Webinar (2023-05-04)

Review of quadratic shell elements in LS-DYNA implicit

Anders Jonsson, DYNAmore Nordic AB,
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Previous work

Shell and solid elements

- Schmied, C., DYNAmore Express: Solid Element Formulations in LS-DYNA, 2022
- Schmied, C., and Erhart, T., Updated review of solid element formulations in LS-DYNA, 2017
- Borrvall, T., Benson, D., and Teng, H., An implicit study of high order elements in LS-DYNA, 11th European LS-DYNA conference, 2017
- Haufe, A., et al., Predictive fracture modelling in crashworthiness: A discussion on the limits of shell discretized structures, LS-DYNA Forum 2016.
- Haufe, A., Schweizerhof, K., and DuBois, P., Properties and limits: Review of shell element formulations, Developer Forum 2013

Previous work

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11th European LS-DYNA Conference 2017, Salzburg, Austria

An Implicit Study of High Order Elements in LS-DYNA

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[1]DYNAmore Nordic AB, Linköping, Sweden
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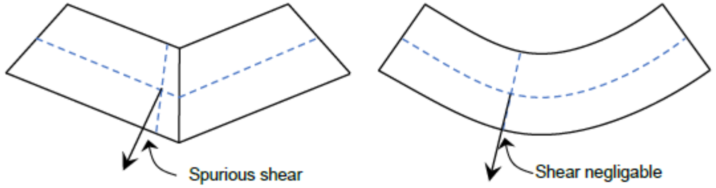

Figure 1 High order elements tend to alleviate spurious shear deformation in bending, for pure bending the shear is exactly zero in the center of the elements. The latter observation is taken advantage of in the 6-noded shell.

1 Introduction

High order elements have always been of interest in linear finite element analysis. The primary reason is that mesh convergence rate is proportional to the polynomial order of the isoparametric shape functions used, see for instance Hughes [2]. An intuitive understanding can be obtained through the illustration in Figure 1; basically the deformation space of low order elements is restricted to the extent that pure bending will inevitably induce spurious transverse shear and result in a locking phenomenon. Even though this anomaly is present in high order elements, the effect is significantly reduced with increasing polynomial order.

For decades, LS-DYNA [1] was developed with sole emphasis on explicit dynamic analyses. Computational efficiency of the involved model features, element formulations in particular, has therefore been of uttermost importance. In this context, the compromise between efficiency and accuracy has made low order elements the preferred choice while high order elements have been pushed down the priority list. The last few years, owing to a number of factors including the desire for more accuracy, improved computer technology, and an increasing use of implicit analysis, tables have turned. Users are more open to pay the price of longer simulation times with better results in return. This is true not only for implicit analysis; in explicit crash, high order elements may be required to capture the stress response necessary for assessing failure of critical components.

The present paper has focus on implicit analysis of high order shells and solids, with the intention to give an overview of the current state of the LS-DYNA capabilities in this area. Sections 2 and 3 provide theories of high order shells and solids, respectively, together with some examples and discussion. In Section 4, a description of the consistent contact treatment is given, according to the implementation of the Mortar contact in LS-DYNA, and the paper ends with a summary and outlook in Section 5.

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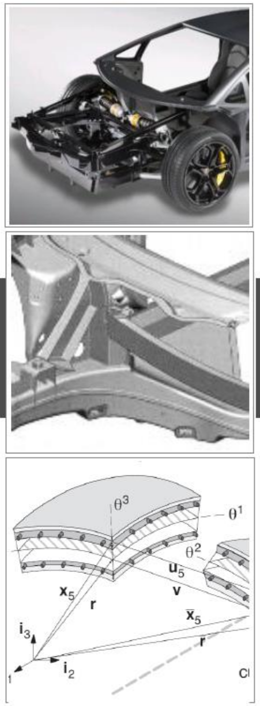
13. November 2017

Slide 1 of 62



Developer Forum

Properties & Limits:
Review of Shell Element Formulations

hell

André Haufe[1], Karl Schweizerhof[1,2], Paul DuBois[3]

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[3]Independent Consultant
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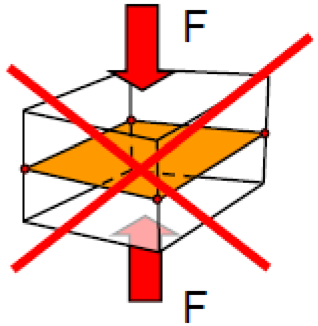
Motivation

Shell elements

- Shell elements are structural elements, with built-in assumptions on deformation behaviour etc.
  - Plane stress assumption ($\sigma_{33} = 0$)
  - 6 Degrees Of Freedom / node
- Efficient for thin walled structures
  - Thickness is a parameter, only mid surface needs to be meshed
  - Sheet metal, composite structures, paper ...
- Mesh refinement is relatively cheap due to 2D representation
  - Number of integration points (NIP) – through-thickness refinement
- But ...
  - Incorrect stress state in for example, T-junctions
  - Loading on top or bottom shell surface not possible for “standard” shell formulations



Motivation

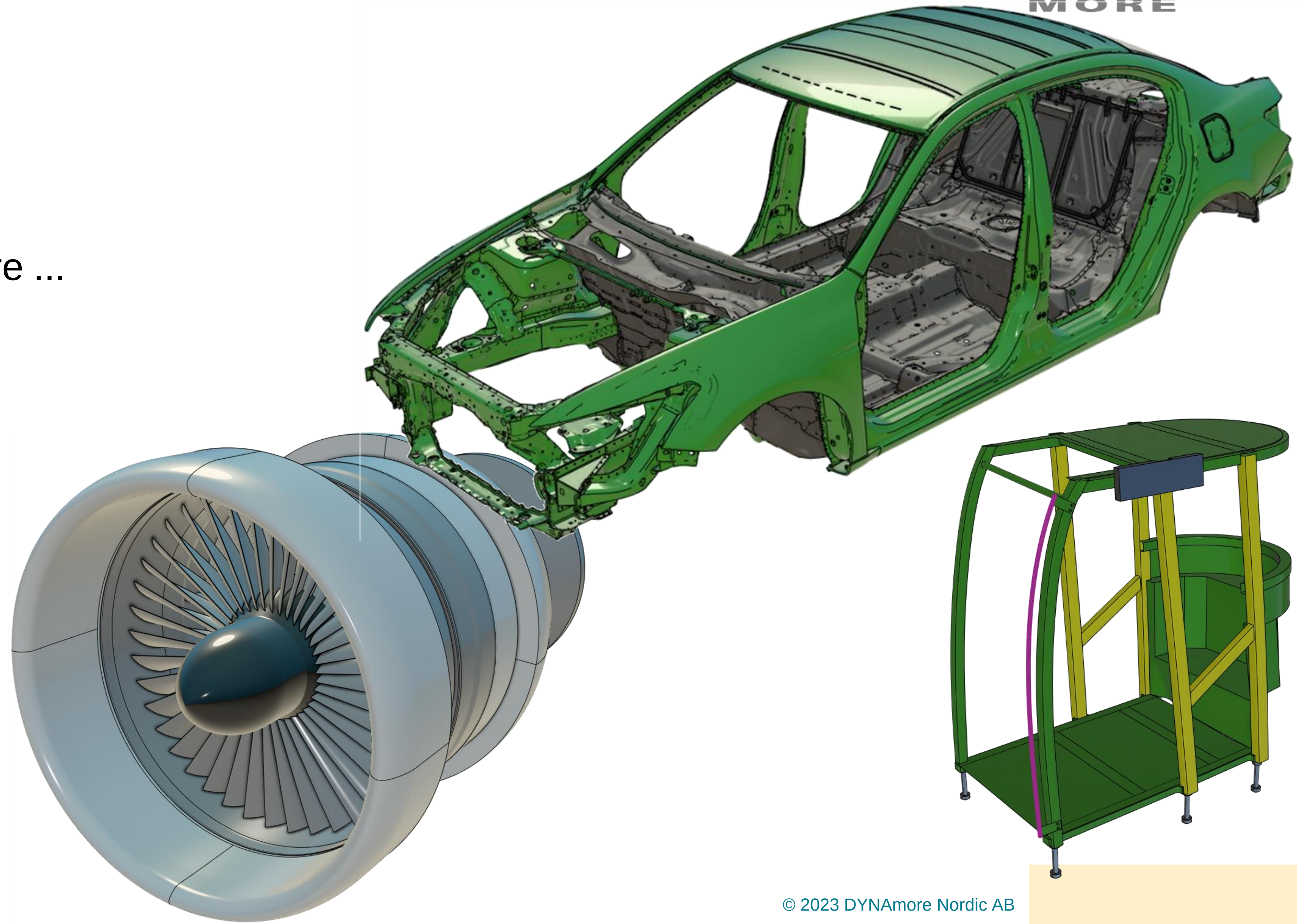
2nd order shell elements

- Higher accuracy in local stress
  - Fatigue and durability evaluations
- Recommended by some standards
  - IIW Fatigue Recommendations IIW-1823-07 / IIW-2141-07 / XV-1254-07 (2008)
- ... and textbooks
  - Eriksson, Å, et al., Svetsutvärdering med FEM, Industriliteratur, Stockholm (2002)
  - Barsom, Z., Guidelines for fatigue and static analysis of welded and un-welded steel structures, KTH Royal Institute of Technology, 2020

Applications

Shell elements

- Car BiW
  - IP, suspension
- Tubes, beam structure ...
- Containers, casings
- Ship hull
- Offshore platforms
- Wind turbine



Overview

***SECTION_SHELL**

- Over 50 shell element formulations available
- The main focus of the present review is on 1st order shell element formulation 16 vs. 2nd order formulation 23

EQ.16:	Fully integrated shell element (very fast)
EQ.23:	8-node quadratic quadrilateral shell
EQ.24:	6-node quadratic triangular shell

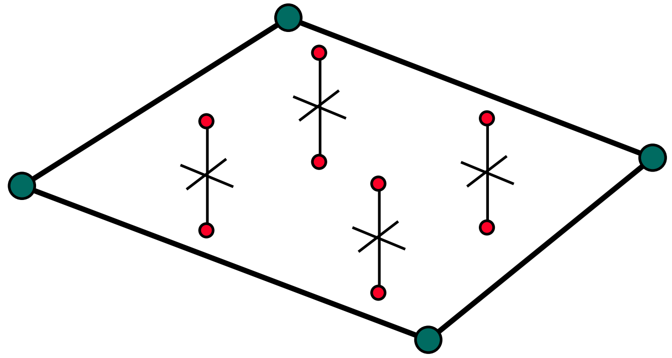
- For both 1st and 2nd order shells, quads and trias can be mixed in the same part.
  - By *ESORT* = 1 on `*CONTROL_SHELL`, 1st order trias will be sorted to elform 4 (C0 triangular shell)
  - By *ESORT* = 2 on `*CONTROL_SHELL`, 1st order trias will be sorted to elform 17 (DKT triangular shell)
  - 2nd order trias will be sorted to elform 24.

Shell elements in LS-DYNA

Element formulations

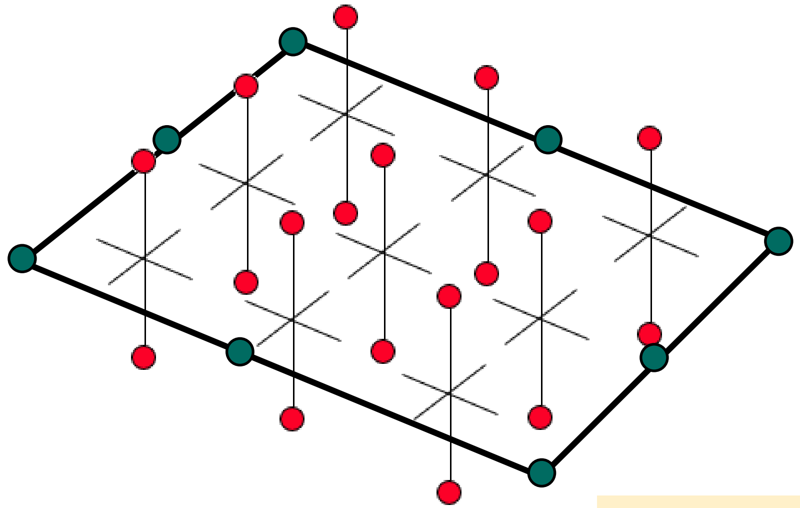
ELFORM 16

- Fully integrated, with selective reduced integration
- May need hourglass stabilization in some situations
  - Hourglass type 8, Full projection warping stiffness
  - Not used in the present study



ELFORM 23, 24

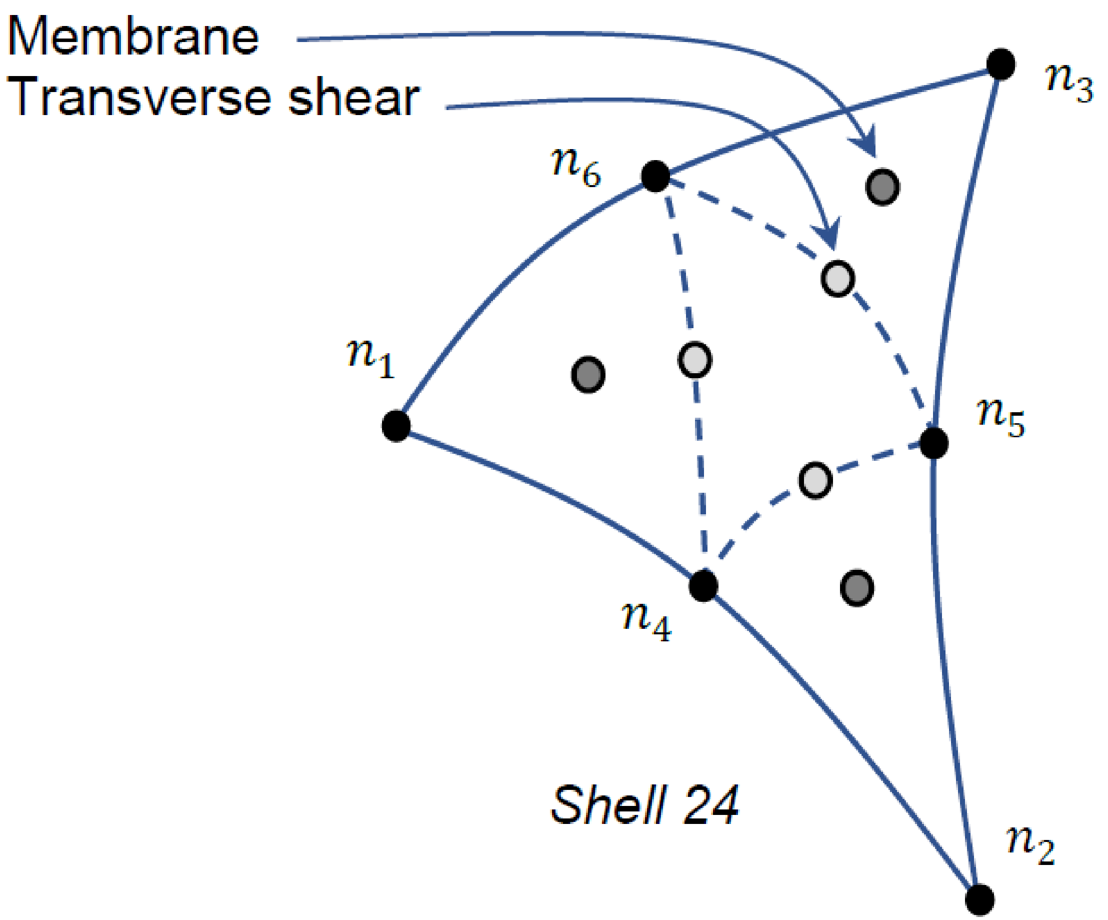
- 8 nodes for quad, 6 nodes for trias
  - Serendipity-type
- 3x3 (default) or 2x2 (optional) in-plane integration points
  - *IRQUAD* on `*CONTROL_SHELL`



