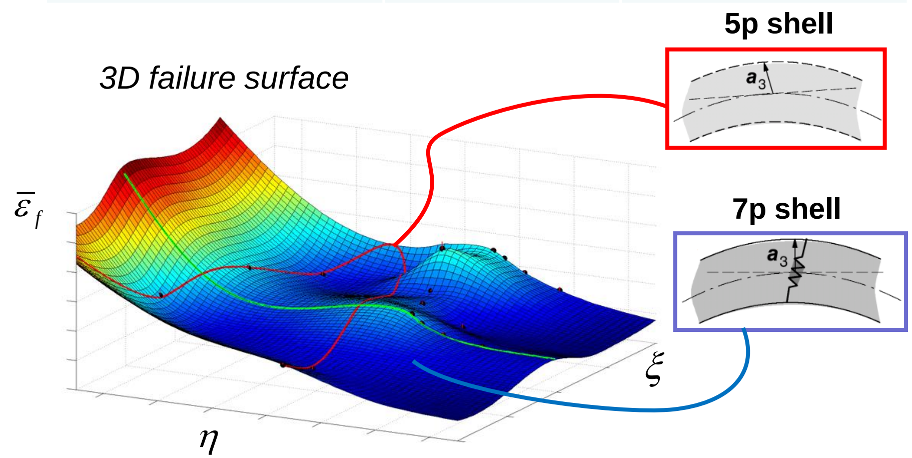
[Funding by RFCS greatly acknowledged]



Element Type	Shells	Solids
Element formulation	2 / 16 => 5p 25 / 26 => 7p	-1 / -2
Number of integration points across thickness	6	1
Number of elements in thickness direction	1	6
Element edge length	0,25mm	0,25mm
Selective mass scaling	✓	✓
Number of integration points that should fail before element fails	5	1

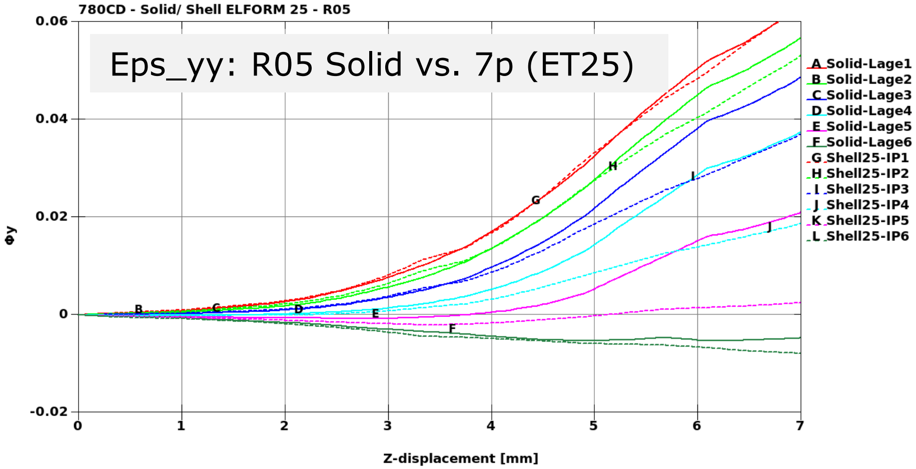


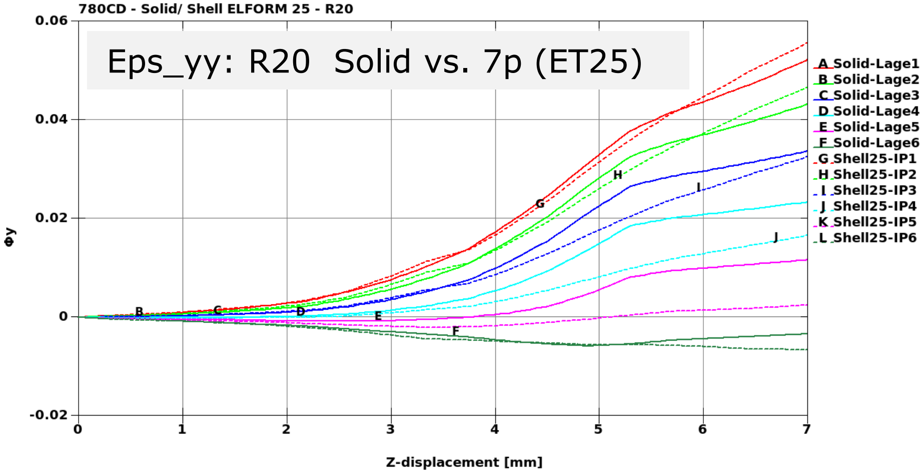
Different radii r05/r07/r10/r20
in shells and solids

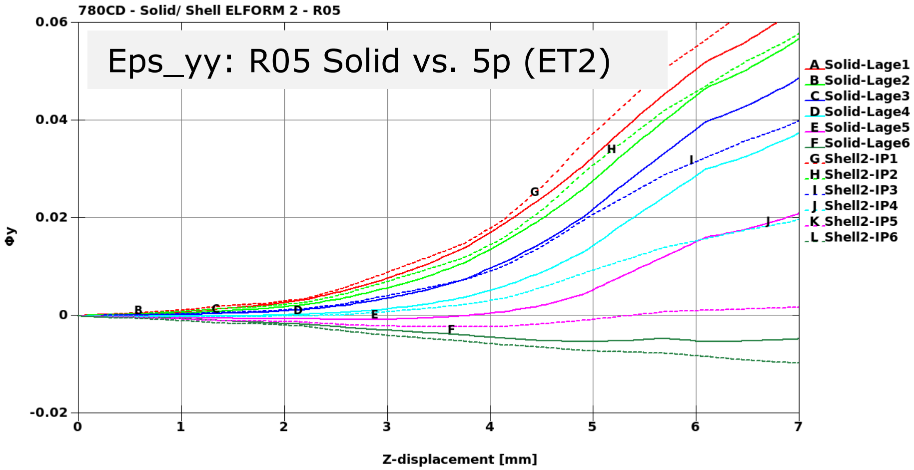


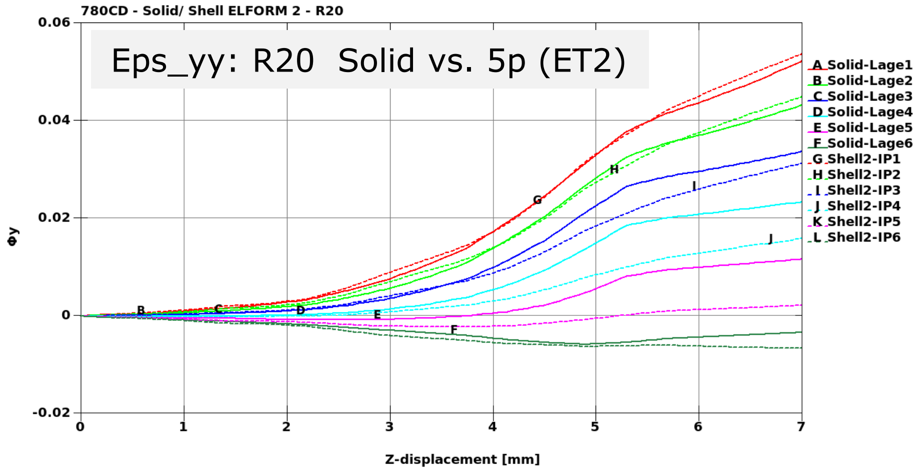
Stretch bending test: 780CD with solid, 5p and 7p shell

