Applications of *MAT_258

A through-thickness regularization model for shells

DYNAMore NORDIC USERS' CONFERENCE

19 October 2018

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Outline

1. A through-thickness regularization model for shells
2. Executive summary of the model formulation
3. Calibration using one **uniaxial tension** test
4. Effects of **regularization**
5. Validation using **three-point bending** and **crushing** tests
6. What about **coarser meshes**?
7. Summary

1

INTRODUCTION

Introduction

Available in LS-DYNA starting with version R9.3

*MAT_258 *MAT_NON_QUADRATIC_FAILURE

*MAT_NON_QUADRATIC_FAILURE

This is material 258. This is an elastic-(visco)plastic material with a non-quadratic yield surface where isotropic work hardening is included. A ductile failure model is included in the form of a damage indicator model. The extended Cockcroft-Latham criterion is

Basic idea:

1. To compute failure as a function of the bending-to-membrane loading ratio of each element
2. To reduce the mesh dependency of the failure strain under membrane loading
3. To have a conservative but accurate model that requires few tests to calibrate

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MODEL FORMULATION

Constitutive model

- Hershey-Hosford yield criterion for isotropic plasticity:

$$f = \bar{\sigma} - \left(\sigma_Y + R(\bar{\varepsilon}^p)\right) \qquad \bar{\sigma} = \left[\frac{1}{2}\left(|\sigma_1 - \sigma_2|^a + |\sigma_2 - \sigma_3|^a + |\sigma_3 - \sigma_1|^a\right)\right]^{\frac{1}{a}}$$

- Three-term voce hardening rule (7 parameters):

$$R(\bar{\varepsilon}^p) = \sum_{i=1}^{3} Q_i \left(1 - \exp\left(-\frac{\theta_i}{Q_i}\bar{\varepsilon}^p\right)\right)$$

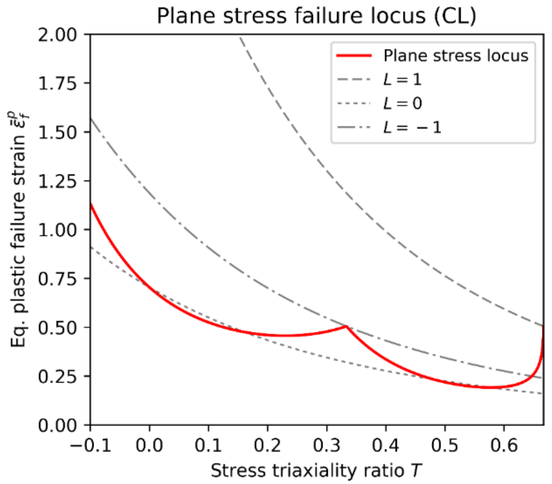
- Viscoplasticity is available:

$$\bar{\sigma} = \left(\sigma_Y + R(\bar{\varepsilon}^p)\right)\left(1 + \frac{\dot{\bar{\varepsilon}}^p}{\dot{\bar{\varepsilon}}^p_\sigma}\right)^{C_\sigma} \text{ for } f > 0$$

Failure model

- Uncoupled version of the **Extended Cockcroft-Latham** (ECL) criterion:

$$\dot{D} = \frac{\bar{\sigma}}{W_C}\left\langle \phi \frac{\sigma_I}{\bar{\sigma}} + (1-\phi)\left(\frac{\sigma_I - \sigma_{III}}{\bar{\sigma}}\right)\right\rangle^{\gamma} \dot{\bar{\varepsilon}}^{p}$$

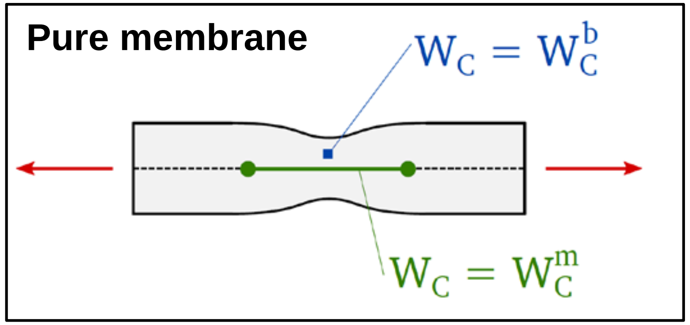


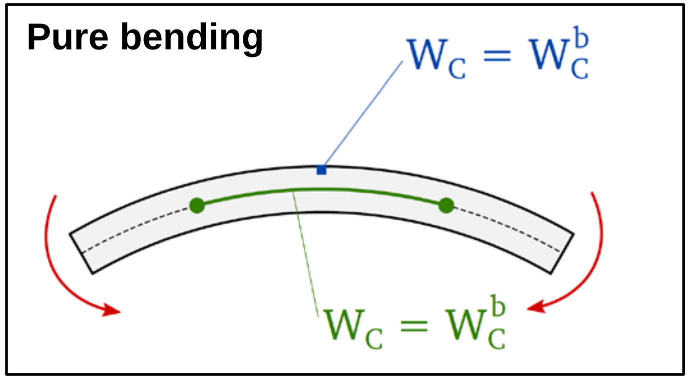
- The model parameters W_C, ϕ, and γ govern the damage evolution and its dependence on stress triaxiality and Lode parameter
  - W_C determines the overall level of the failure strain and is used in the regularization

Gruben G, Hopperstad OS, Børvik T. *Evaluation of uncoupled ductile fracture criteria for the dual-phase steel Docol 600DL*. International Journal of Mechanical Sciences 2012; 62: 133-146.

Regularization procedure

- The **bending-to-membrane loading ratio** Ω is computed using the through-thickness variation of the through-thickness plastic strain
- W_C^l, W_C^s, and c determine the **element size regularization**





$$W_C^b = W_C^b$$

$$W_C^m = W_C^l + \left(W_C^s - W_C^l\right)\exp\left(-c\left(\frac{l_e}{t_e} - 1\right)\right)$$

$$\boxed{W_C = \Omega W_C^b + (1 - \Omega) W_C^m}$$

$$\Omega = \frac{1}{2}\frac{\left|\varepsilon_{33p}^T - \varepsilon_{33p}^B\right|}{\left|\max\left\{\varepsilon_{33p}^T, \varepsilon_{33p}^B\right\}\right|}$$

Costas M, Morin D, Hopperstad OS, Børvik T, Langseth M. *A through-thickness damage regularization scheme for shell elements subjected to severe bending and membrane deformations*. Journal of the Mechanics and Physics of Solids. In press.

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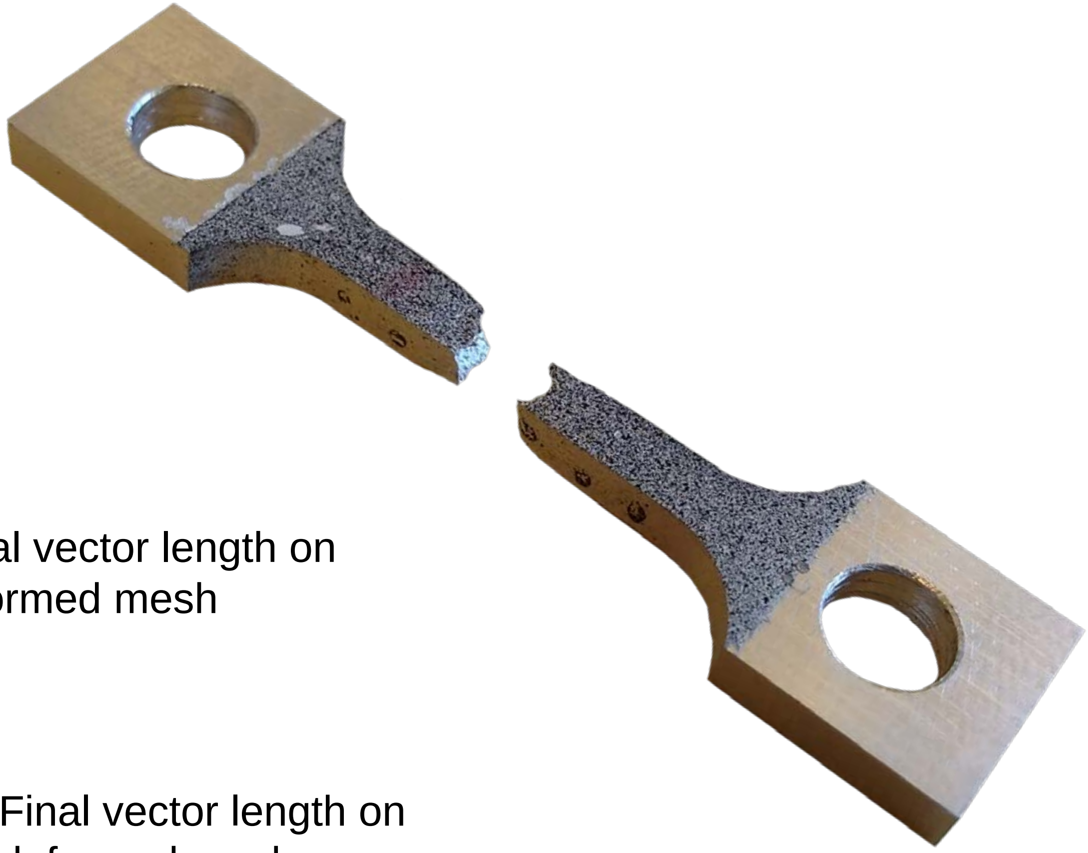
CALIBRATION USING A UNIAXIAL TENSION TEST

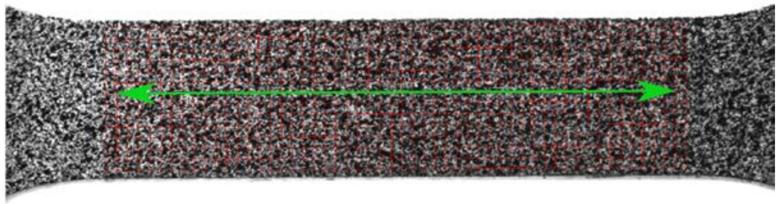
Calibration procedure

1. Conduct tension test
2. Simulate tension test with solid elements
   - Determine the hardening parameters using inverse modeling techniques (σ_Y, θ_1, C_1, θ_2, C_2, θ_3, C_3)
   - Integrate the major principal stress over the equivalent plastic strain until fracture to find the "true/bending" CL parameter W_C^b
3. Stretch single shell elements of various sizes using elongation from DIC virtual extensometers of corresponding length as boundary conditions
   - Integrate the major principal stress over the equivalent plastic strain until fracture to find the membrane CL parameters (W_C^m) for different element sizes and thus W_C^l, W_C^s, and c