Second-order shells in LS-DYNA

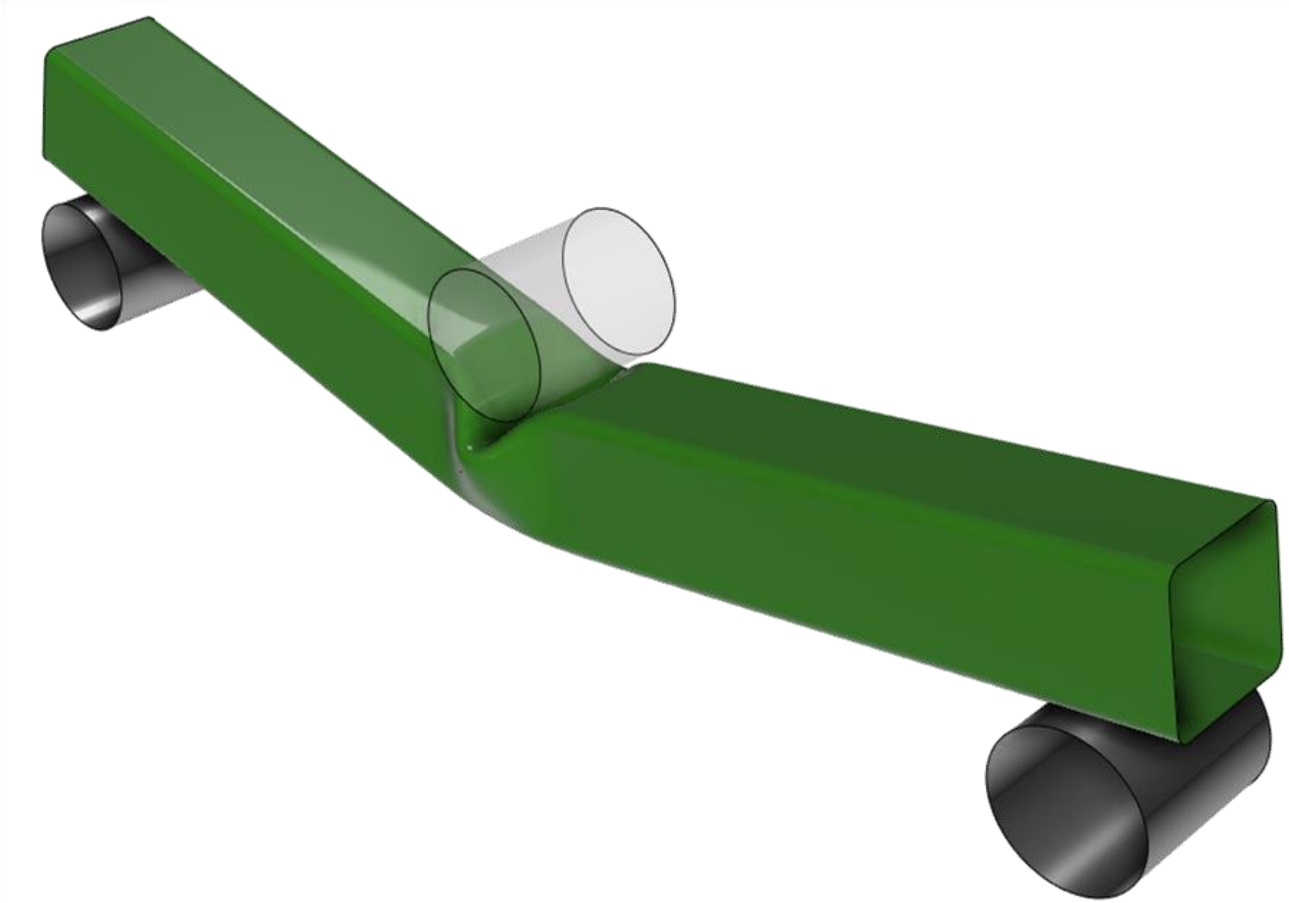
Shell element formulations 23, 24

- With *IACC* = 1 on `*CONTROL_ACCURACY`, the 2nd triangular element formulation 24 is switch to an enhanced assumed strain formulation to alleviate shear locking
  - See Borrvall, T., Benson, D., and Teng. H. "An implicit study of high order elements in LS-DYNA", 11th European LS-DYNA Conference.
- The option to have 2×2 or 3×3 in-plane integration points for 8-node quadratic shells
  - *IRQUAD* on `*CONTROL_SHELL`
  - In this presentation, only the default option (3×3) was used
- `*PART_COMPOSITE` supported from R14



Examples

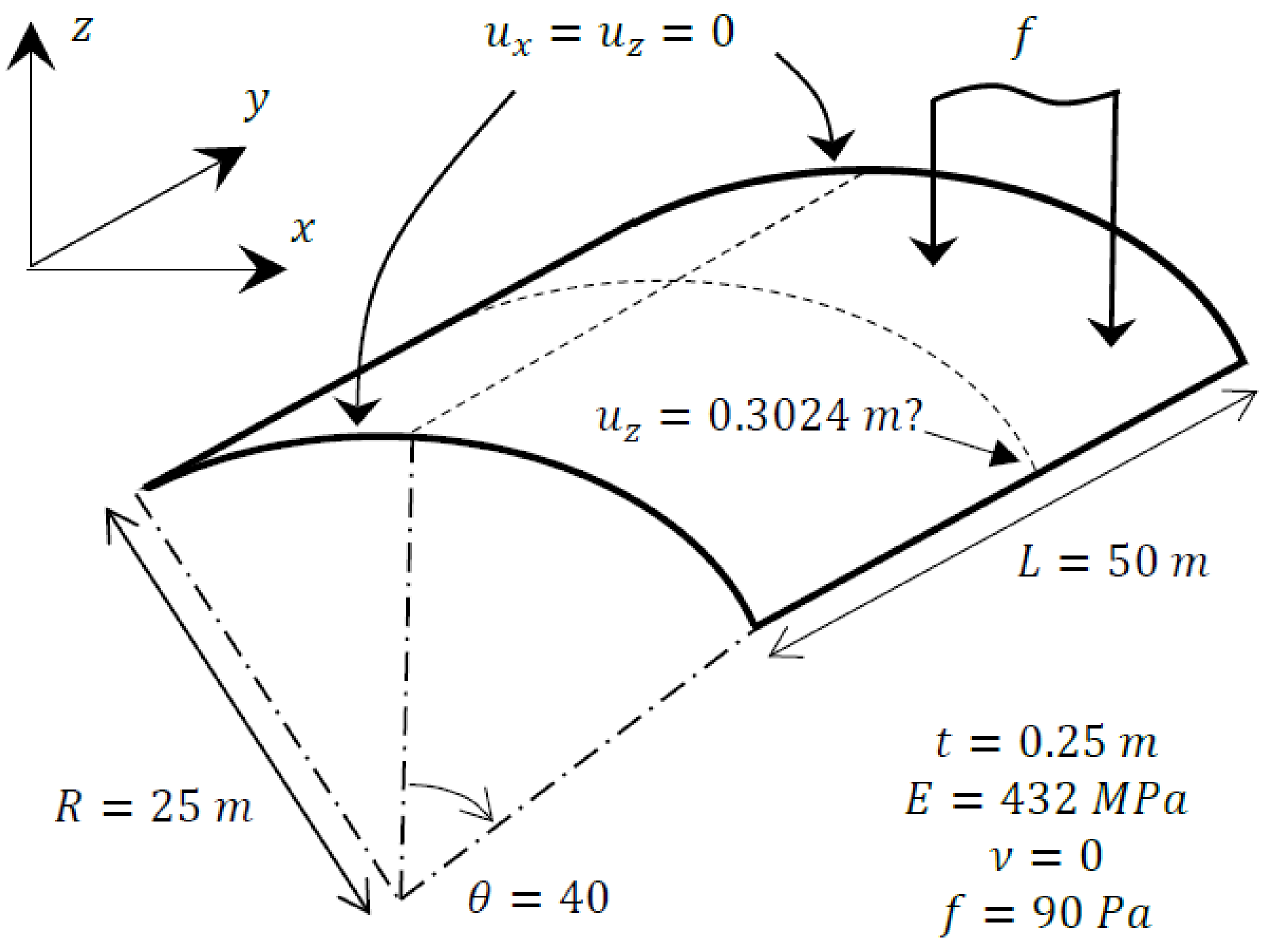
Linear and non-linear, focusing on implicit



The Scordelis-Lo roof

Linear analysis

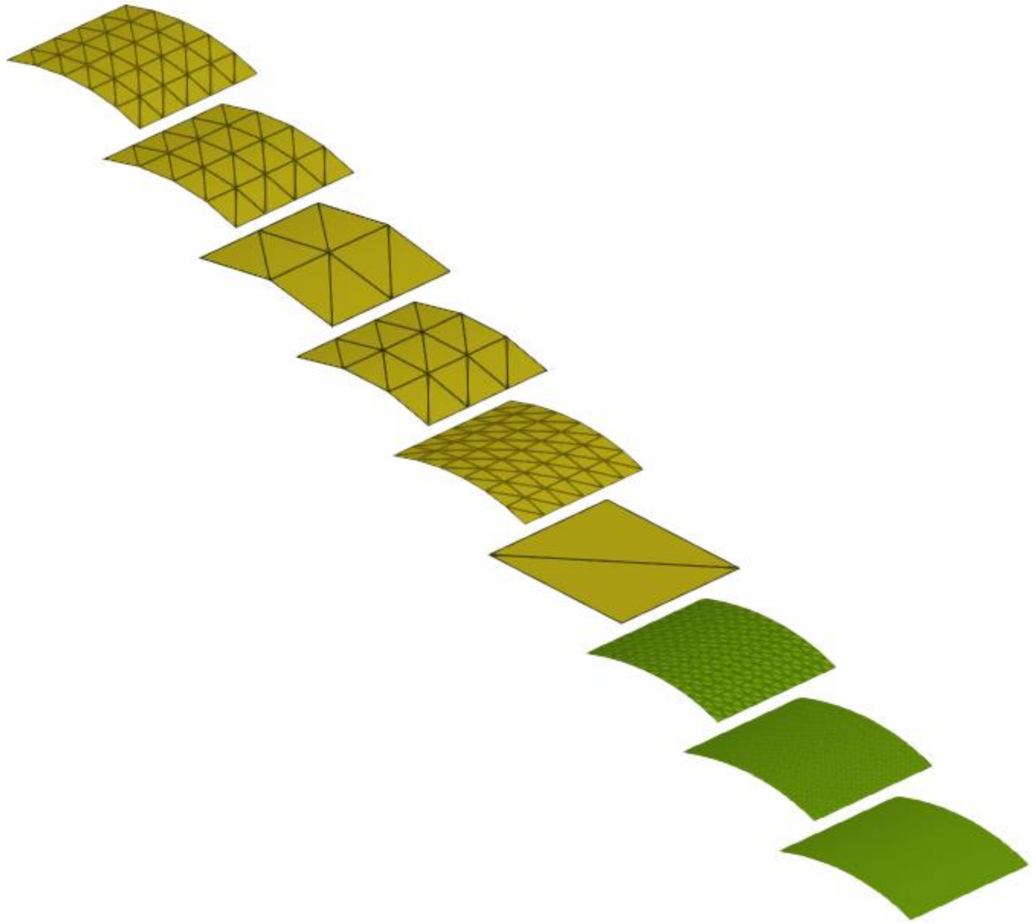
- Standard test example for validating a shell element implementation
- Uniform load applied
- Target deflection at the mid point of the free edge: 0.3024 m
- Useful for studying mesh convergence
- Comparison between
  - 1st order trias and quads, and
  - 2nd order trias and quads