Comparison GISSMO (Solids and shells ET2 / ET25) – Eps yy

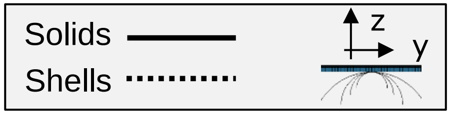






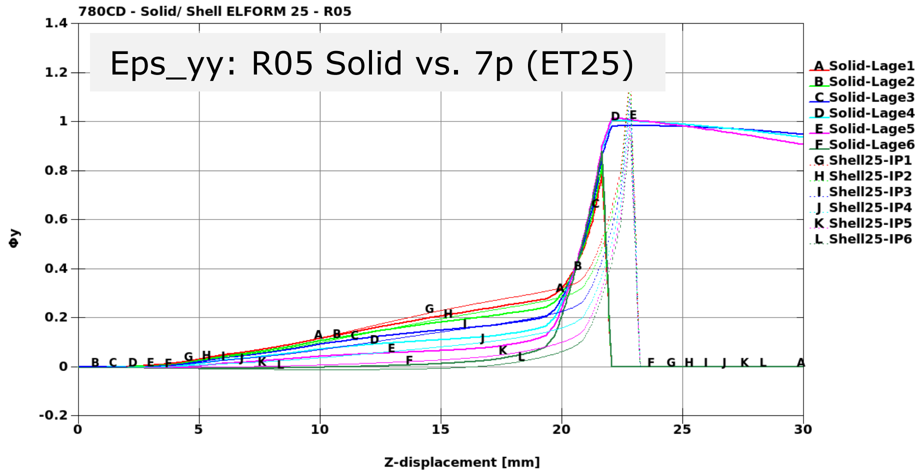


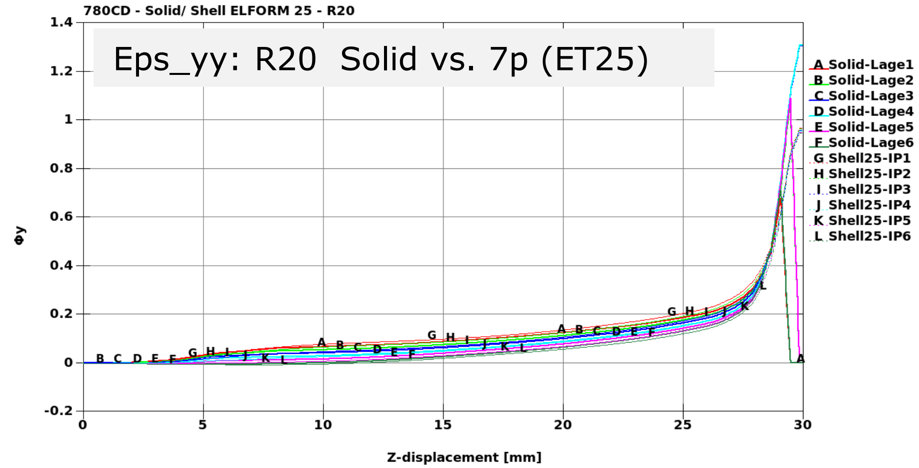
Not much difference at small strains

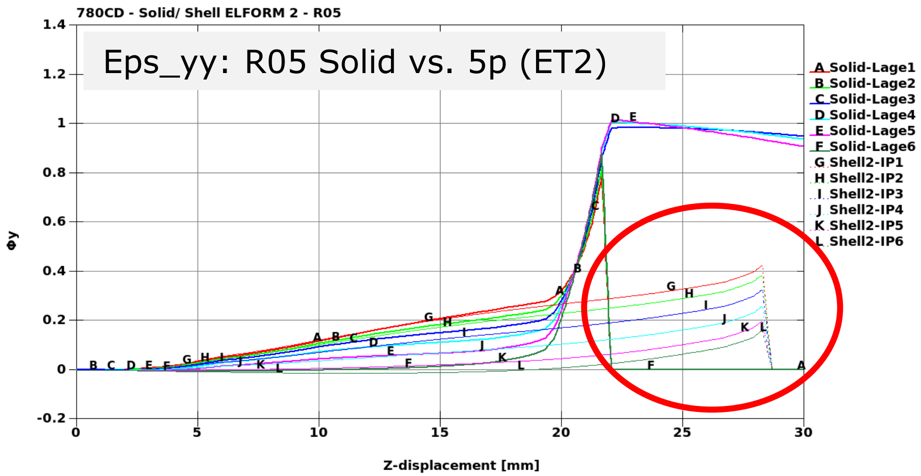


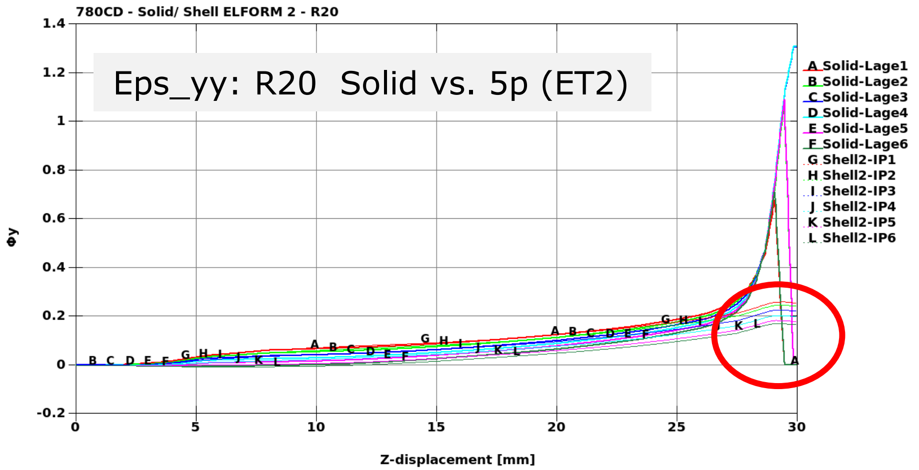
Stretch bending test: 780CD with solid, 5p and 7p shell

Comparison GISSMO (Solids and shells 5p-ET2 / 7p-ET25) – Eps yy

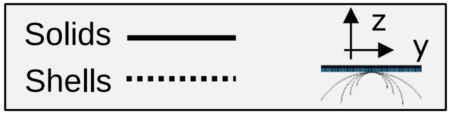






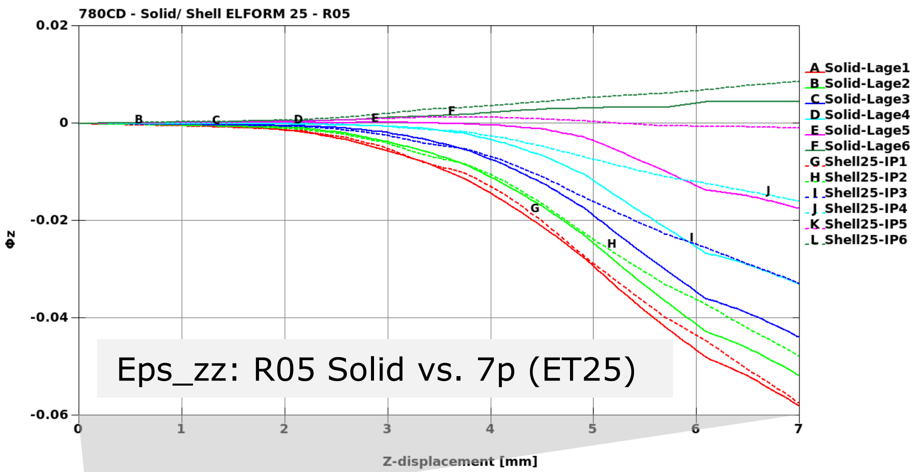


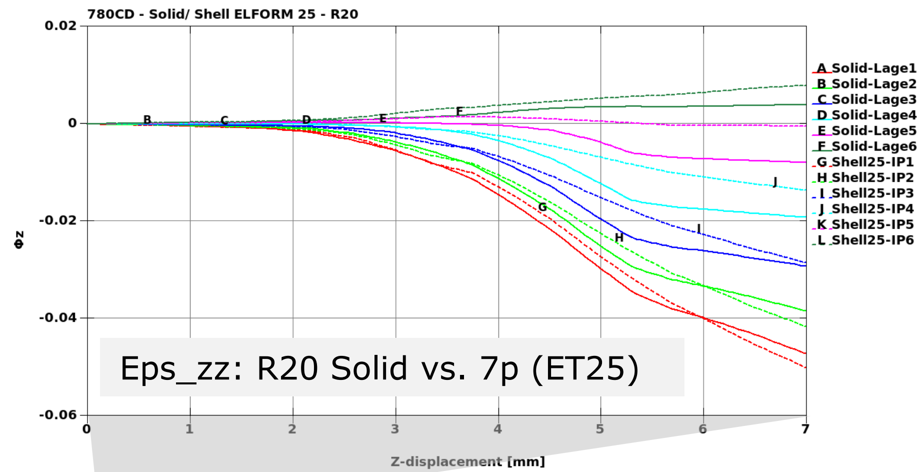
Failure of 5p-shell is totally different compared to 7p-shell!