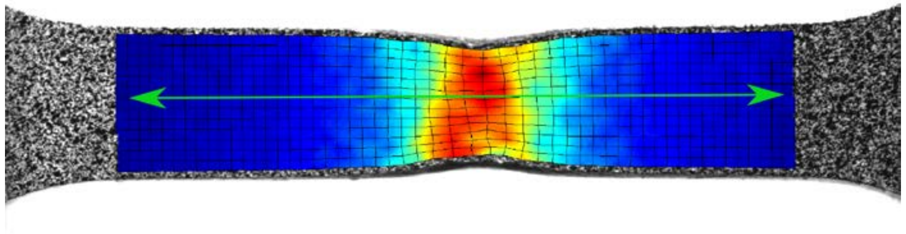
Tension testing

- UT specimens : 3 mm wide in gauge area
- Crosshead velocity : 0.67 mm/min
- Test duration ≈ 4 minutes
- DIC : 2 fps
- Vector length ≈ 10 mm





Original vector length on undeformed mesh



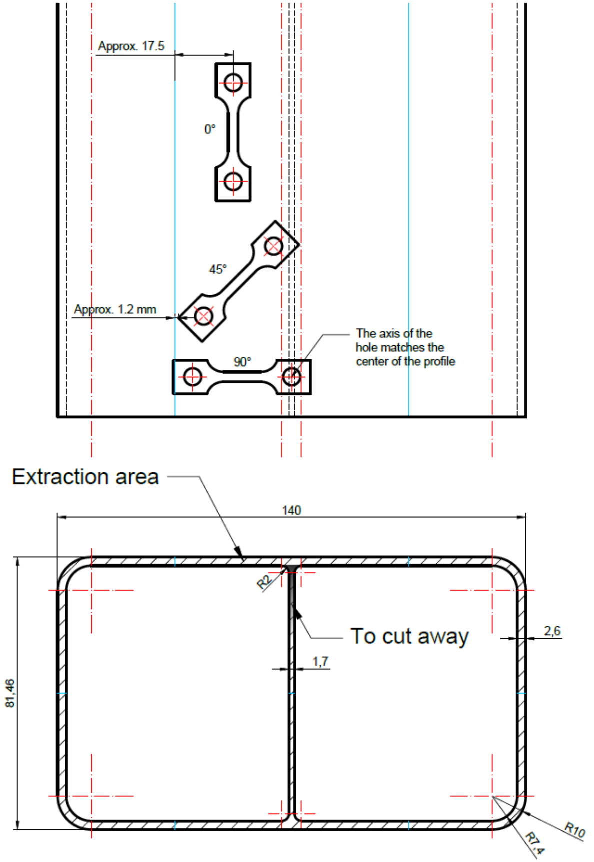
Final vector length on deformed mesh

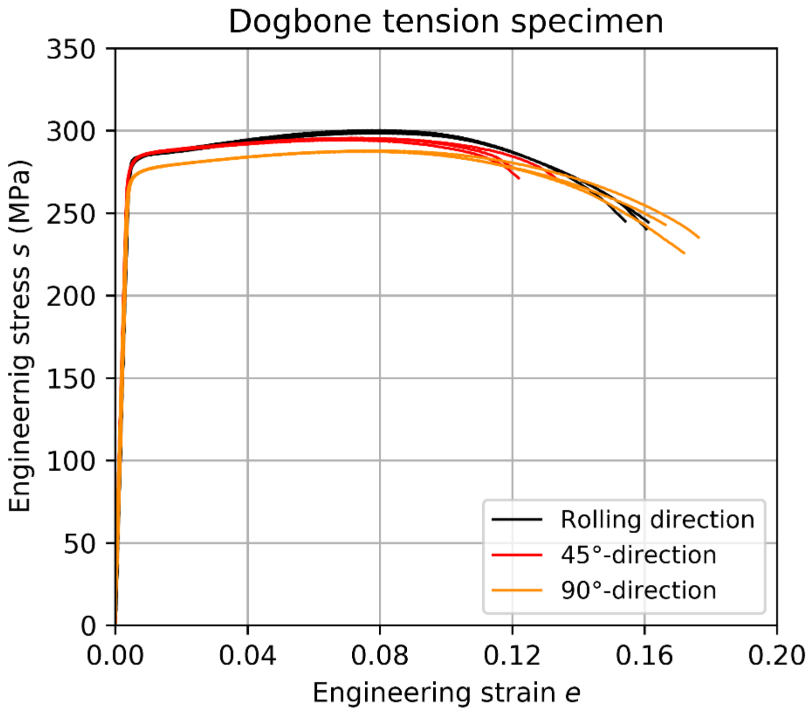
Tension testing

AA6005-T6

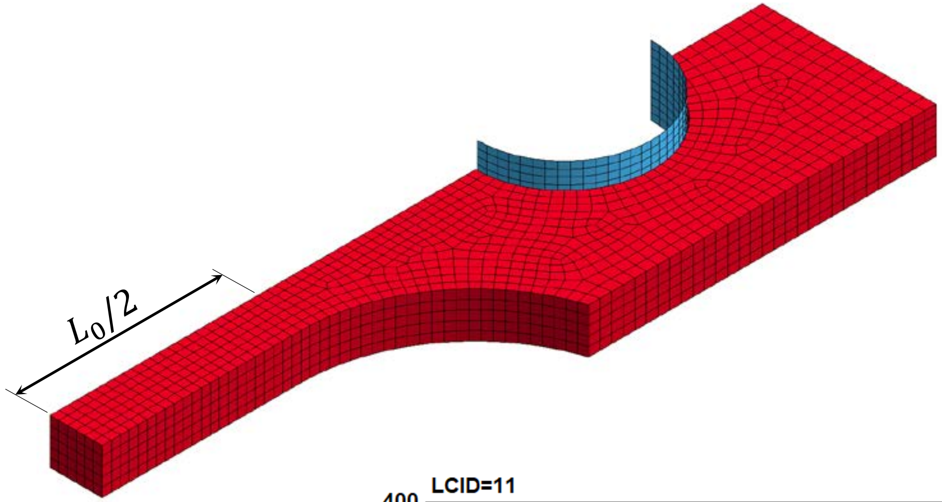
- Extracted specimens from the base material in the outer wall
- Three repetitions per orientation
- $s = F/A_0$, $e = \Delta L/L_0$

- **One test** from the **extrusion direction** is used in the following



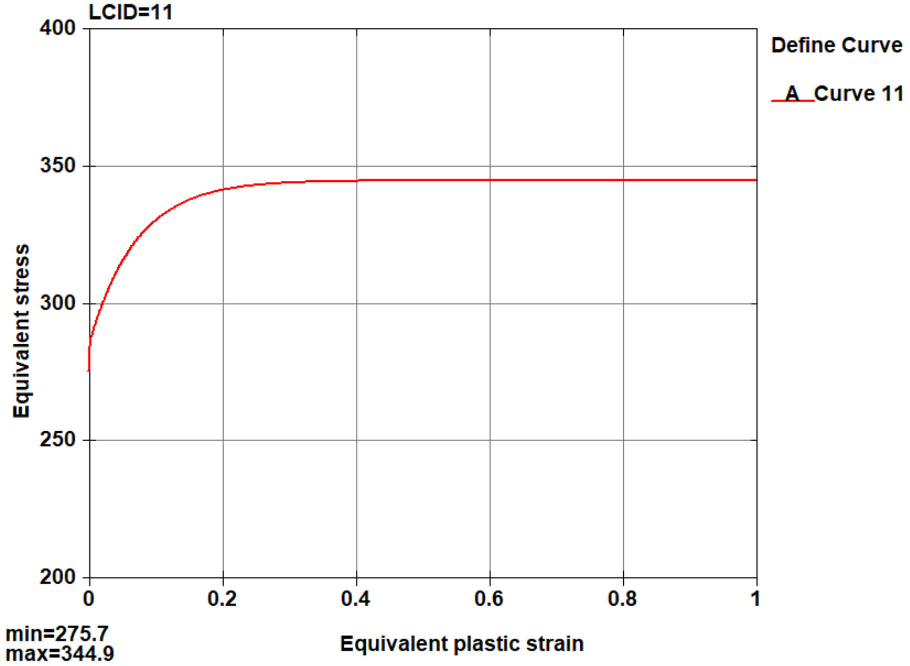


Solid element model



- Solid element model
  - XYZ symmetry
  - ELFORM = 1
  - Element size : ≈ 0.26 mm
  - Gauge length L_0 : 9.87 mm

- *MAT_033/ *MAT_BARLAT_ANISOTROPIC_PLASTICITY
  - A = B = C = D = E = F = G = H = 1.0
  - M = 8.0
  - Yield stress and hardening defined by LCID that was determined using LS-OPT