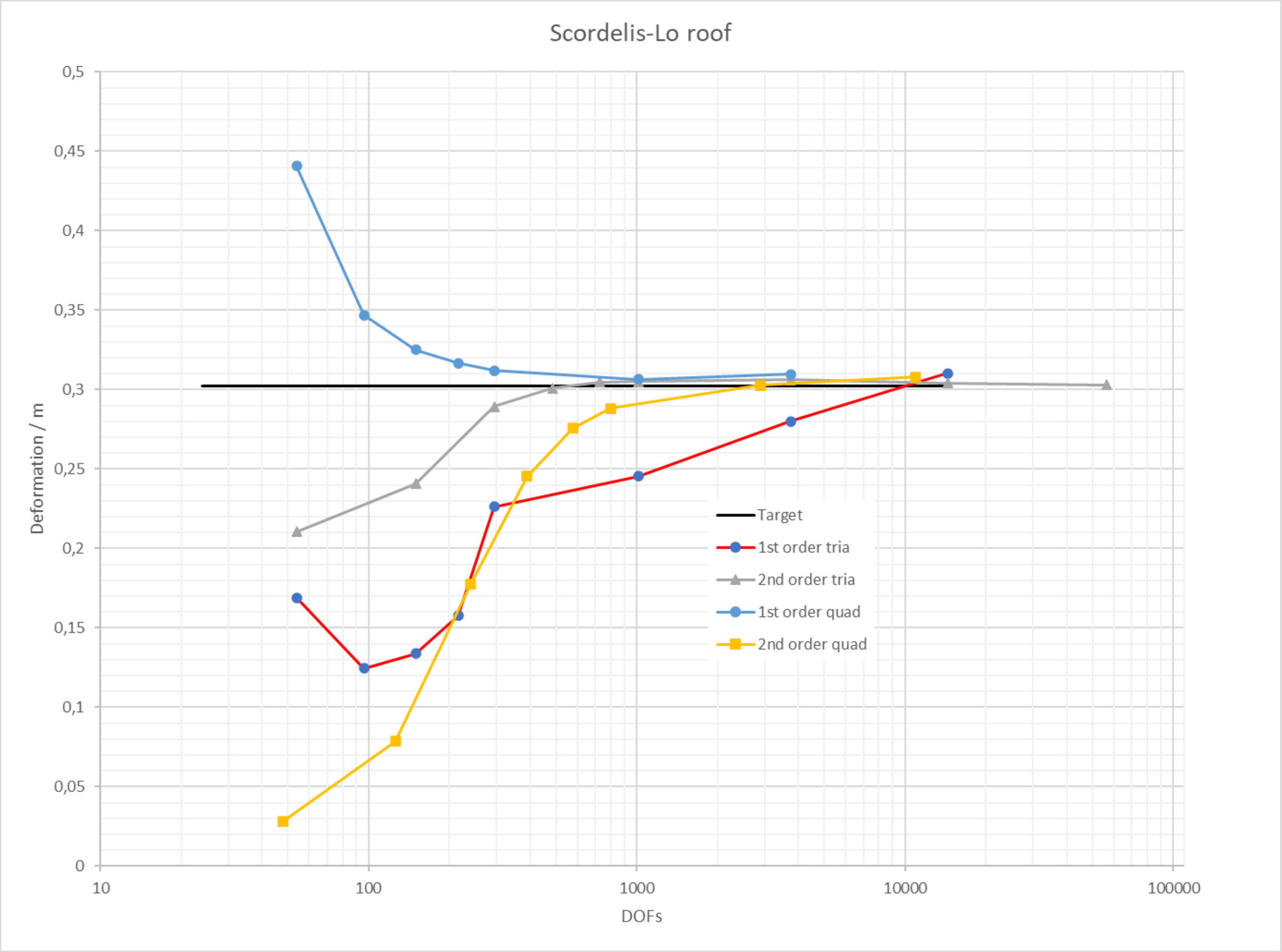
The Scordelis-Lo roof

Linear analysis

- Geometries



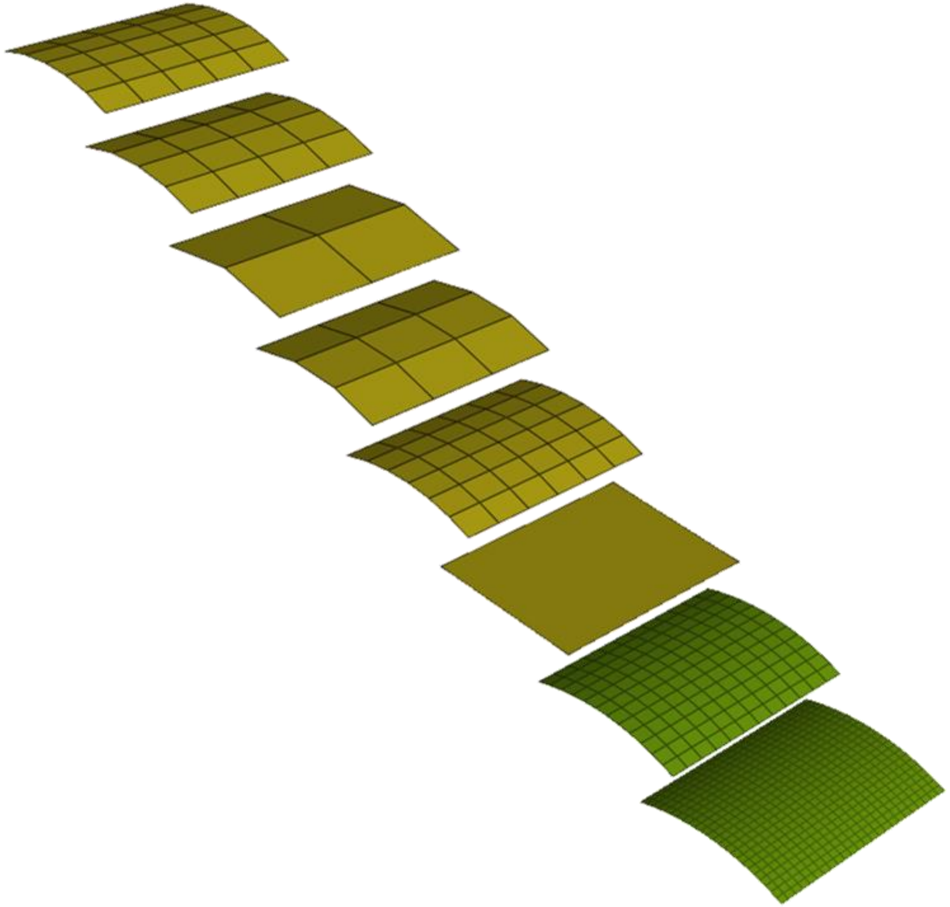
- Results



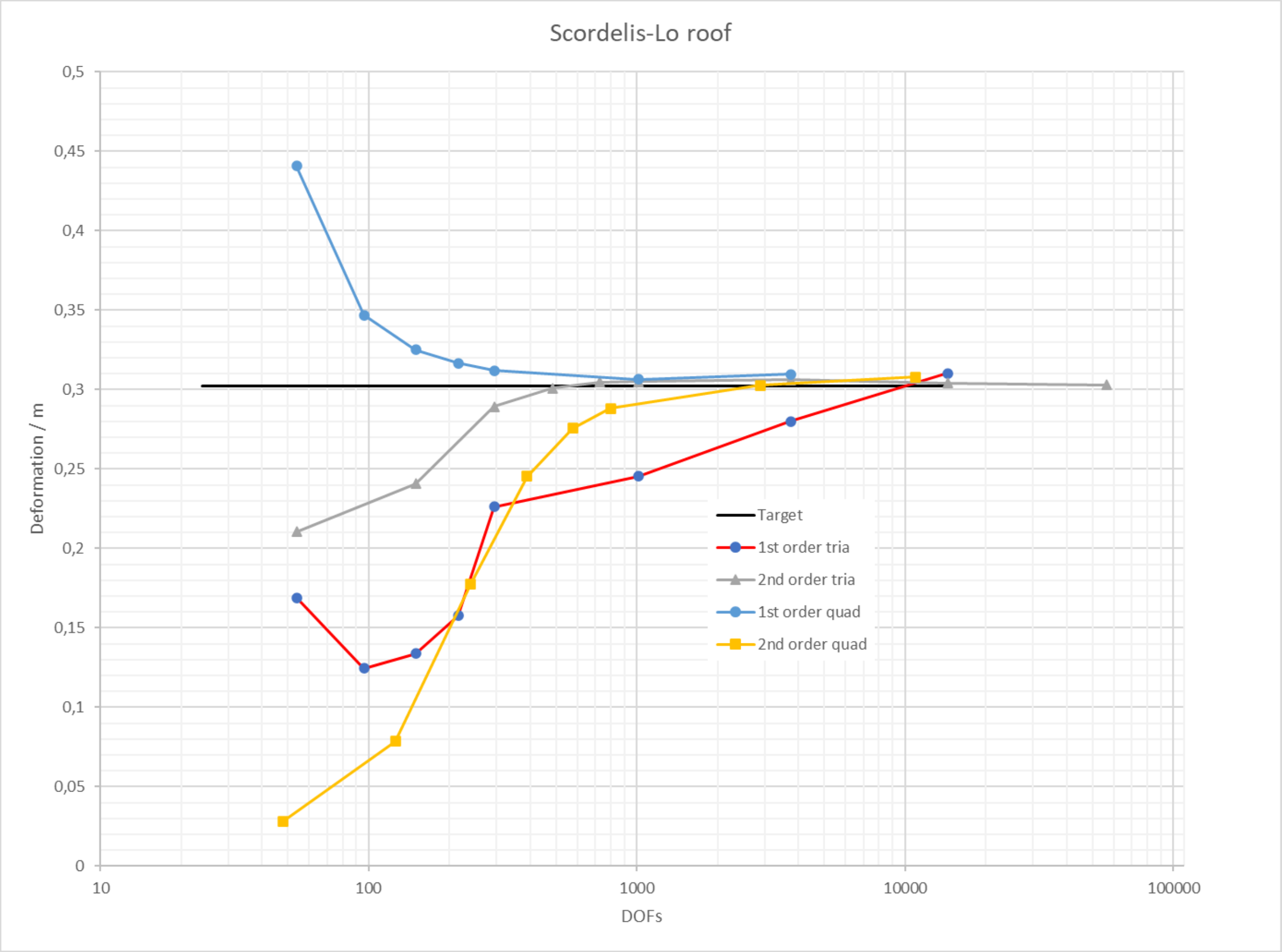
The Scordelis-Lo roof

Linear analysis

- Geometries (Quads)

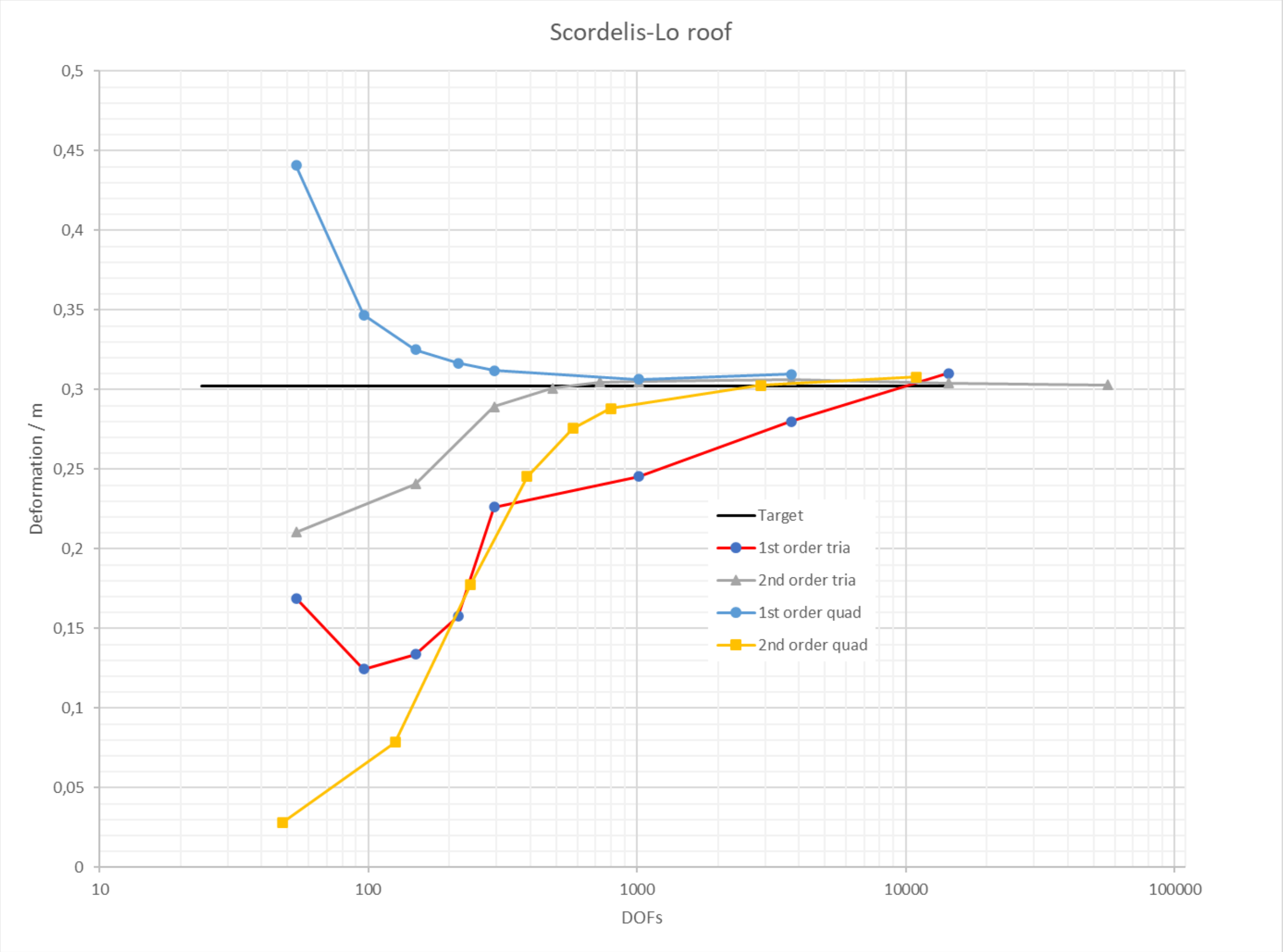


- Results



The Scordelis-Lo roof

Linear analysis

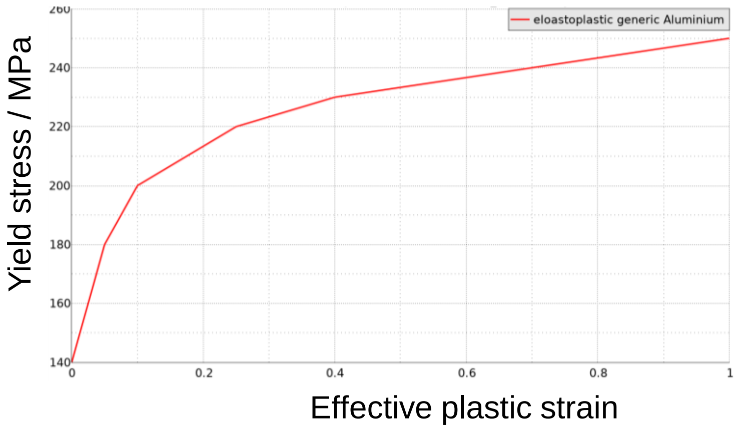


- Results
  - In this case the 2nd order tria (enhanced assumed strain IACC=1 version) shows the best performance
  - 2nd order quads require more DOFs to converge than 1st order quads
  - 1st order trias perform quite poorly

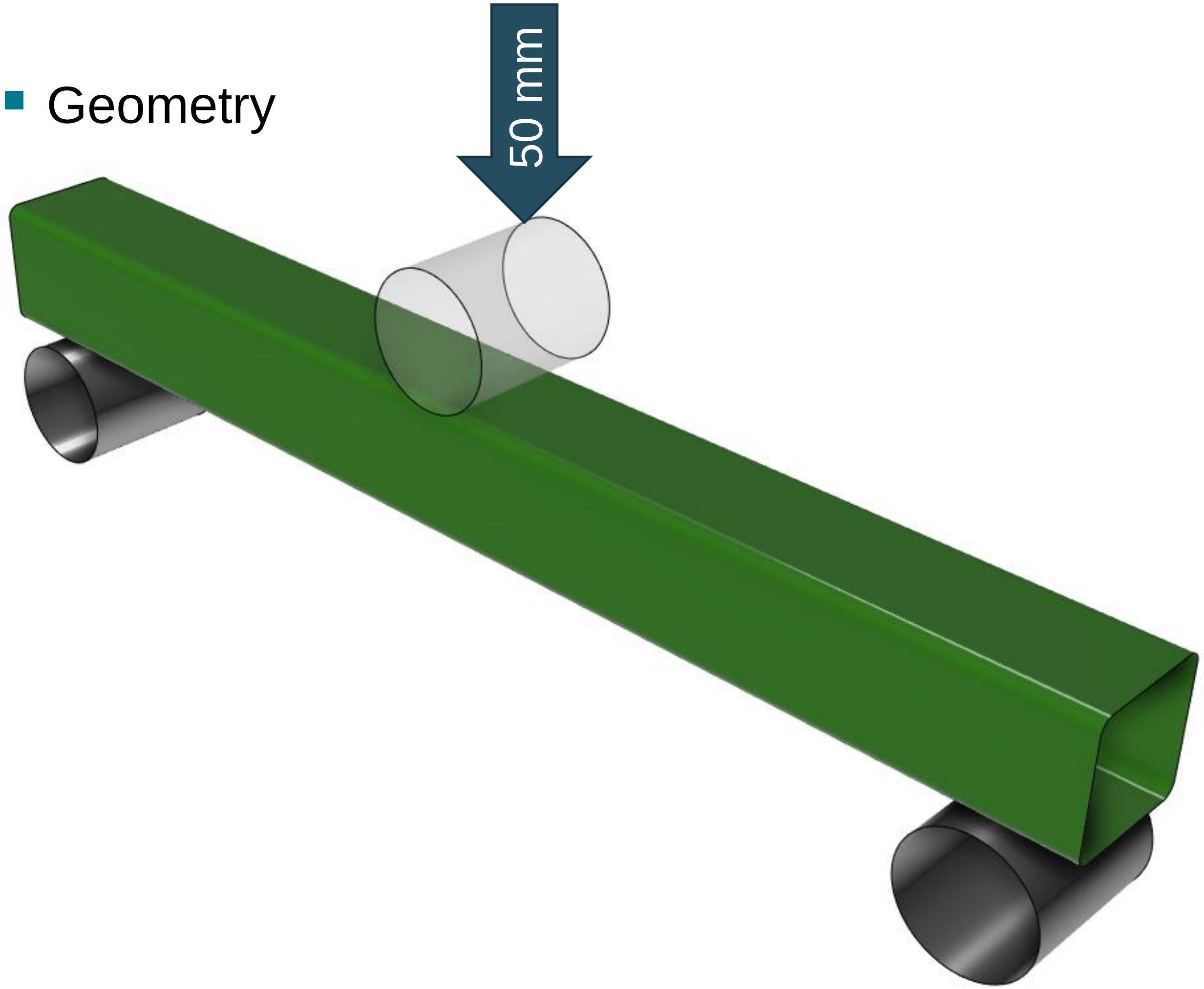
Three-point bending

Non-linear analysis

- Implicit 3 point bending by prescribed motion
  - 50 mm
- Square tube
  - 50×50 mm, t = 2 mm
  - Length = 500mm
  - Distance between supports = 440 mm
  - Supporting cylinders ∅ = 50 mm
- *MAT_24 with assumed material properties