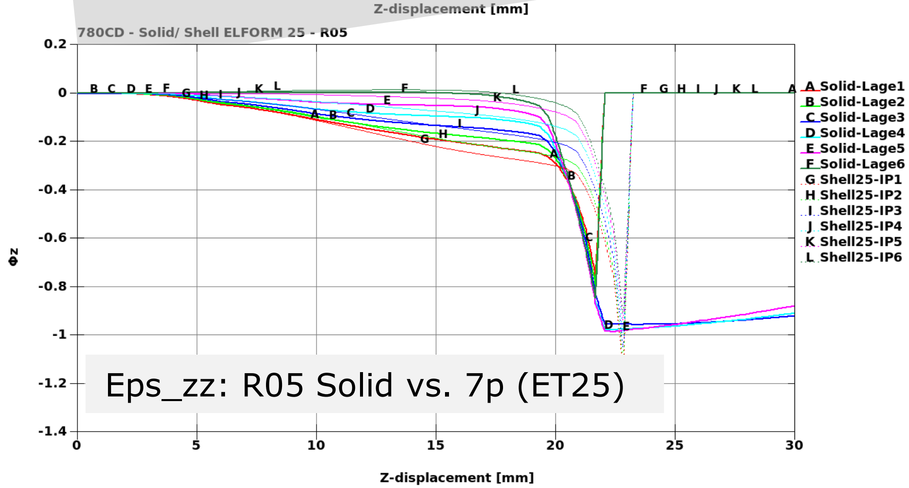


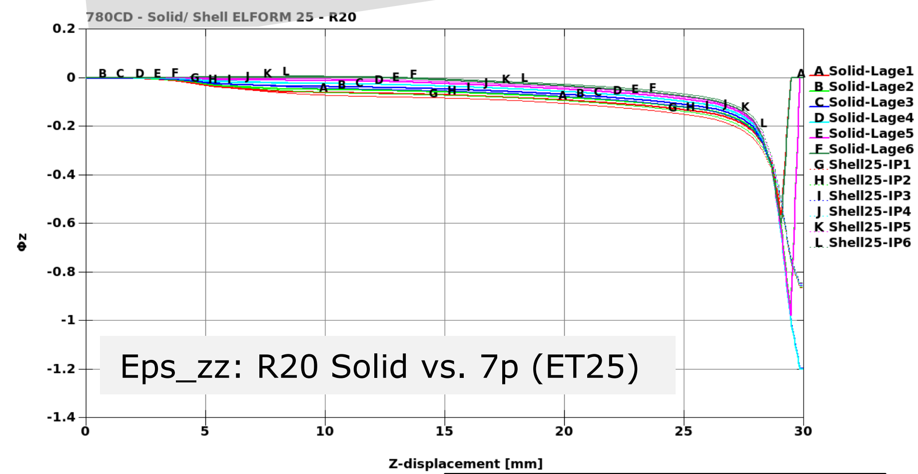
Stretch bending test: 780CD with solid and 7p shell

Comparison GISSMO (Solids and shells 7p ET25) – Eps zz







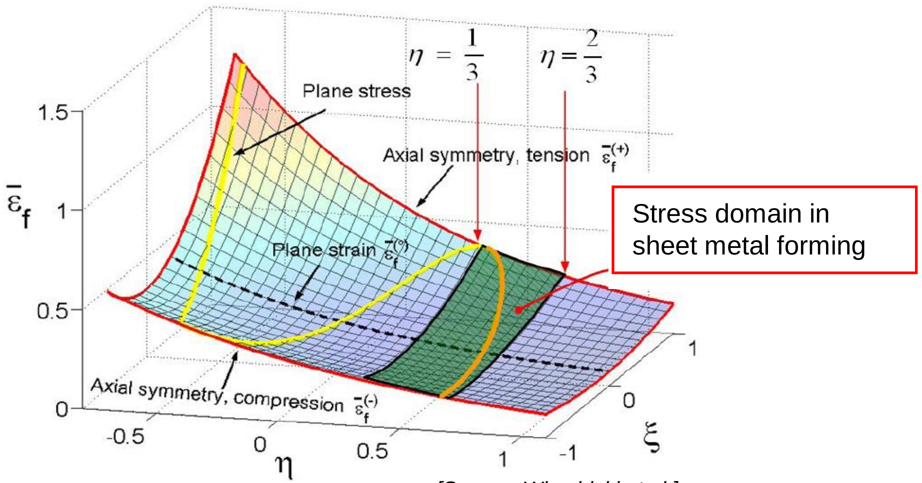


Failure modeling

A brief introduction to failure modelling in invariant stress space

GISSMO

Failure criterion in plane stress and 3D stress states

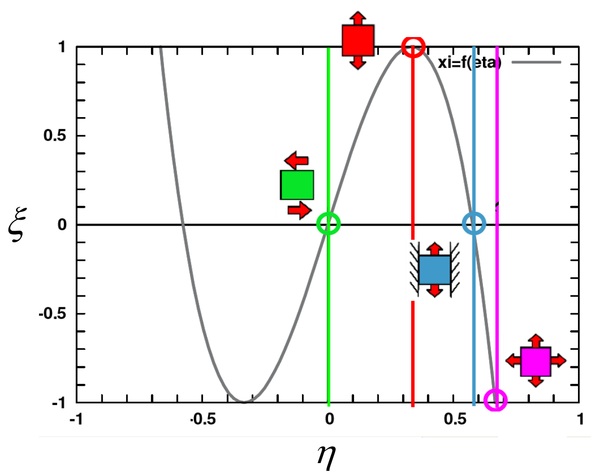


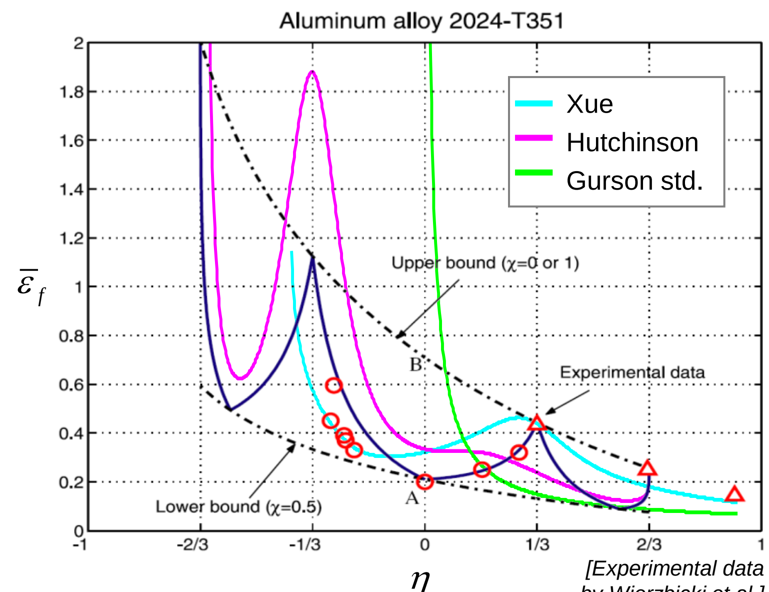
[Source: Wierzbicki et al.]

Parameter definition

$$\eta = \frac{\sigma_m}{\sigma_{vM}} = \frac{I_1}{3\sigma_{vM}}$$

$$\xi = \frac{27}{2}\frac{J_3}{\sigma_{vM}^3} \quad \text{with} \quad J_3 = s_1 s_2 s_3$$

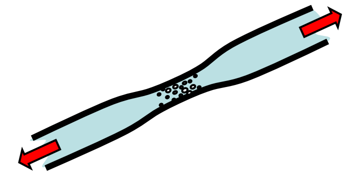




[Experimental data by Wierzbicki et al.]

