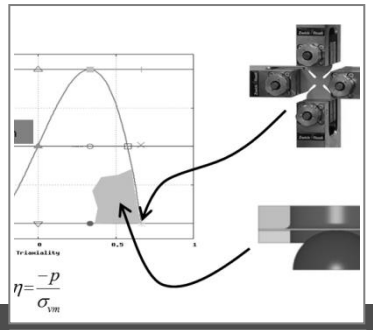
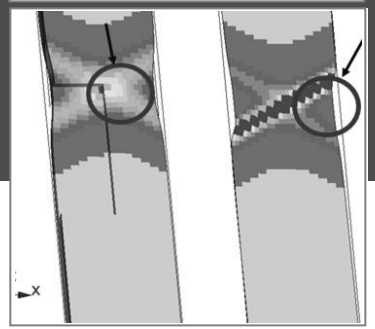
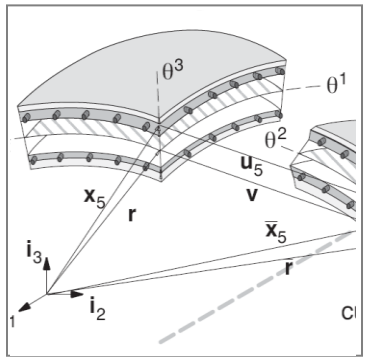






LS-DYNA Forum 2016

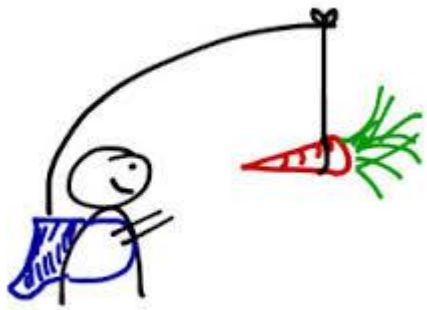
Bamberg

Predictive fracture modelling in crashworthiness: A discussion of the limits of shell discretized structures

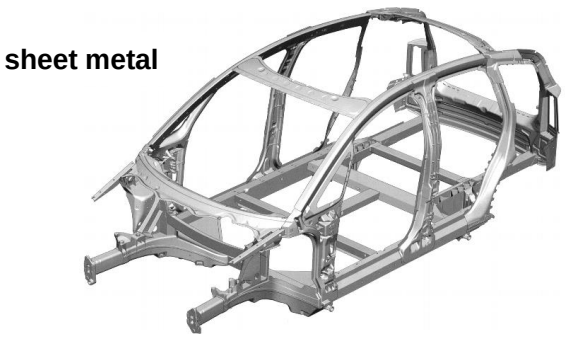
A. Haufe[1], F. Andrade[1], M. Feucht[2], D. Riemensperger[3], K. Schweizerhof[1]

[1]DYNAmore GmbH, 70569 Stuttgart, Germany
[2]Daimler AG, 71059 Sindelfingen, Germany
[3]Adam Opel AG, 65423 Rüsselsheim, Germany

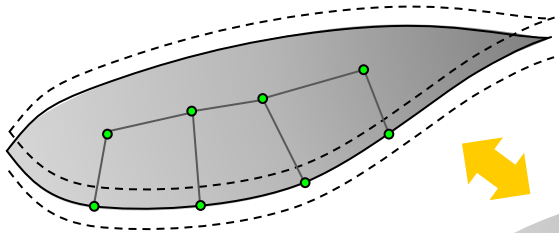
Motivation



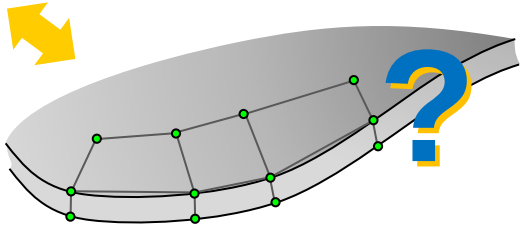
Motivation – transition from shells to solids?



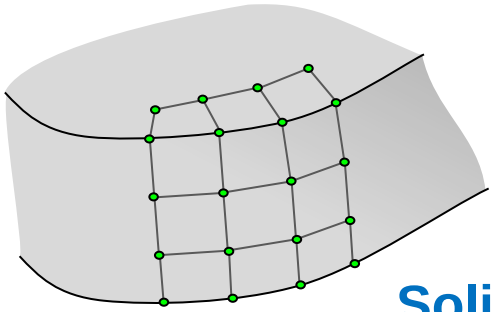
steel
cast aluminium
aluminium sheets
extruded aluminium



Shell



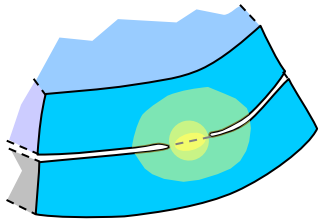
Solid-shell



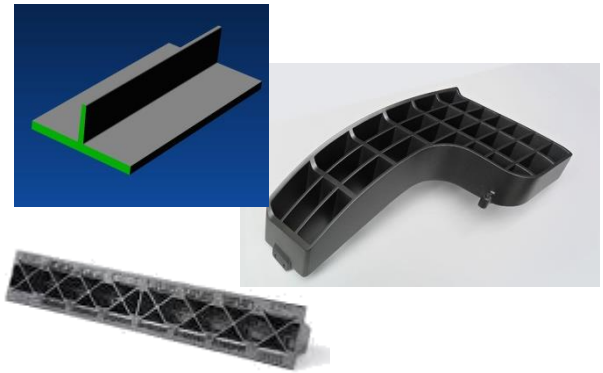
Solid

Motivation – transition from shells to solids?

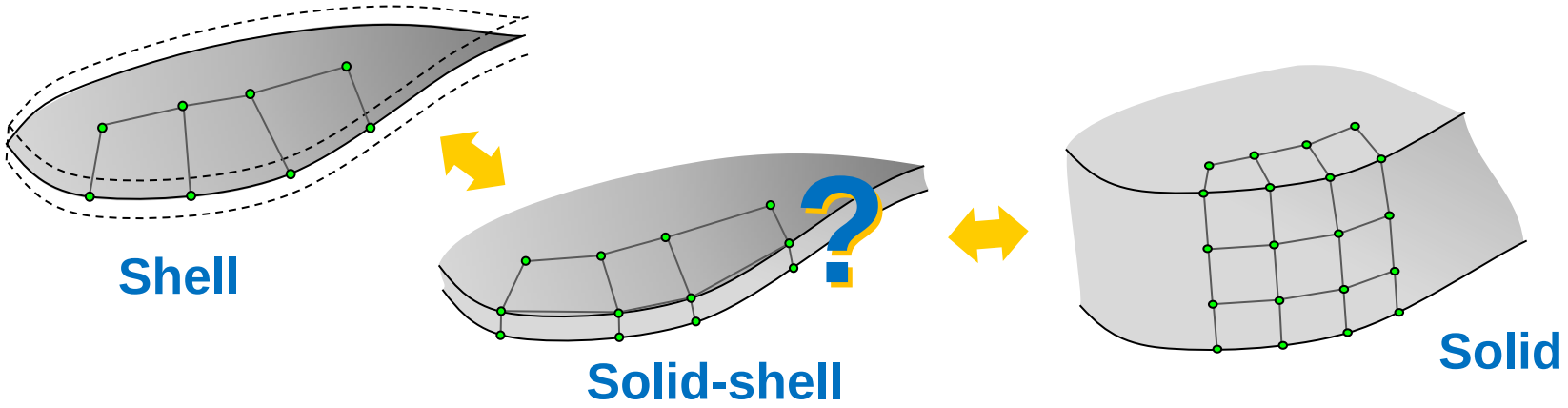
lateral contact



connections

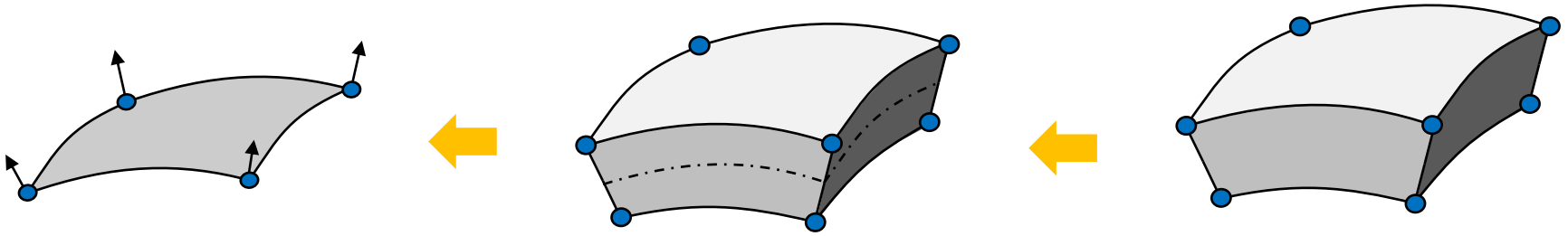


intersections



Derivation of shell formulation: Degenerated solid

[Ahmad, Irons and Zienkiewicz 1968]



Shell assumptions (all quantities expressed w.r.t. mid surface)

Mid surface of characteristic plane

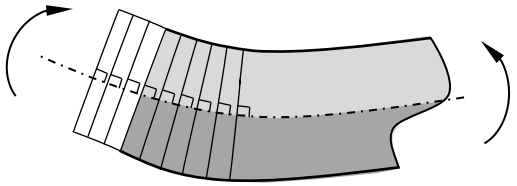
Solid element

Kirchhoff-Love [Bernoulli]

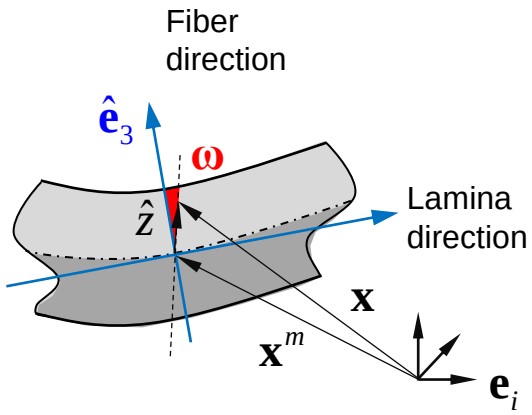
cross section straight, perpendicular and unstretched

Reisser-Mindlin [Timoshenko]

Mid-surface displacement plus rotations to describe plate (shell) deformation (shear deformation possible)



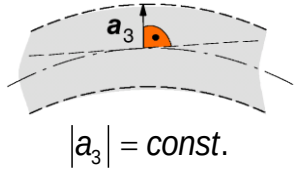
$$\mathbf{x} = \mathbf{x}^m + \hat{z}\,\hat{\mathbf{e}}_3 \times \boldsymbol{\omega}$$



Shell theories / Shell models

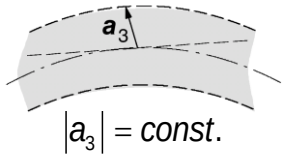
- **3-parameter shell model: Kirchhoff-Love**
  (cross section **straight** and unstretched,
  no shear deformations, i.e. normal to mid surface)

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



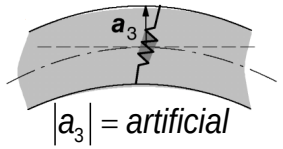
- **5-parameter shell model: Reissner-Mindlin**
  (cross section **straight** and unstretched,
  shear deformations possible)

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



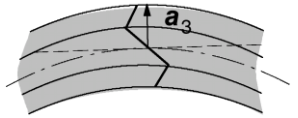
- **6- or 7-parameter shell model:**
  (cross section **straight** but stretchable)

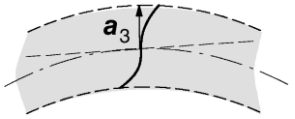
$$\sigma_{zz} \neq 0, \varepsilon_{zz} \neq 0$$
$$\gamma_{xz} \neq 0;\ \gamma_{yz} \neq 0$$



- **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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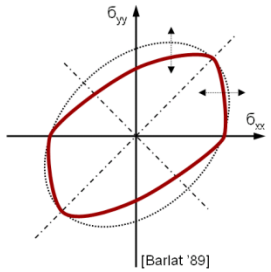
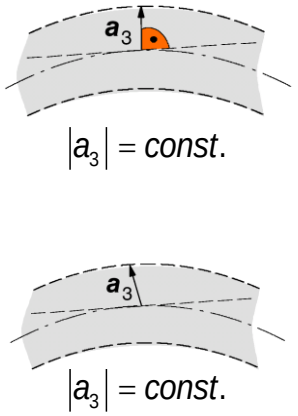
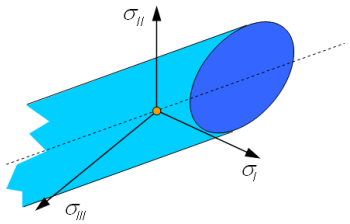
  (cross section **straight** but stretchable)

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

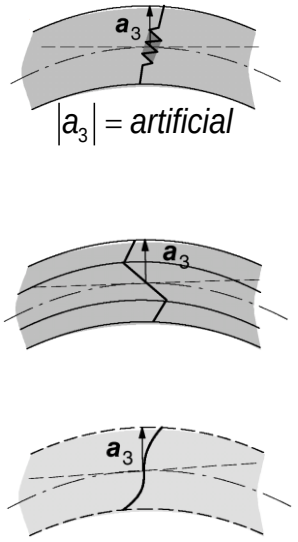


Reduced constitutive models
(2D *„plane stress“*)





Full 3D constitutive models



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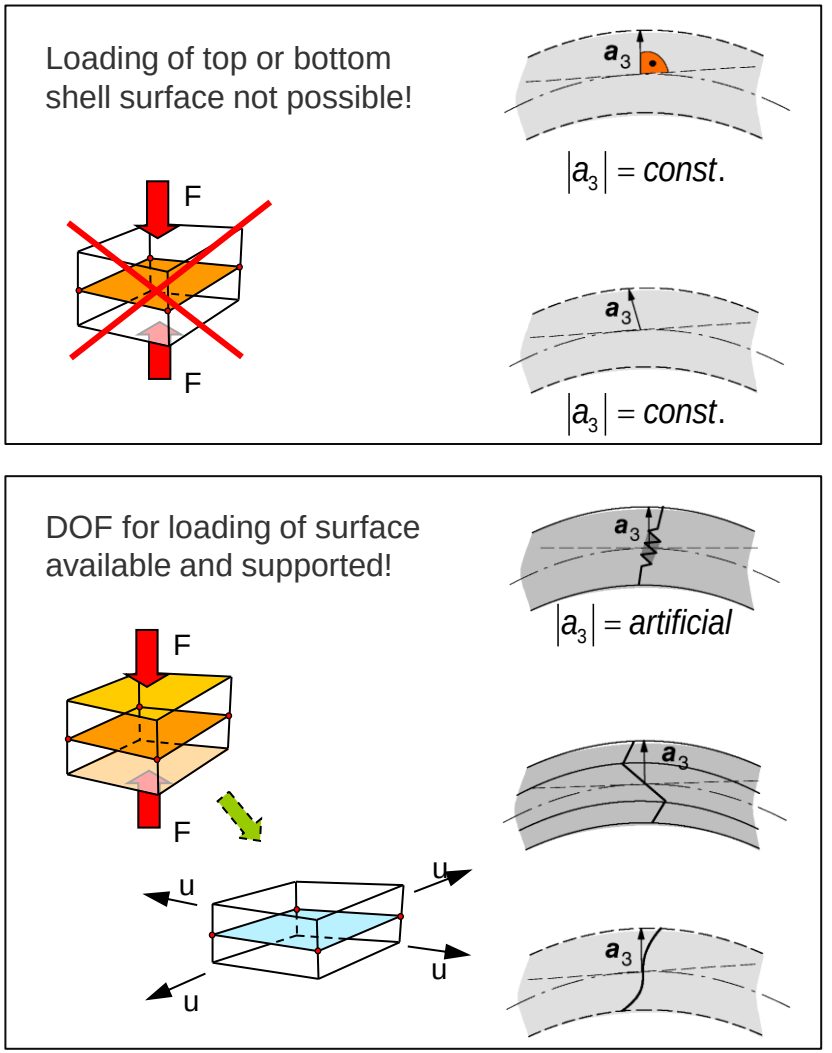
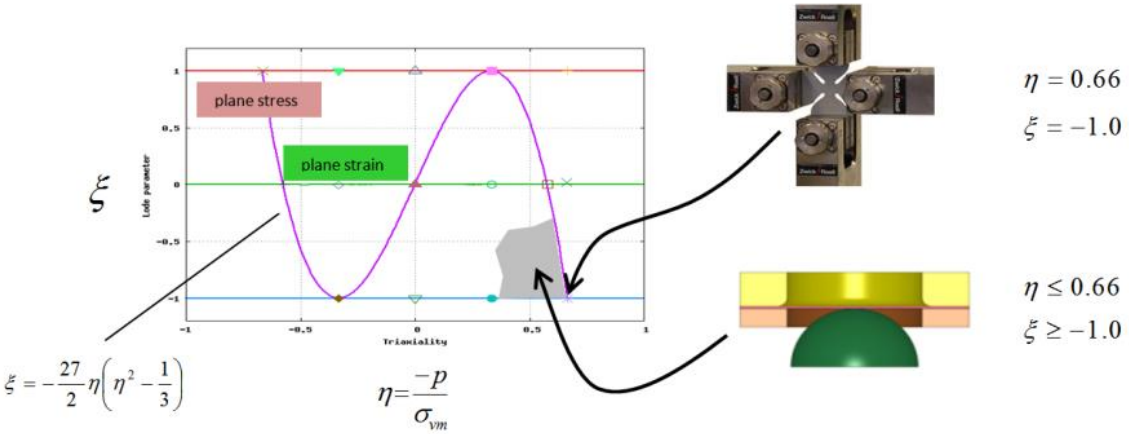
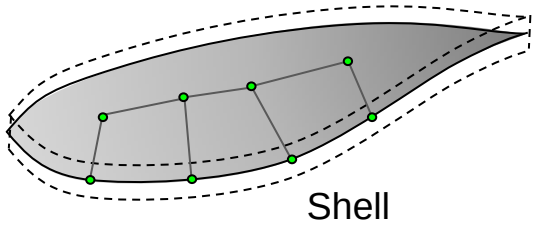


The effect of lateral loading?