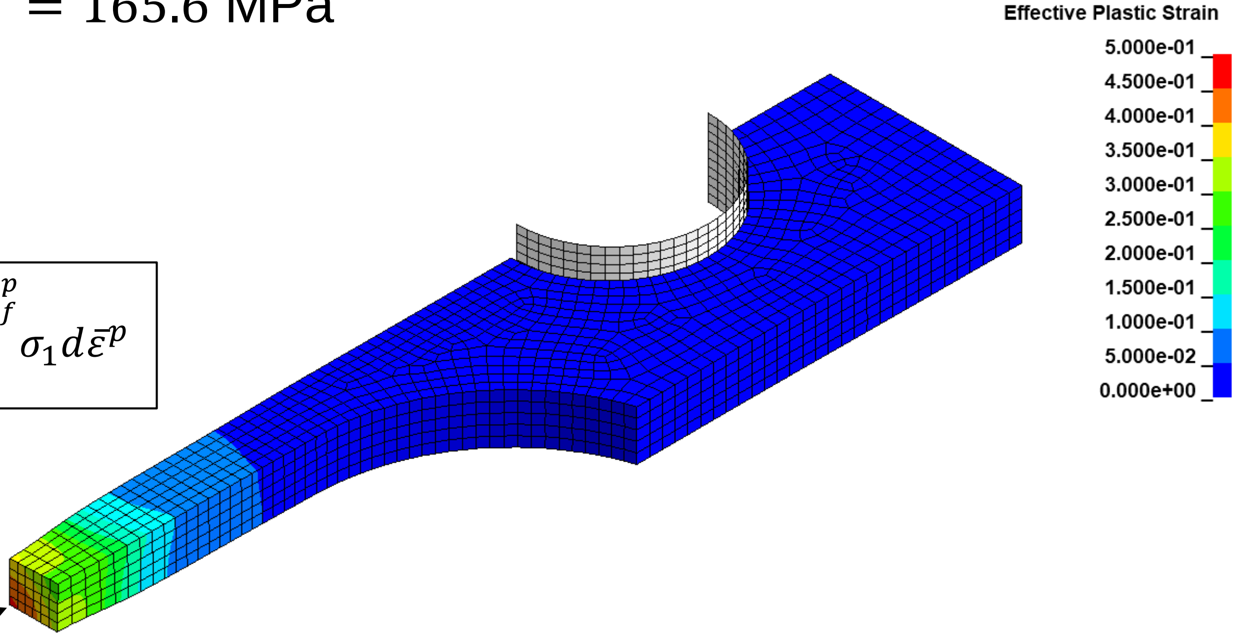


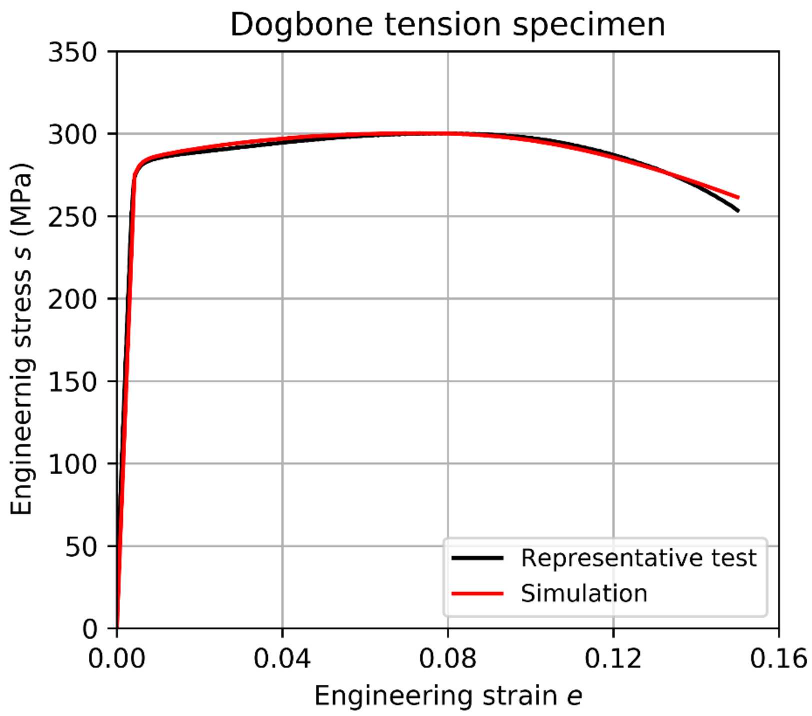
- Load the model with *DEFINE_CURVE_SMOOTH and a 20% ramp-up time

Solid element model

- Determine failure from the centermost element in a simulation of a tension test
- This is how we find W_C^b
- $W_C^b = 165.6$ MPa

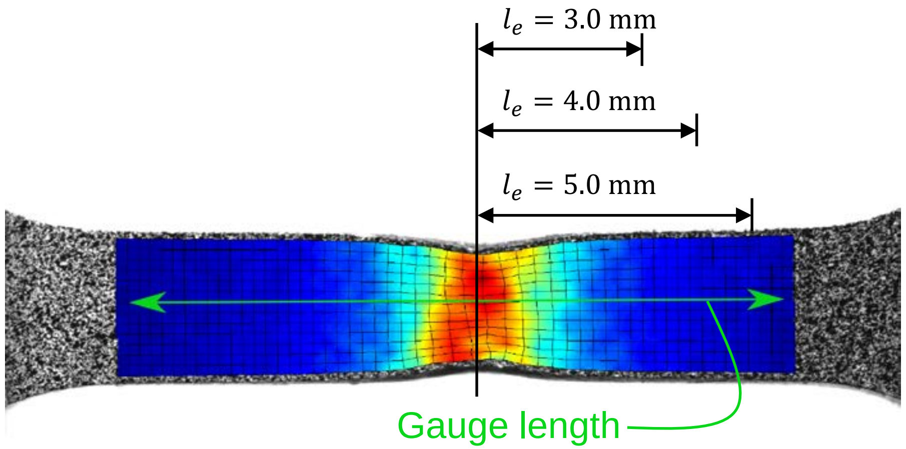
$$W_C^b = \int_0^{\bar{\varepsilon}_f^p} \sigma_1 d\bar{\varepsilon}^p$$

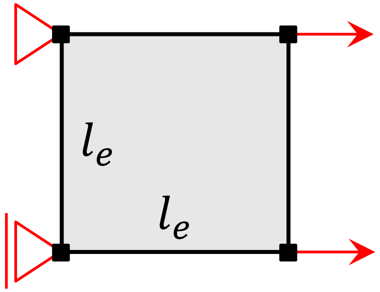




Single element models

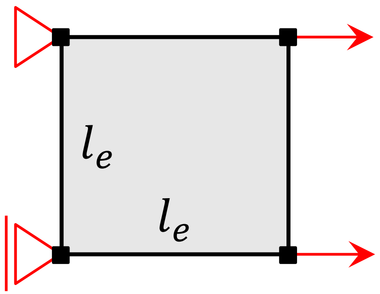
- From the DIC analysis:
  - Find the elongations at fracture at various points away from the neck
  - **This definition is conservative**
- Stretch the single element models to the corresponding elongation at fracture and calculate the different W_C^m



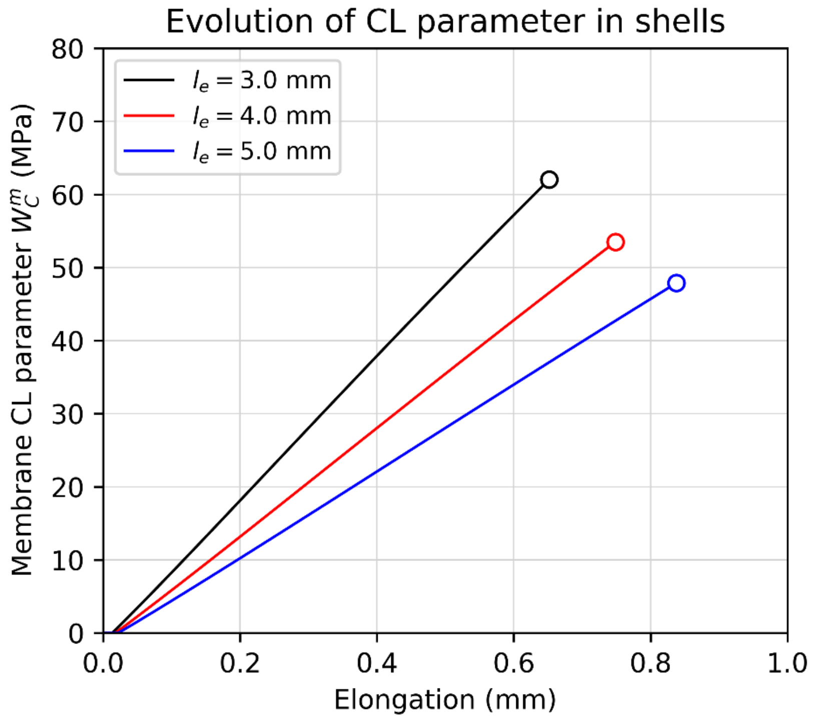


Shell element models

- Large elements → Low CL parameter (W_C^m)



l_e/t_e	W_C^m
1.17	62.1 MPa
1.56	53.4 MPa
1.95	48.0 MPa



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EFFECT OF REGULARIZATION AND FAILURE PARAMETERS

Element-size regularization

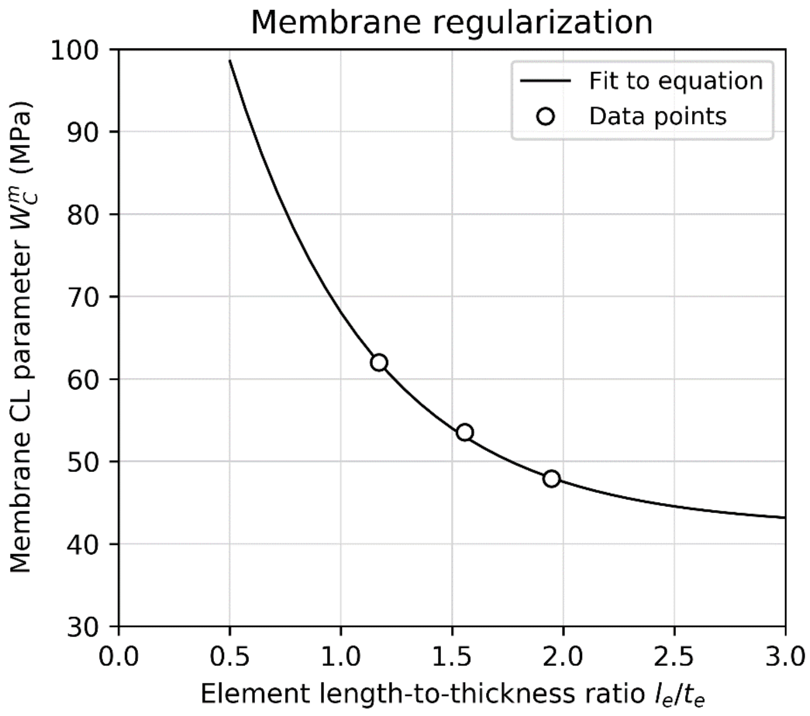
From 1-element models

$$W_C^m = W_C^l + \left(W_C^s - W_C^l\right)\exp\left(-c\left(\frac{l_e}{t_e} - 1\right)\right)$$

l_e/t_e	W_C^m
1.17	62.1 MPa
1.56	53.4 MPa
1.95	48.0 MPa

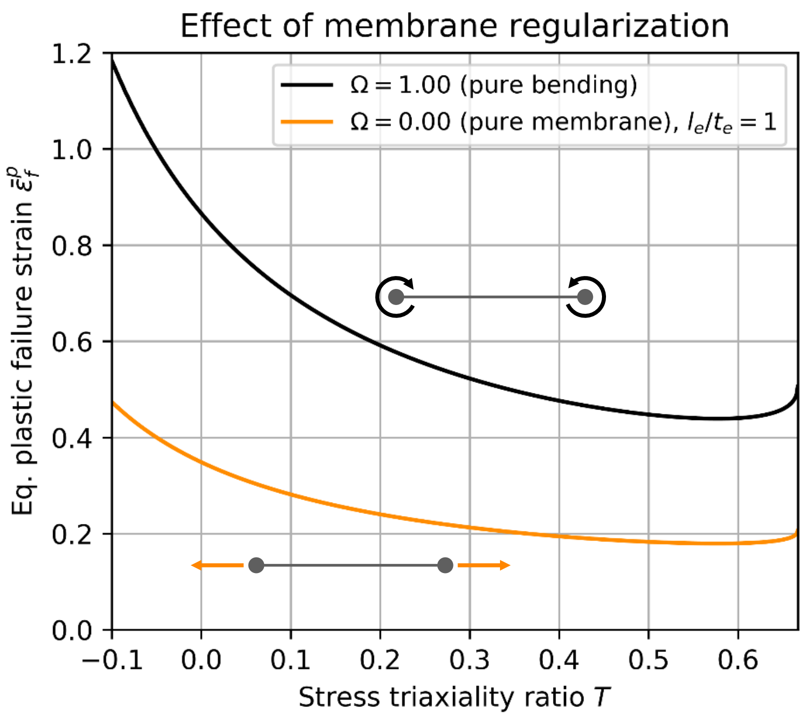
Best fit

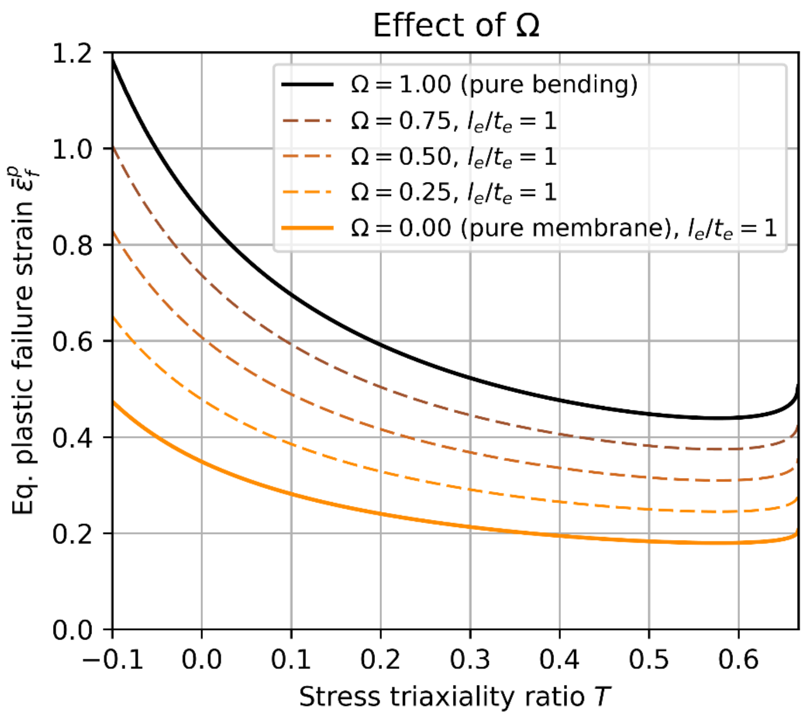
param	value
W_C^s	42.0 MPa
W_C^l	68.1 MPa
c	1.549