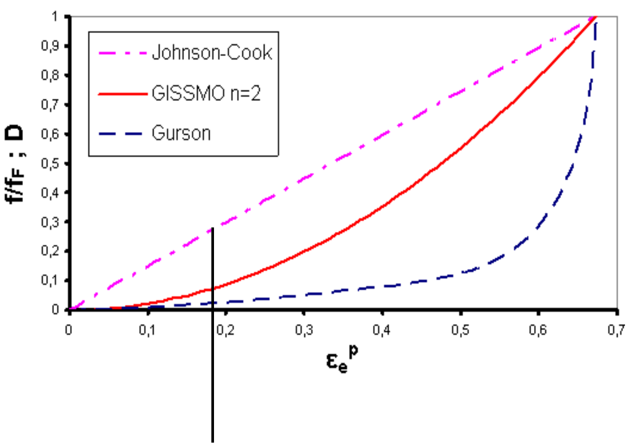
GISSMO - a short description

Ductile damage and failure



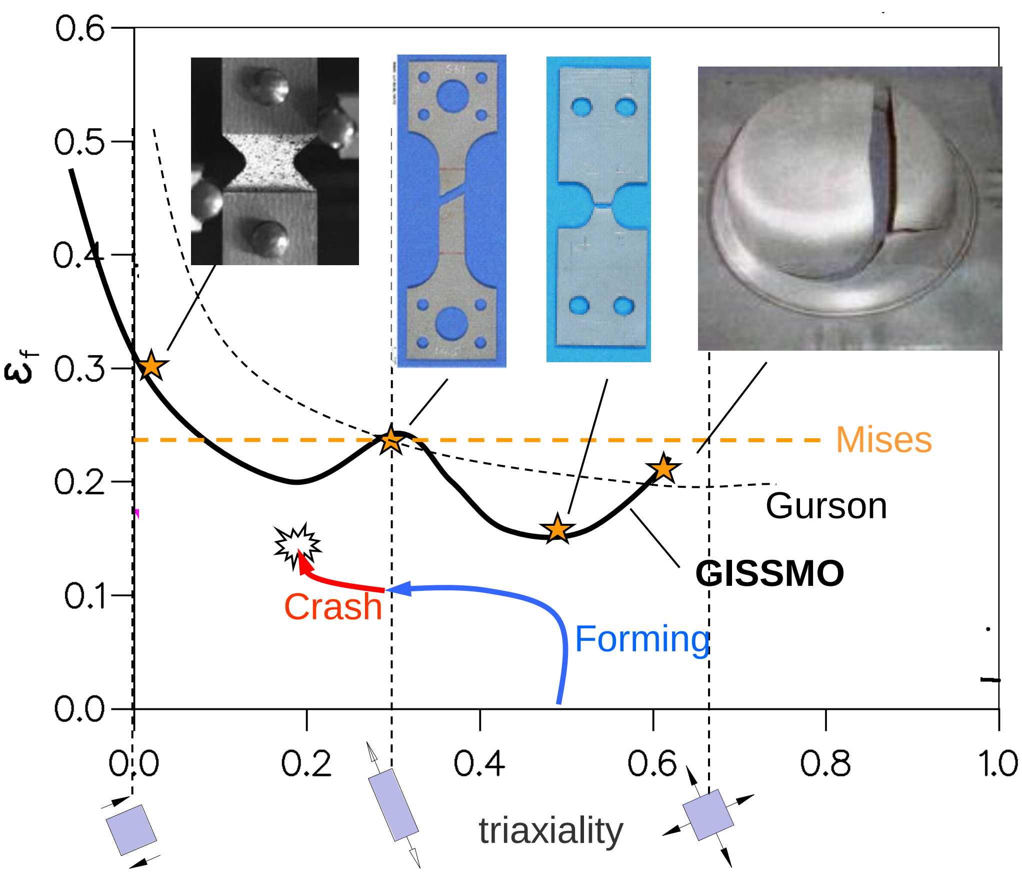
Damage evolution

$$\dot{D}_f = \frac{n}{\varepsilon_f} D_f^{\left(1-\frac{1}{n}\right)} \dot{\varepsilon}_p$$



Damage regularly overestimated for linear damage accumulation!!

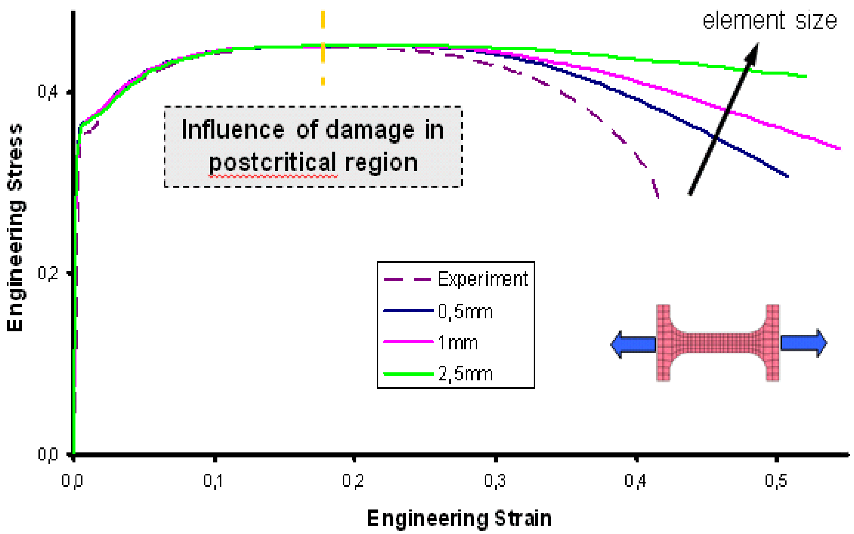
Failure curve



Neukamm, Feucht, DuBois & Haufe [2008-2010]

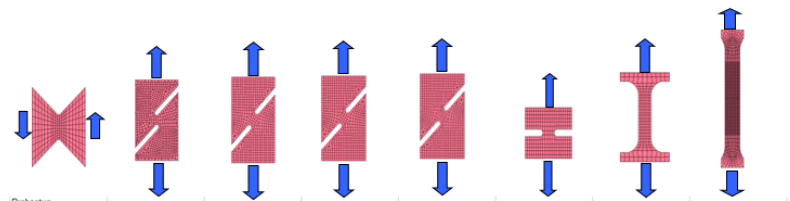
GISSMO – a short description: Shell calibration

Mesh size dependency: Simple regularisation



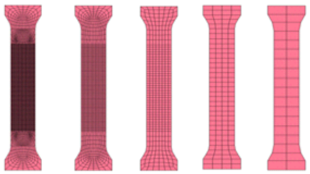
- Inherent mesh-size dependency of results in the post-critical region
- Simulation (and calibration) of tensile test specimen with different mesh sizes