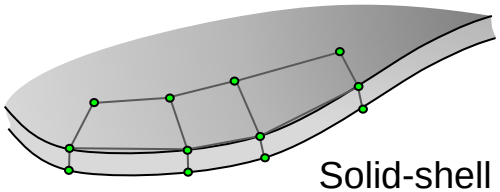


Where are the limits of classical shell models?

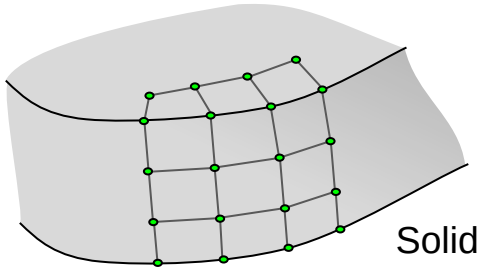
The issue of lateral loading



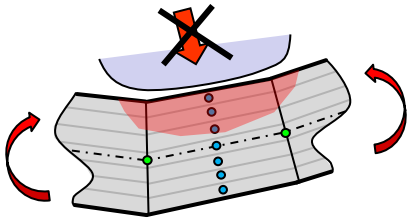
Shell

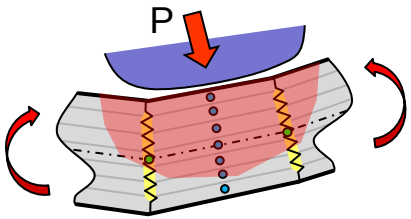


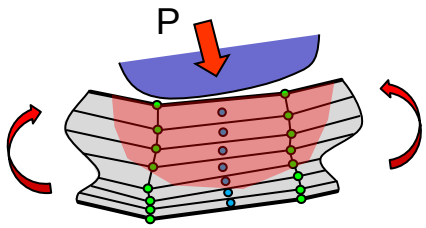
Solid-shell



Solid





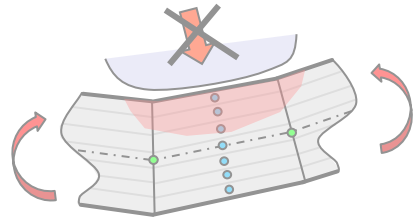


No lateral loading possible

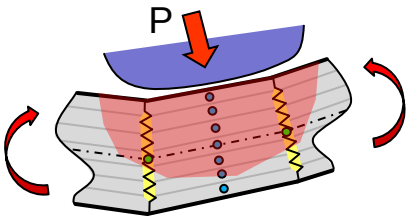
Lateral loading possible

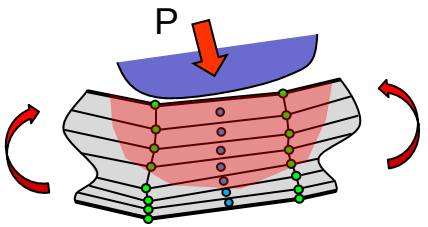
Where are the limits of classical shell models?

The issue of lateral loading



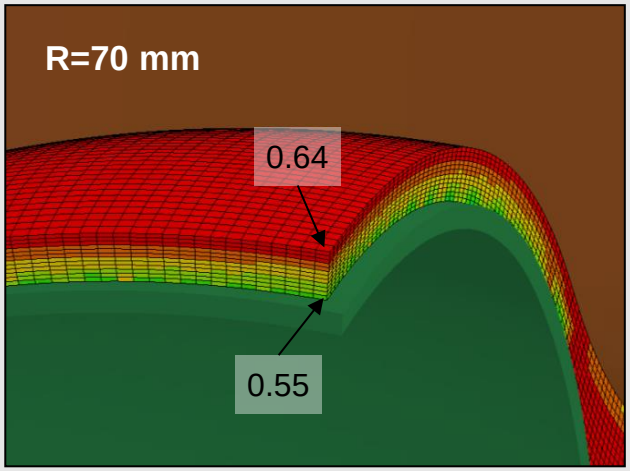
No lateral loading

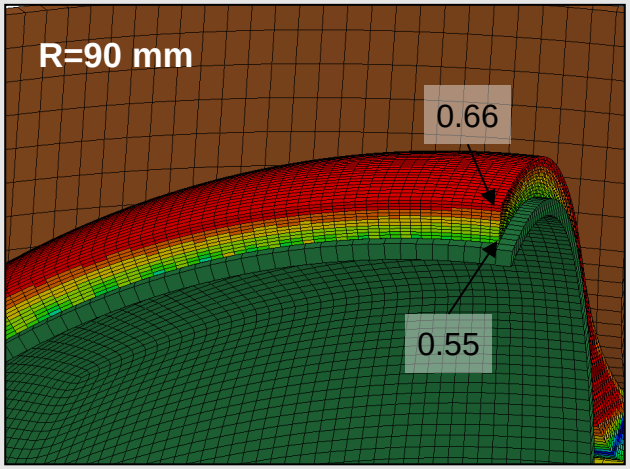


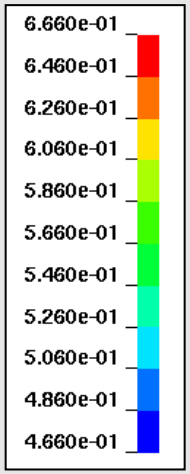


Lateral loading possible

Nakazima specimen: Triaxiality value from classical shell $\eta = 2/3$







A „trick“ to take lateral stresses into account

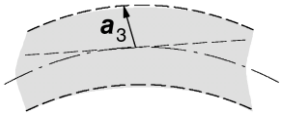
ELTYP=2/16 & IDOF=3

Development of IDOF=3 in shell type 2/16

[Th. Borvall, DYNAmore Nordic]

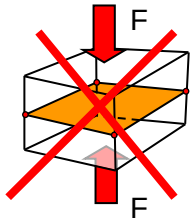
5-parameter shell: - No stresses in thickness direction

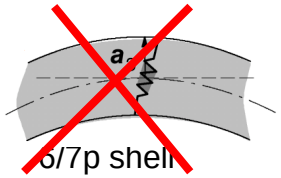
$\sigma_{zz} = 0, (\varepsilon_{zz} = 0)$ and $\gamma_{xz} \neq 0;\ \gamma_{yz} \neq 0$



5p shell

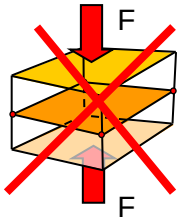
- No degree of freedom in thickness direction

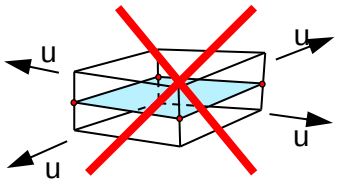




6/7p shell

- 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

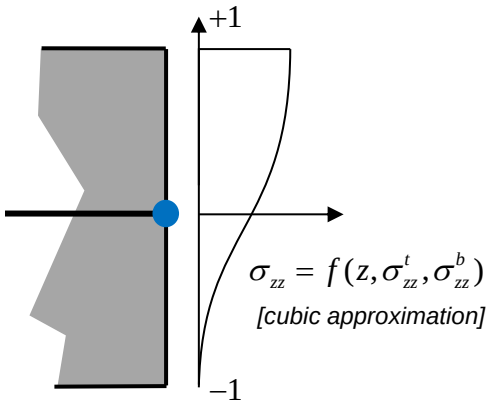
[Th. Borvall, DYNAmore Nordic]

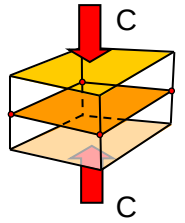
Take the contact pressure onto the shell surface (top/bottom) into account and modify the stress in the material model:

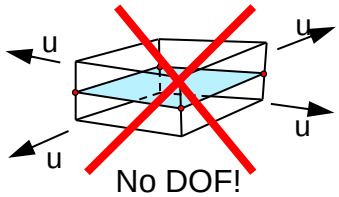
$$\sigma_{zz} = \alpha \sigma_c(z)$$ *[α = scaling parameter]*

where

$$\sigma_c(z) = -\frac{\sigma_c^b - \sigma_c^t}{4}(z^3 - 3z) - \frac{\sigma_c^b + \sigma_c^t}{2}$$







Constitutive update for J2 plasticity:

From: $\boldsymbol{\sigma}^n,\ \Delta\boldsymbol{\varepsilon}^n,\ \sigma_c^n, \sigma_c^{n+1}$

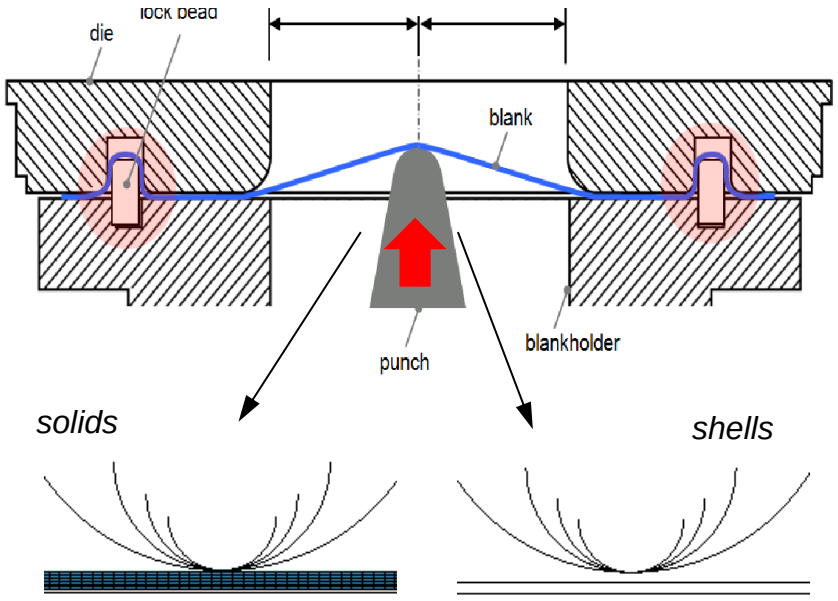
Modify: $\tilde{\boldsymbol{\sigma}}^n = \boldsymbol{\sigma}^n - \sigma_c^n \mathbf{I} \qquad \Delta\tilde{\boldsymbol{\varepsilon}} = \Delta\boldsymbol{\varepsilon} - \frac{\sigma_c^{n+1} - \sigma_c^n}{3K}\mathbf{I}$

Update: $\tilde{\boldsymbol{\sigma}}^{n+1}$ *and* $\Delta\tilde{\boldsymbol{\varepsilon}}^{n+1}$

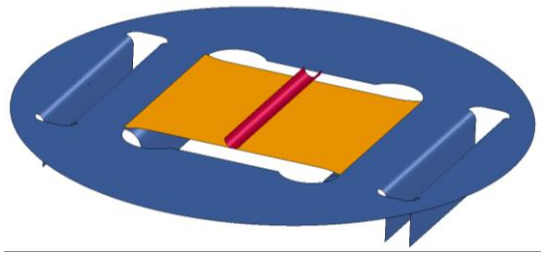
Solve for: $\tilde{\boldsymbol{\sigma}}^{n+1} = \boldsymbol{\sigma}^{n+1} - \sigma_c^{n+1}\mathbf{I} \qquad \Delta\tilde{\boldsymbol{\varepsilon}} = \Delta\boldsymbol{\varepsilon} - \frac{\sigma_c^{n+1} - \sigma_c^n}{3K}\mathbf{I}$

Stretch bending test: Effect of IDOF=3 in shell type 2/16

[Funding by RFCS greatly acknowledged]

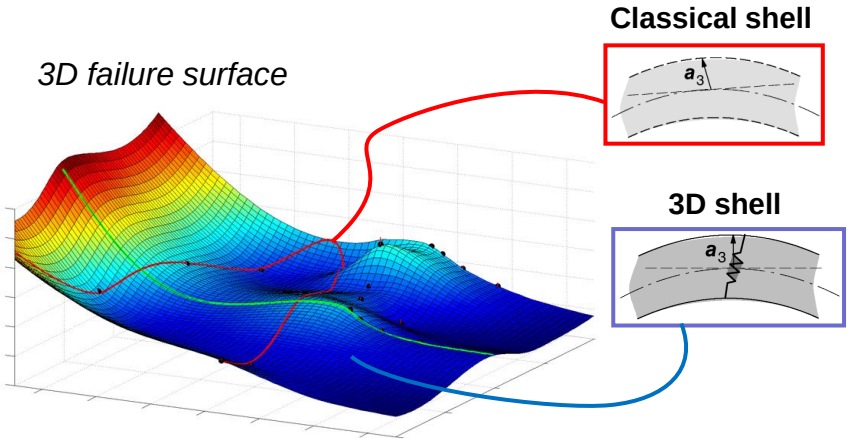


Element Type	Shells	Solids
Element formulation	2 / 16 / 25 / 26	-1 / -2
Number of integration points over thickness	6	1
Number of elements across thickness direction	1	6
Element edge length	0,25mm	0,25mm
Selective mass scaling	✓	✓
Number of integration points that should fail before element fails	5	1



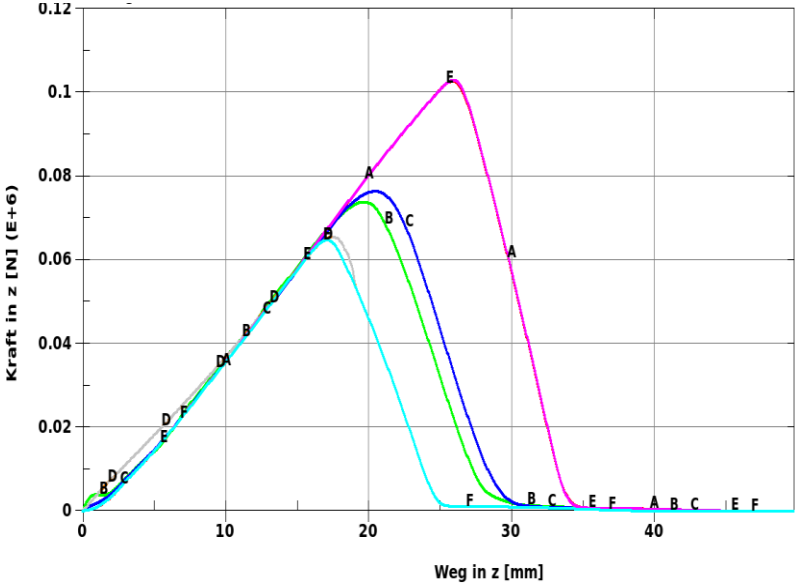
Different radii r05/r07/r10/r20 in shells and solids

3D failure surface

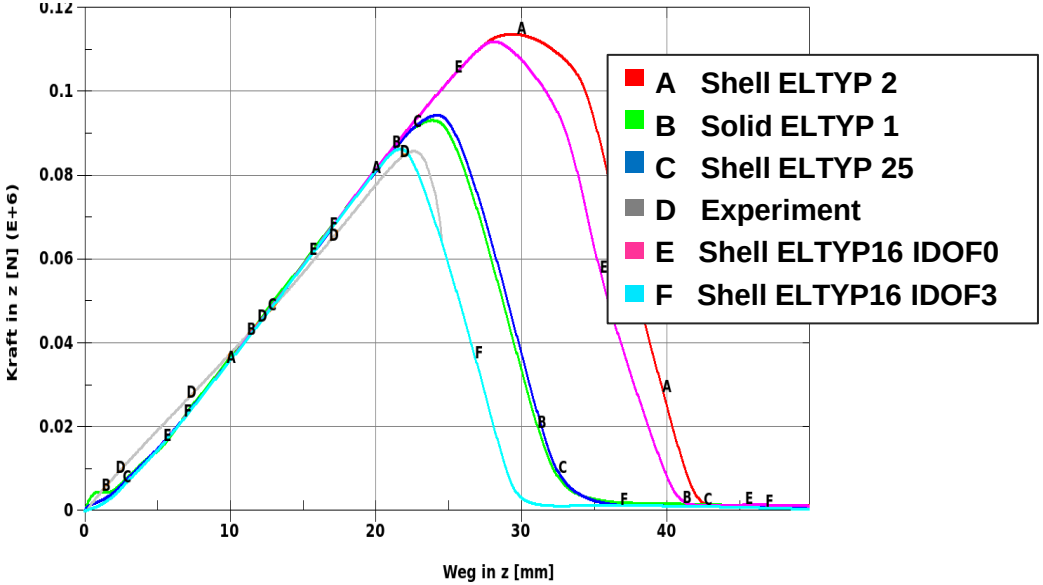


Stretch bending: CP800 and R05 / R10

CP800 and R05



CP800 and R10



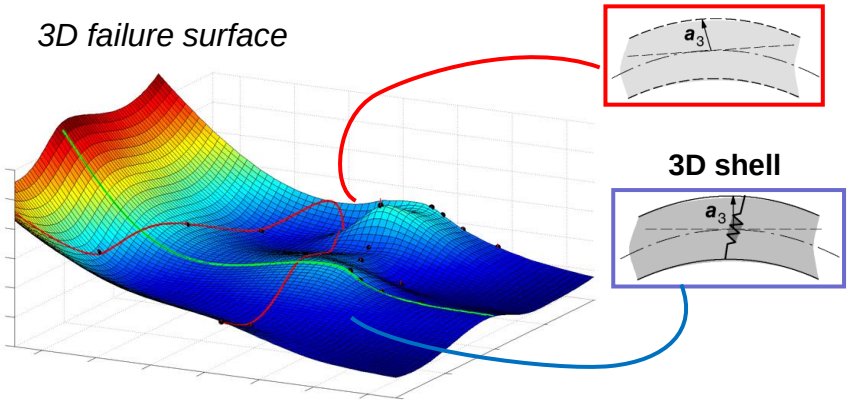
Failure data has been calibrated for plane stress states using DIEM, TYP=1 shear failure model:

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

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

Cyan curve is ELTYP=16 (5parameter shell) with IDOF=3 and shear criteria!