Membrane/bending regularization

$$W_C = \Omega W_C^b + (1-\Omega) W_C^m$$





Extended Cockcroft-Latham (ECL) failure

- ECL assumes that damage evolution is driven by plastic power amplified by a stress state dependent term

$$D = \frac{1}{W_C}\int_0^{\bar{\varepsilon}_f^p} \left\langle \phi \frac{\sigma_I}{\bar{\sigma}} + (1-\phi)\left(\frac{\sigma_I - \sigma_{III}}{\bar{\sigma}}\right)\right\rangle^{\gamma} \bar{\sigma}\, d\bar{\varepsilon}^p$$

Invariant expression. Used to plot the failure surface

$$\boxed{W_C = \int_0^{\bar{\varepsilon}_f^p} \left\langle \frac{\phi\left(3T\sqrt{3+L^2} - 3 - L\right)}{3\sqrt{3+L^2}} \right\rangle^{\gamma} \bar{\sigma}\, d\bar{\varepsilon}^p}$$

$$D = \frac{1}{W_C}\int_0^{\bar{\varepsilon}_f^p} \langle \sigma_I \rangle\, d\bar{\varepsilon}^p$$

Cockcroft-Latham criterion ($\phi = \gamma = 1$)

$$D = \frac{1}{W_C}\int_0^{\bar{\varepsilon}_f^p} \bar{\sigma}\, d\bar{\varepsilon}^p$$

Freudenthal criterion ($\gamma = 0$)

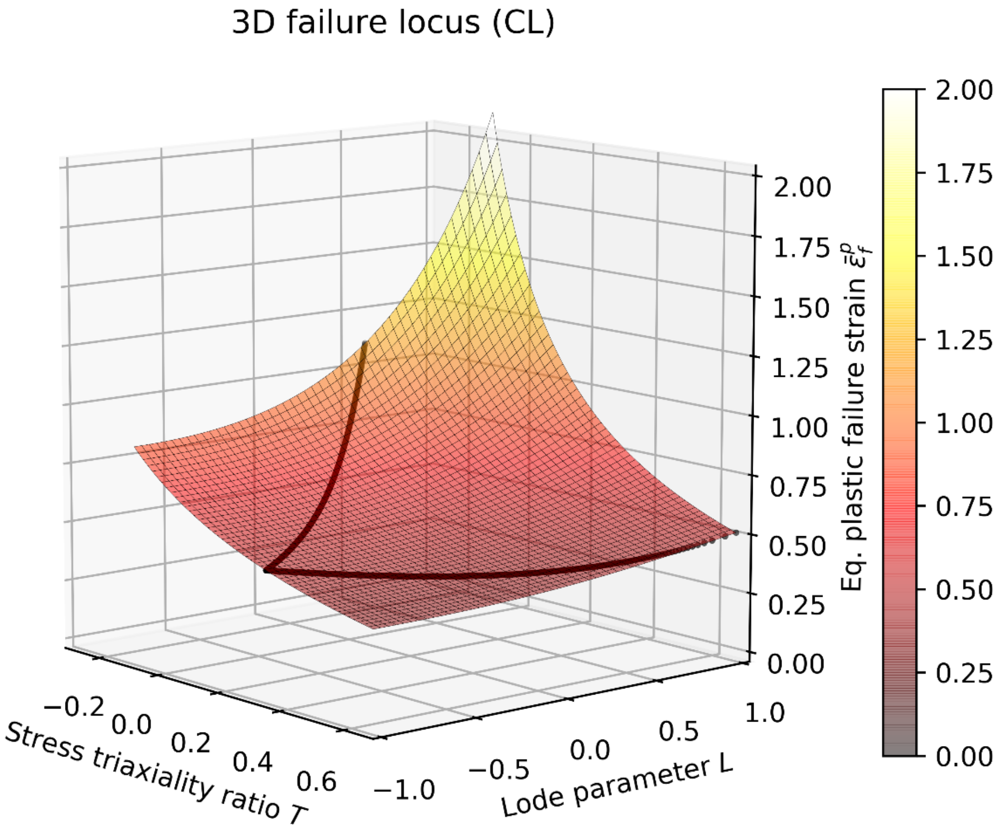
$$D = \frac{1}{W_C}\int_0^{\bar{\varepsilon}_f^p} (\sigma_I - \sigma_{III})\, d\bar{\varepsilon}^p$$

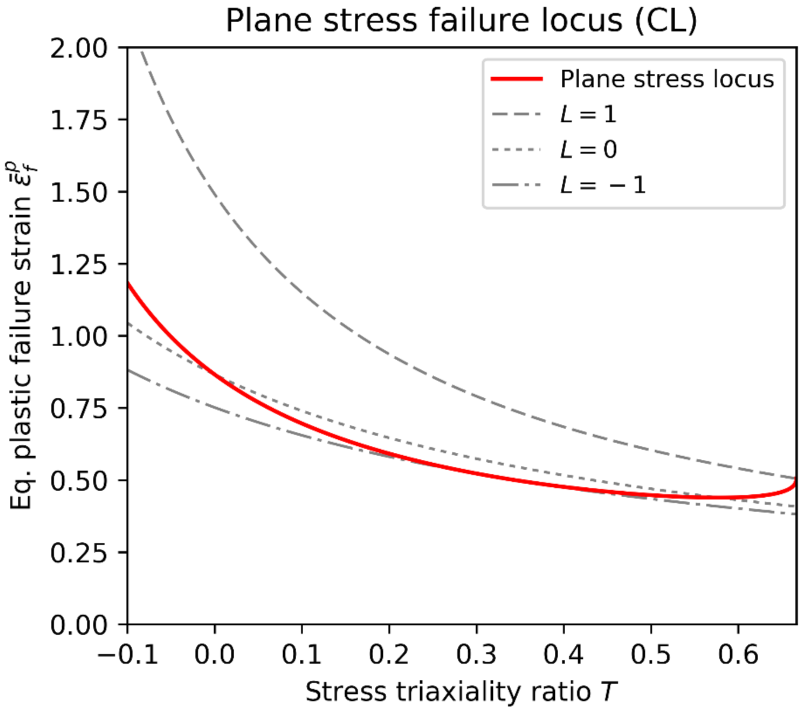
Integral based Tresca criterion ($\phi = 0, \gamma = 1$)

Gruben G, Hopperstad OS, Børvik T. *Evaluation of uncoupled ductile fracture criteria for the dual-phase steel Docol 600DL*. International Journal of Mechanical Sciences 2012; 62: 133-146.