- Geometry



Three-point bending

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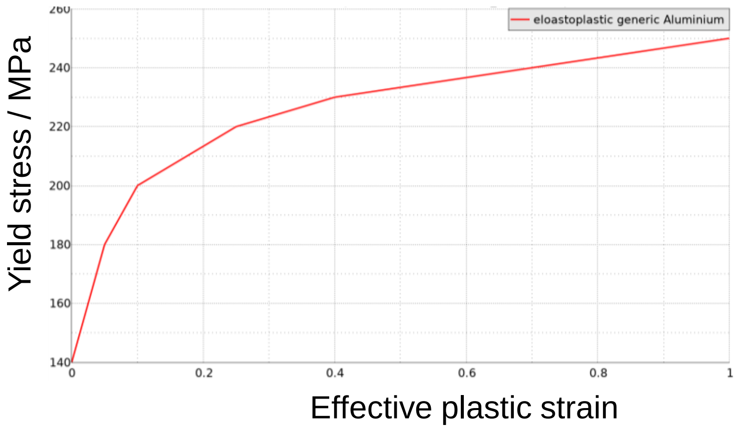
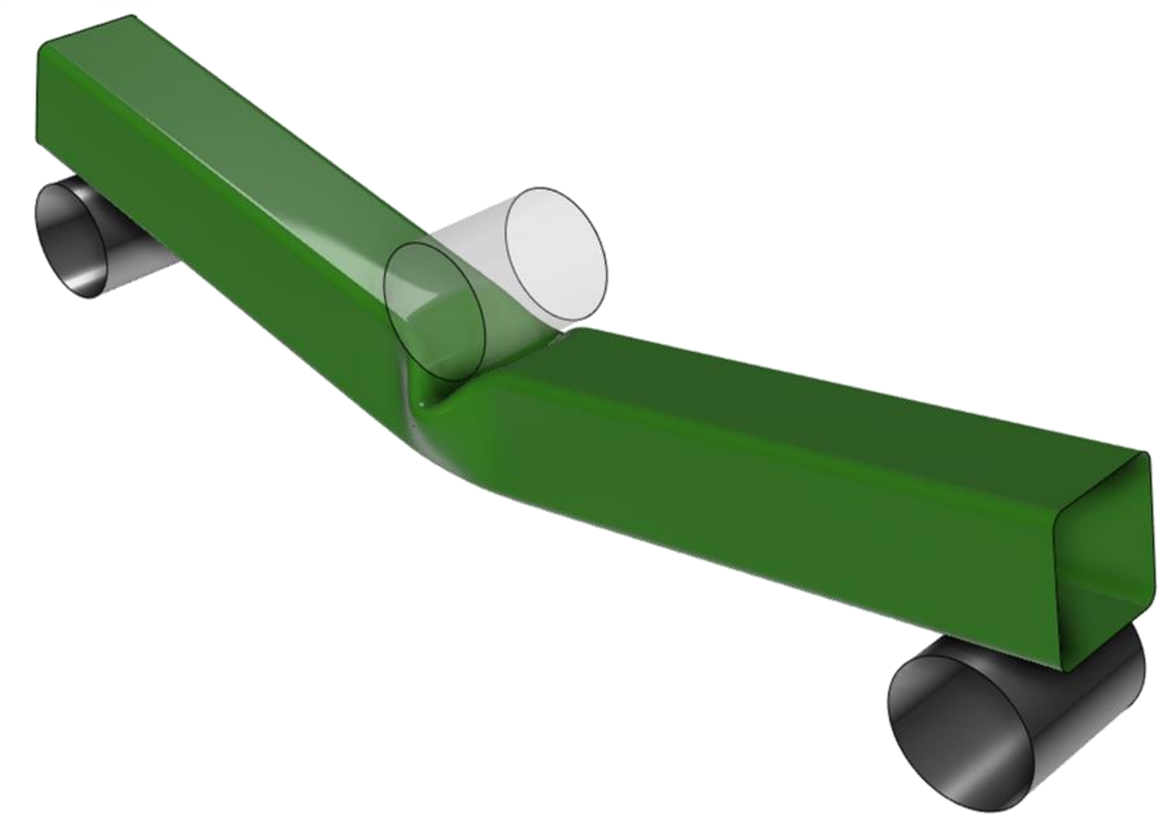
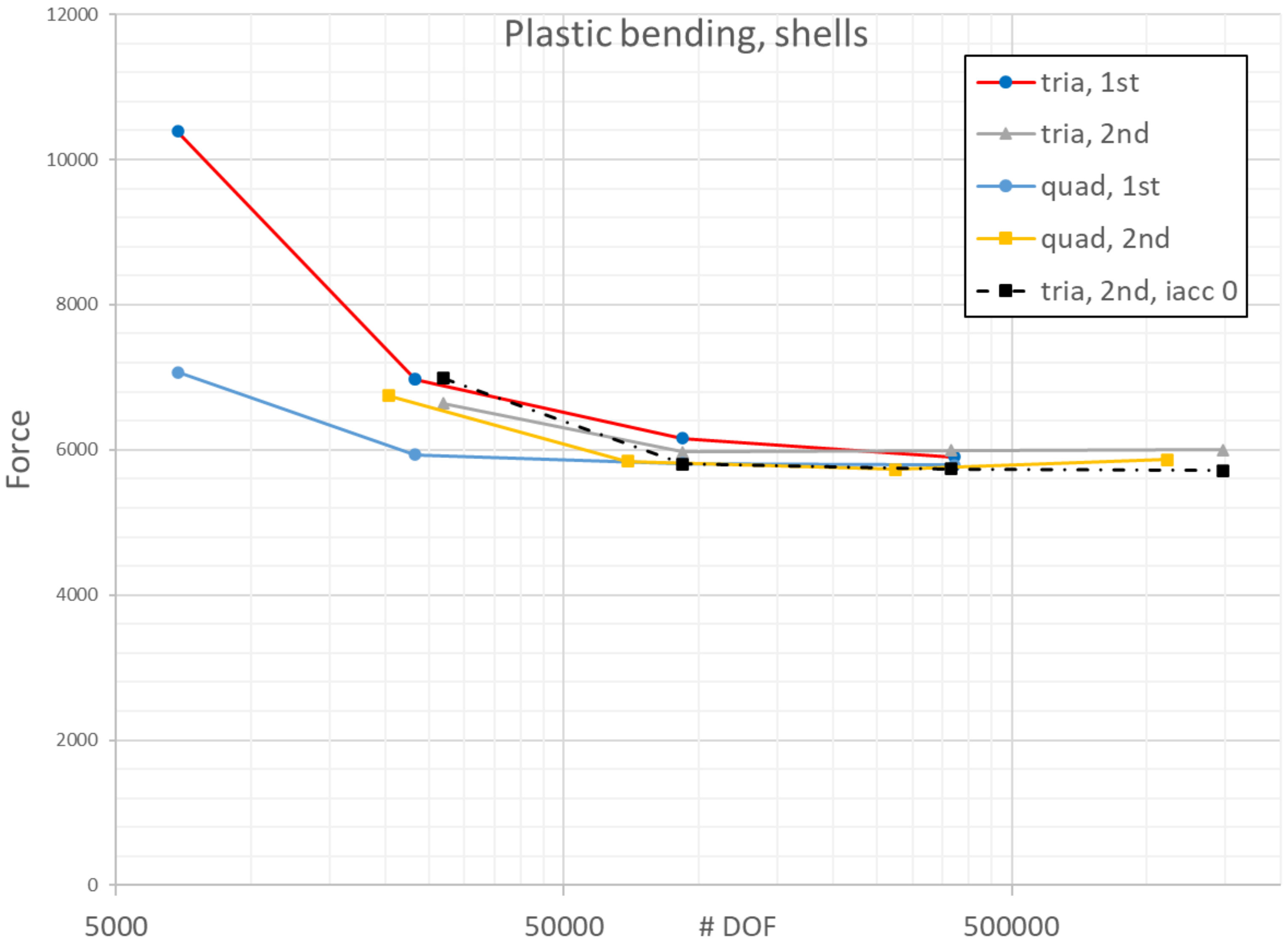


- Deformation



Three-point bending

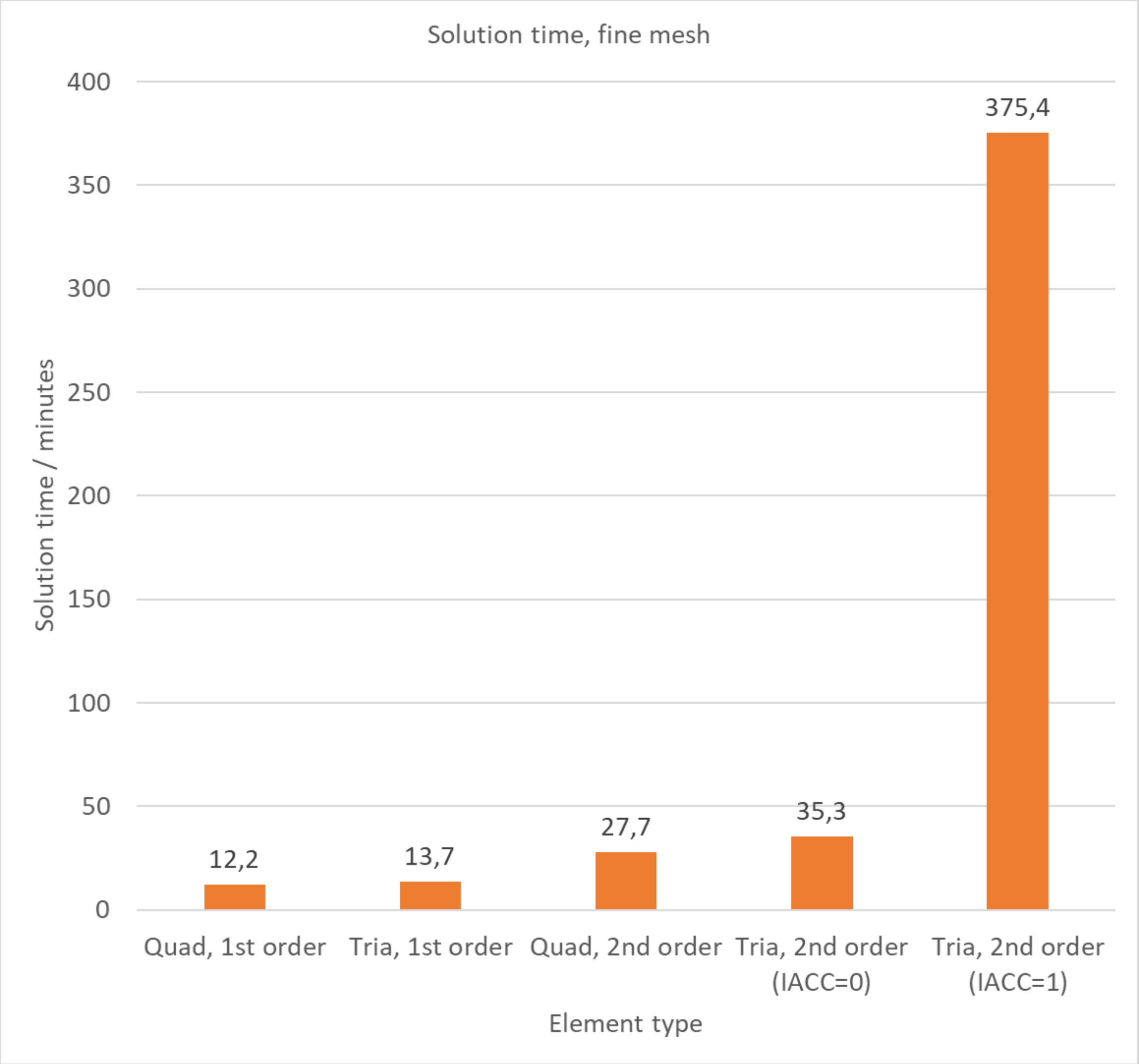
Results



- Good convergence with ELFORM 16 and 23
  - Lower force for IACC=0 version of the 2nd order tria (ELFORM 24)
- Quite poor convergence for 1st order trias in this case

Three-point bending

CPU Time in minutes



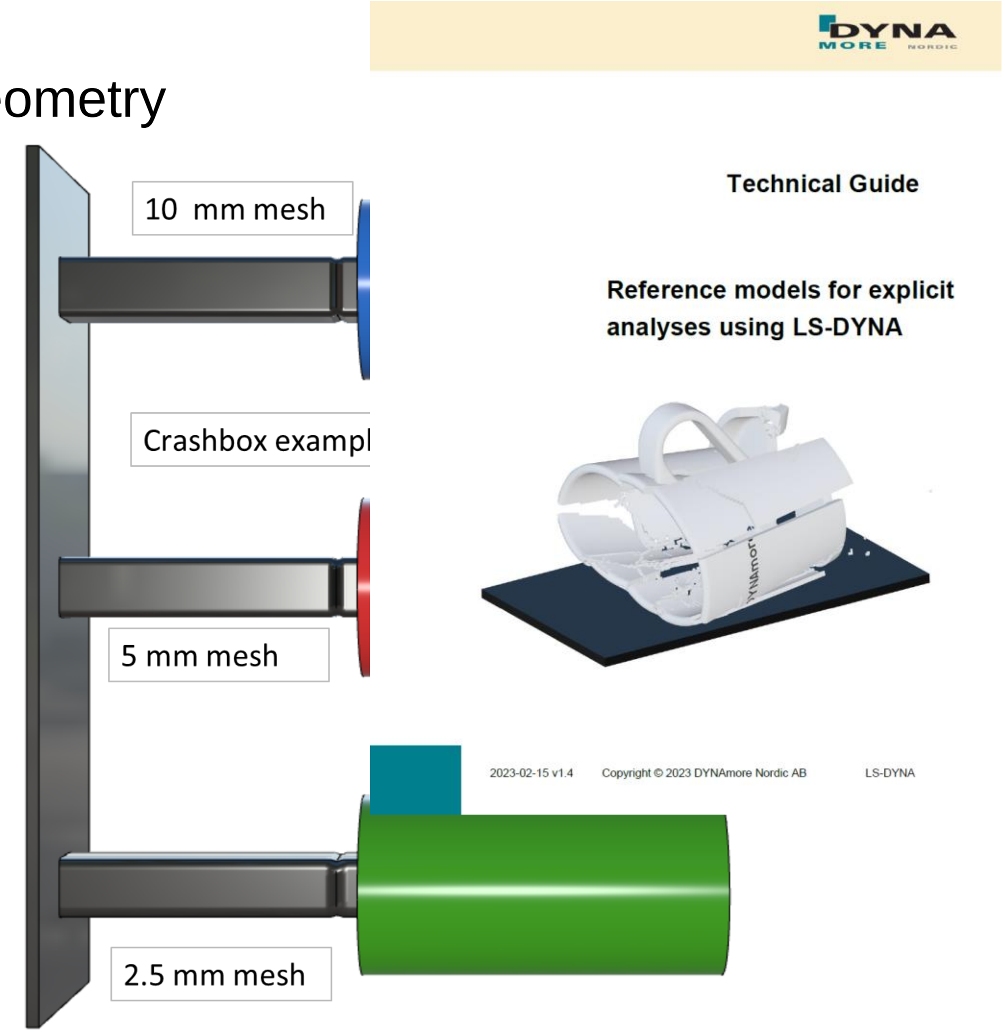
- The 2^{nd} order trias are very expensive in this case, if the `IACC = 1` version (assumed enhanced strain) is used
  - More iterations / retries are required, since the enhanced assumed strain formulation is more sensitive to the (relatively large) deformation that occurs in this case.

Crash box

Explicit analysis

- Example 2: Crash box from the Technical Guide – Reference models for explicit analyses using LS-DYNA
- Existing models converted to 2nd order mesh
- 1st order Shells elform -16 vs. 2nd order shells elform 23
  - Pure quad mesh