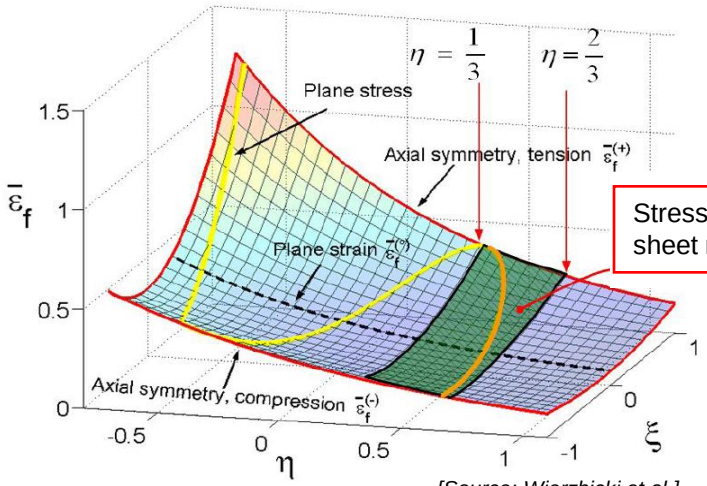
3D failure surface



A reminder:
Failure modelling (with any model)
depends on stress state

GISSMO

Failure criterion in planes stress and 3D stress states



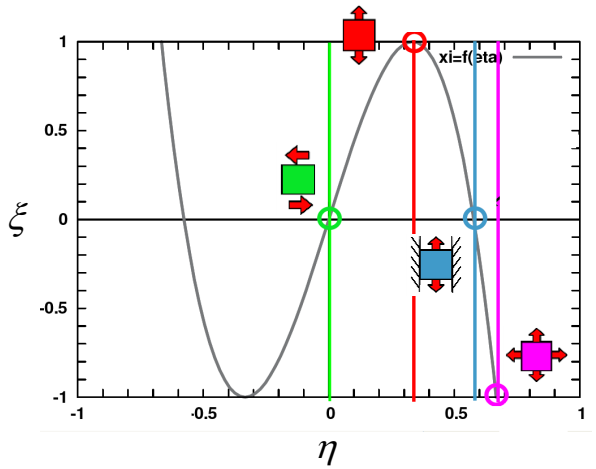
Stress domain in sheet metal forming

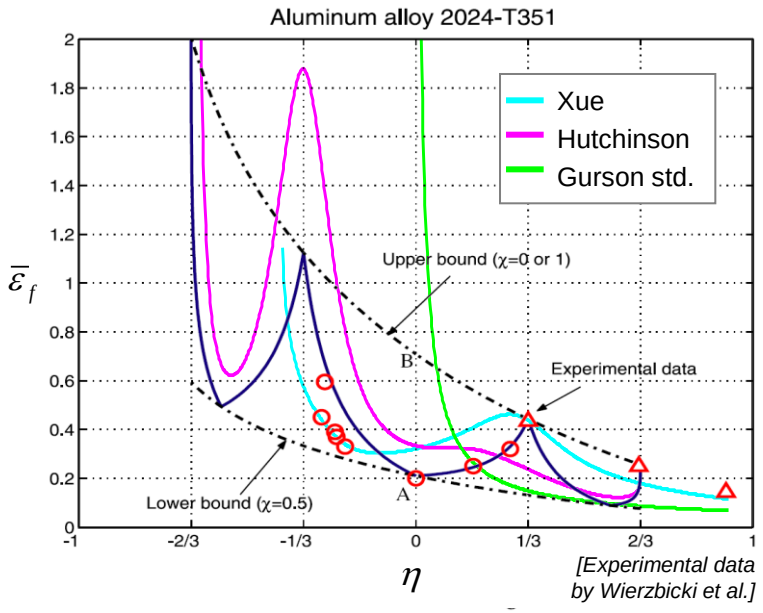
[Source: Wierzbicki et al.]

Parameter definition

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

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





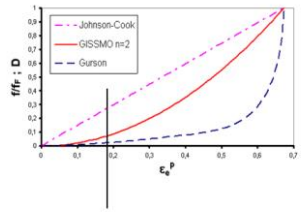
[Experimental data by Wierzbicki et al.]

GISSMO – short overview

GISSMO - Generalized Incremental Stress State dependent damage MOdel

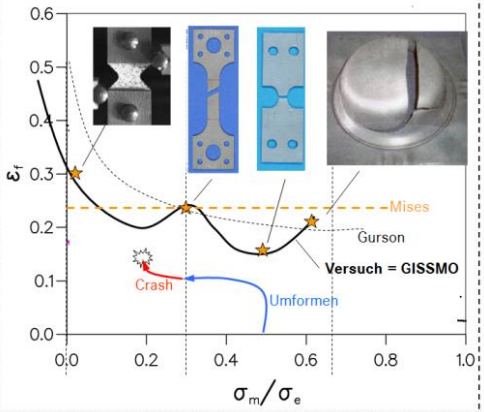
Schädigungsevolution

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

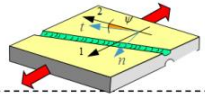


Schädigung nach Tiefziehprozess zu hoch bei linearer Akkumulation!

Versagenskurve

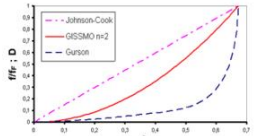


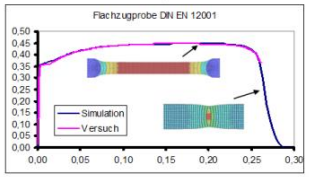
GISSMO Instabilität



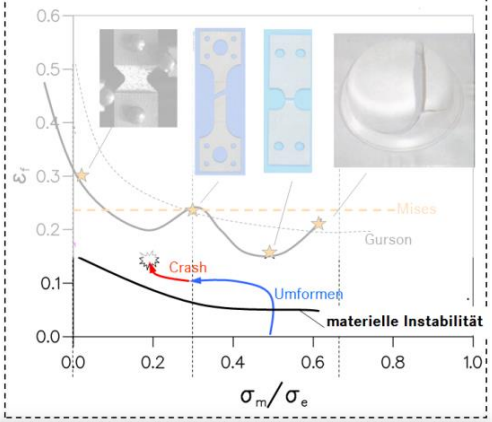
Evolution der Instabilität

$$\Delta F = \frac{n}{\varepsilon_{v,loc}} F^{\left(1-\frac{1}{n}\right)} \Delta\varepsilon_v$$





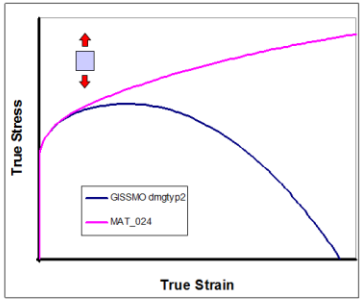
Materielle Instabilitätskurve



GISSMO Effective Stress Concept

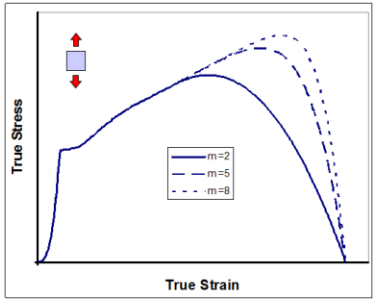
DGTYP: Flag für Rückkoppelung nach Lemaitre:

$$\sigma^* = \sigma\left(1-D\right)$$

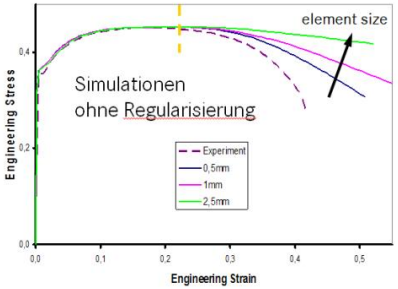


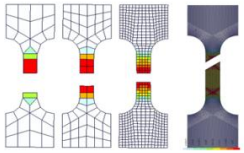
DCRIT, FADEXP: Postkritisches Verhalten:

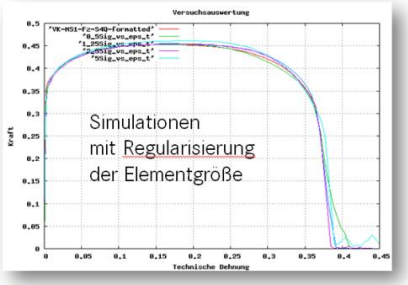
$$\sigma^* = \sigma\left(1-\left(\frac{D-D_{CRIT}}{1-D_{CRIT}}\right)^{FADEXP}\right)$$



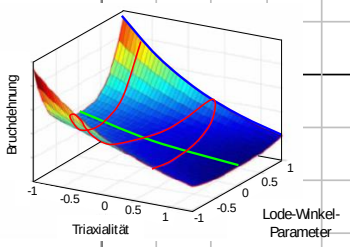
GISSMO Regularisierung der Netzabhängigkeit (Zugversuch)







Experiments for full 3D calibration of GISSMO



Lode-angle parameter

Round specimen:
R4mm, R2mm, R1mm, R0.5mm

Flat specimen:
glatt, R2mm, R4mm

Butterfly coupons

Plane strain specimen:
R4mm, R2mm, R1mm, R0.5mm

Plane strain

Plane stress

Nakazima

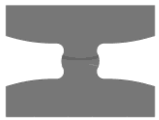
Triaxiality

1
0.5
0
-0.5
-1
-1
-0.5
0
0.5
1
1.5
2

Round tension

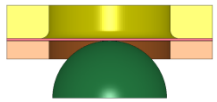
Flat tension

Butterfly



Plane strain test

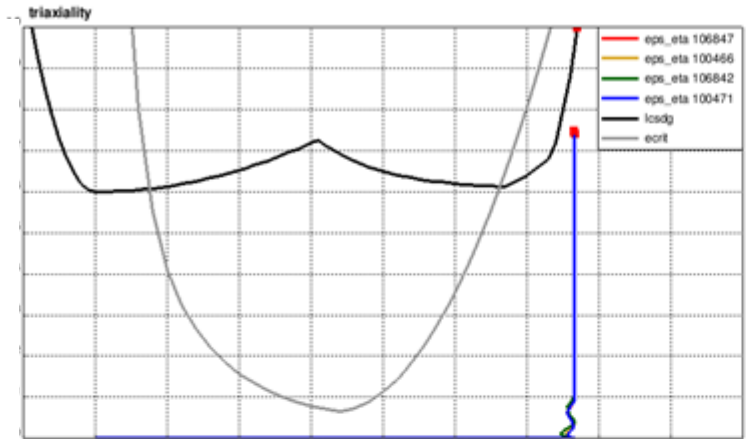
Nakazima

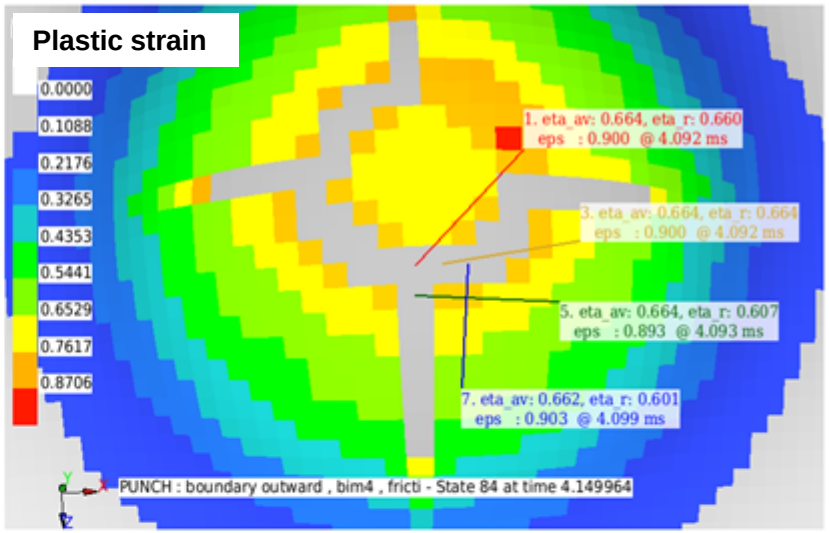


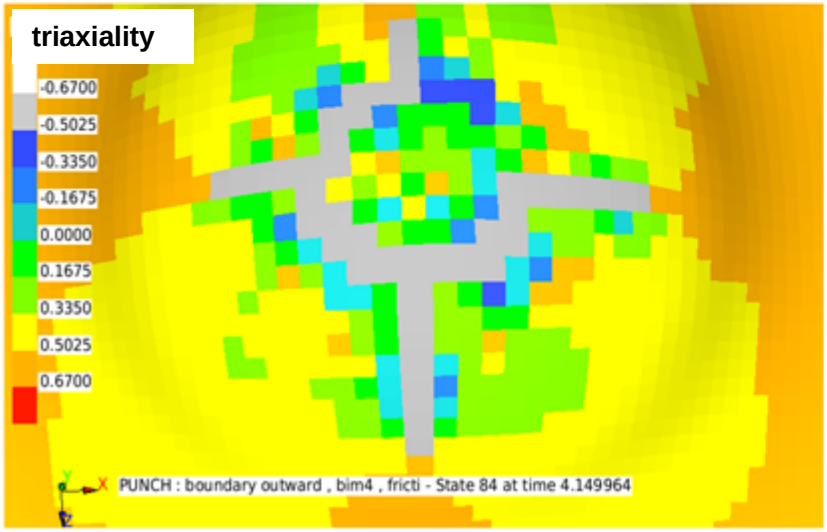
More on this lateral effects in shells and IDOF3…