Failure locus for CL failure

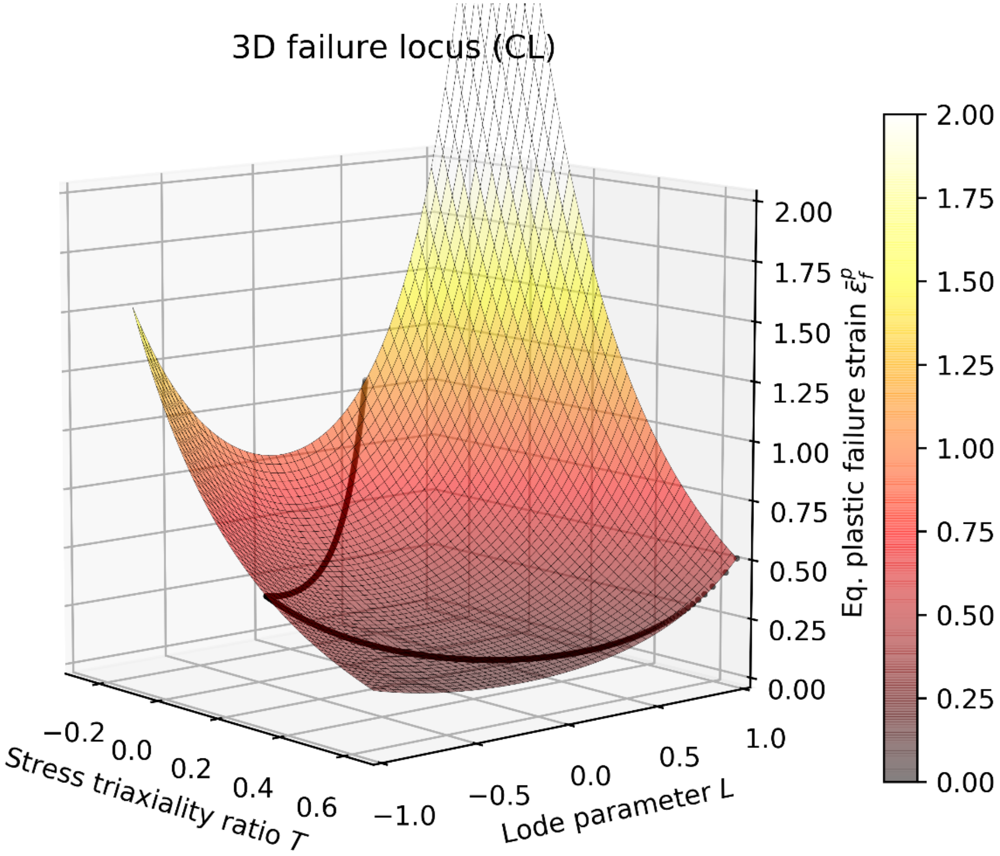
W_C = 165.6 MPa, γ = 1, φ = 1

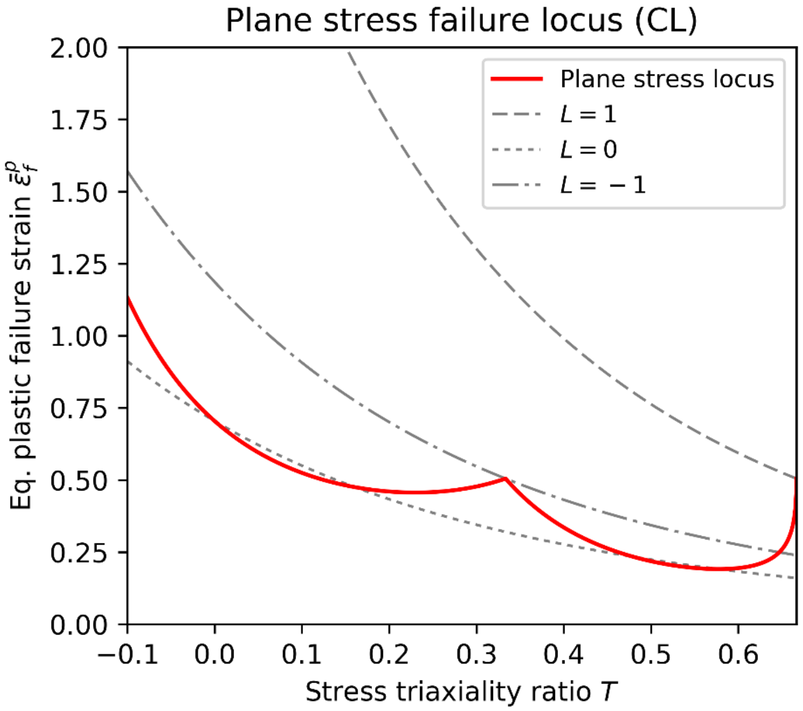




Failure locus for ECL failure

W_C = 165.6 MPa, γ = 0.35, φ = 7.0





*MAT_258 material card

	TITLE							
	Aluminum 6005-T6							
Yielding	MID	RO	E	PR	SIGY	A	KSI	
	1	2.7e-09	70.0e+03	0.3	275.68	8.0	0.0	
Hardening	THETA1	Q1	THETA2	Q2	THETA3	Q3		
	7095.1	8.61	702.3	48.47	166.2	12.16		
Rate sensitivity	CS	PDOTS						
	0.0	0.0						
Failure	DCRIT	WCB	WCL	WCS	CC	PHI	GAMMA	THICKNESS
	1.0	165.6	42.0	68.1	1.549	1.0	1.0	2.57

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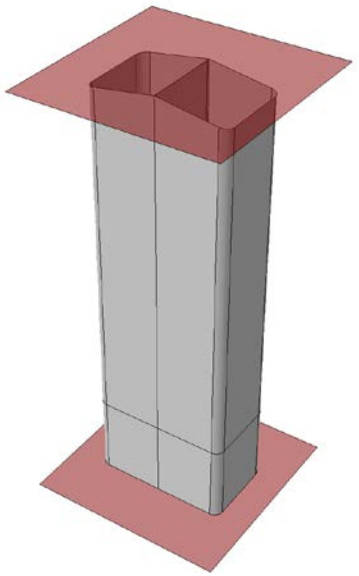
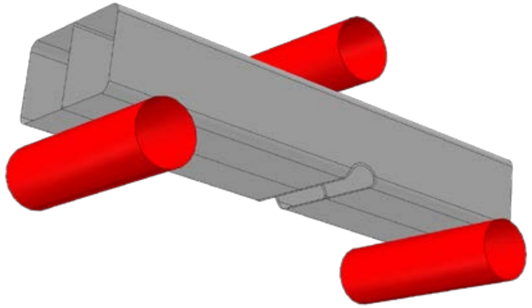
VALIDATION

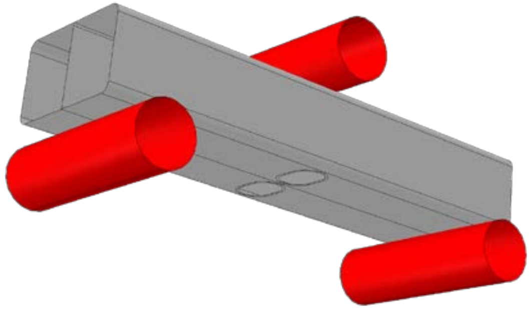
Validation tests



Quasi-static crushing



3-point-bending w/notch

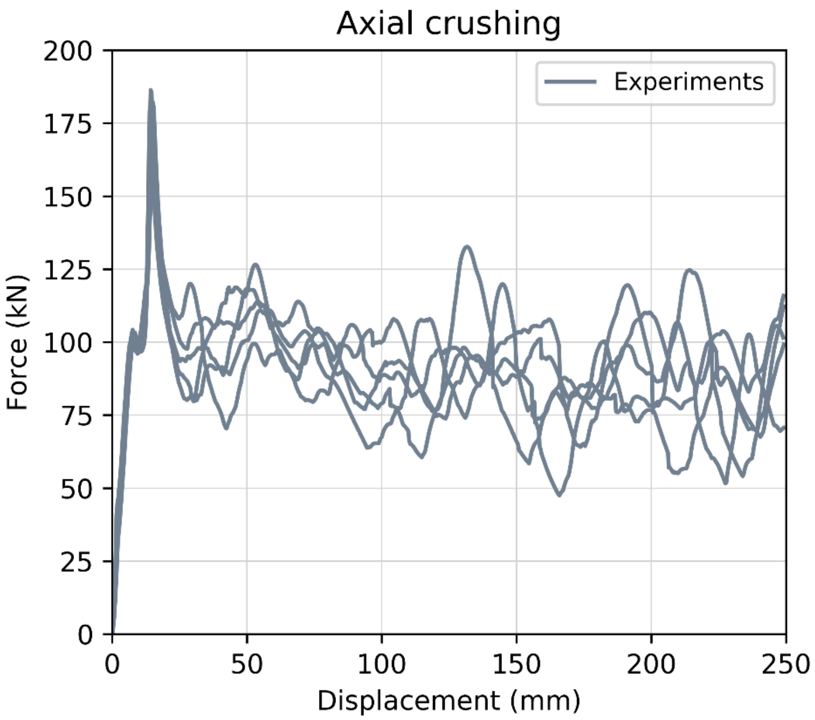


3-point-bending w/holes

Costas M, Morin D, Hopperstad OS, Børvik T, Langseth M. *A through-thickness damage regularization scheme for shell elements subjected to severe bending and membrane deformations*. Journal of the Mechanics and Physics of Solids. In press.

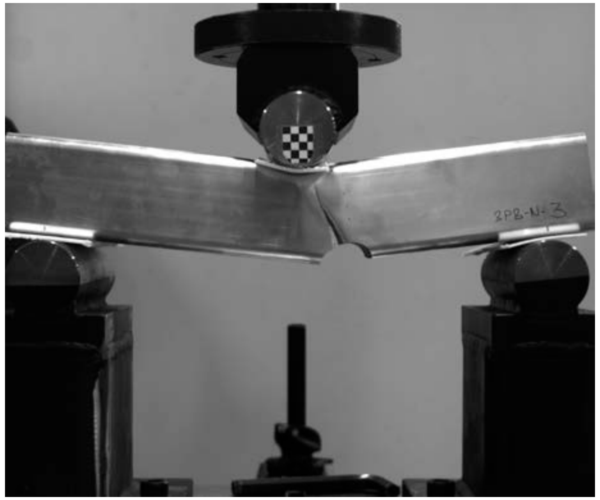
Axial crushing tests

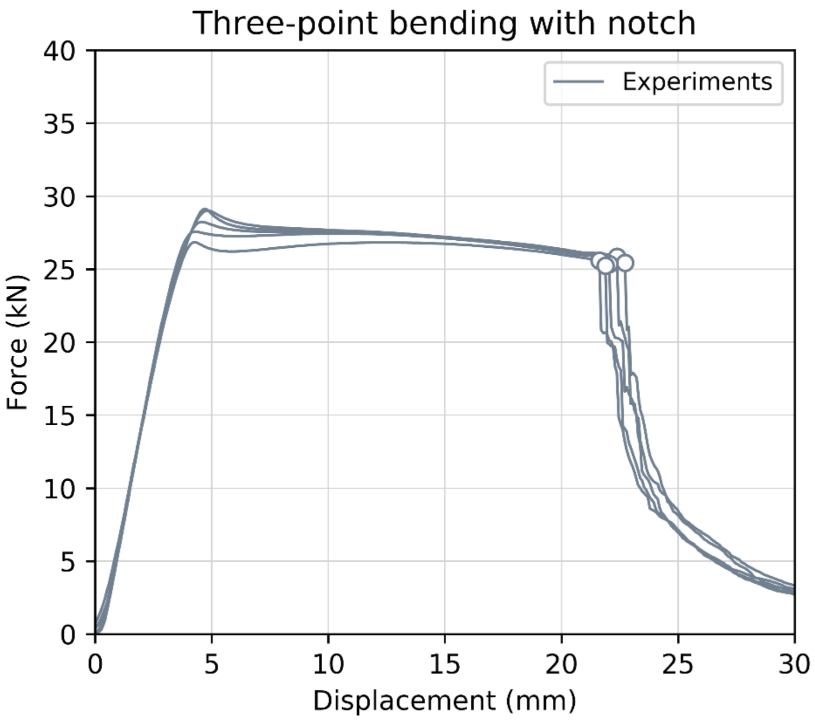
- Five successful repetitions
- Cracks at the corners and along both ends of the middle wall
- Collapse mode transitions from asymmetric to symmetric



3-point-bending tests with notch

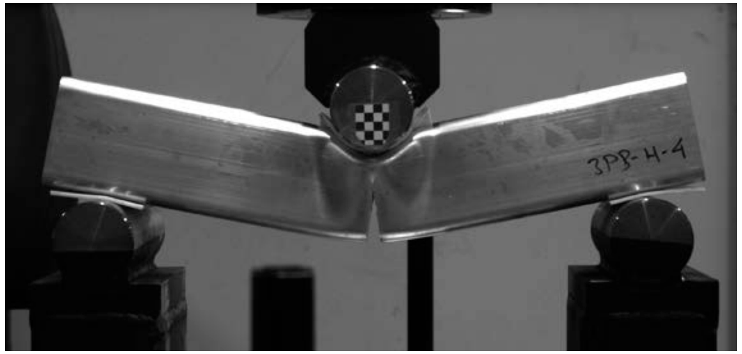
- Failure takes place after approx. 23 mm displacement
- Inclined crack-growth from the notch toward the punch