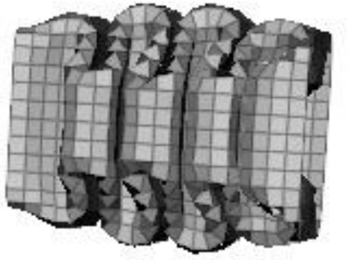
- Geometry



Crash box

Final deformation

1st order , ELFORM -16



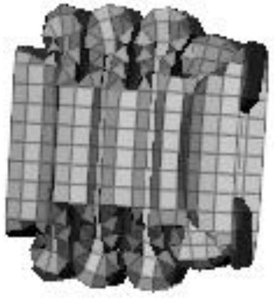
10 mm

5 mm

2 .5 mm

2nd order shells, ELFORM 23

-



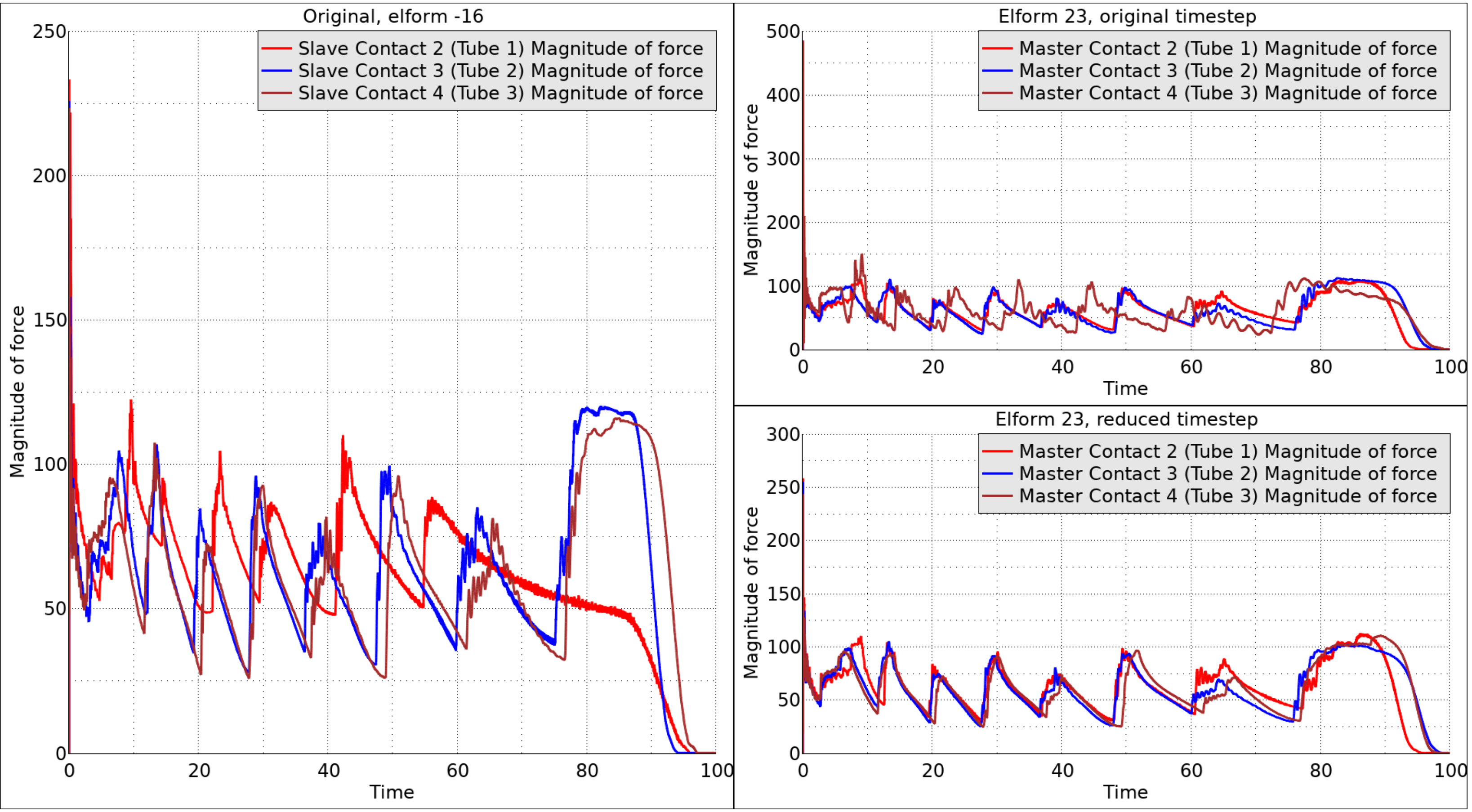
10 mm

5 mm

2 .5 mm

Crash box

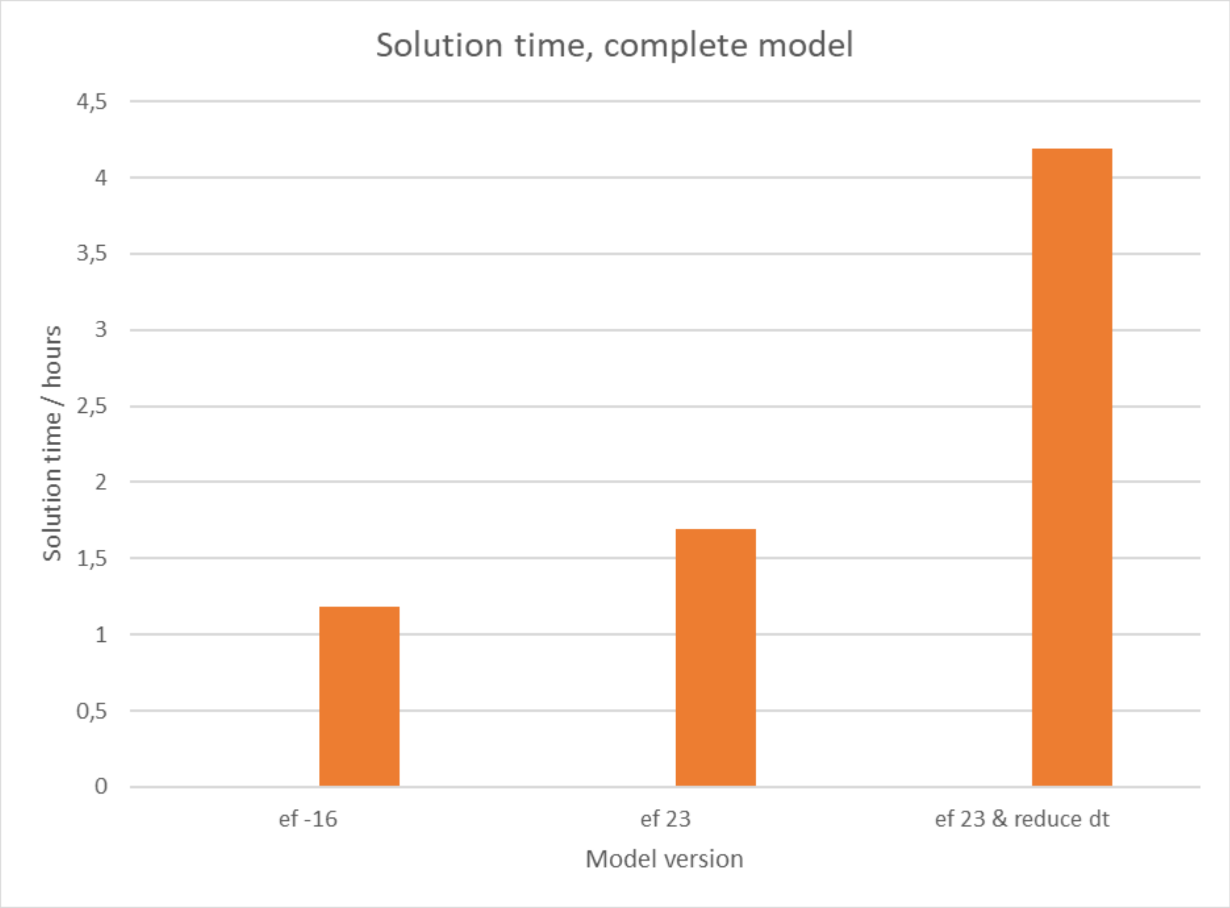
Results: Force vs. time



- To get useful results for 2nd order shells, the explicit time step was reduced to 1.2111E-4 ms, compared to 3.3333E-4 ms for 1st order shells.
  - The reduced time step gives 0.4 % added mass on the deformable parts.
- For 2nd order shells, similar results are obtained for all three mesh sizes.
- For 1st order shells, results for the coarse mesh are most likely not converged.

Crash box

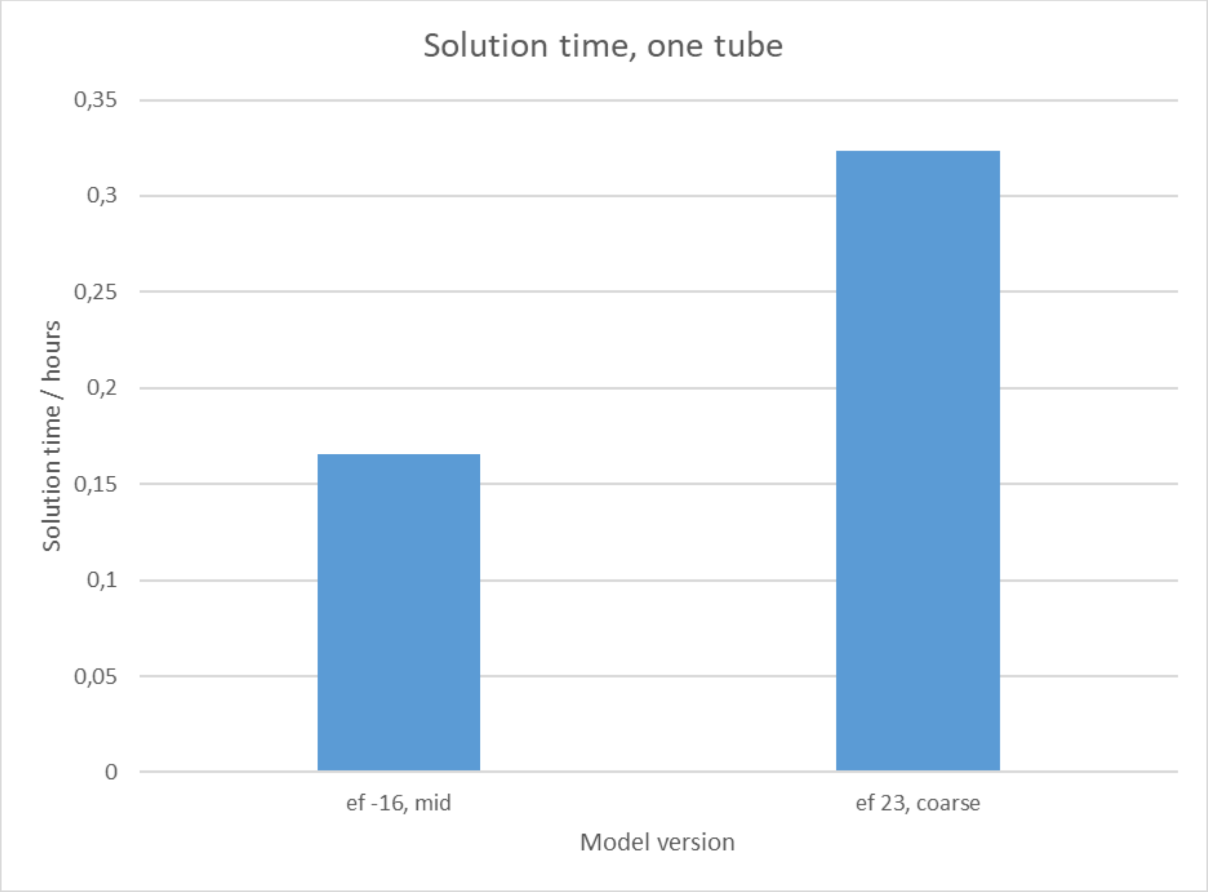
CPU Time in hours for the explicit analysis



- Results for the complete model, 3 mesh sizes
- With the reduced time step, solution time is about 3.5 times longer for quadratic shells.

Crash box

CPU Time in hours for the explicit analysis



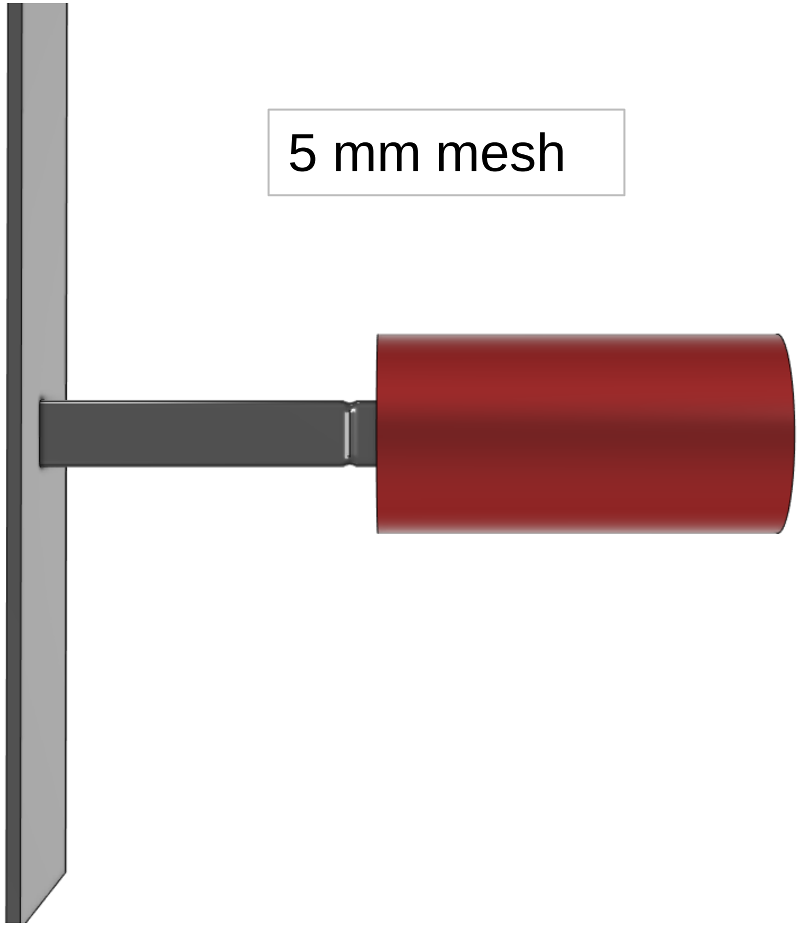
- Results for one tube
- Comparing refined 1st order mesh with coarse 2nd order mesh
- Considering the possibility to use a coarser mesh with the quadratic elements, the solution time for 2nd order shells is about twice as long as for 1st order shells.

Crash box

Non-linear implicit analysis

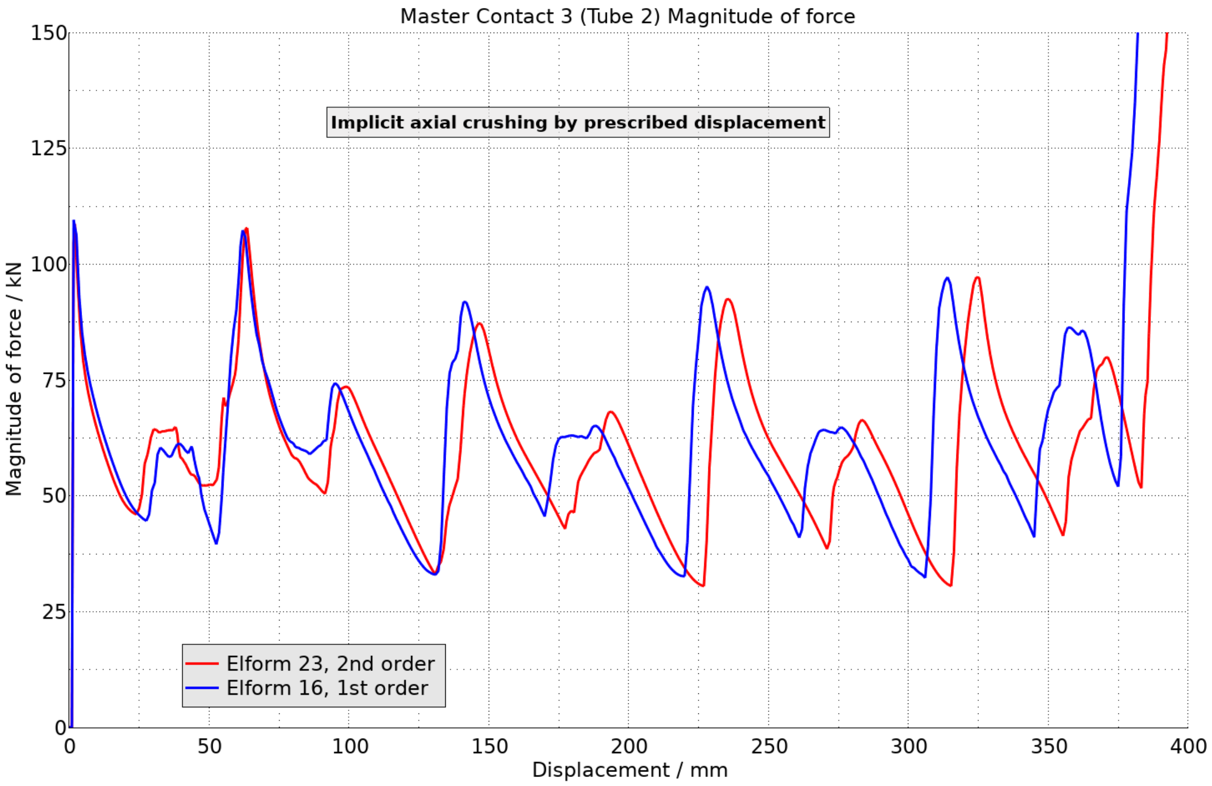
- Example 2: Crash box from the Technical Guide – Reference models for explicit analyses using LS-DYNA
- Existing models converted to 2nd order mesh
- Converted to implicit static analysis by prescribed displacement of the impactor
- Only one mesh size was studied