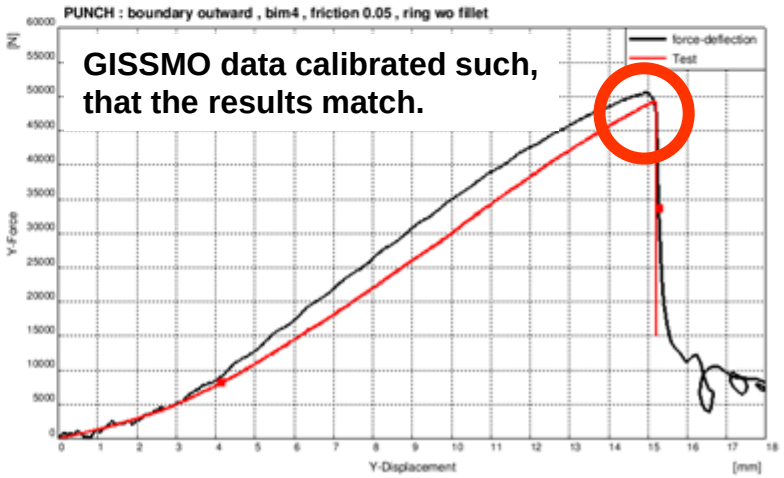
The limits of classical shell models

Nakazima with ELTYP16 elements with IDOF=1



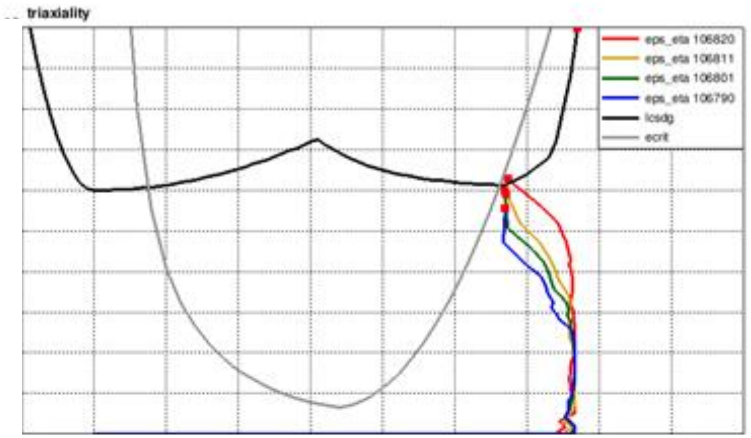


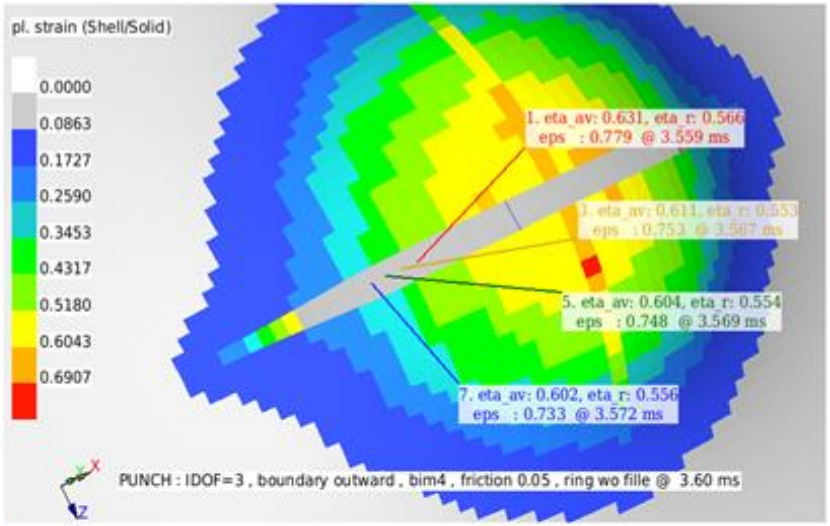


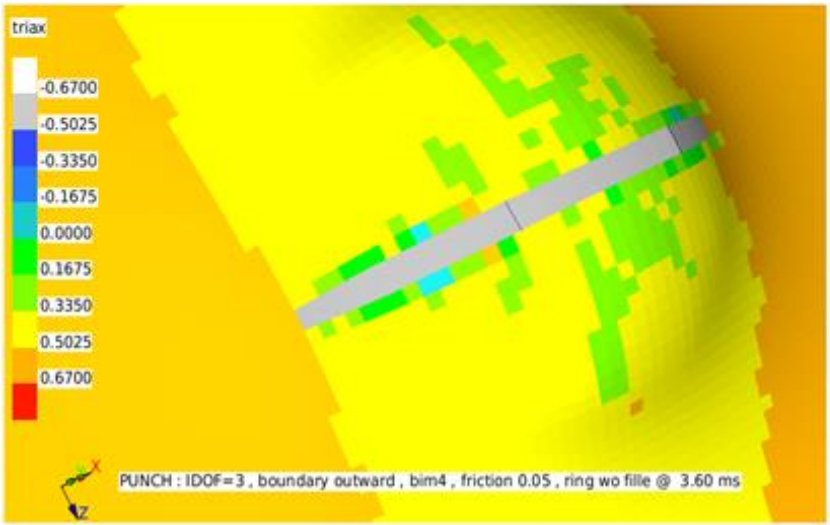


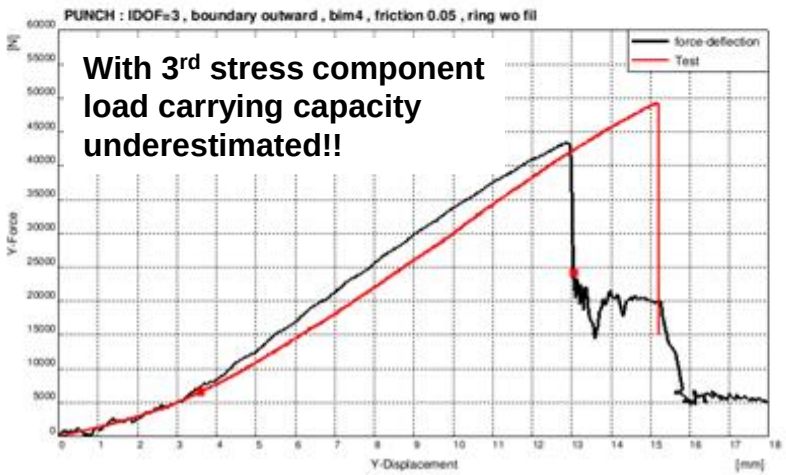
The limits of classical shell models

Nakazima with ELTYP16 elements with IDOF=3







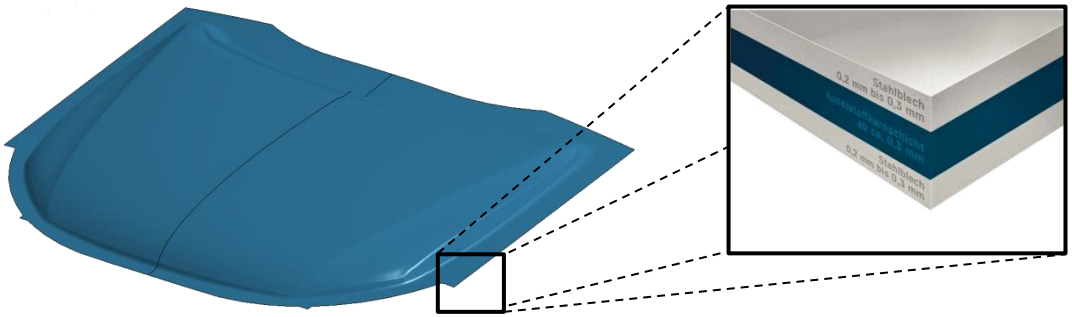


Plane sections remain plane!

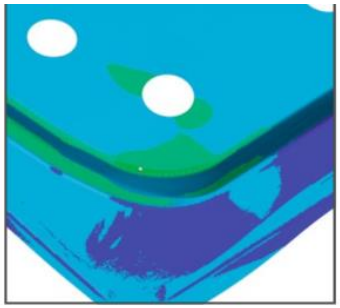
(the zero radius requirement)

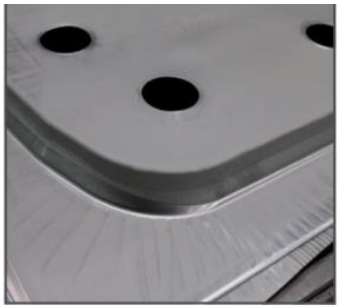
The limits of classical shell models

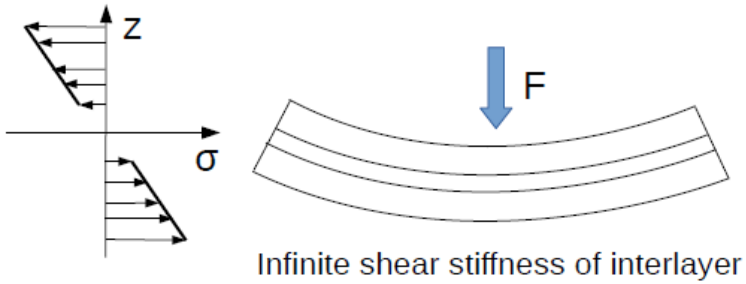
No plane sections: Most obvious in sandwich structures

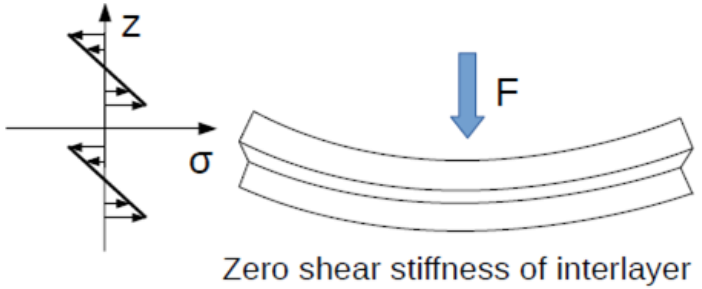


Modelling with one layer of shells obviously not sufficient!









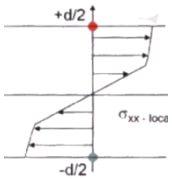
Limits of shell elements in bending

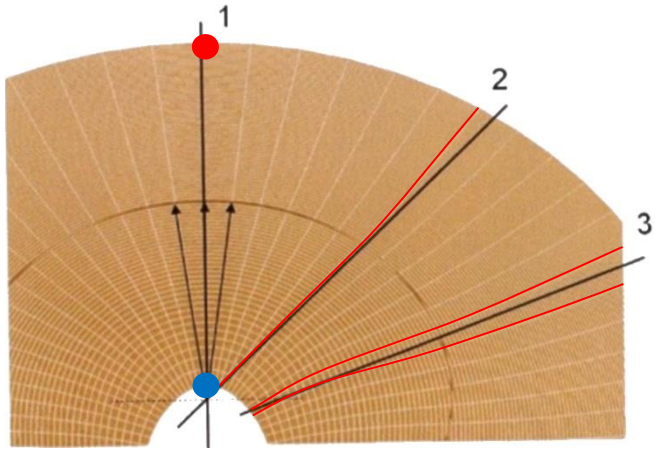
[Dissertation Michael Fleischer]

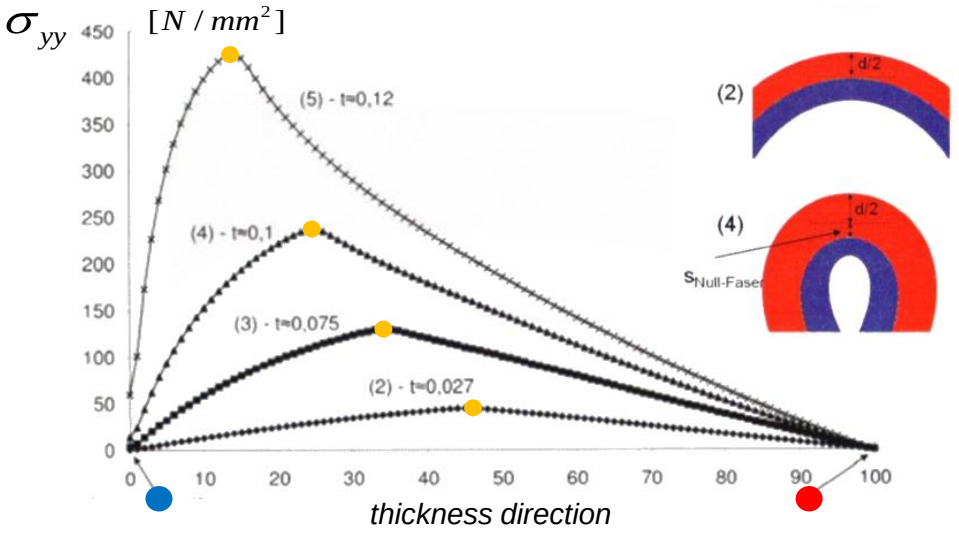
Virtual ring-tension test

$$R_{M,RZ} = 5mm,\ d = 1.0mm,\ l_c = 1mm$$

Fine discretization with solid elements:
Possible violation of Bernoulli hypothesis (straight sections remain straight)







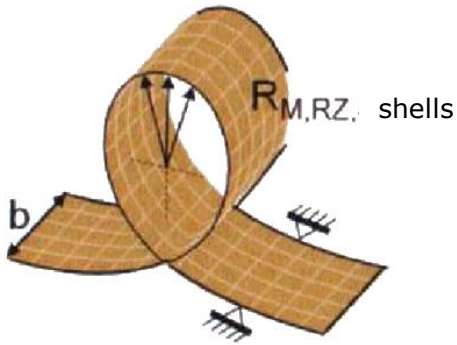
Limits of shell elements in bending

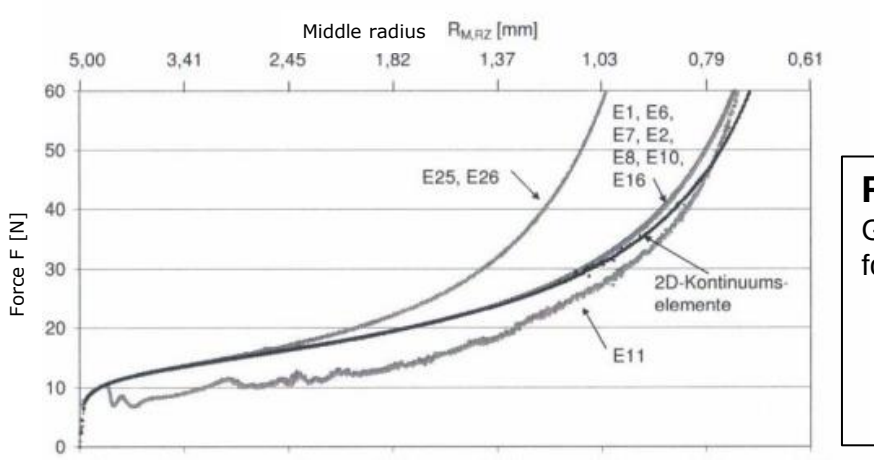
[Dissertation Michael Fleischer]

Virtual ring-tension test

$$R_{M,RZ} = 5mm,\ d = 1.0mm,\ l_c = 1mm$$

Discretization with different shell formulations:
Possible violation of Bernoulli hypothesis (straight sections remain straight)



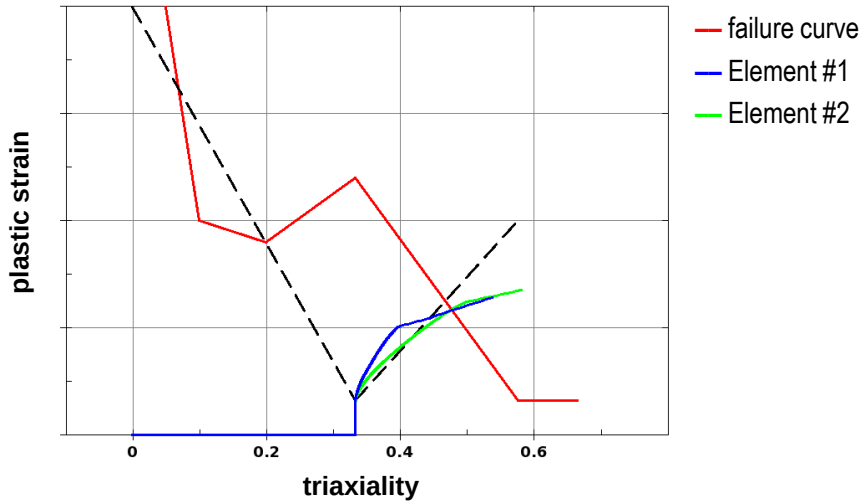


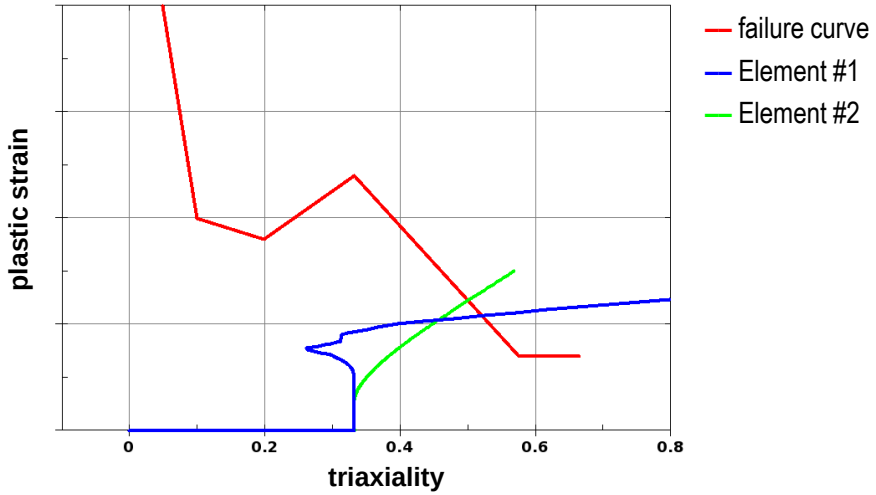
Recommendation:
Geometrical limit (justified by force & deformation)