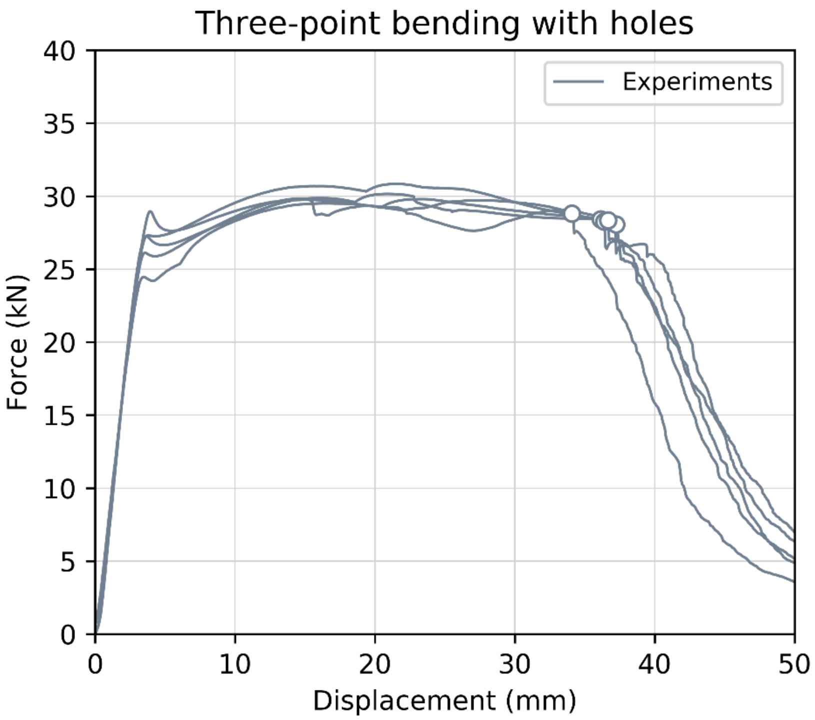




3-point-bending tests with holes

- Failure takes place after approx. 35 mm displacement
- Straight crack-growth from the holes toward the punch





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The Research Council of Norway
CASA
Centre for Advanced Structural Analysis
NTNU

Modeling details

***CONTACT_AUTOMATIC_SINGLE_SURFACE**

- Use LSTC recommended values
  - (SOFT = 1, VDC = 20)

Element type and hourglass formulation

- Use default ELFORM=2 and LSTC recommended values IHQ = 4, QM = 0.03
- Compare to ELFORM=16 and IHQ = 8, QM = 0.03

Updating of shell normals

- *Default:*
  - Recompute fiber directions at every cycle, IRNXX = -1
- *Alternative:*
  - Unique nodal fibers are incrementally updated based on the nodal rotation at the location of the fiber, IRNXX = -2

Modeling details

Three simulation setups presented in the following:

“ELFORM = 2”:

Simulations with ELFORM = 2 and IRNXX = -1

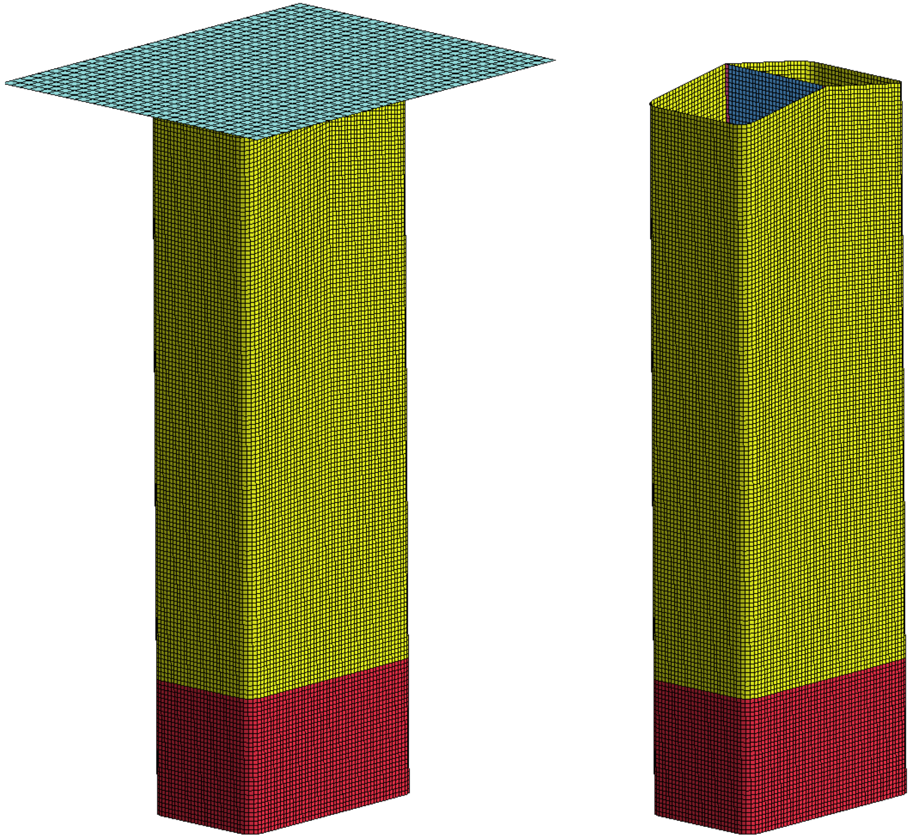
“ELFORM = 16”:

Simulations with ELFORM = 16 and IRNXX = -1

“IRNXX = -2”:

Simulations with ELFORM = 2 and IRNXX = -2

Axial crushing

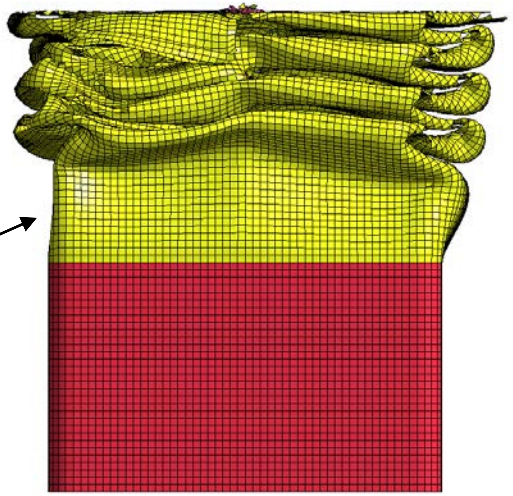


- Elem. size ≈ 2.7 mm
- 350 mm free length (incl. 9° trigger)
- 80 mm clamping length
- 250 mm crushing distance
- Time scaling factor of 25 000
  - Negligible kinetic energy. Lower factor did not affect the results
- Smooth ramping of the load
- Friction coefficient FS = FD = 0.2
- Account for thickness change (ISTUPD = 1)
- Rigid punch (teal) and bottom part (red) of profile

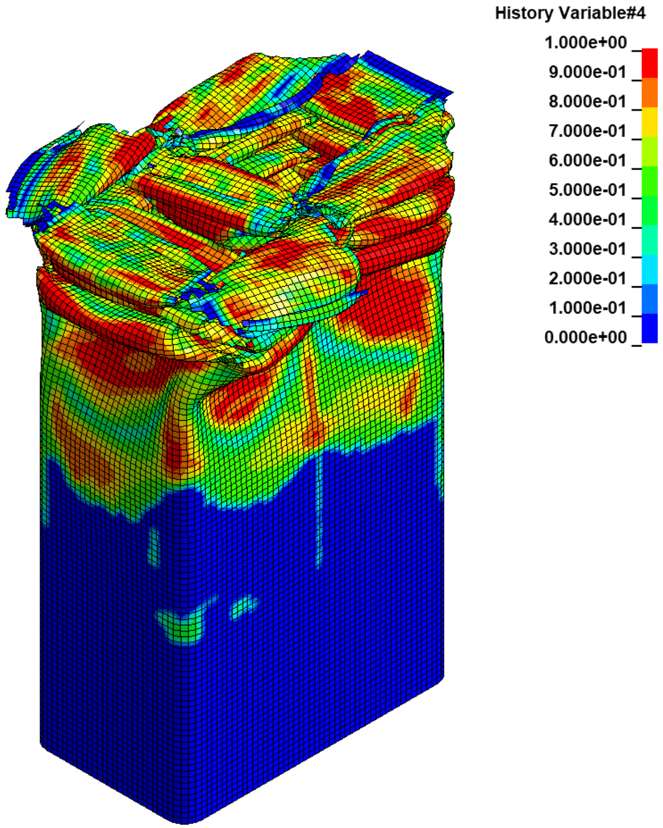
Axial crushing

- Pictures of deformed shapes after significant deformation
- Predict more fracture in the simulation than in the test
- History variable #4 = Ω
- Red = pure bending
- Blue = pure membrane

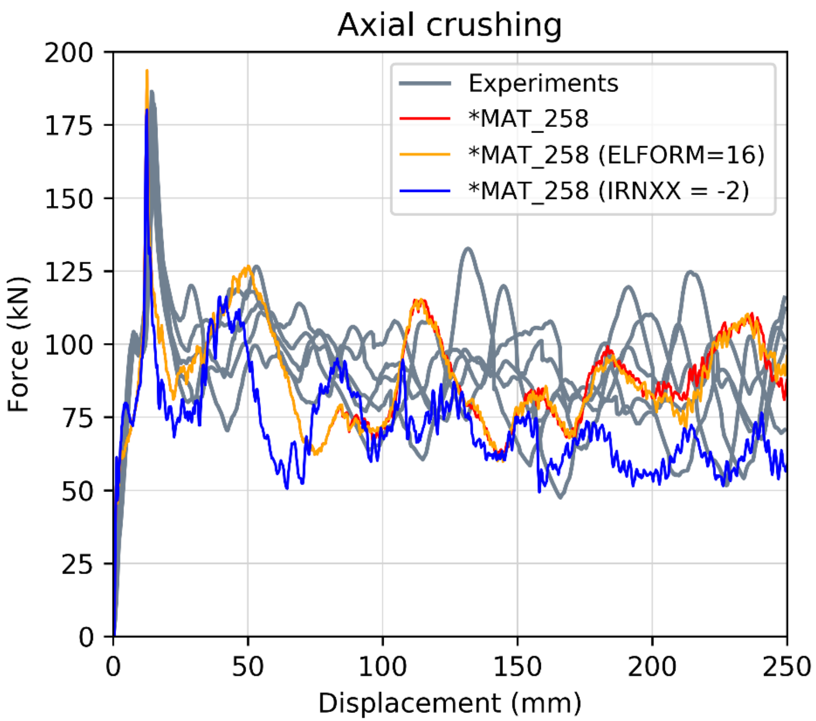
At intermediate deformation (194 mm)



At maximum deformation (250 mm)



Axial crushing

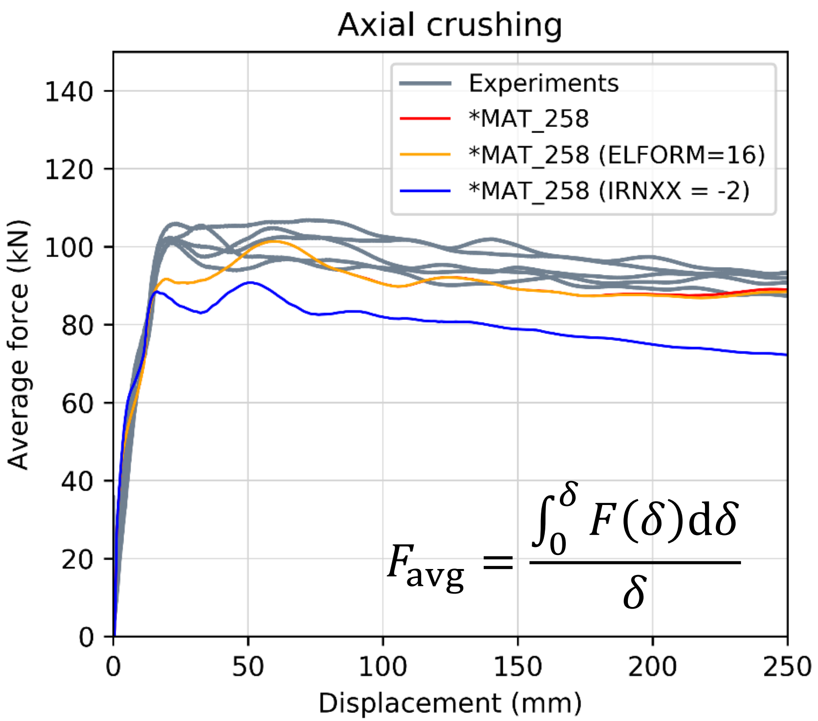


Force-displacement curves:

ELFORM=2 and ELFORM=16 give almost identical results.