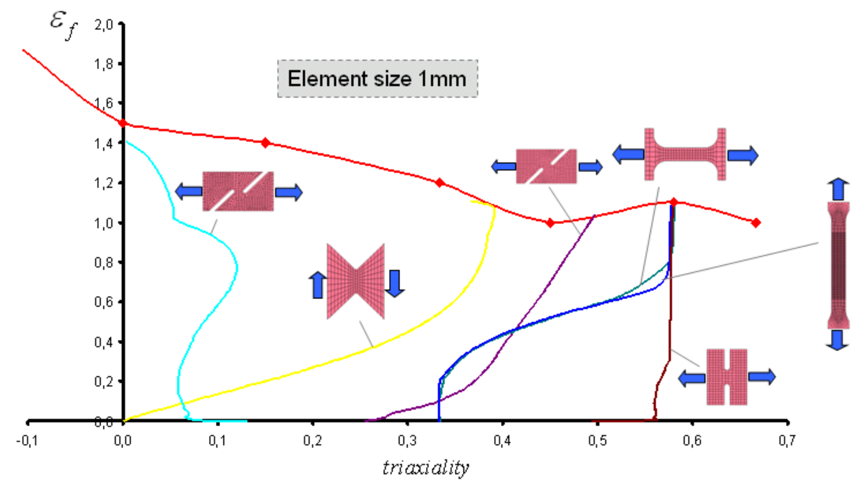
Test program and calibration



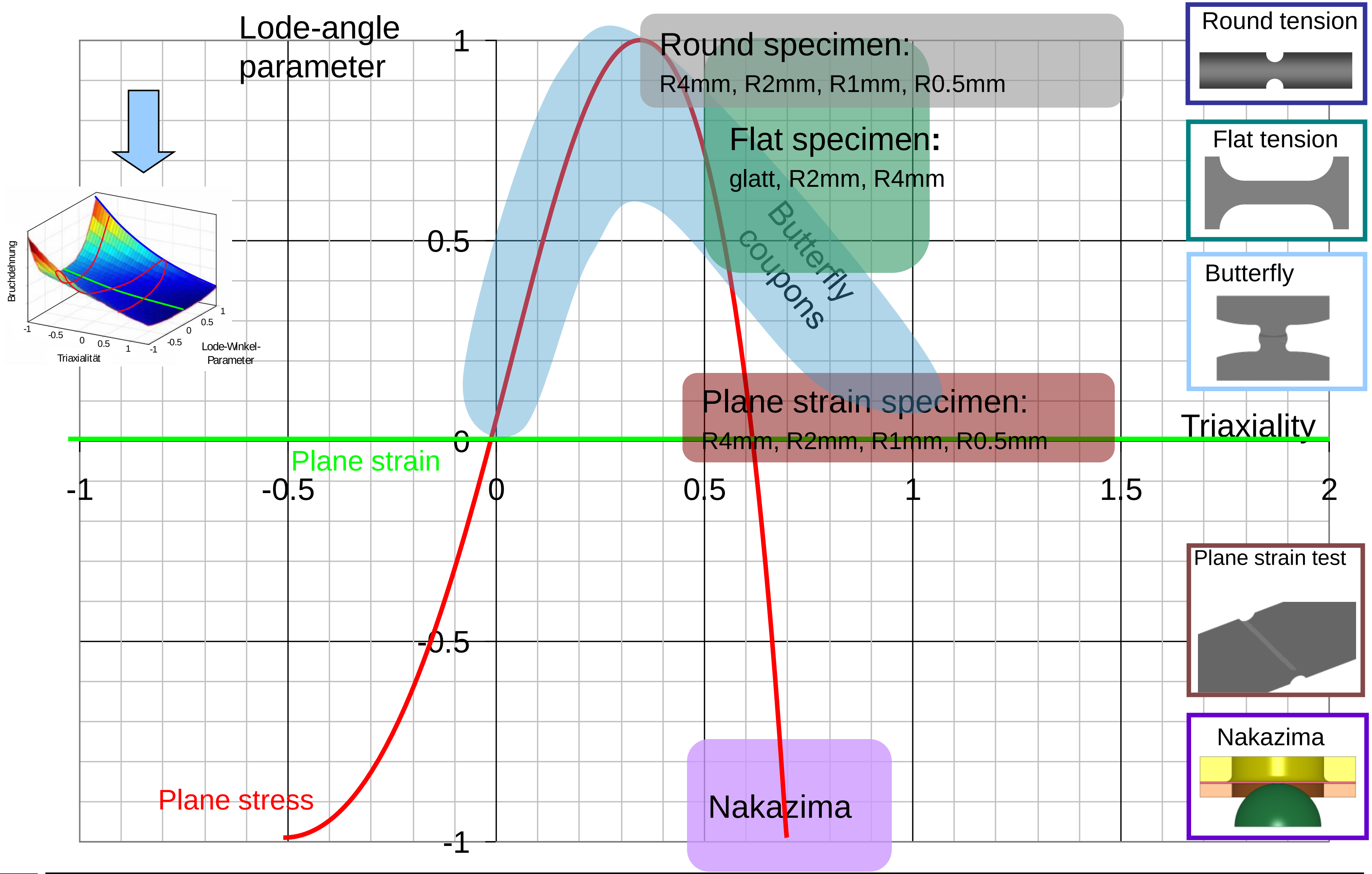
Netzfeinheit	Probentyp Arcan	Scherzug 0°	Scherzug 15°	Scherzug 30°	Scherzug 45°	Kerbzug R1	Mini-Flachzug	DIN-Flachzug
0,5mm								
1mm								
2,5mm								
5mm								
10mm								

To be considered:
8 Specimen geometries
5 Discretisations





Experimental setup for full 3D calibration



Calibration of parameters

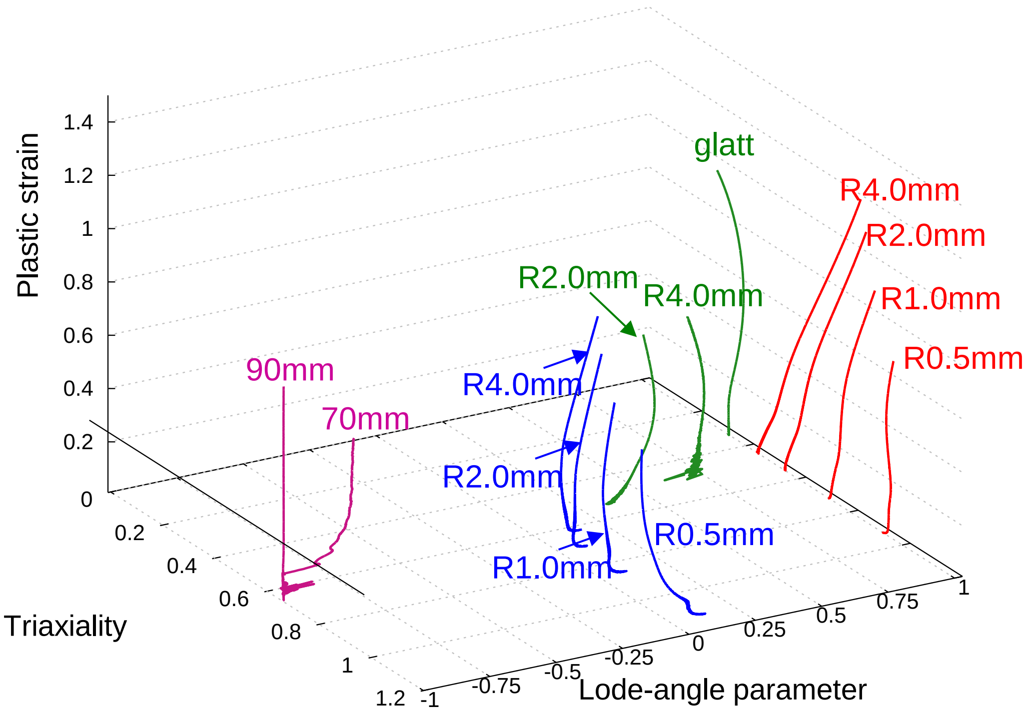
Diagram: Triaxiality, Lode-angle parameter, plastic strain