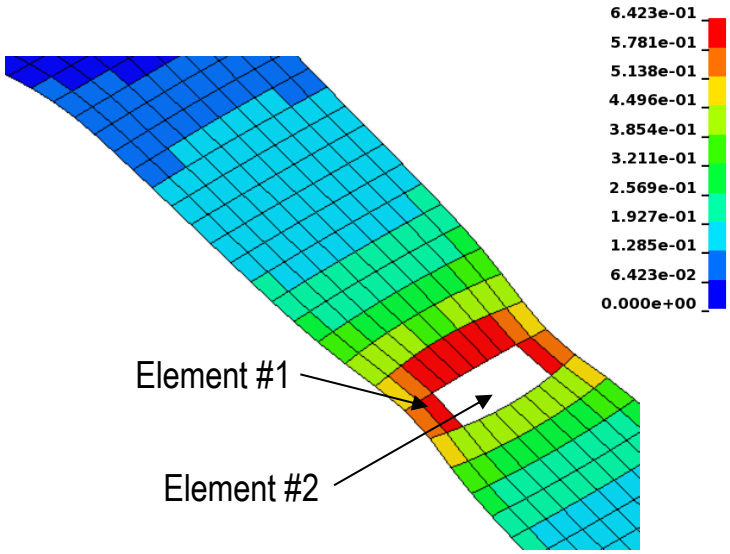
$$\frac{R_{M,RZ}}{d} \geq 1$$

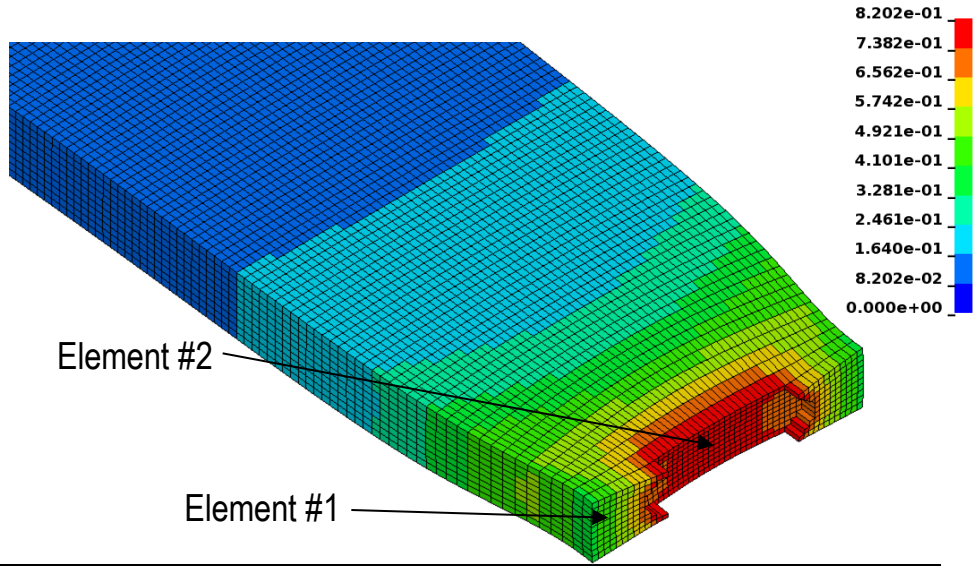
Shell vs. solid: tension test

Comparison of a finite element model with small volume elements



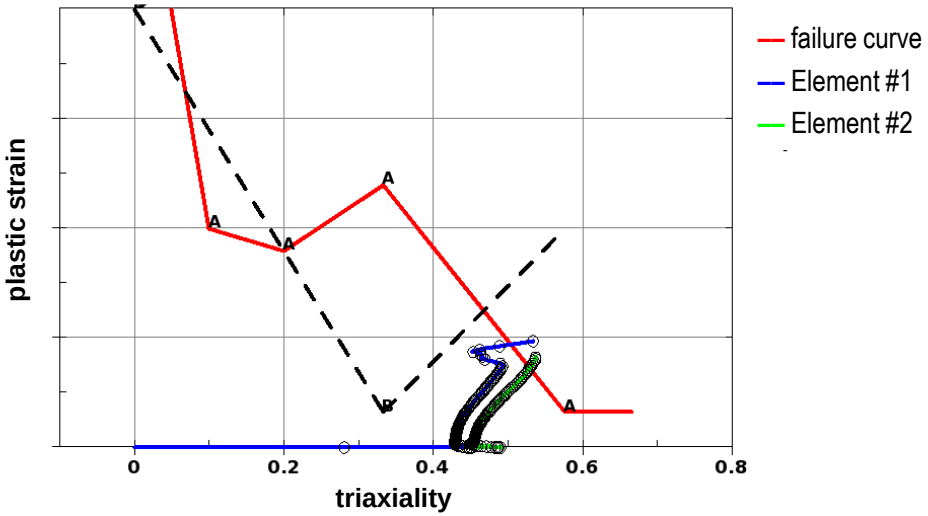


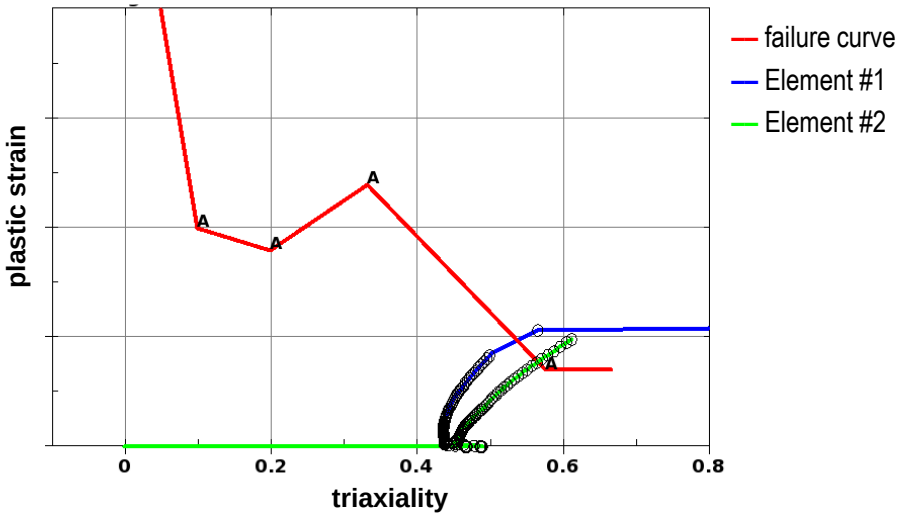


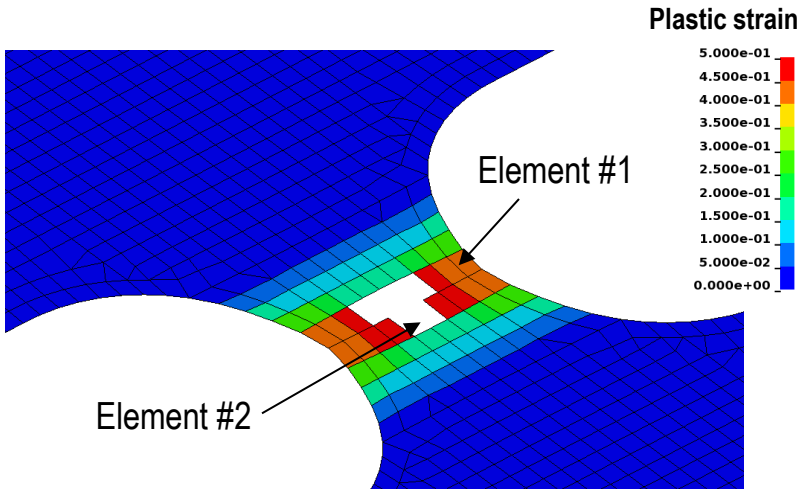


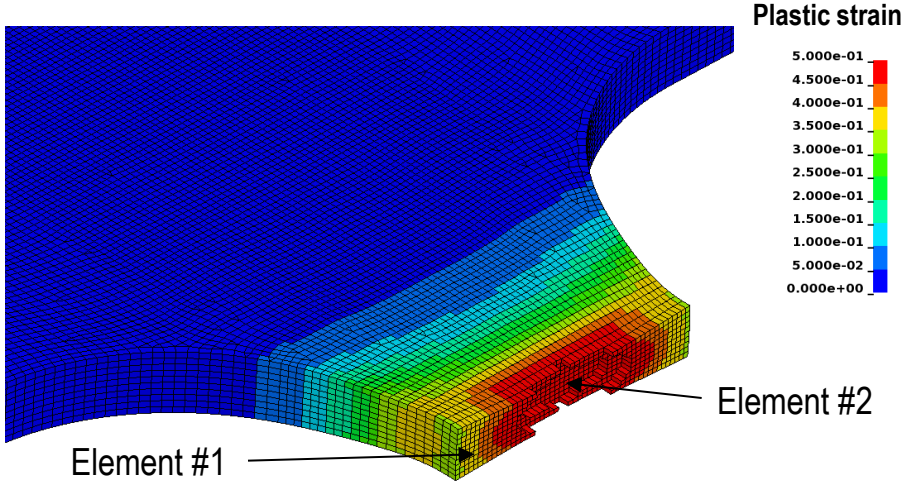
Shell vs. solid: Plane strain test

Comparison of a finite element model with small volume elements



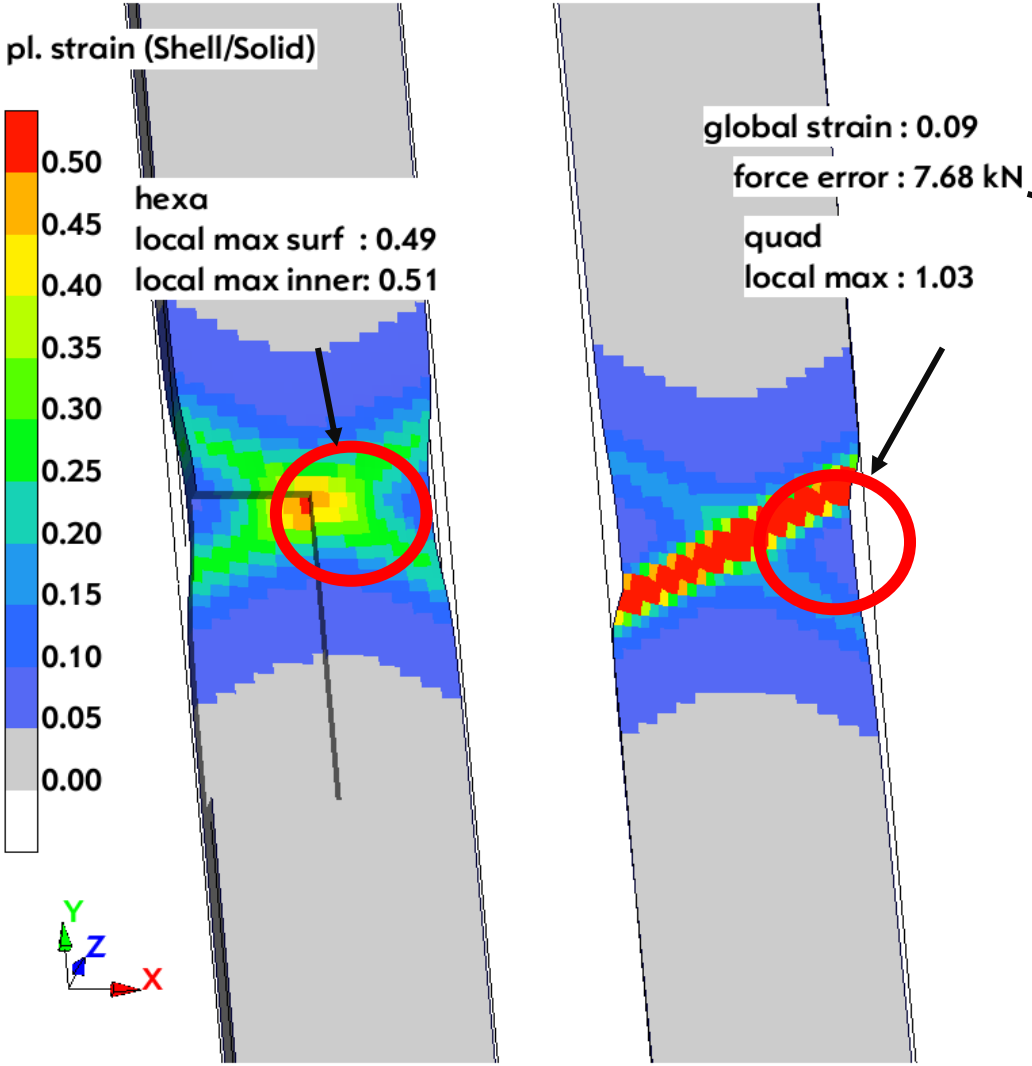


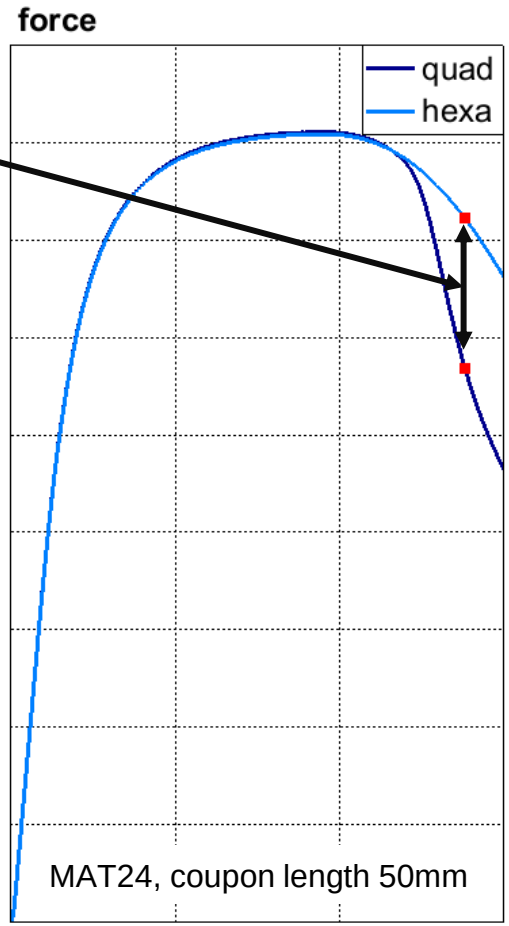




The limits of shell models

Plane vs. non plane section (i.e. solids vs. shell)

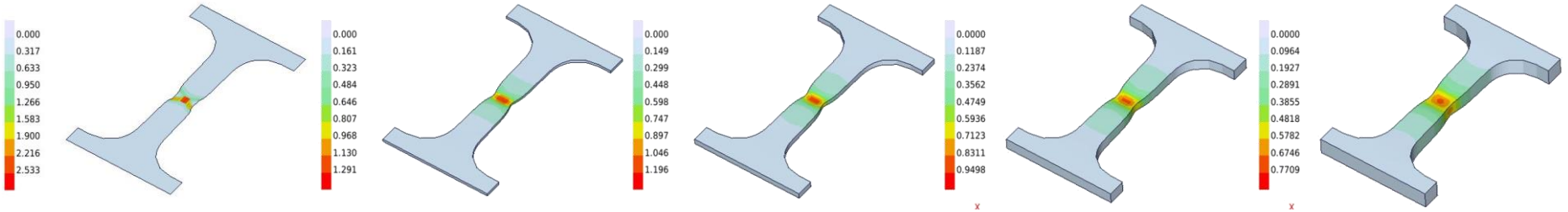




The limits of classical shell models

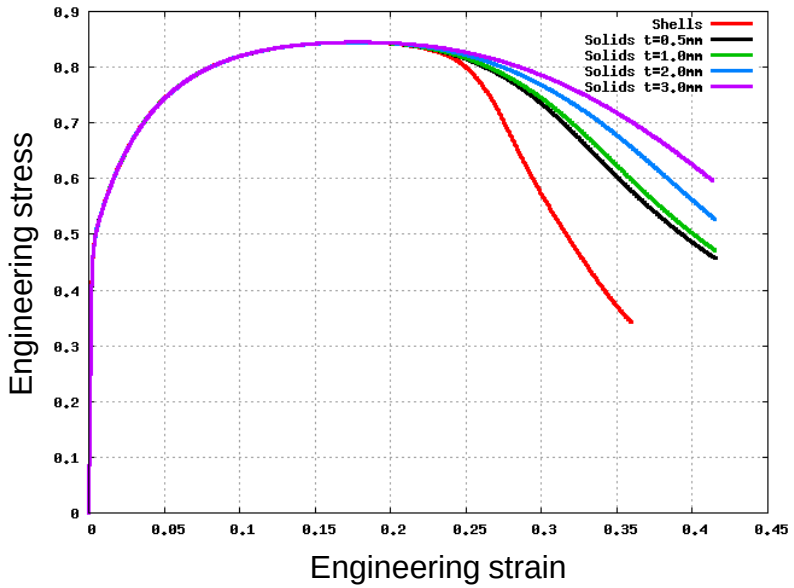
No plane sections: mini tension test coupon with MAT_24

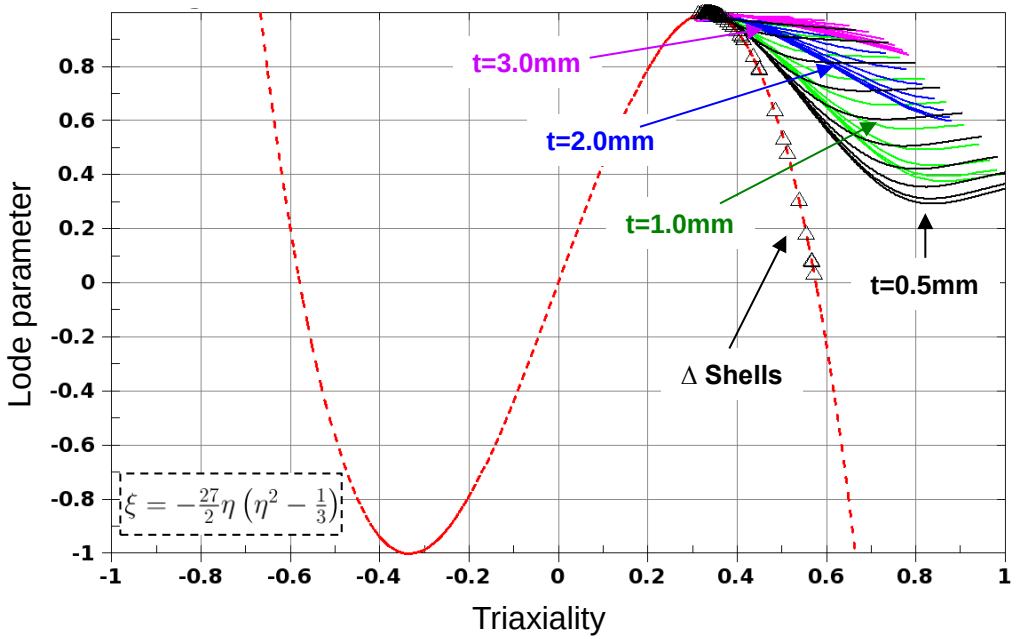
Shells t=1.0mm *Solids t=0.5mm* *Solids t=1.0mm* *Solids t=2.0mm* *Solids t=3.0mm*



[etyp=16]

Contours of plastic strain
Le=0.125mm

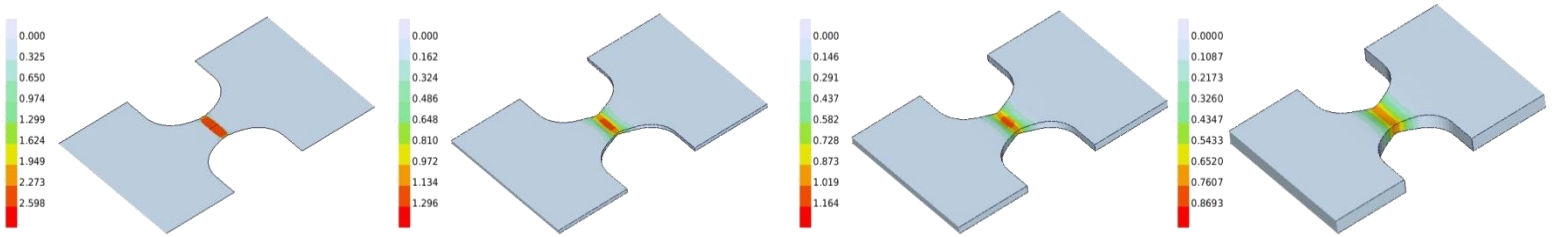




The limits of classical shell models

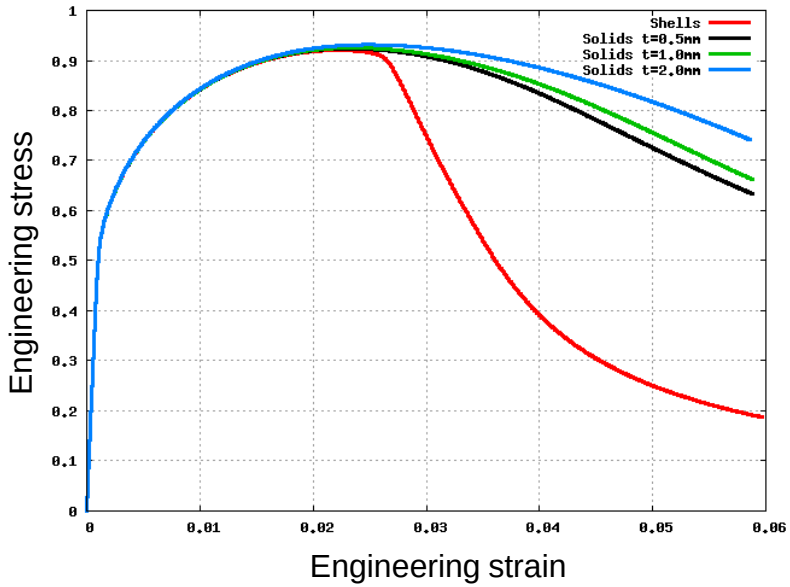
No plane sections: notched tension R4 coupon with MAT_24

