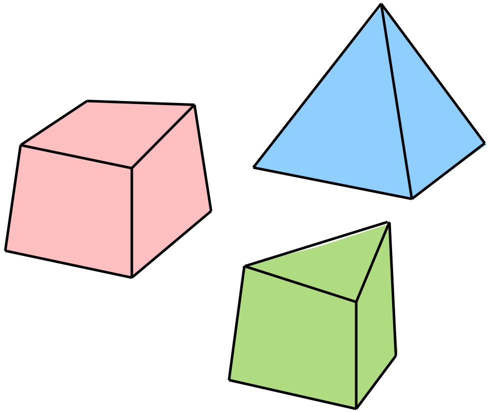


15. Deutsches LS-DYNA Forum

Updated Review of Solid Element Formulations in LS-DYNA

Properties, Limits, Advantages, Disadvantages

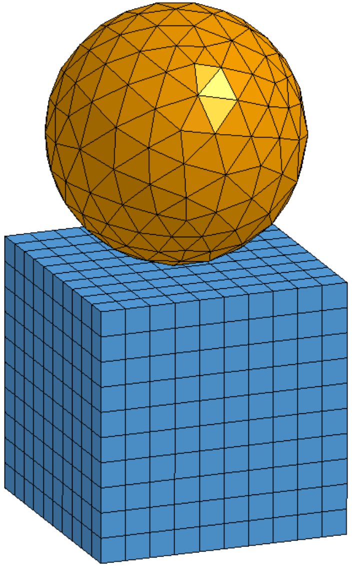
Christoph Schmied, DYNAmore

Tobias Erhart, DYNAmore

Bamberg, 17 October 2018

Motivation

Solid elements are three-dimensional finite elements that can model solid bodies and structures without any a priori geometric simplification.



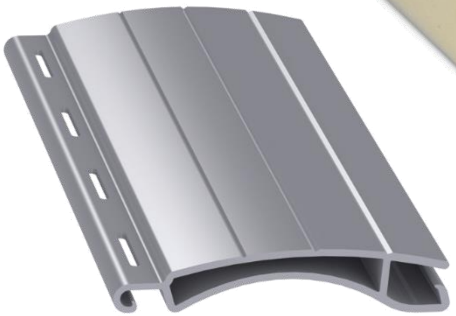
- No geometric, constitutive and loading assumptions required.
- Boundary conditions treated more realistically.
  (compared to shells or beams).
- FE mesh visually looks like the physical system.

but…

- Higher effort: mesh preparation, CPU time, post-processing, …
- Expensive mesh refinement: Curse of dimensionality.
- Often poor performance for thin-walled structures (locking problems).

Applications

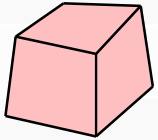
- Foam Structures
- Rubber components
- Cast iron parts
- Solid barriers
- Plastic parts
- Bulk forming
- Thick metal sheets
- Elastic tools
- Impact analysis
- …



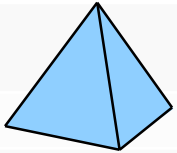
Overview

LS-DYNA User‘s manual: *SECTION_SOLID, parameter ELFORM

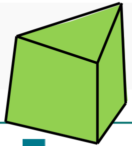
EQ.-2	Fully integrated S/R solid intended for elements with poor aspect ratio, accurate formulation
EQ.-1	Fully integrated S/R solid intended for elements with poor aspect ratio, efficient formulation
EQ.1	Constant stress solid element: default element type
EQ.2	Fully integrated S/R solid.
EQ.3	Fully integrated quadratic 8-node element with nodal rotations



EQ.4	S/R quadratic tetrahedron element with nodal rotations
EQ.10	1 point tetrahedron
EQ.13	1 point nodal pressure tetrahedron
EQ.15	2 point pentahedron element
EQ.16	4 or 5 point 10-noded tetrahedron
EQ.17	10-noded composite tetrahedron
EQ.23	**20-node solid formulation**
EQ.24	**27-noded, fully integrated S/R quadratic solid element**
EQ.115	1 point pentahedron element with hourglass control



New quadratic Elements (use R10)



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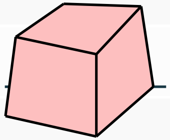
Standard hexahedral elements

EQ.1	**Constant stress solid element: default element type**
EQ.2	**Fully integrated S/R solid.**
EQ.3	Fully integrated quadratic 8-node element with nodal rotations