IRNXX=2 generates a completely different collapse mode

Axial crushing



Average force-displacement:

ELFORM = 2 and ELFORM = 16:

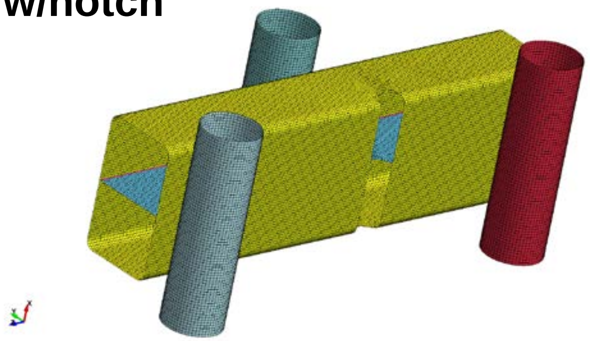
Mean force within experimental scatter starting at a displacement of 40 mm

IRNXX = -2:

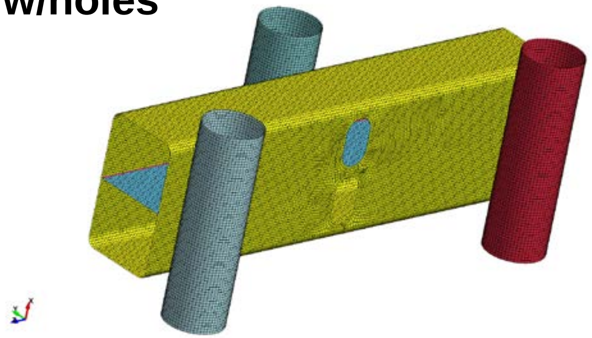
Mean much too low due to a peeling collapse mechanism instead of a buckling mechanism

3-point-bending

w/notch



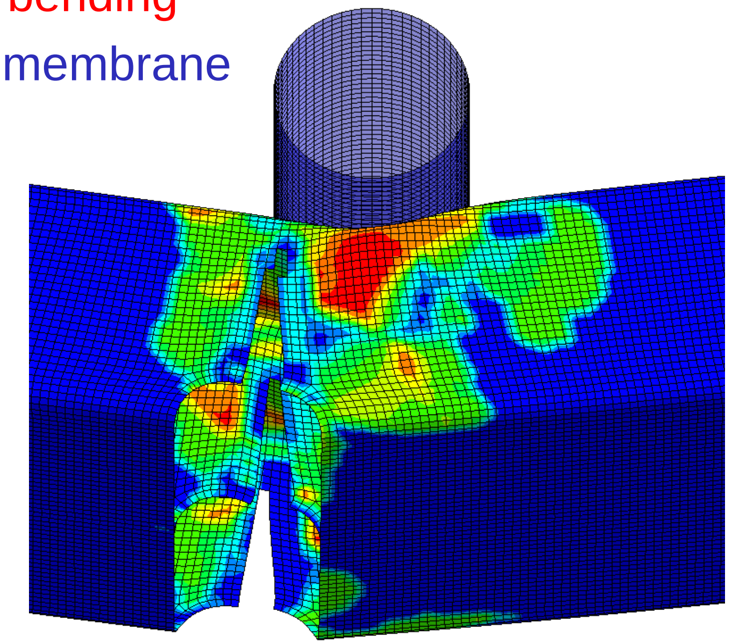
w/holes



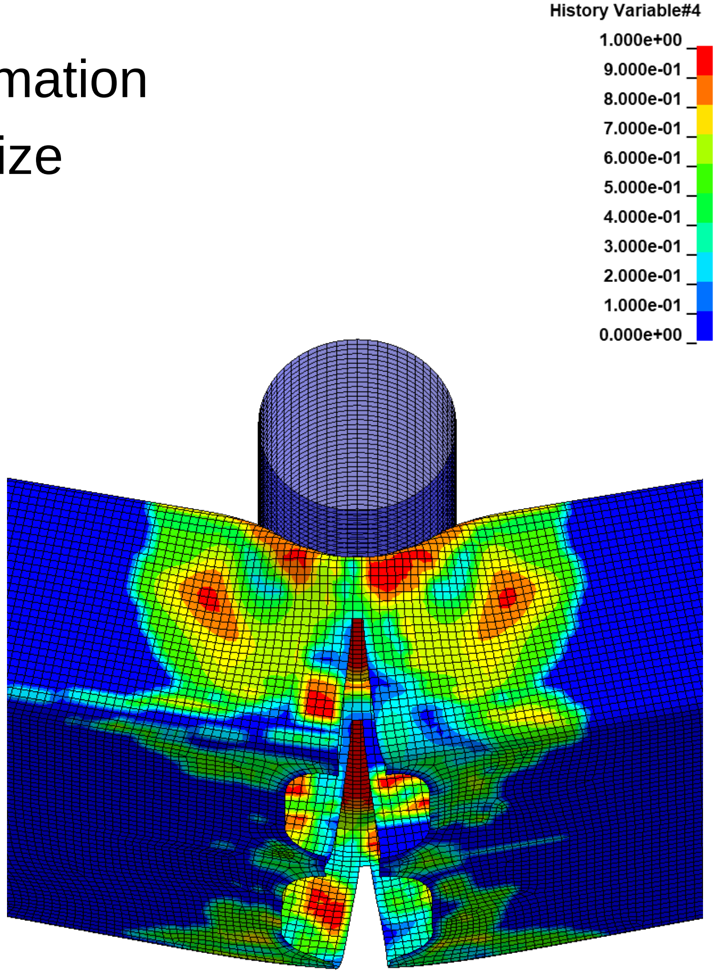
- Elem. size ≈ 2.7 mm
- 400 mm between the supports
- Punch is centered
- Time scaling factor of 3000
  - Negligible kinetic energy. Lower factor did not change the results
- Smooth ramping of the load
- Friction coefficient FS = FD = 0.05
- Account for thickness change (ISTUPD = 1)
- Rigid punch and supports

3-point-bending

- Pictures of deformed shapes after significant deformation
- Crack growth similar, but constrained by element size
- History variable #4 = Ω
  - Red = pure bending
  - Blue = pure membrane