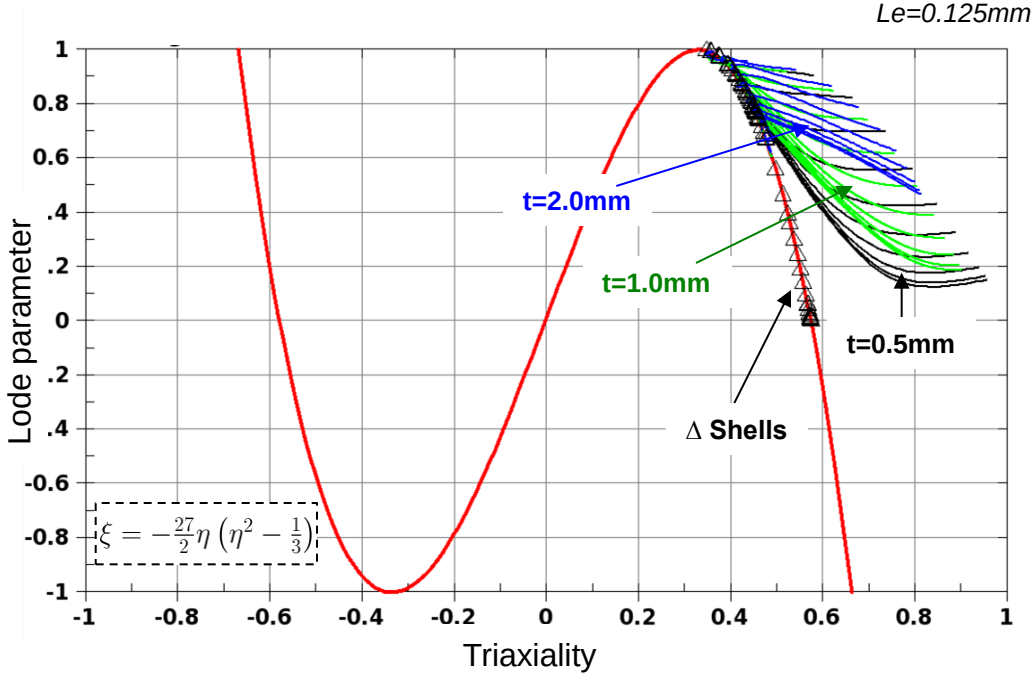
Shells t=1.0mm *Solids t=0.5mm* *Solids t=1.0mm* *Solids t=2.0mm*



[etyp=16]

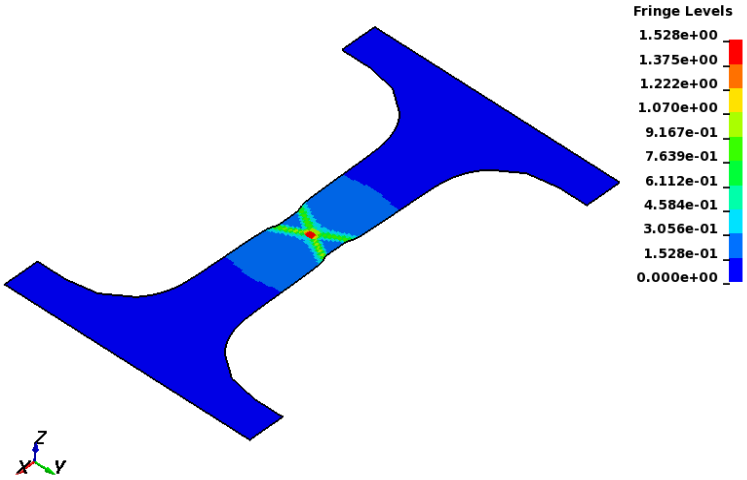
Contours of plastic strain
Le=0.125mm





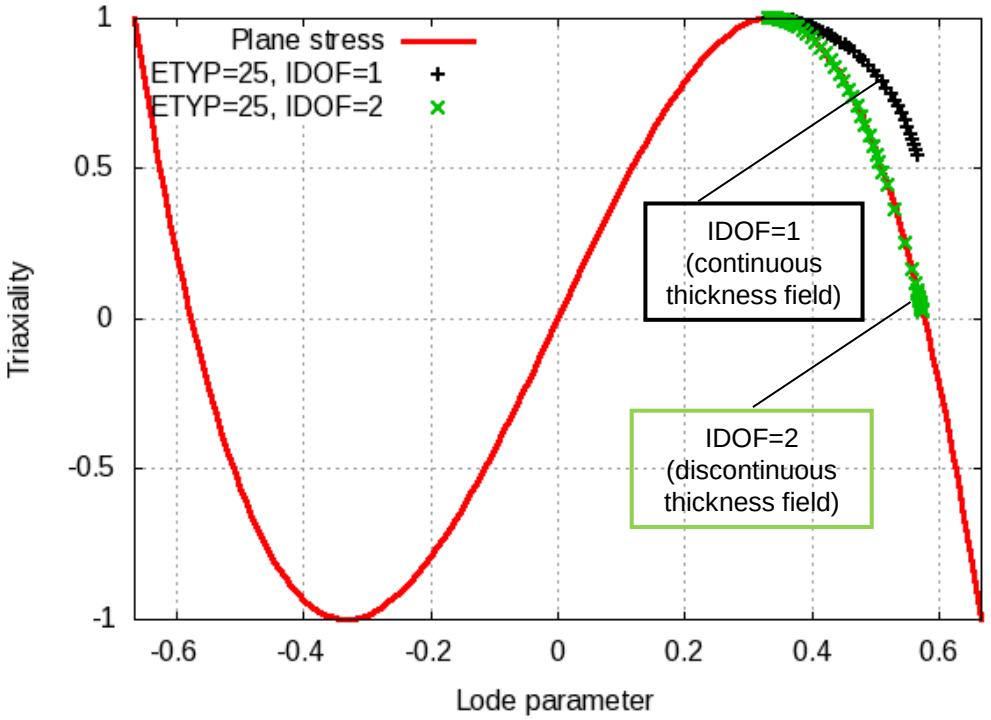
The limits of shell models

Effect of 7p-shell (thin-thick, ETYP25, IDOF=1/2, MAT_24)

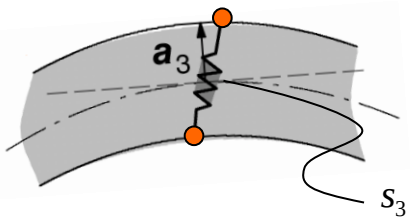


Plane stress condition is of course conserved with ETYP=25/IDOF=2 when simulating the tensile test.

Plane sections remain plane!



Remember:

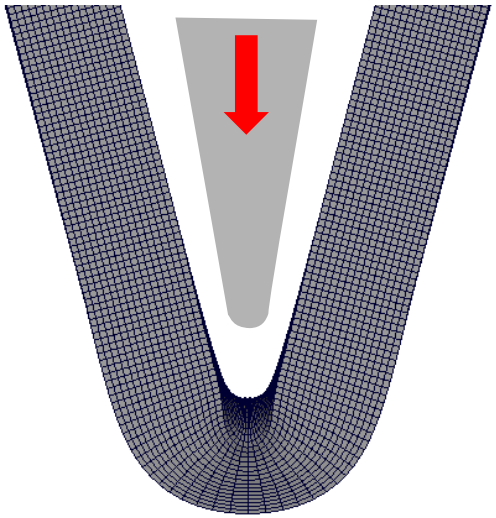


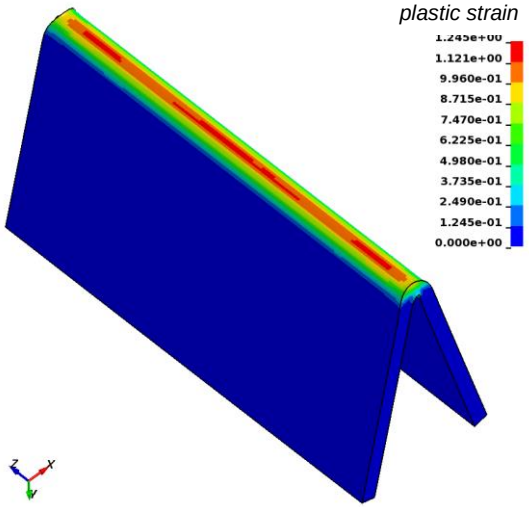
$$s_3 = \frac{\xi_3}{2} t_3 + (1 - \xi_3^2) q_3$$

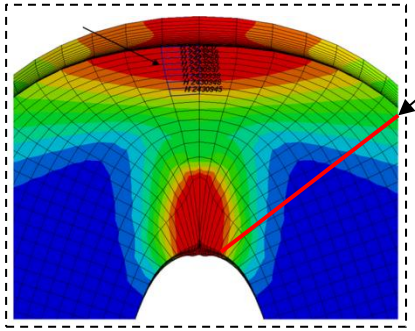
Stress states in bending

Bending test: base line with solids

Simulation with solids (Le = 0.125mm, ETYP=2, MAT_24)



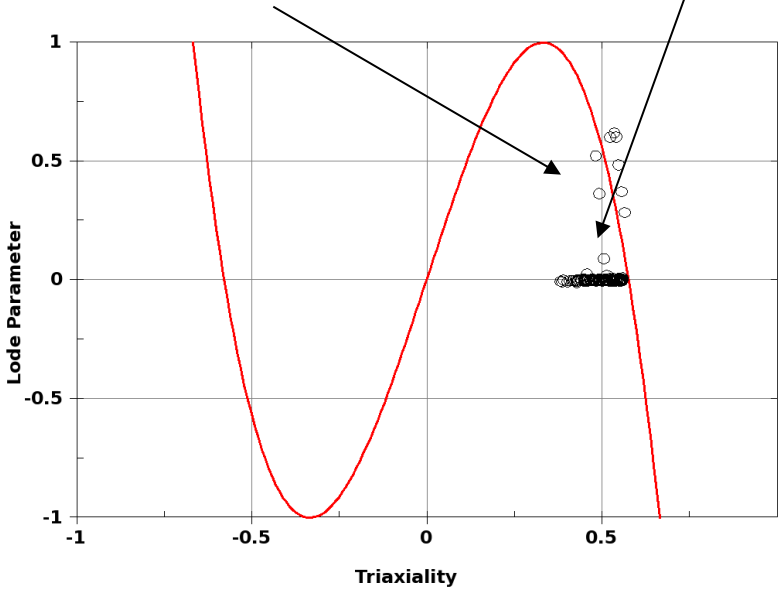




No plane section!

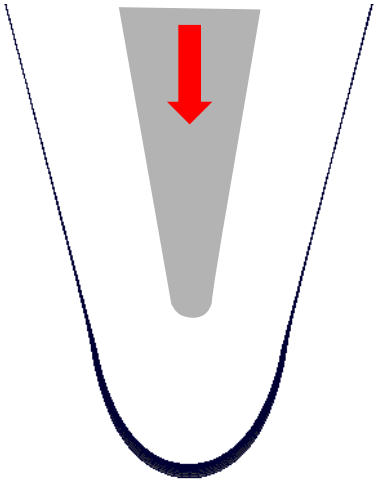
Only the elements under tension were considered

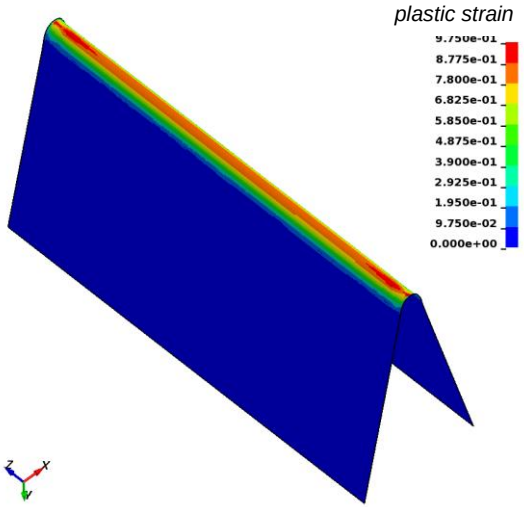
The predominant stress state when working with solids is around Lode parameter “zero”



Bending test

Simulation with shells (Le = 0.125mm, ETYP=2, IDOF=0, MAT_24)

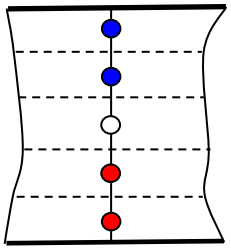




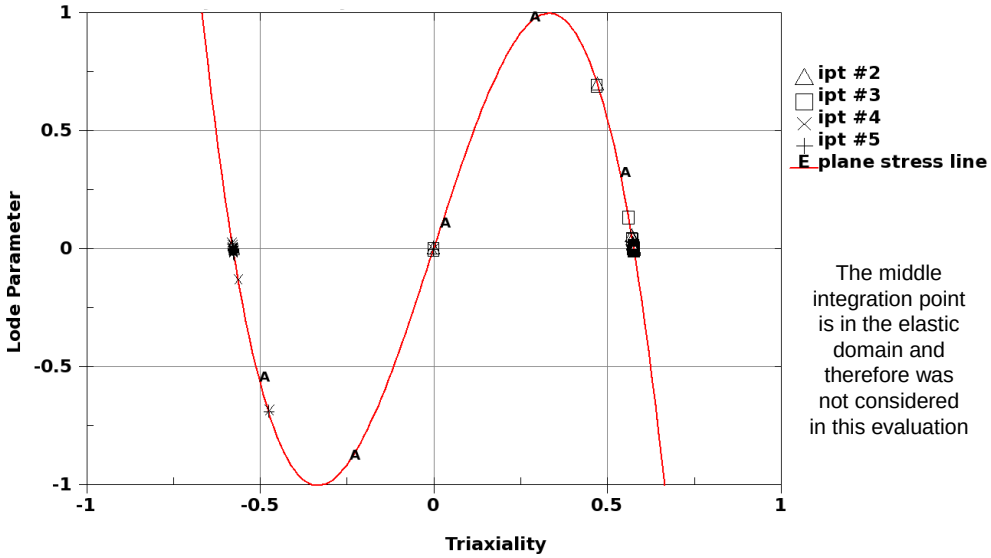
compression

neutral

tension



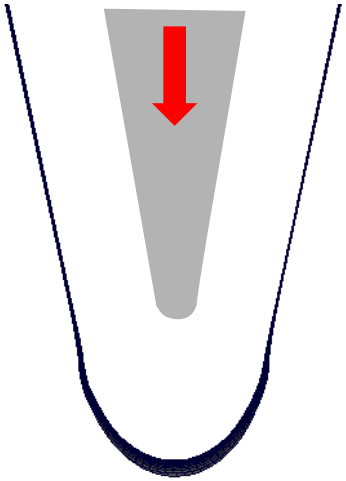
All points are laying on the plane stress line

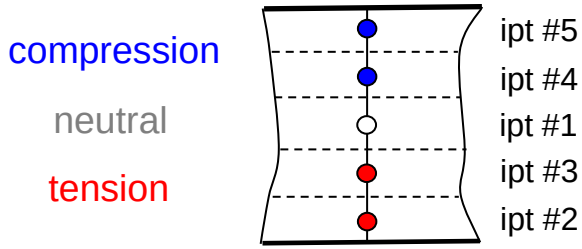


The middle integration point is in the elastic domain and therefore was not considered in this evaluation

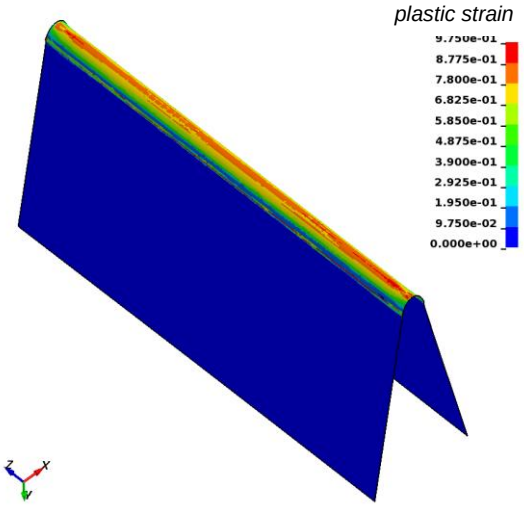
Bending test

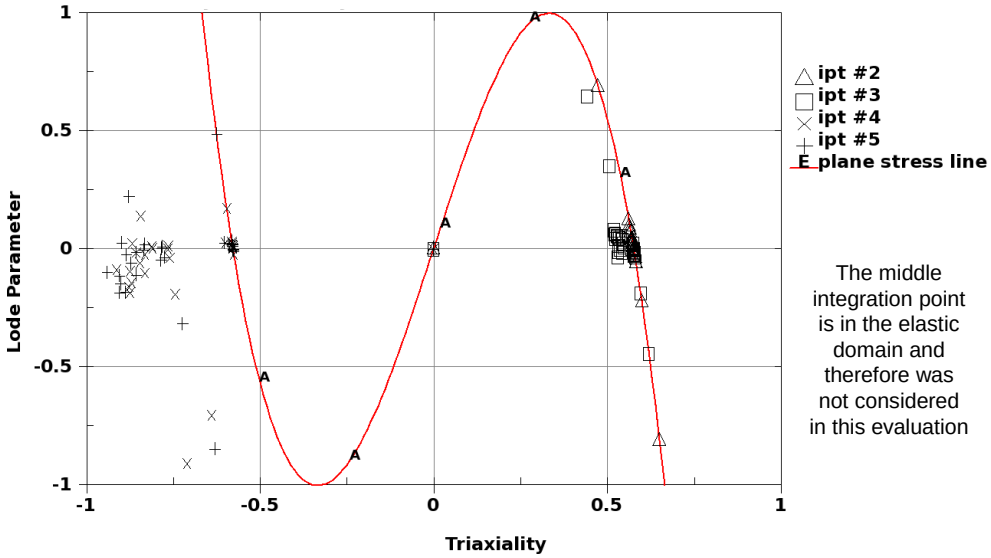
Simulation with shells (Le = 0.125mm, ETYP=2, IDOF=3, MAT_24)