- Geometry



Crash box implicit

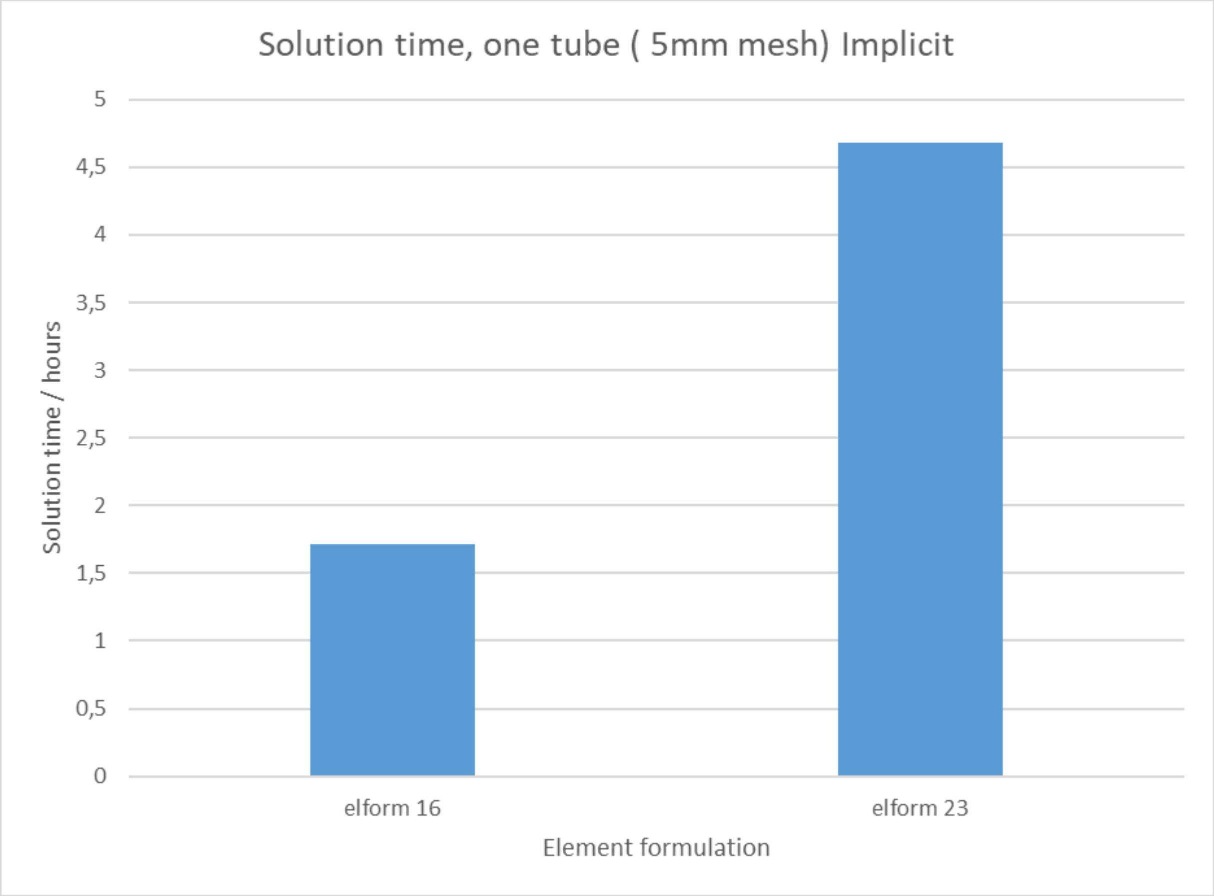
Results: Force vs. displacement



- Good agreement between results for 1st and 2nd order shell elements for this mesh size (5 mm)
- Also reasonable agreement to explicit results, considering differences in load case
  - Explicit: Dynamic impact
  - Implicit: Static crushing by prescribed motion

Crash box

CPU Time in hours for the implicit version

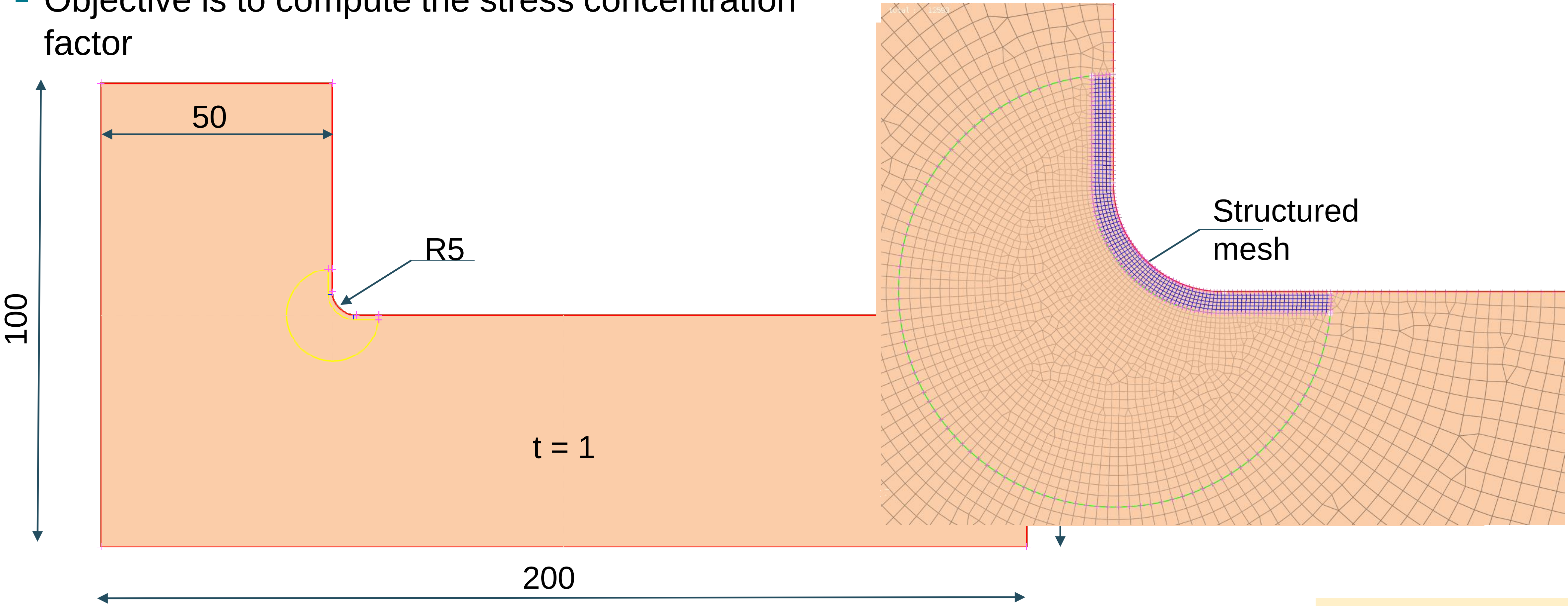


- Results for one tube, middle mesh size (5 mm)
- Using quadratic elements (elform 23) the solution time is about 1.7 times longer than for the 1st order shells (elform 16).

Stress concentration

Non-linear analysis

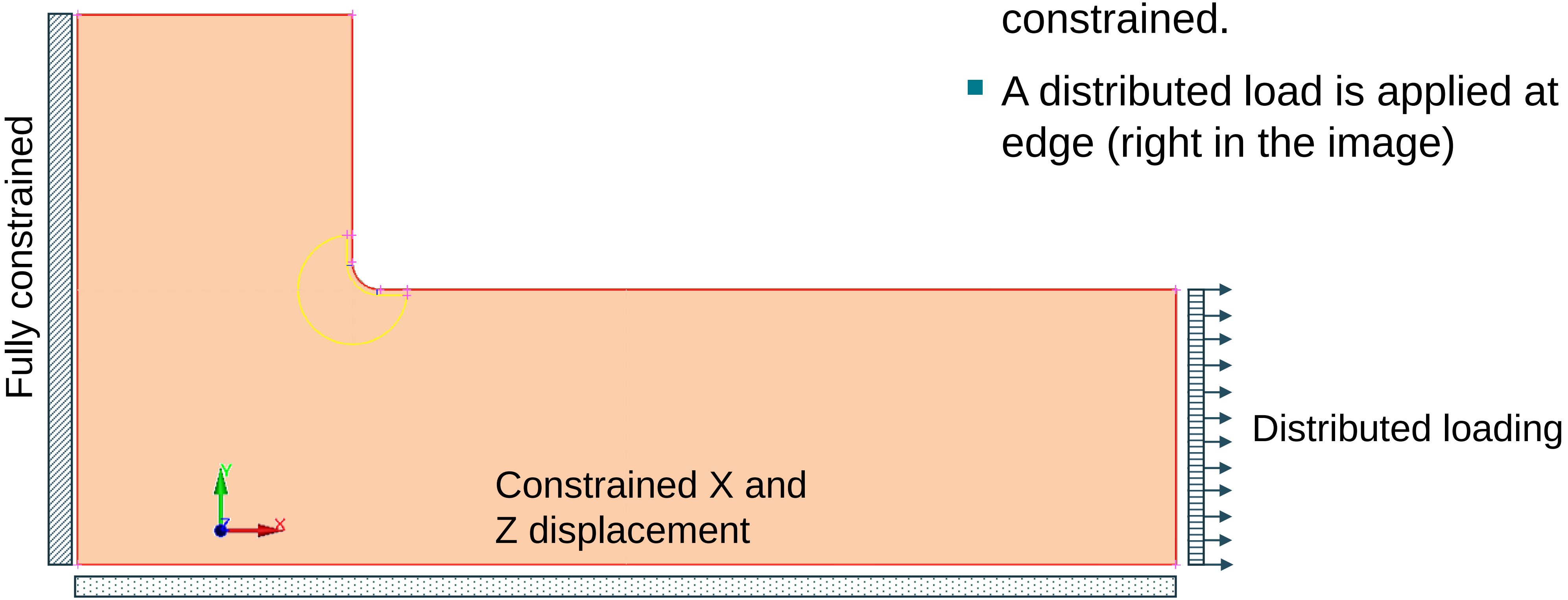
- A flat plate with a radius is studied
- Objective is to compute the stress concentration factor
- Local partitioning is applied to obtain a structured mesh at the radius



Stress concentration

Boundary conditions

- A flat plate with a radius is studied
- Objective is to compute the stress concentration factor



- The X and Z displacements are constrained along the horizontal long edge.
- The vertical long edge (left in the image) is fully constrained.
- A distributed load is applied at the vertical short edge (right in the image)

Stress concentration

Results

- A flat plate with a radius is studied
- Stress concentration is evaluated as the quote between the maximum effective stress and the nominal stress,

$$K_t = \frac{\sigma_{e,max}}{\sigma_{nom}}$$

- where the nominal stress is

$$\sigma_{nom} = \frac{F}{A} = 20 \text{ MPa}$$

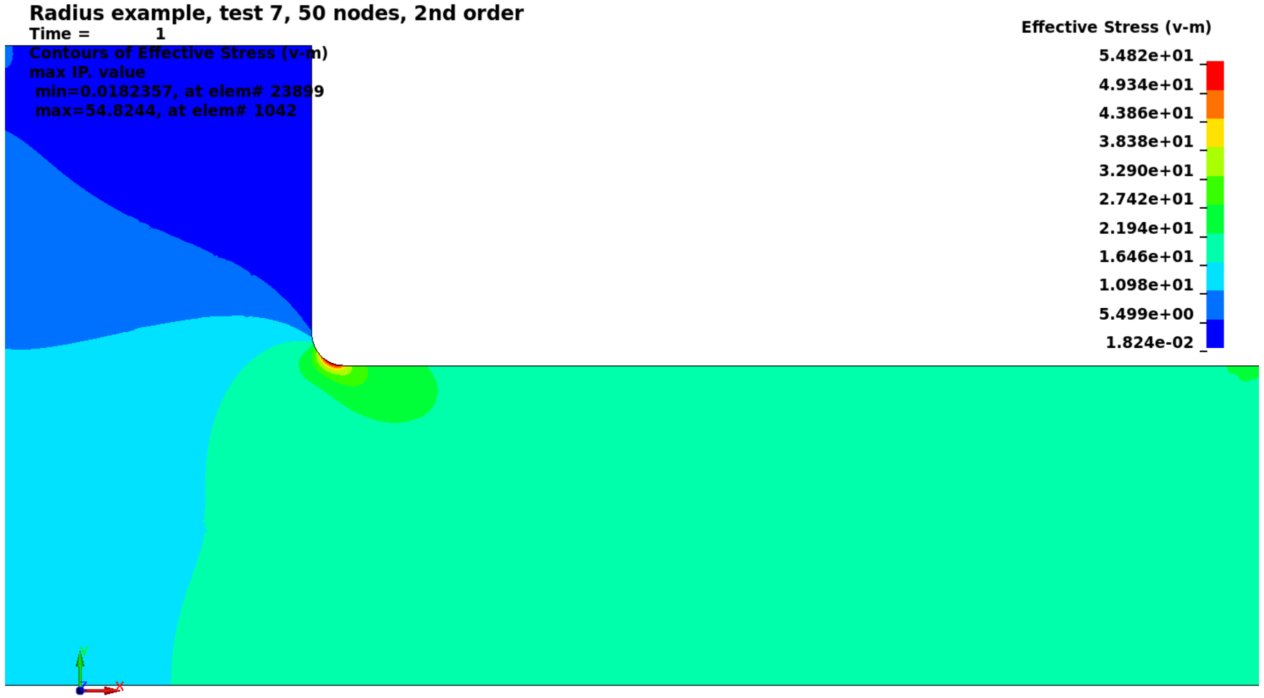
  in this case.
- The maximum effective (von Mises) stress is evaluated as the maximum integration point value from any element at the radius, using LS-PrePost.

- The reference solution was taken as a very fine mesh (50 elements over the radius) using 2nd order shells.
- Both trias and quads were studied.
  - Tria mesh is 100 % trias
  - Quad mesh is 100 % quads in the structured zone at the radius, but away from the radius, trias are also present in the mesh

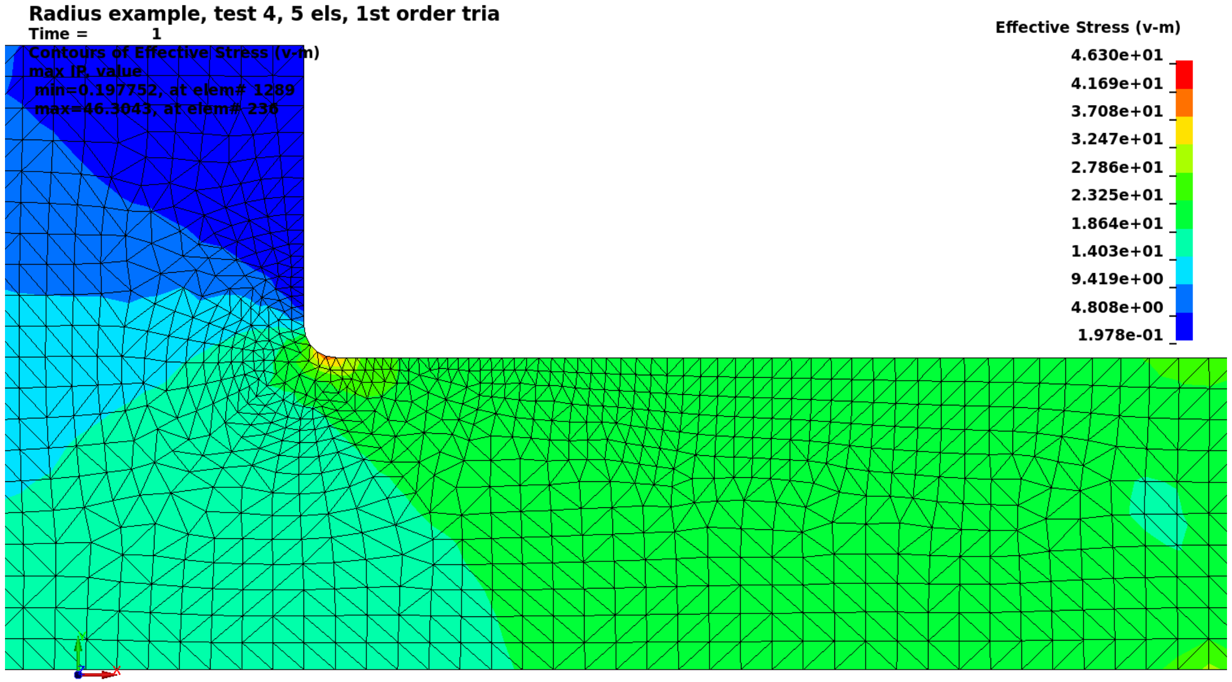
Stress concentration

Results

- Example of stress distribution (reference solution)
  - 50 elements over the radius