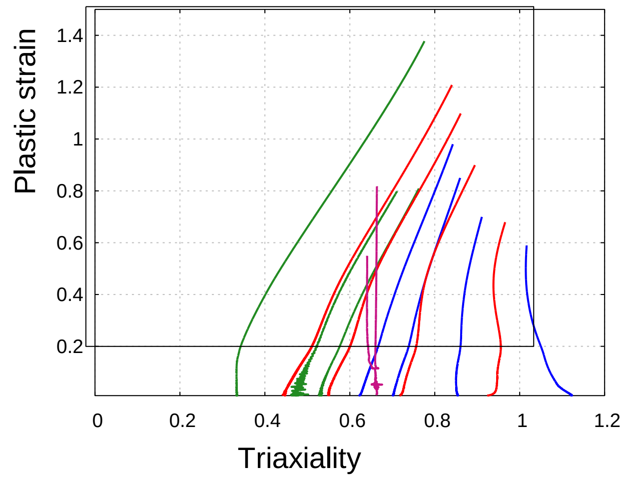
Round specimen : R0.5mm, 1mm, 2mm, 4mm

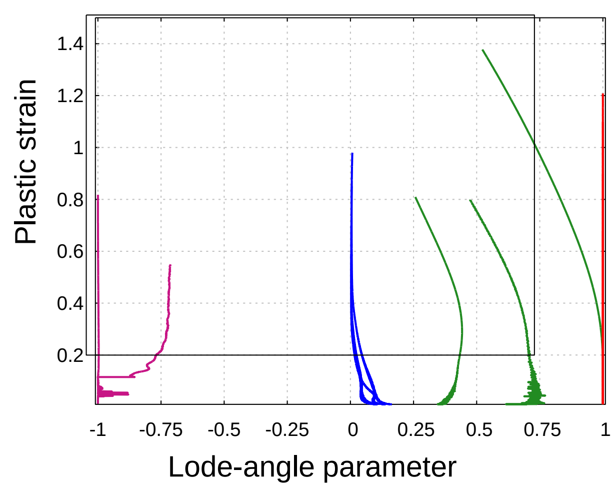
Flat specimen: smooth,2mm,4mm

Plane strain coupons: R0.5mm, 1mm, 2mm, 4mm

Nakazima specimen: 70mm, 90mm

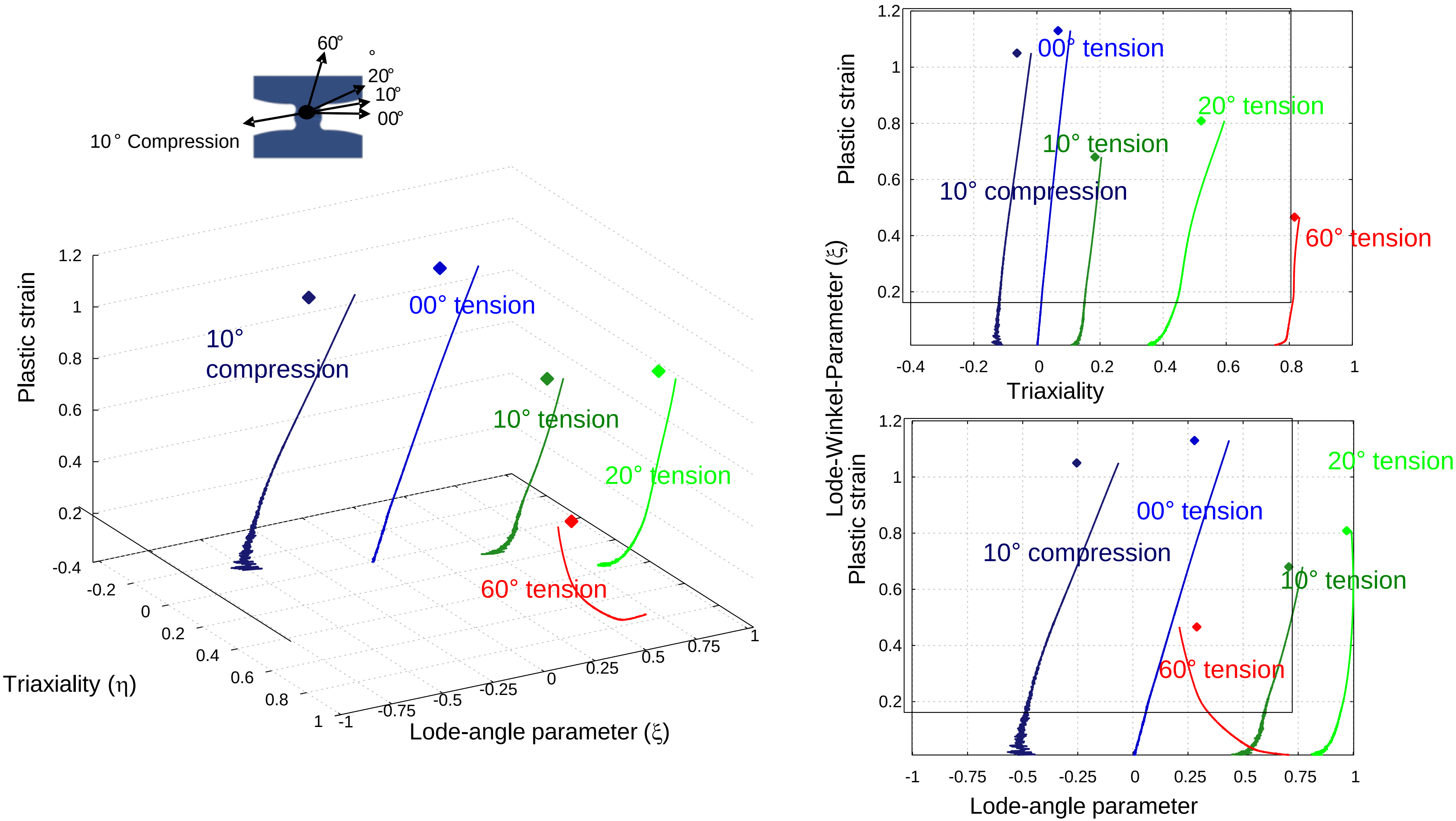




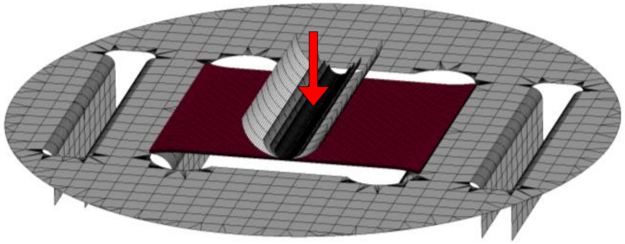


Calibration of parameters

Butterfly coupon – Diagram: Triaxiality, Lode-angle, plastic strain (1)

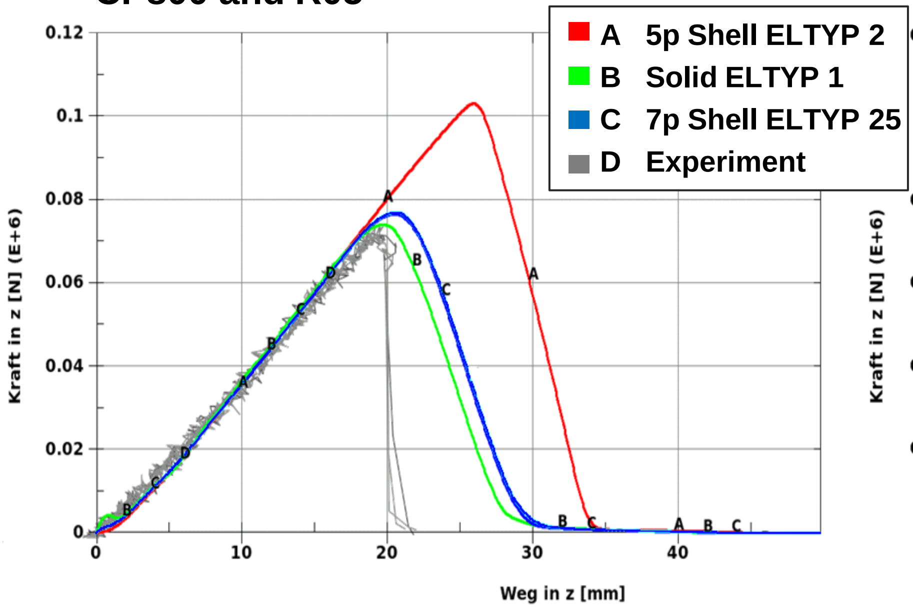


Finally: Application !!