Some points deviate from the plane stress line

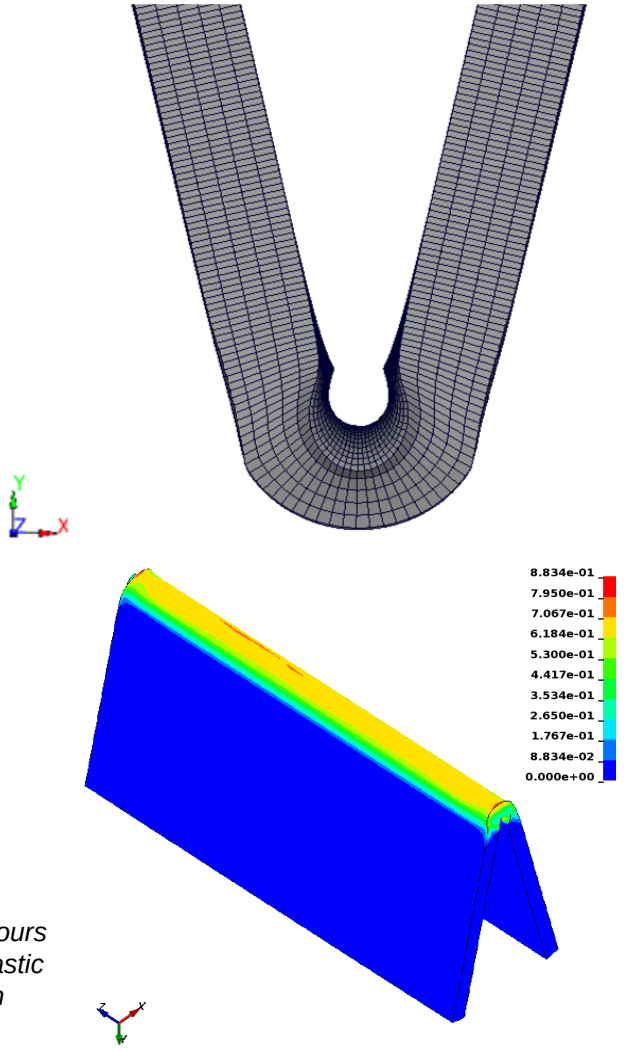




The middle integration point is in the elastic domain and therefore was not considered in this evaluation

Bending test

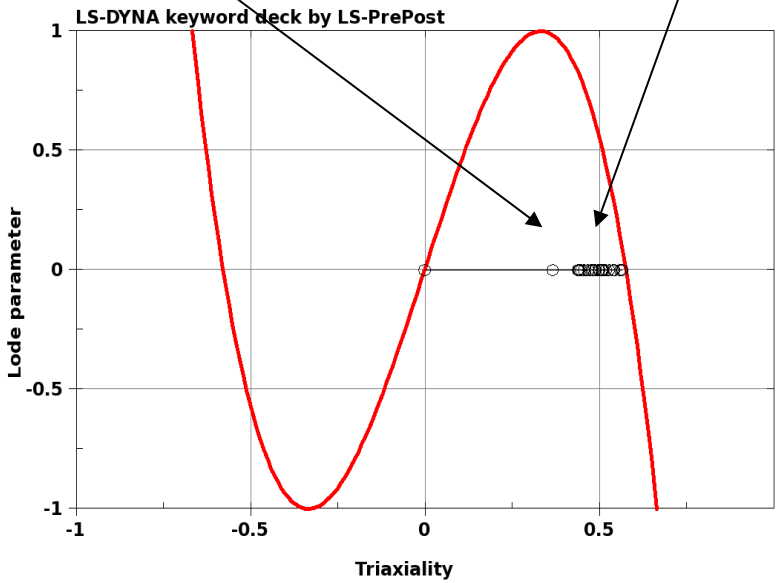
Simulation with Thick-Shells (Le = 0.125mm, ETYP=5, NIP=3)



Contours of plastic strain

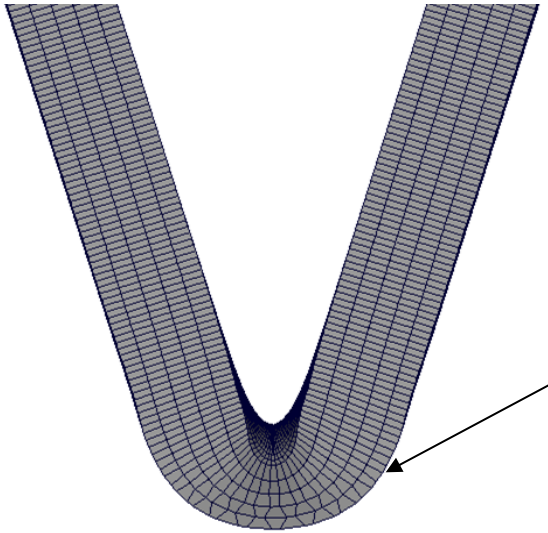
An element on the surface under tension was considered

Similar stress state than when working with solids, i.e., Lode parameter is around “zero”

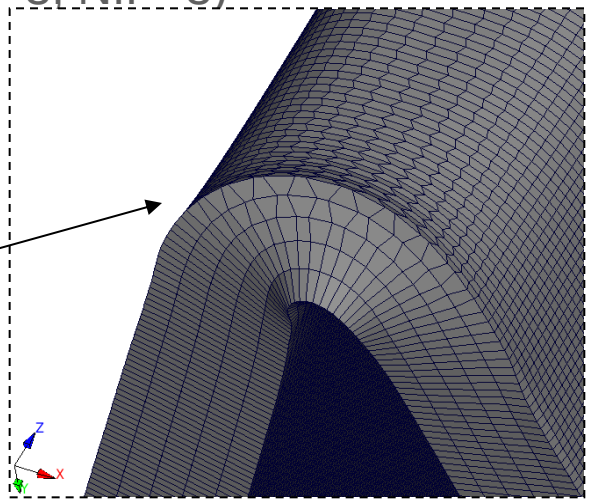


Bending test

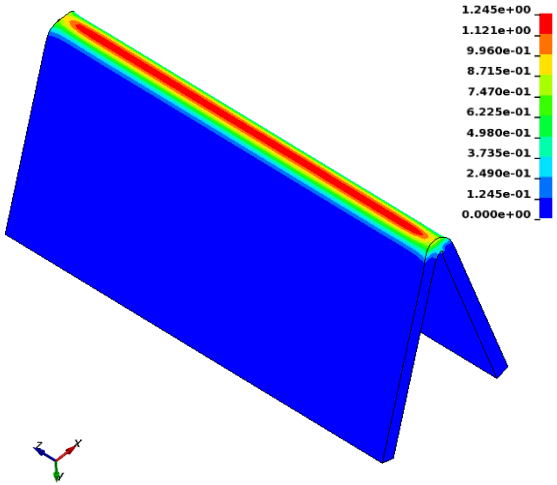
Simulation with Thick-Shells (Le = 0.125mm, ETYP=3, NIP=3)



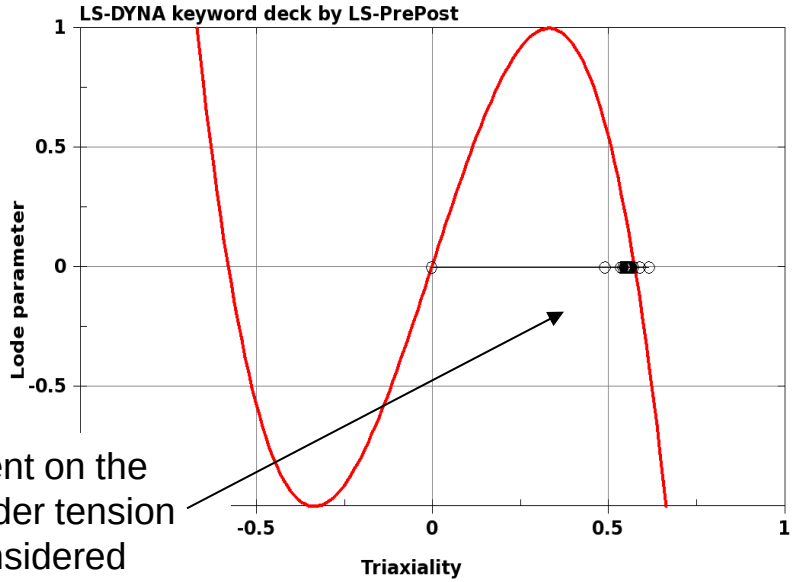
*Simulation stopped after 162 running hours on 96 CPUs due to excessively small time step; final bending angle slightly smaller than in other simulations



Hourglassing tendencies observed in the plate



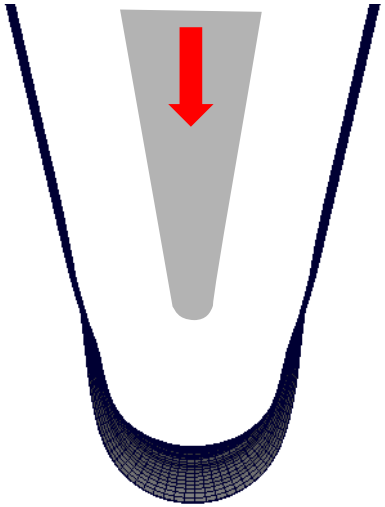
Contours of plastic strain

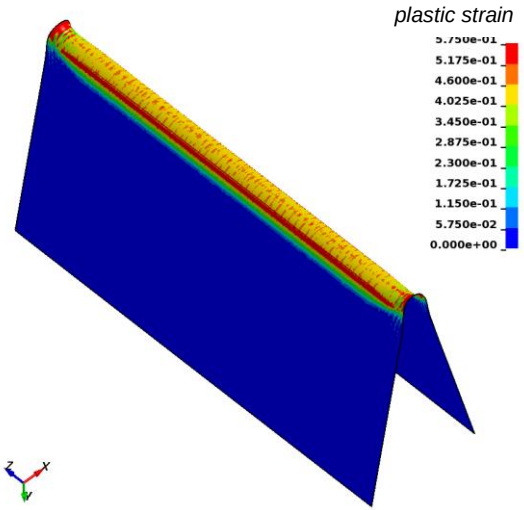


An element on the surface under tension was considered

Bending test

Simulation with shells (Le = 0.125mm, ETYP=25, IDOF=1, MAT_24)

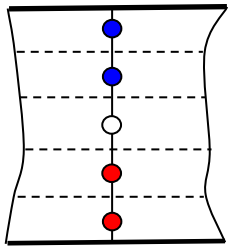




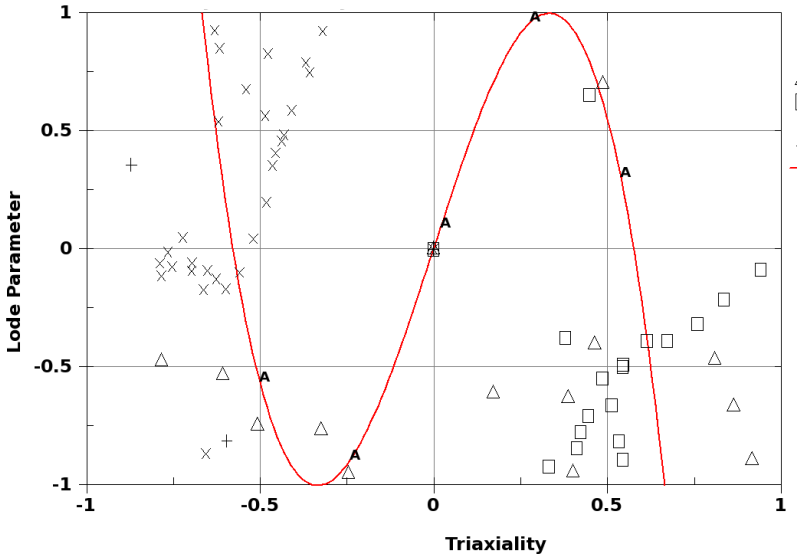
compression

neutral

tension



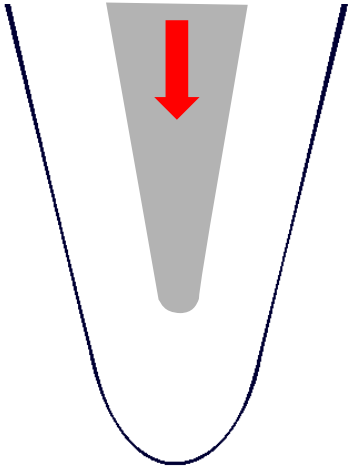
Several points deviate from the plane stress line; however, they do not depict the 3D case.

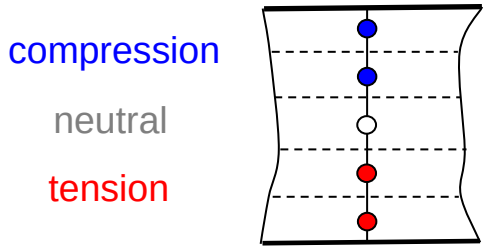


The middle integration point is in the elastic domain and therefore was not considered in this evaluation

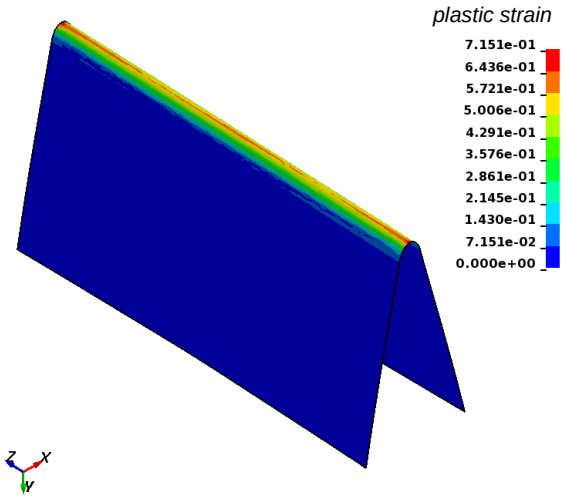
Bending test: Closer look!

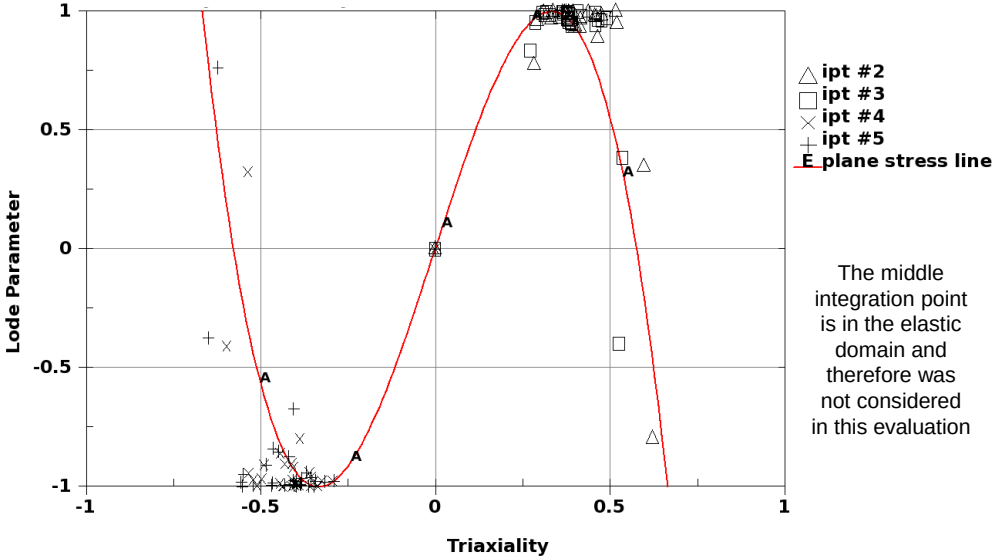
Simulation with shells (Le = 0.125mm, ETYP=25, IDOF=1, SAMP with ν_p=0.0)





Results are more consistent, but plasticity here is unrealistic for metals due to ν_p=0.0

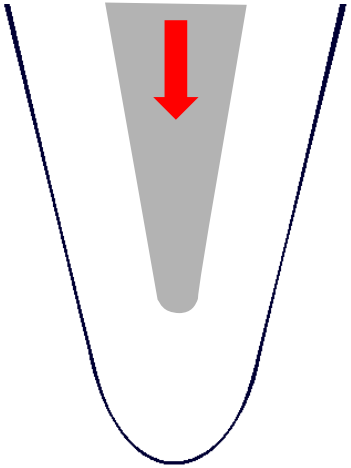


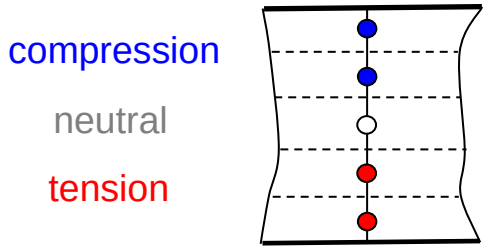


The middle integration point is in the elastic domain and therefore was not considered in this evaluation

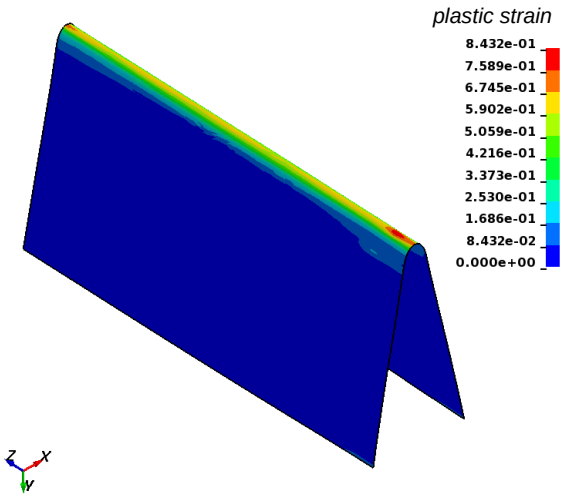
Bending test: Closer look!