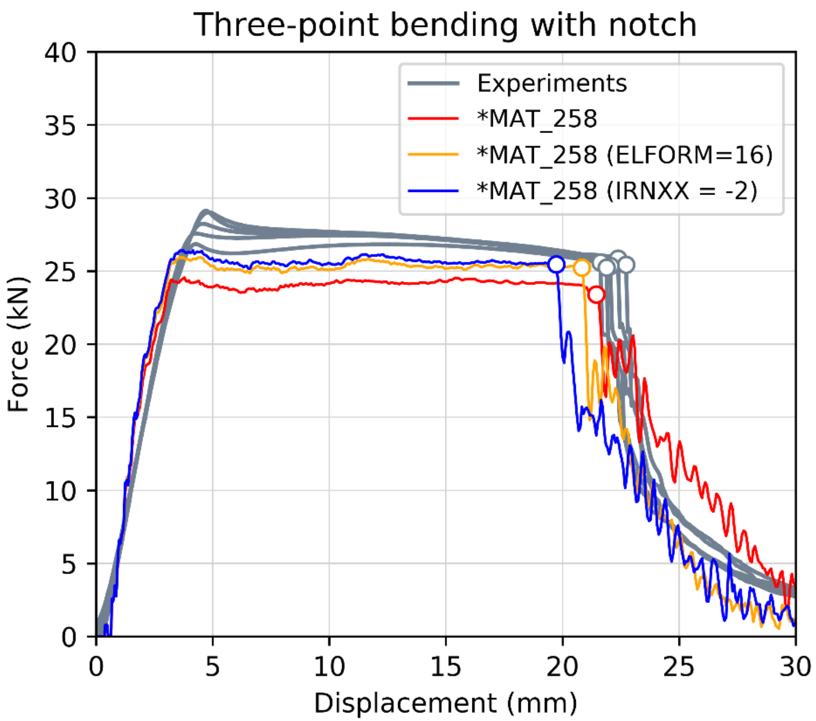


w/notch



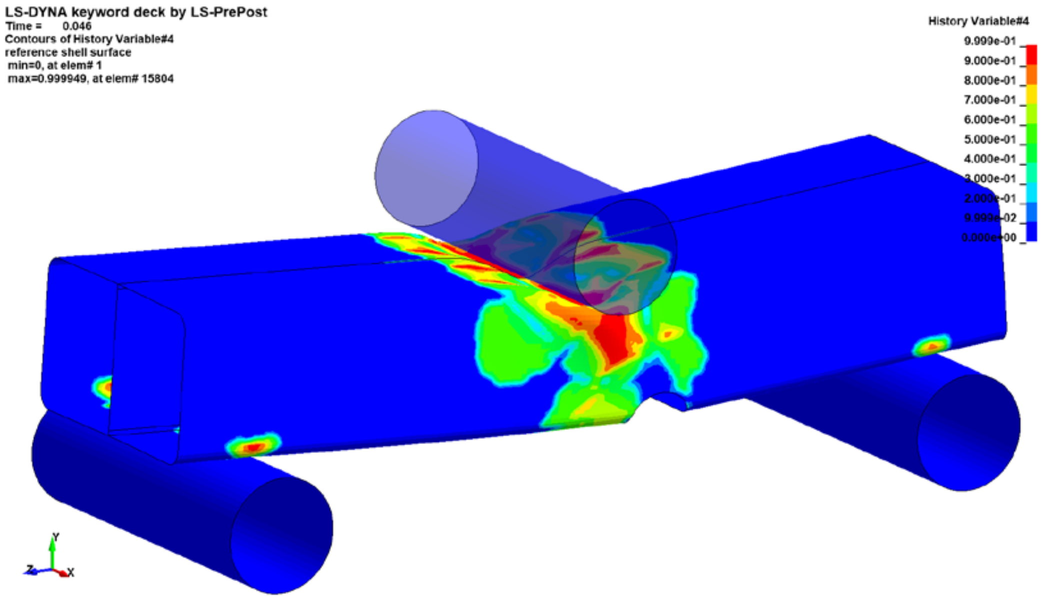
w/holes

3-point-bending with notch

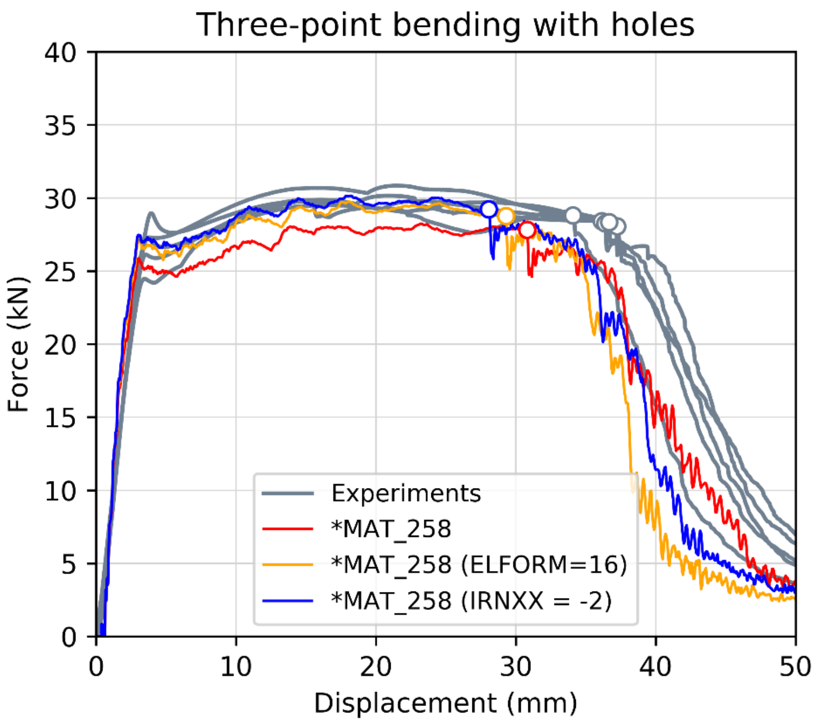


ELFORM = 2: Low force and decent point of failure.

ELFORM = 16 and IRNXX = -2: Higher force which induces earlier failure due to increased growth of *D*.

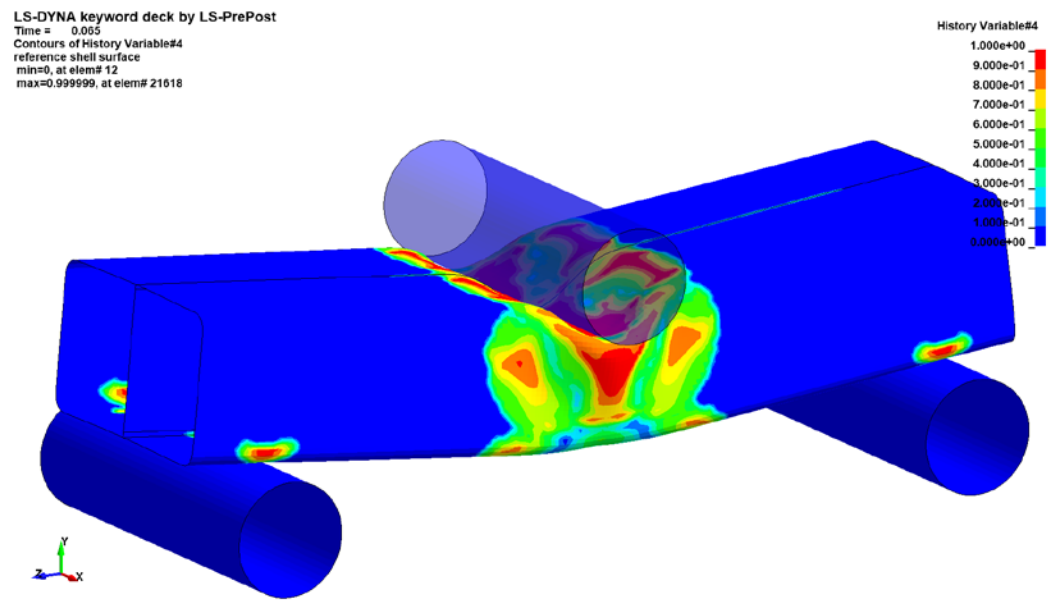


3-point-bending with holes



ELFORM = 2: Low force and early failure.

ELFORM = 16 and IRNXX = -2: Higher force which induces earlier failure due to faster growth of *D*.



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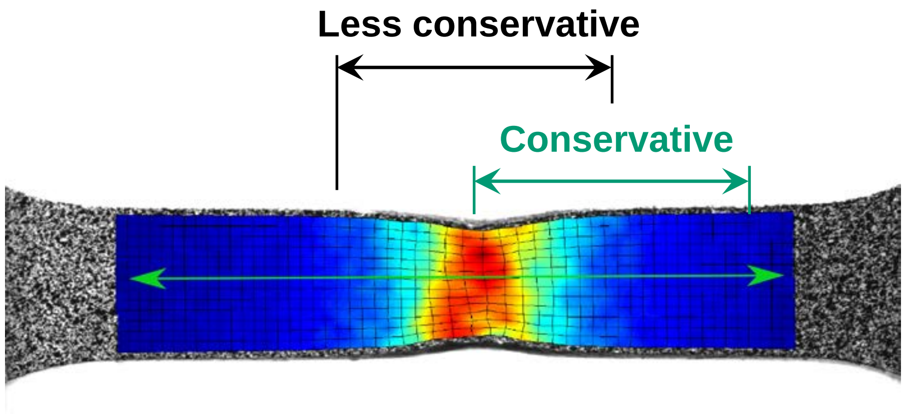
Summary – simulation results

- The mean force is **strongly** dependent upon the element formulation

- Failure initiation is conservative, which was the **intention** of the model
- Superimposing the shell elements used for calibration over the entire notch, instead of half the notch, will give less conservative results



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COARSER MESHES

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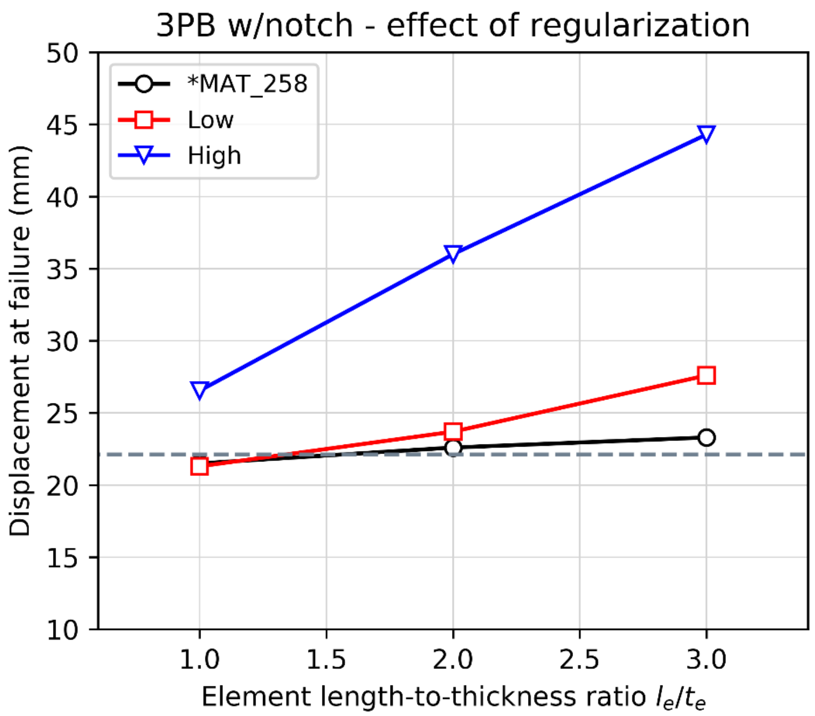
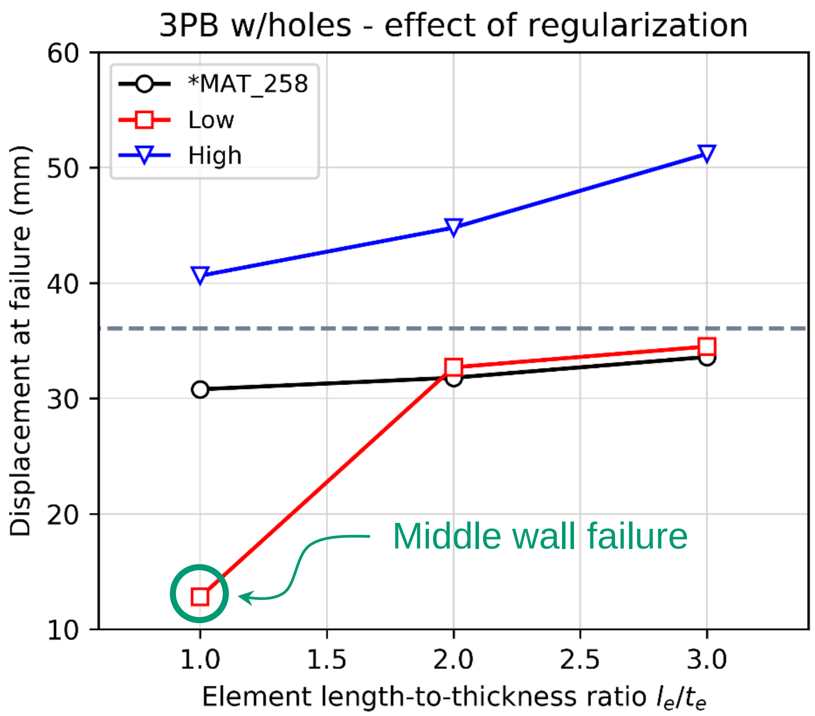
Coarser meshes

- Simulations with $l_e/t_e = 1$, 2 and 3 for three-point bending with holes and notch
- **Low** : Used $W_C = W_C^m$ for $l_e/t_e = 1$ (**68.1 MPa**)
- **High**: Used $W_C = W_C^b$ from the solid element model (**165.6 MPa**)





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SUMMARY

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Model summary

- The flexible hardening rule can represent a variety of hardening curves
- Hosford-Hershey yield function can represent von Mises, Tresca, and everything in between
- The ECL failure criterion offers great flexibility with few parameters
- Viscoplasticity is implemented
- Simple calibration
  - In this presentation is was calibrated with only one tension test
  - For more control of the failure locus, more tests can be used

References

Costas M, Morin D, Hopperstad OS, Børvik T, Langseth M. *A through-thickness damage regularization scheme for shell elements subjected to severe bending and membrane deformations*. Journal of the Mechanics and Physics of Solids. In press.

Gruben G, Hopperstad OS, Børvik T. *Evaluation of uncoupled ductile fracture criteria for the dual-phase steel Docol 600DL*. International Journal of Mechanical Sciences 2012; 62: 133-146.