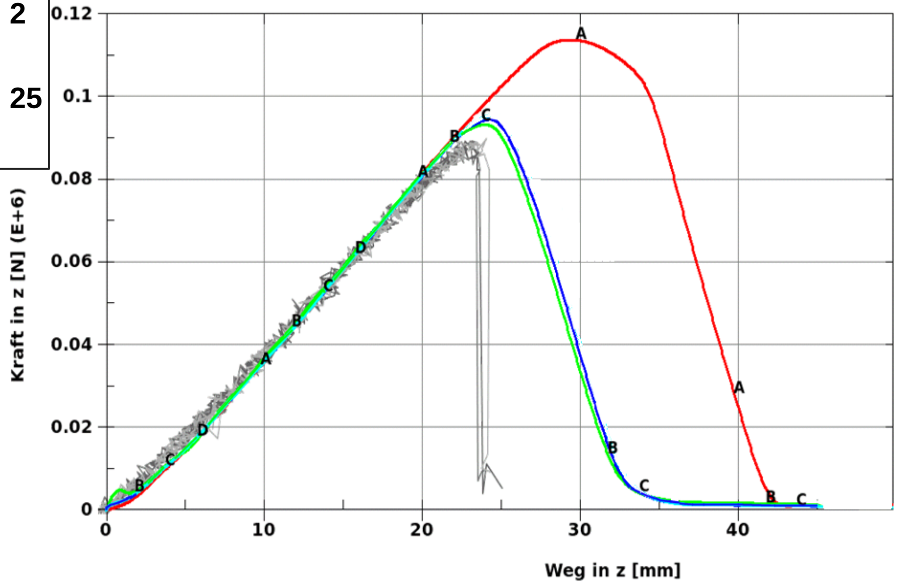


Stretch bending: CP800 and R05 / R10

CP800 and R05



CP800 and R10

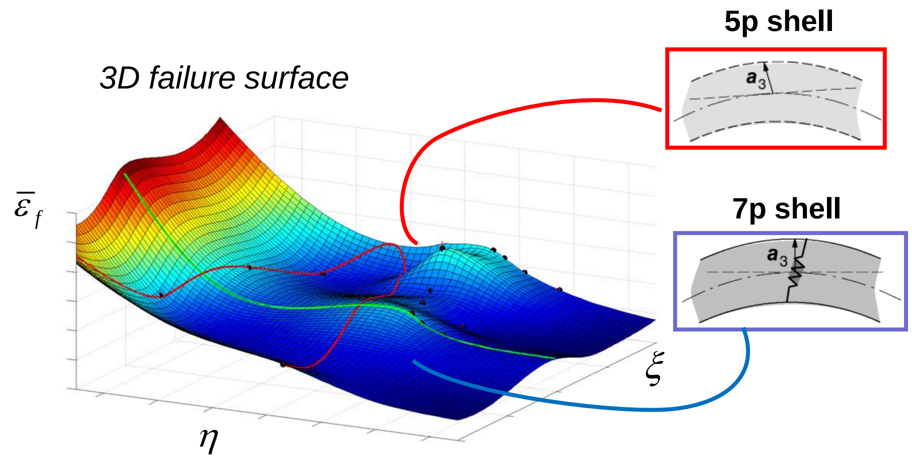


Failure data has been calibrated for plane stress using the shear failure criteria of DIEM (IDS):

$$\varepsilon_D^p = \varepsilon_D^p(\theta, \dot{\varepsilon}^p) \quad \text{where} \quad \theta = (q + k_S\, p)/\tau$$

$$\text{and} \quad \tau = \left(\sigma_{\text{major}} - \sigma_{\text{minor}}\right)/2$$

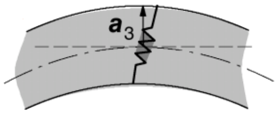
Data was then converted to GISSMO-curves and applied directly without any other modification to the application shown.



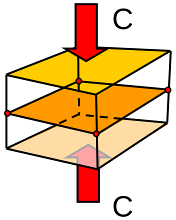
Time for a quick summary…

We could be happy – but we aren‘t!

Why?



7p shells come with DOF in thickness direction. In explicit finite elements this eventually governs the time step. Hence 7p-shells are more expensive than their 5p-siblings.



Remedy:

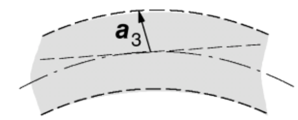
Extension of 5-parameter shell formulation to take lateral stresses due to contact into account.

(ELTYP=2/16 & IDOF=3)

Development of IDOF=3 in shell type 2/16

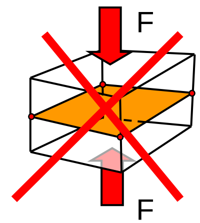
5parameter shell: - No stresses in thickness direction

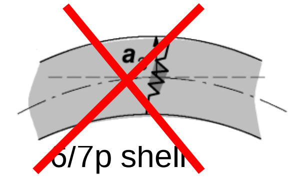
$\sigma_{zz} = 0, (\varepsilon_{zz} = 0)$ and $\gamma_{xz} \neq 0; \ \gamma_{yz} \neq 0$



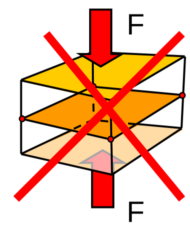
5p shell

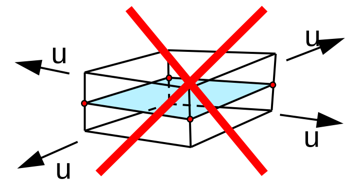
- No degree of freedom in thickness direction





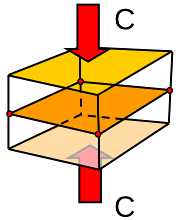
- Hence no loading in thickness direction!

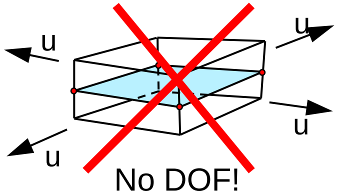




What can be done to take thickness loading nevertheless into account?

Development of IDOF=3 in shell type 2/16





By specifying IDOF=3 on *SECTION_SHELL for ELFORM=2 and ELFORM=16, the following algorithm is invoked that has been developed to take the contact pressure onto the shell surface (top/bottom) into account. This influences the stress in the material model.

The z-stress in a shell element is usually restricted to be zero, but in this case we intend to solve the constitutive update using the constraint

$$\sigma_{zz} = \alpha\sigma_c(z) \quad \text{where} \quad \sigma_c(z) = -\frac{\sigma_c^b - \sigma_c^t}{4}(z^3 - 3z) - \frac{\sigma_c^b + \sigma_c^t}{2} \qquad (1)$$

σ_c^b = contact pressure at bottom surface of shell

σ_c^t = contact pressure at top surface of shell

z = isoparametric coordinate through the thickness between -1 and 1

α = scaling parameter

*The scaling parameter α can be set as the 8th parameter on card 3 on *CONTROL_CONTACT.*

[early idea by Riel & van den Boogaard 2007]

Development of IDOF=3 in shell type 2/16

The constitutive update for an elastic-plastic (J2) material can be written

$$\boldsymbol{\sigma}^{n+1} = \boldsymbol{\sigma}^{n} + K\Delta\varepsilon_{\text{vol}}\mathbf{I} + \Delta\mathbf{s}\left(\mathbf{s}_n, \Delta\boldsymbol{\varepsilon}_{\text{dev}}\right) \qquad (2)$$

where

$\boldsymbol{\sigma}^{n+1}$ = stress in step $n+1$

$\boldsymbol{\sigma}^{n}$ = stress in step n

K = bulk modulus

$\Delta\boldsymbol{\varepsilon}$ = strain increment

$\Delta\varepsilon_{\text{vol}} = \Delta\boldsymbol{\varepsilon} : \mathbf{I}$ = volumentric strain increment

$\mathbf{I}$ = unit tensor

$\Delta\mathbf{s}$ = deviatoric stress increment

$\mathbf{s}_n = \boldsymbol{\sigma}^{n} - \frac{\boldsymbol{\sigma}^{n} : \mathbf{I}}{3}\mathbf{I}$ = deviatoric stress in step n

$\Delta\boldsymbol{\varepsilon}_{\text{dev}} = \Delta\boldsymbol{\varepsilon} - \frac{\Delta\varepsilon_{\text{vol}}}{3}\mathbf{I}$ = deviatoric strain increment

[early idea by Riel & van den Boogaard 2007]

Development of IDOF=3 in shell type 2/16

The independent variables in (2) are

$$\sigma_{xx}^{n+1}, \sigma_{yy}^{n+1}, \sigma_{xy}^{n+1}, \sigma_{yz}^{n+1}, \sigma_{xz}^{n+1}, \Delta\varepsilon_{zz}$$

Of course it is assumed that the stress response can be decoupled into a volumetric and deviatoric part and the deviatoric stress increment depends only on the deviatoric part of the stress and strain increment as indicated in the formula.