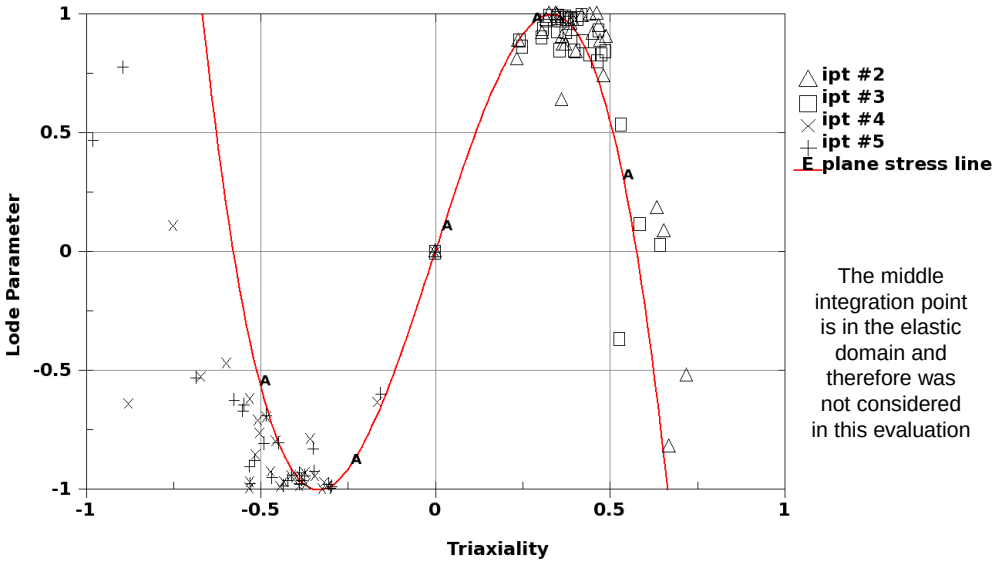
Simulation with shells (Le = 0.125mm, ETYP=25, IDOF=1, SAMP with ν_p=0.01)





Results are more consistent, but plasticity here is unrealistic for metals due to ν_p=0.01

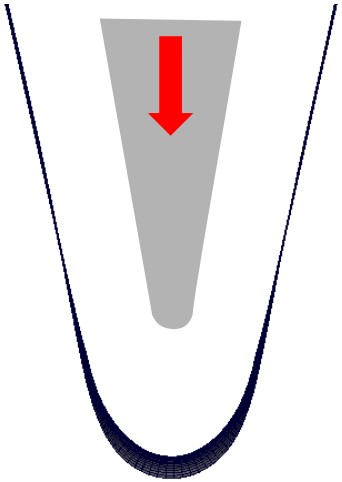


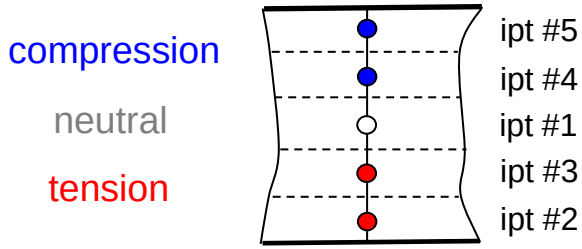


The middle integration point is in the elastic domain and therefore was not considered in this evaluation

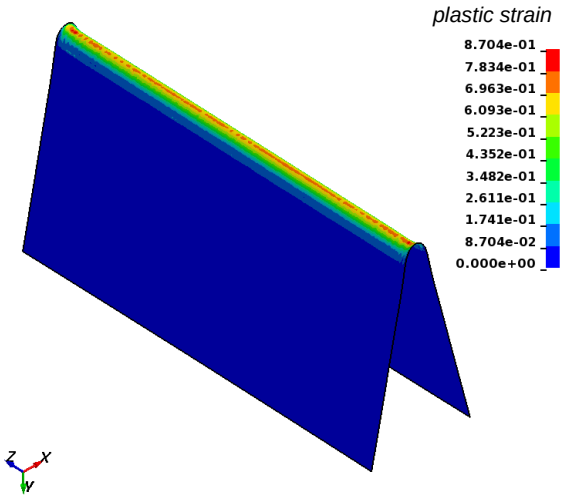
Bending test: Closer look!

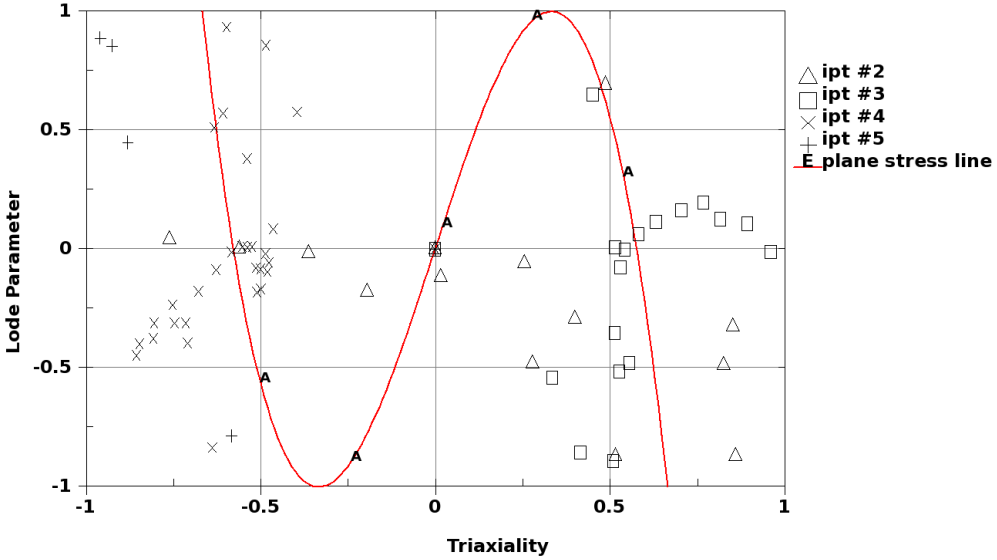
Simulation with shells (Le = 0.125mm, ETYP=25, IDOF=1, SAMP with ν_p=0.3)





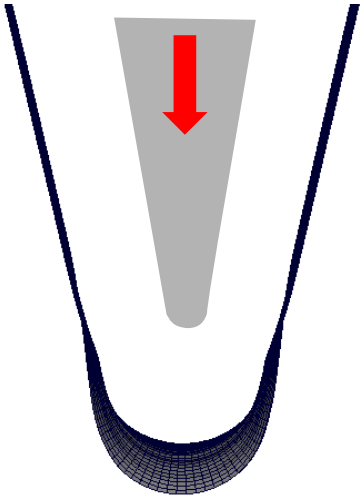
The awkward behavior is in the present case a little more noticeable

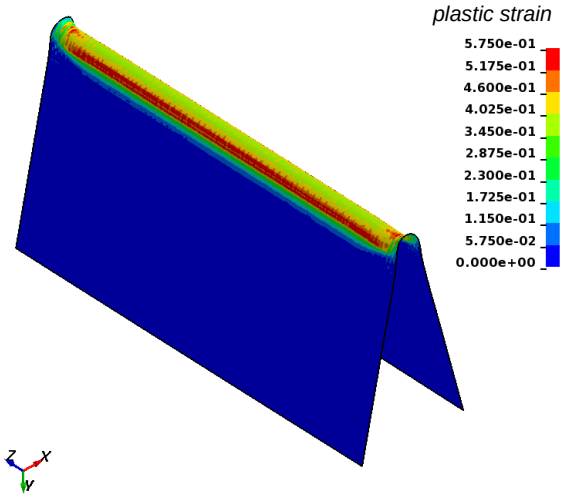




Bending test: Closer look!

Simulation with shells (Le = 0.125mm, ETYP=25, IDOF=1, SAMP with ν_p=0.5)

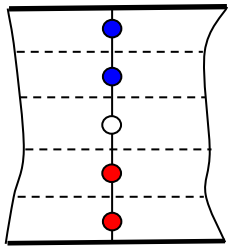




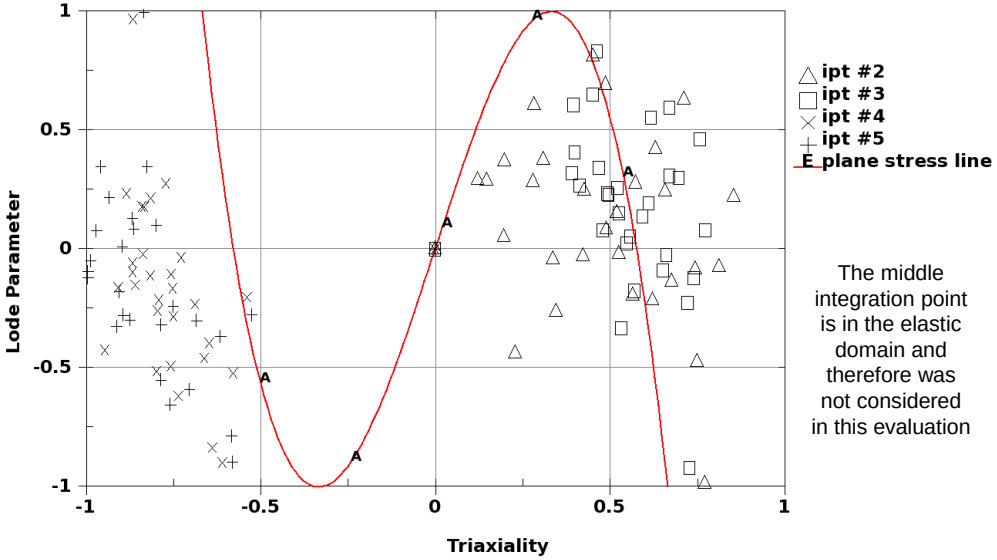
compression

neutral

tension



The awkward behavior is now quite noticeable: the plastic strain distribution is unrealistic and the stress state in the plate is different from expected.

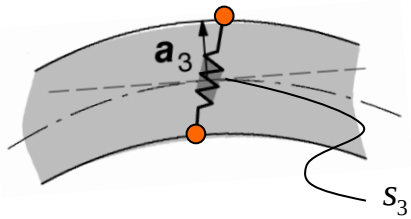


The middle integration point is in the elastic domain and therefore was not considered in this evaluation

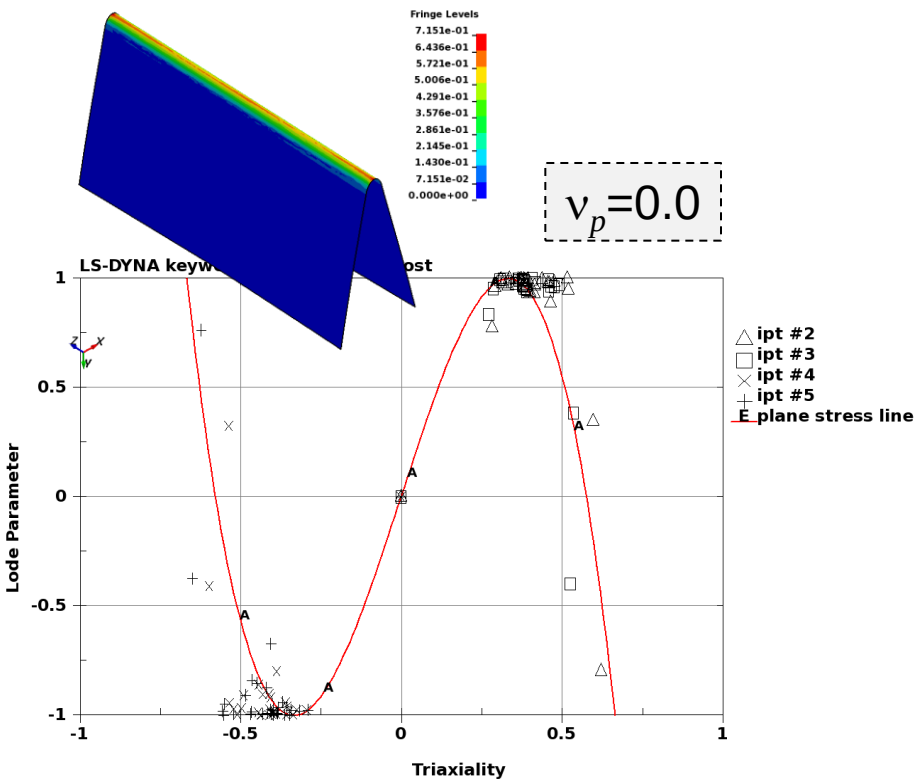
Some findings

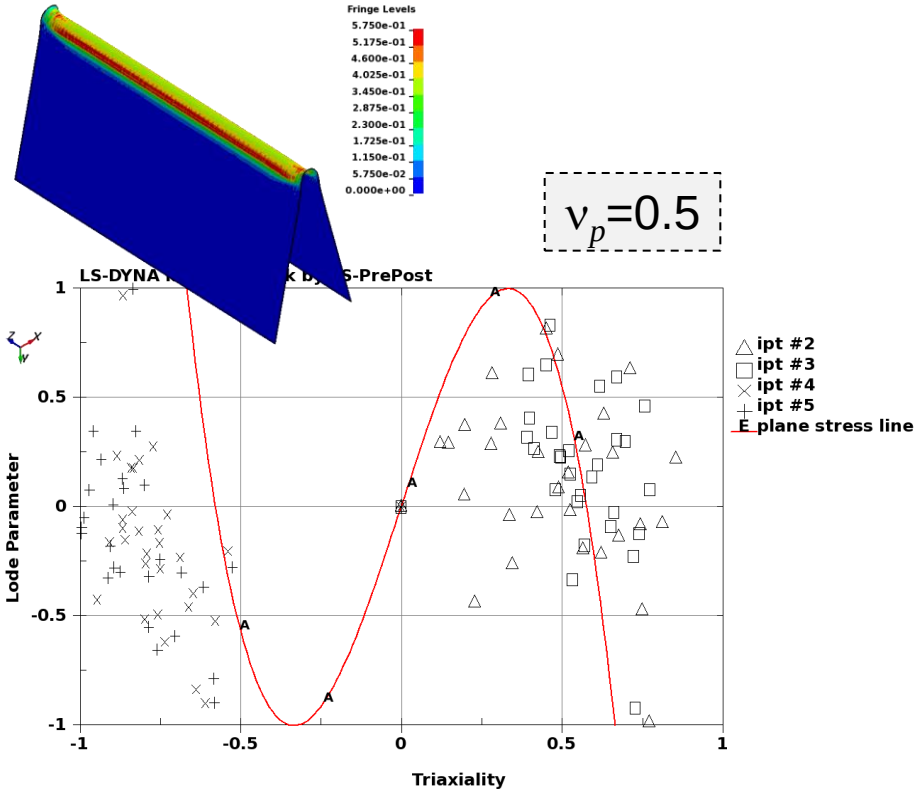
Due to the strain field assumption in lateral direction in ELTYP 25 the physical behavior in plastic loading seems to be questionable.
There is no solution yet:
One would need higher order approximation for strains in thickness direction.

Remember:



$$s_3 = \frac{\xi_3}{2} t_3 + (1 - \xi_3^2) q_3$$



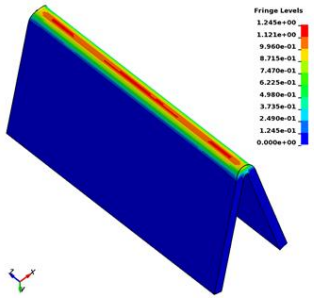


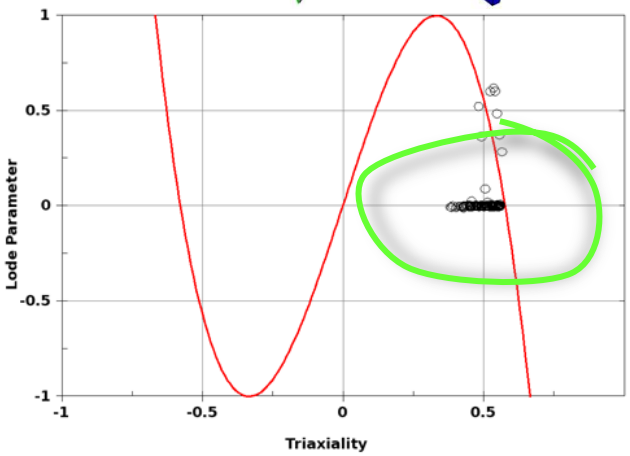
Conclusions?

Some conclusions

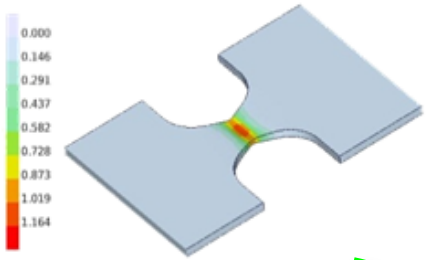
- Different calibration for shells (and its options!) and solids needs to be done.
- 3D material models will be needed and are to be calibrated in thickness direction!
- Regularisation - as always - is a must!
- 7-parameter shells not suited for applications with small bending radius and plastic loading.
- And always remember: After uniform deformation the stress state is 3D!

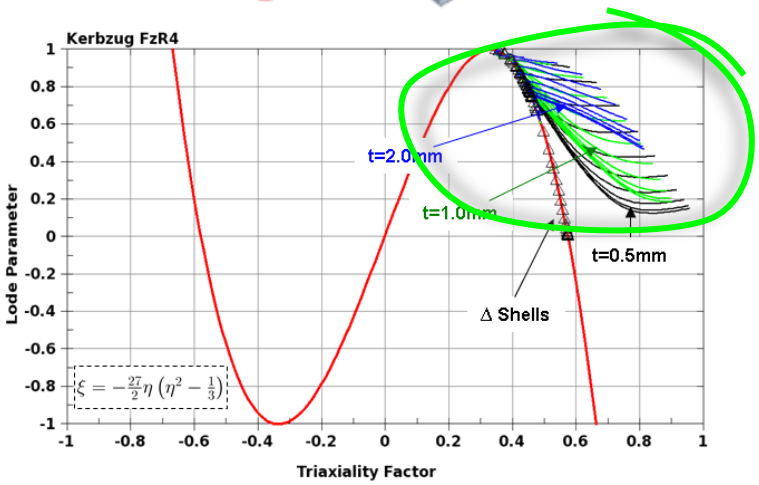
5p-SHELL
(ETYP=16)





SOLID
(ETYP=1/2)





FIN