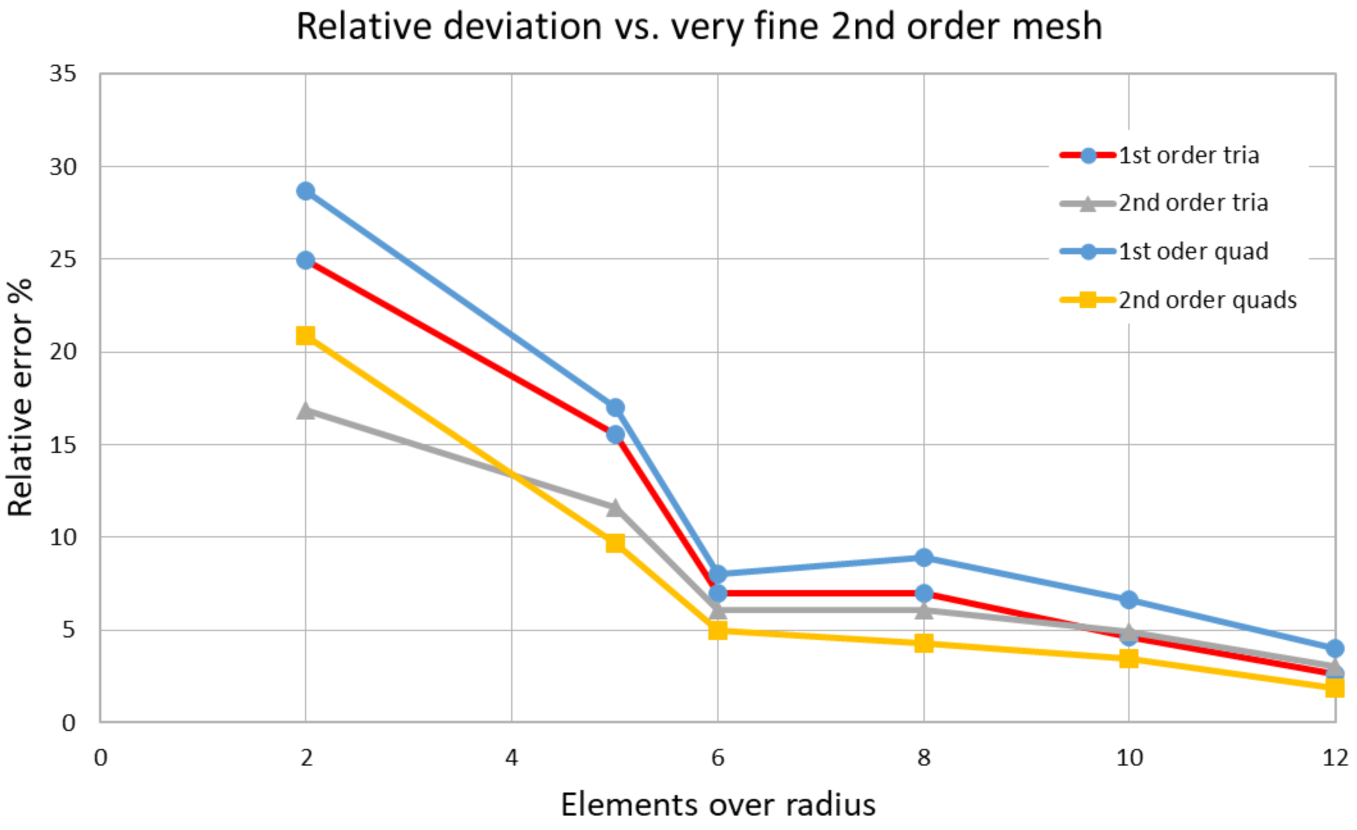


- Example of stress distribution (coarse mesh)
  - 5 elements over the radius



Stress concentration

Results, comparisons



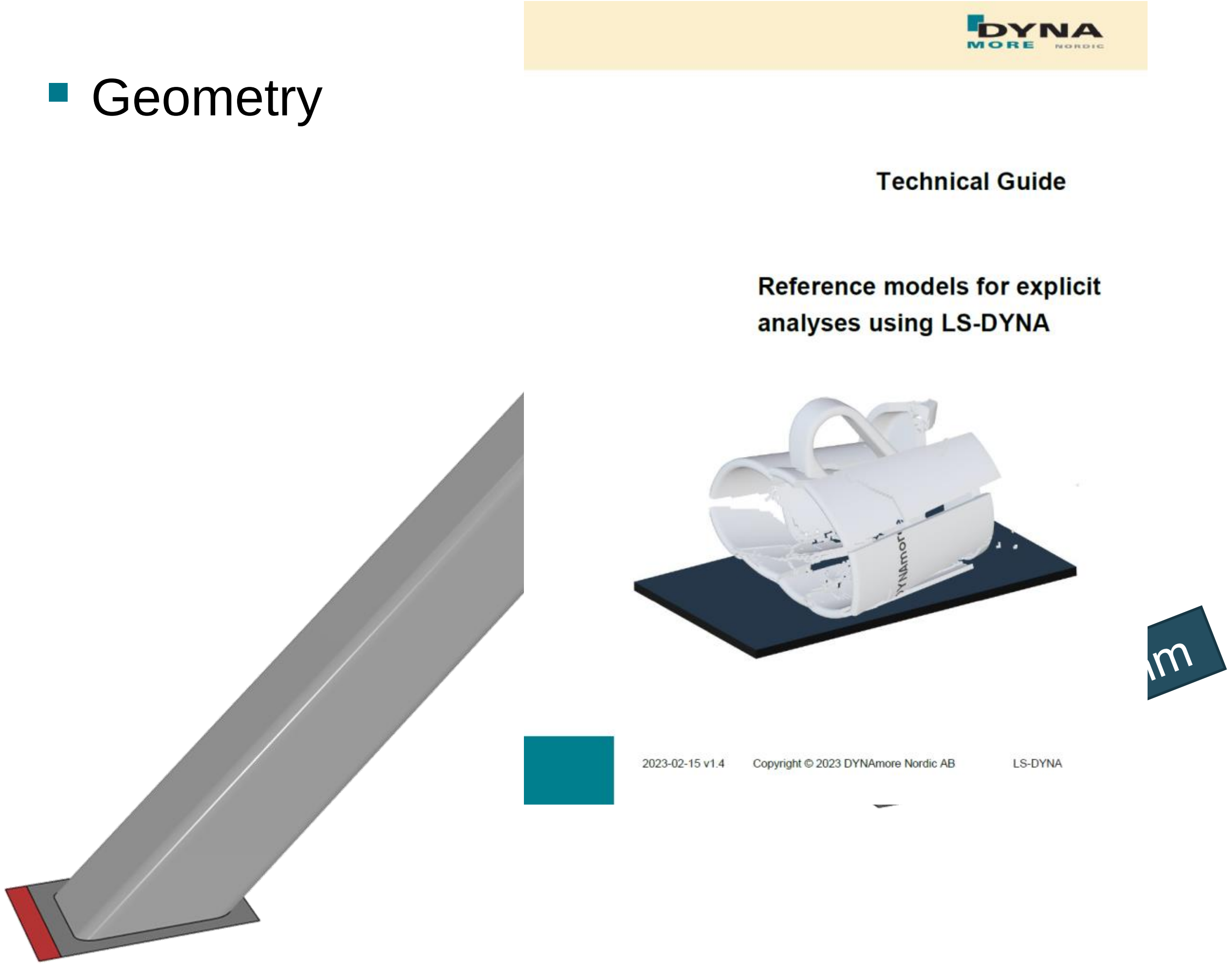
- Six elements over the radius is required to get a reasonably converged result for any element formulation.
- The quadratic quads (elform 23) perform best in this case, while the 1st order quads shows the largest deviation.
- The results for the pure tria meshes are remarkably close to the quad – dominated meshes.

Component

Non-linear implicit static analysis

- Based on Example 7: Fillet weld connection from the Explicit technical guide
  - Simplified version
- Square tube, T - joint
  - 80×80 mm, t = 6 mm
  - Length ≈ 550mm
  - Distance between supports ≈ 780 mm
- Implicit static analysis by prescribed motion
  - 150 mm
- `*MAT_ANISOTROPIC_VISCOPLASTIC` with material properties corresponding to steel with Yield strength 415 MPa.

- Geometry

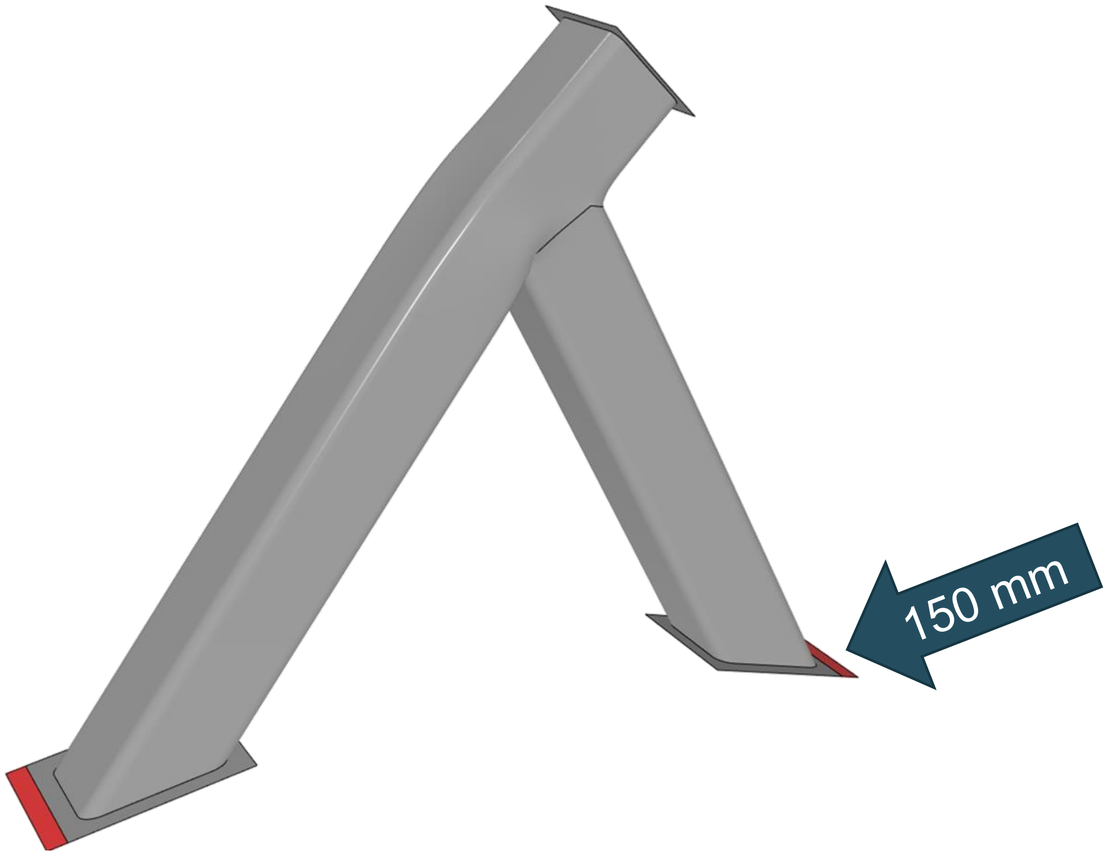


Component

Non-linear implicit static analysis

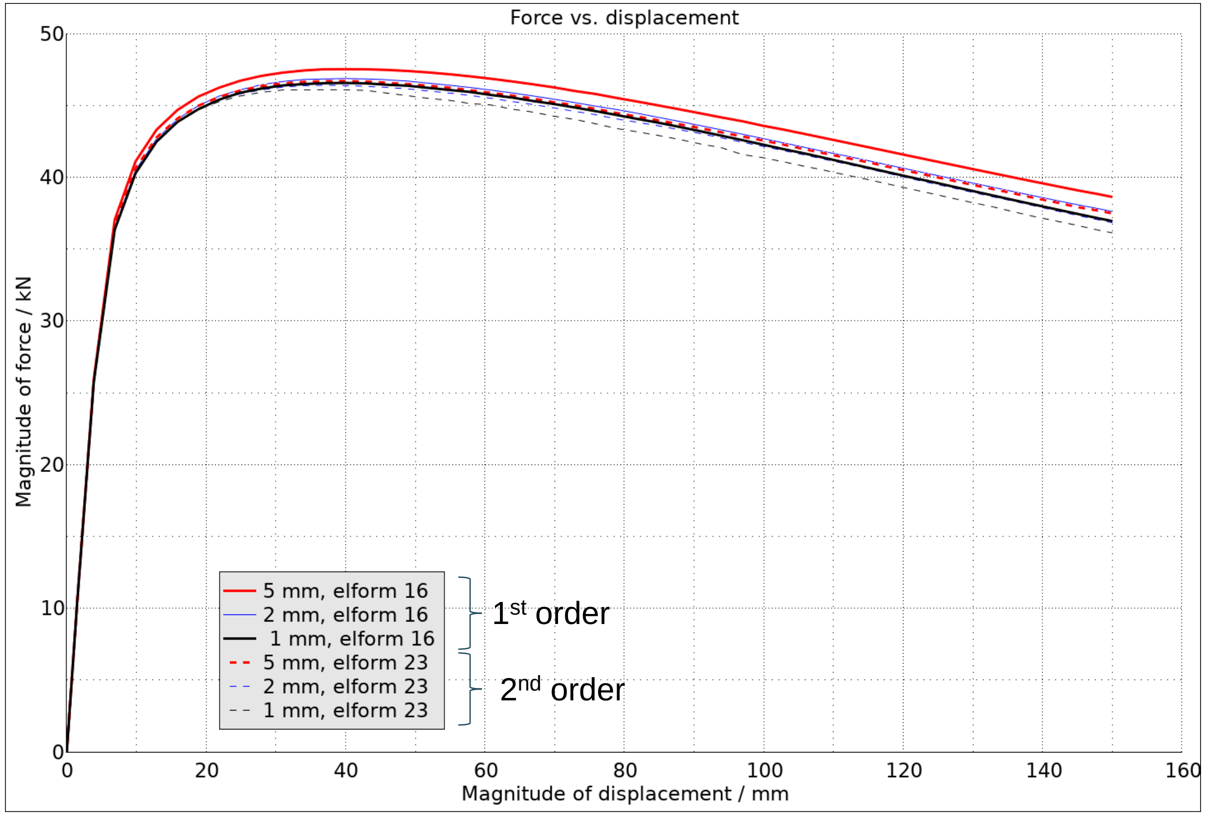
- In this case, due to the severe local deformation, it was required to disable the enhanced assumed strain formulation for quadratic trias by setting *IACC* = 0 on `*CONTROL_ACCURACY`.
- Three different meshes were studied. Element size:
  - 1 mm
  - 2 mm
  - 5 mm
- Quad dominant (element count: less than 1 % trias)