Equation (2) can be rewritten to

$$\begin{aligned} \tilde{\boldsymbol{\sigma}}^{n+1} &= \tilde{\boldsymbol{\sigma}}^{n} + K\Delta\tilde{\varepsilon}_{\text{vol}}\mathbf{I} + \Delta\mathbf{s}\left(\tilde{\mathbf{s}}_n, \Delta\tilde{\boldsymbol{\varepsilon}}_{\text{dev}}\right) \\ \tilde{\sigma}_{zz}^{n+1} &= 0 \end{aligned} \qquad (3)$$

by substituting

$$\begin{aligned} \tilde{\boldsymbol{\sigma}}^{n} &= \boldsymbol{\sigma}^{n} - \sigma_c^n\mathbf{I} \\ \tilde{\boldsymbol{\sigma}}^{n+1} &= \boldsymbol{\sigma}^{n+1} - \sigma_c^{n+1}\mathbf{I} \\ \Delta\tilde{\boldsymbol{\varepsilon}} &= \Delta\boldsymbol{\varepsilon} - \frac{\sigma_c^{n+1} - \sigma_c^n}{3K}\mathbf{I} \end{aligned} \qquad (4)$$

[early idea by Riel & van den Boogaard 2007]

Development of IDOF=3 in shell type 2/16

Since the deviatoric stress and strain increment is not changed, i.e.,

$$\mathbf{s}_n = \tilde{\mathbf{s}}_n$$
$$\Delta\boldsymbol{\varepsilon}_{\text{dev}} = \Delta\tilde{\boldsymbol{\varepsilon}}_{\text{dev}}$$

with this substitution it follows that the existing material routines can be used for solving equation (3) in terms of

$$\tilde{\sigma}_{xx}^{n+1}, \tilde{\sigma}_{yy}^{n+1}, \tilde{\sigma}_{xy}^{n+1}, \tilde{\sigma}_{yz}^{n+1}, \tilde{\sigma}_{xz}^{n+1}, \Delta\tilde{\varepsilon}_{zz}$$

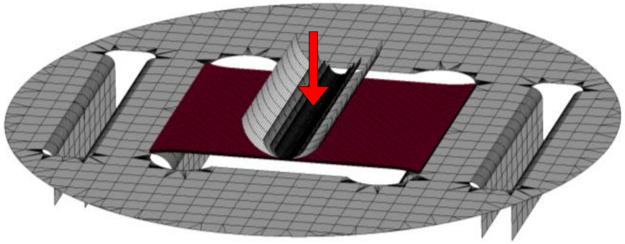
and then use the inverse of (4) to establish the stress and through thickness strain increment. Thus, the algorithm is as follows

1. Given $\boldsymbol{\sigma}^n$, $\Delta\boldsymbol{\varepsilon}$, σ_c^n and σ_c^{n+1}
2. Use the first and third of (4) to compute $\tilde{\boldsymbol{\sigma}}^n$ and $\Delta\tilde{\boldsymbol{\varepsilon}}$: $\tilde{\boldsymbol{\sigma}}^n = \boldsymbol{\sigma}^n - \sigma_c^n\mathbf{I}$ $\quad \Delta\tilde{\boldsymbol{\varepsilon}} = \Delta\boldsymbol{\varepsilon} - \dfrac{\sigma_c^{n+1} - \sigma_c^n}{3K}\mathbf{I}$
3. Do a constitutive update to get $\tilde{\boldsymbol{\sigma}}^{n+1}$ and $\Delta\tilde{\varepsilon}_{zz}$
4. Use the second and inverse of third of (4) to compute $\boldsymbol{\sigma}^{n+1}$ and $\Delta\varepsilon_{zz}$

$$\tilde{\boldsymbol{\sigma}}^{n+1} = \boldsymbol{\sigma}^{n+1} - \sigma_c^{n+1}\mathbf{I} \qquad \Delta\tilde{\boldsymbol{\varepsilon}} = \Delta\boldsymbol{\varepsilon} - \frac{\sigma_c^{n+1} - \sigma_c^n}{3K}\mathbf{I}$$

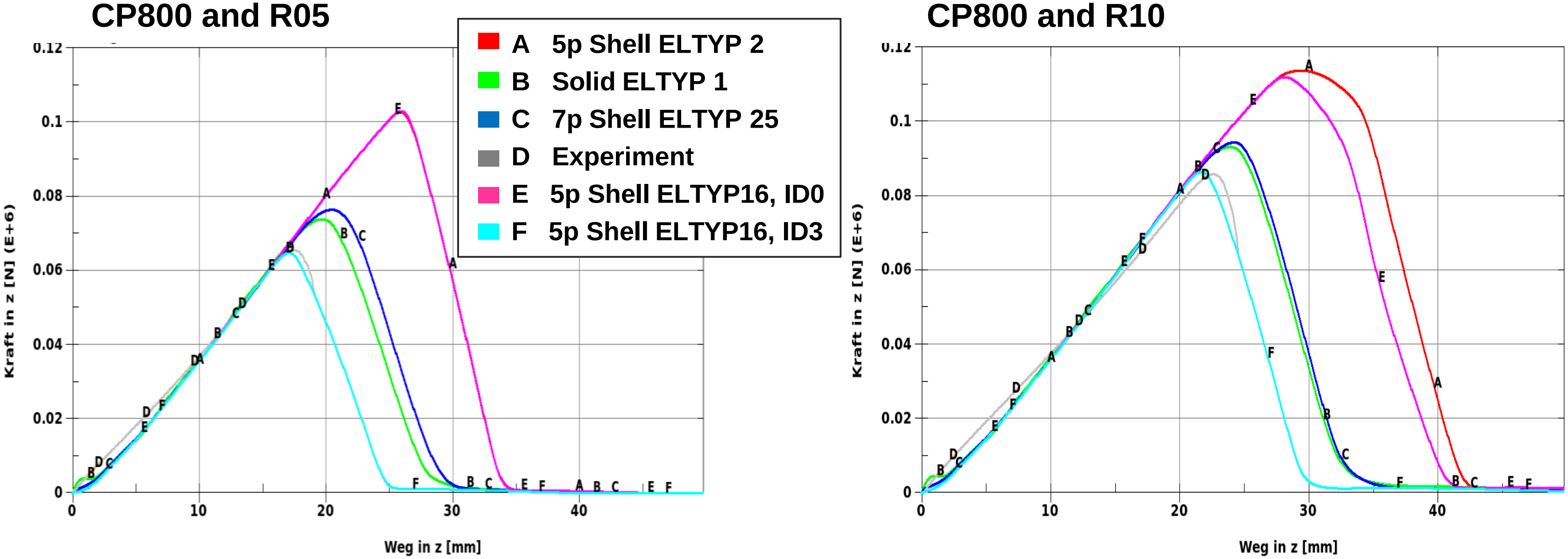
[Riel & van den Boogaard 2007]

More application



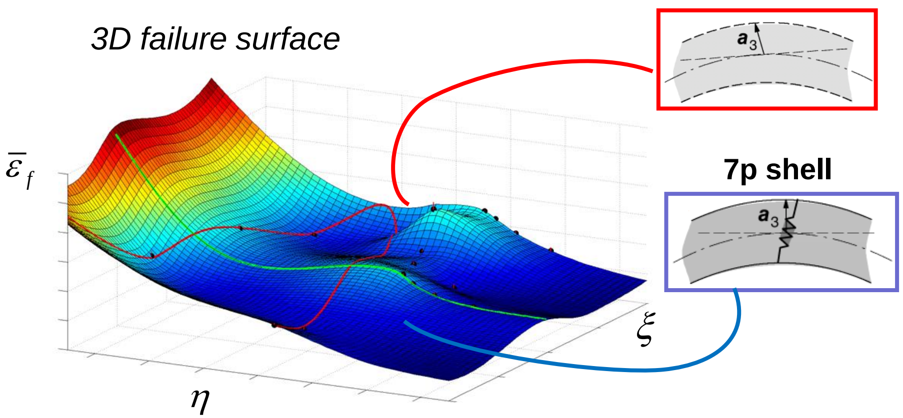
Stretch bending: CP800 and R05 / R10 (ET16 IDOF3 GISSMO)

CP800 and R05 / **CP800 and R10**



- *Magenta curve is ELTYP=16 (5parameter shell) with IDOF=0 and GISSMO failure criteria.*
- *Torquoise curve is ELTYP=16 (5parameter shell) with IDOF=3 and GISSMO failure criteria.*

3D failure surface



FIN

Acknowledgement

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