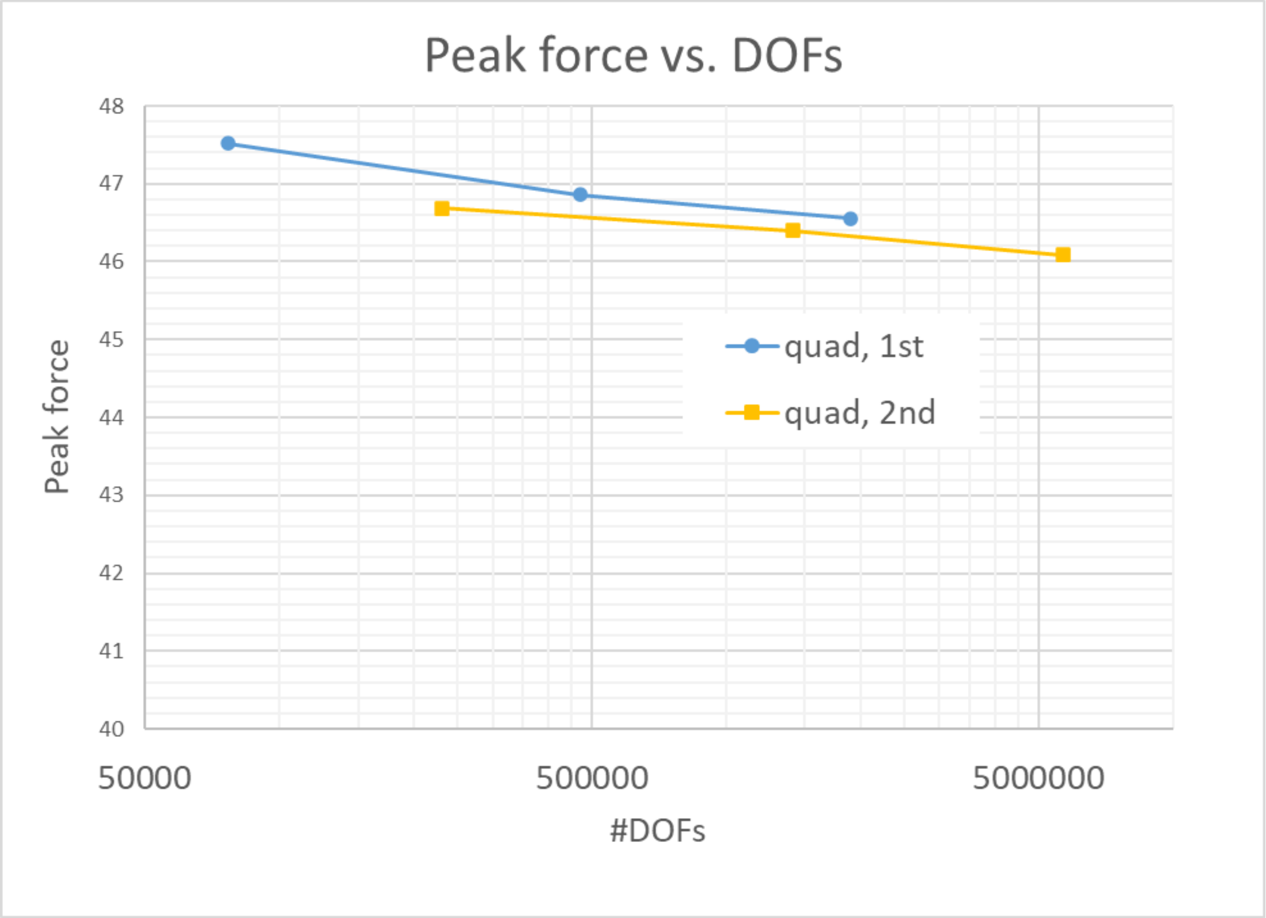
- Deformation



Component

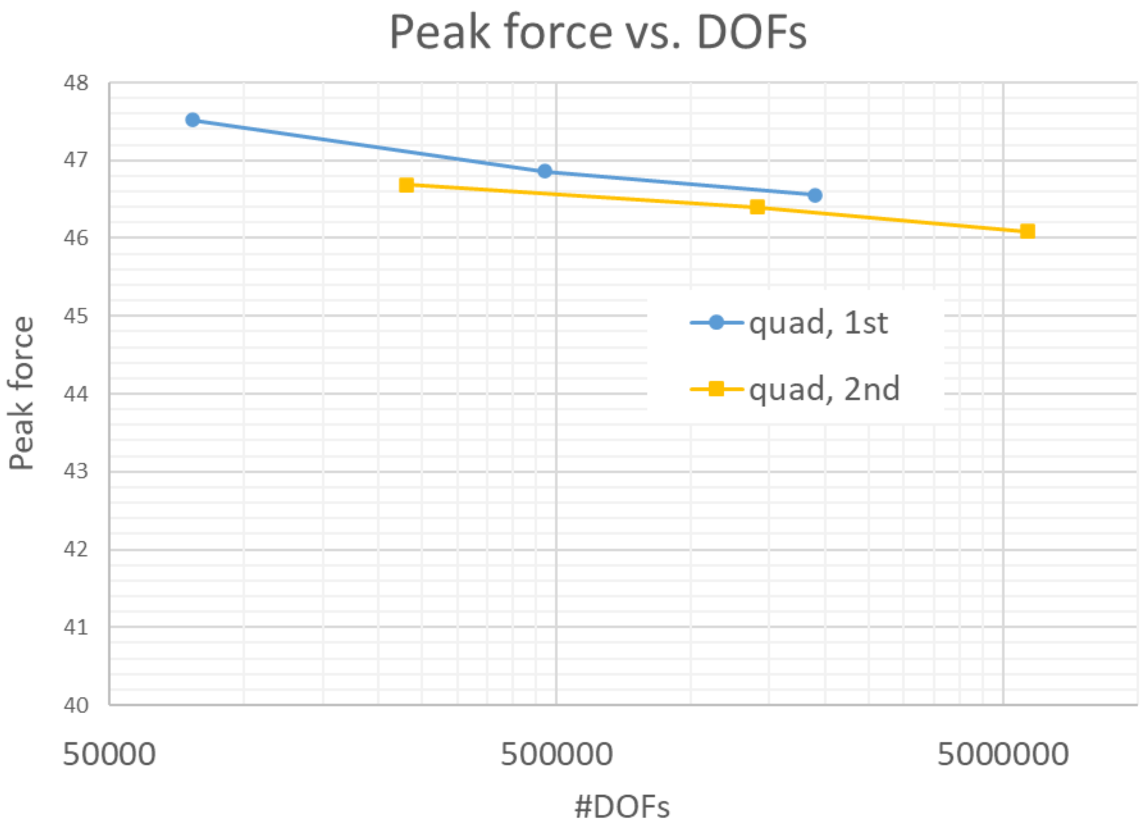
Force vs. displacement

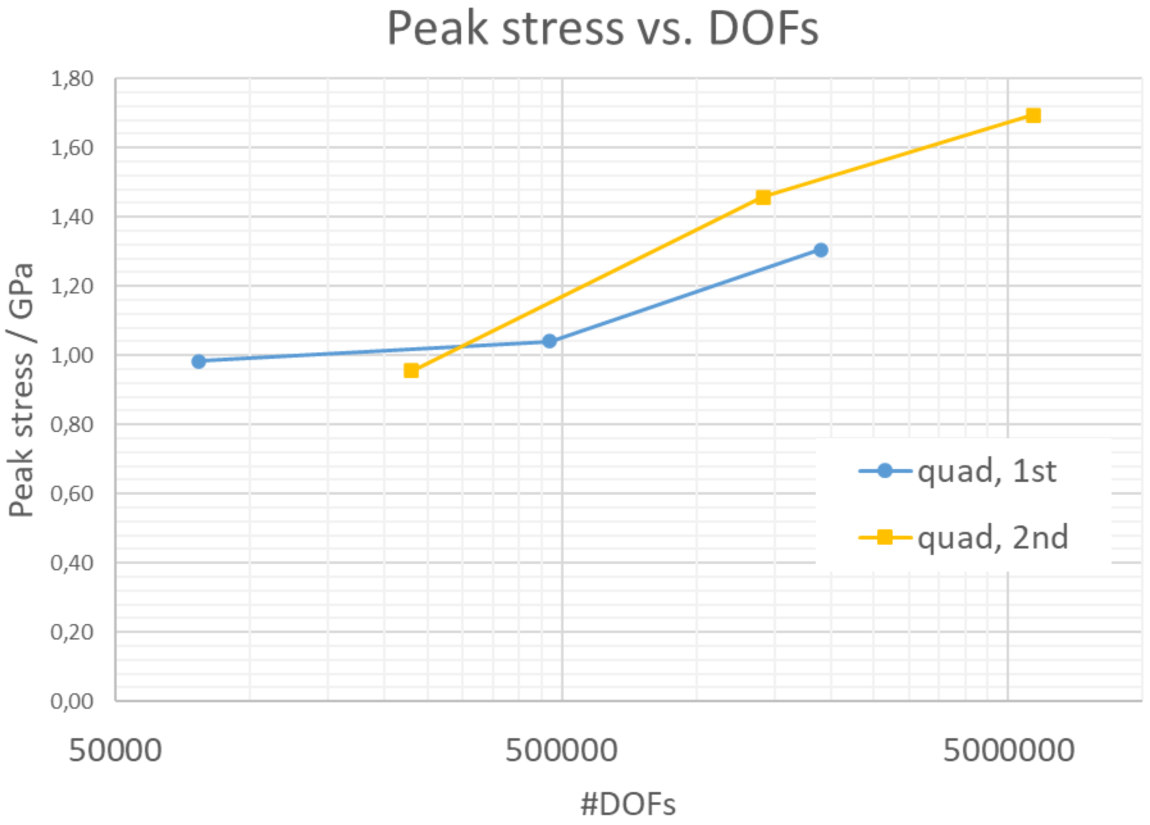




Component

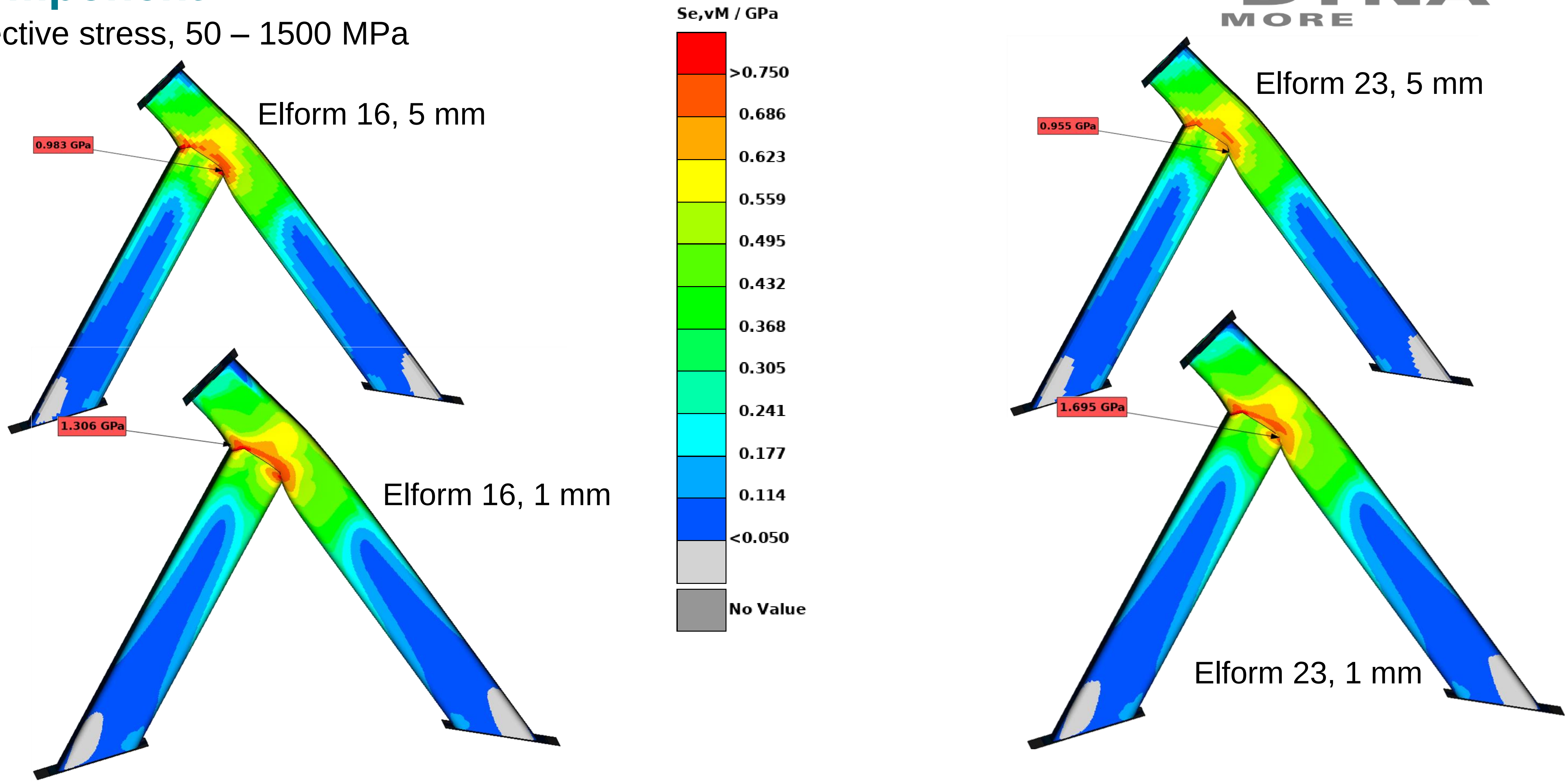
Force and stress vs. #DOF





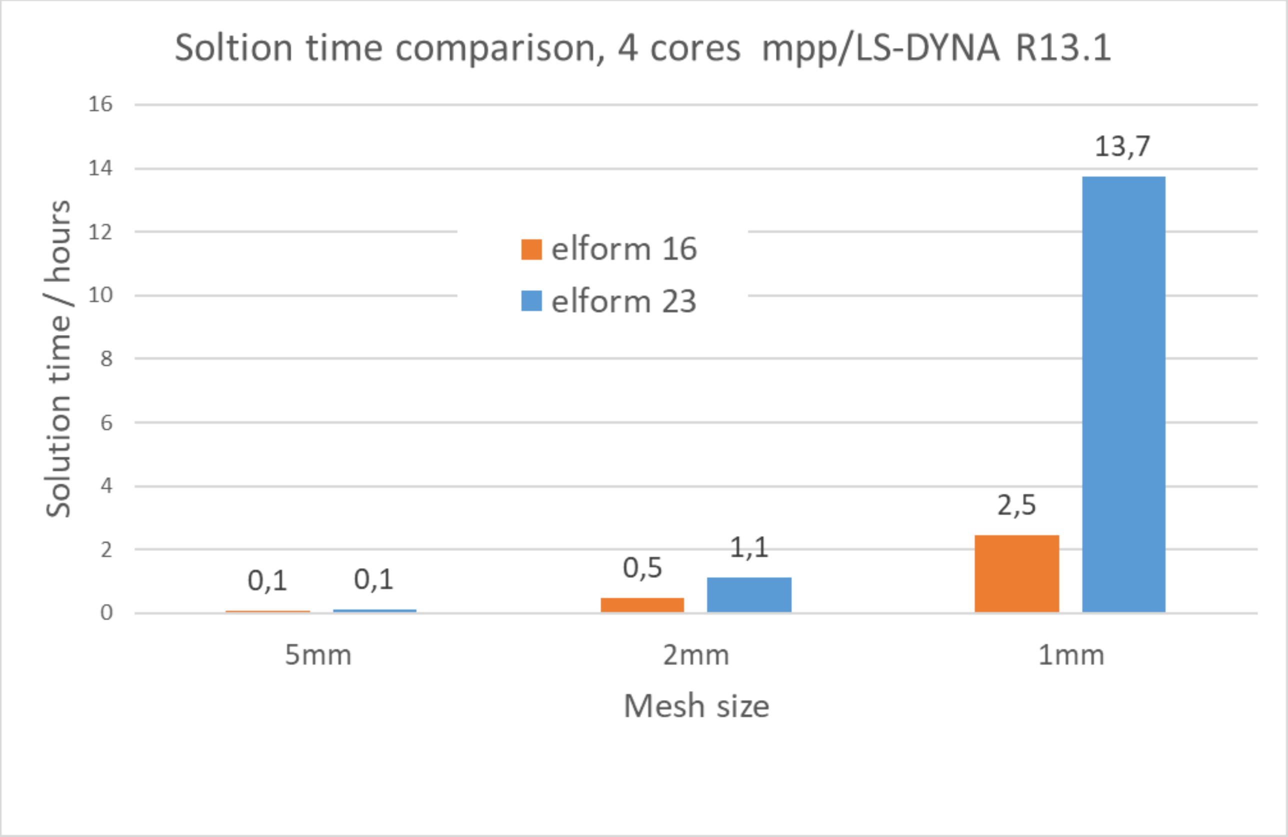
Component

Effective stress, 50 – 1500 MPa



Component

CPU time in hours



- For the coarser meshes (2 mm, 5mm) the difference in solution time is much smaller than for the 1 mm mesh.
- For the 1 mm mesh, using quadratic elements, solution time is 4.5 hours on 16 cores.

Time step control for explicit analyses

*CONTROL_TIMESTEP, *ISDO*

Critical time step

- $$\Delta t_e = \frac{L_s}{c}$$

- L_s is the main information from the element formulation
- The sound speed is

$$c = \sqrt{\frac{E}{\rho(1-\nu^2)}}$$

Characteristic element length

- ELFORM = 16

  ISDO = 0 (default) using side Length

$$L_s = \frac{(1+\beta)A_s}{\max(L_1, L_2, L_3, (1-\beta)L_4)} \qquad \begin{cases} \beta = 1, \text{for tria} \\ \beta = 0, \text{for quad} \end{cases}$$

  ISDO = 1, using Diagonals

$$L_s = \frac{(1+\beta)A_s}{\max(D_1, D_2)}$$

- ELFORM = 23

$$L_s(\text{ELFORM } 23) = \frac{L_s(\text{ELFORM } 16)}{3}$$

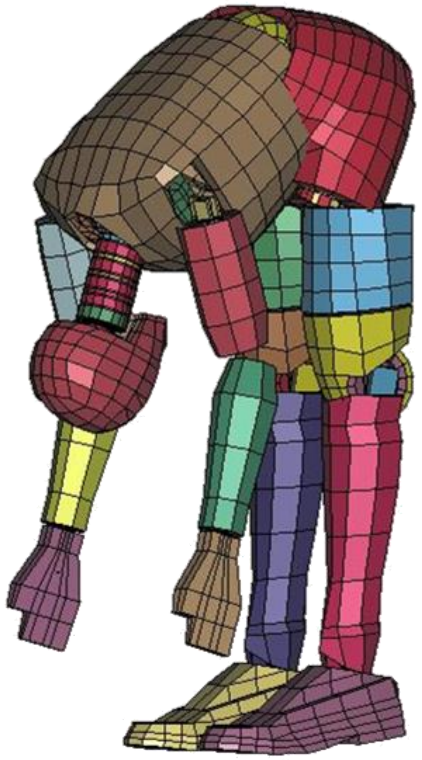
  - Mid-side nodes not considered

Summary and conclusions

ELFORM 23, 24

- Mainly intended for implicit analyses
  - Explicit timestep = (timestep for elform 16)/3
- Aim for a quad-dominated mesh
  - Avoid trias in critical areas
  - *IACC* = 1 on `*CONTROL_ACCURACY` switches the 2^{nd} triangular element formulation 24 to an enhanced assumed strain formulation to alleviate shear locking. This may be more sensitive to mesh distortion than the default 2^{nd} order tria.
- May give better stress resolution
  - Mainly an advantage for membrane state
  - Smaller gain if bending is dominating
  - Fatigue and durability analyses
- Increased solution time
  - Due to the increased number of DOF:s and IP:s

Thank You



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