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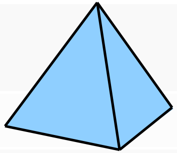
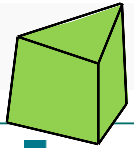
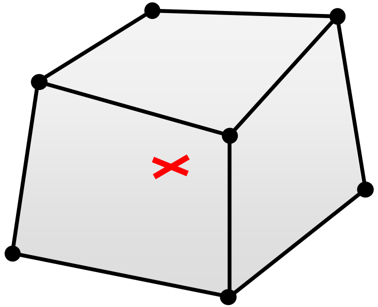




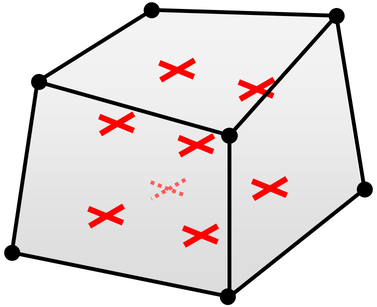
Standard hexahedra elements in LS-DYNA

ELFORM = 1



- underintegrated constant stress
- efficient and accurate
- even works for severe deformations
- needs hourglass stabilization: choice of hourglass formulation and values remains an issue

ELFORM = 2



- selective reduced integrated brick element (volumetric locking alleviated)
- slower than ELFORM=1
- more unstable in large deformation applications
- no hourglass stabilization needed
- too stiff in many situations, especially for poor aspect ratios (shear locking)

Hourglass control for ELFORM=1

*HOURGLASS: IHQ = 1…5

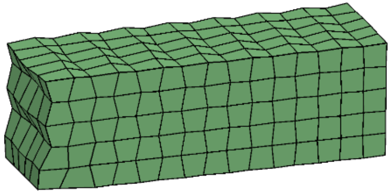
- viscous form (1,2,3) for higher velocities
- stiffness form (4,5) for lower velocities
- exact volume integration recommended (3,5)

*HOURGLASS: IHQ = 6

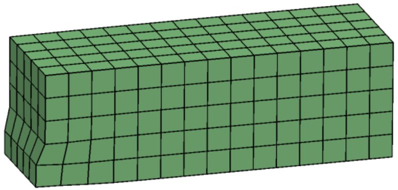
- the QBI (Quintessential Bending Incompressible) hourglass control by Belytschko and Bindeman
- hourglass stiffness uses elastic constants
- **recommended in most situations**
- sometimes modified QM makes sense (watch hourglass energy)

*HOURGLASS: IHQ = 7/9

- similar to type 6, but less experience
- type 7 uses total deformation instead of updated
- type 9 should provide more accurate results for distorted meshes



Hourglassing pattern



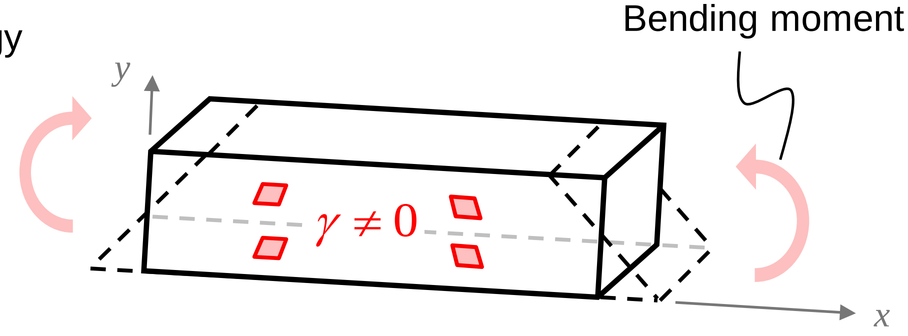
Hourglass control

Property of **ELFORM=2**

Shear locking

- Pure bending modes trigger spurious shear energy
- Getting worse for poor aspect ratios

$$\varepsilon_{xx} = 2\xi_y / l_x,\ \varepsilon_{yy} = 0,\ \gamma_{xy} = \xi_x / l_y$$



Alleviation of shear locking

1. Underintegration → ELFORM = 1
2. Modified strain formulations → modified Jacobian matrix

➡ $\varepsilon_{xx} = 2\xi_y / l_x,\ \varepsilon_{yy} = 0,\ \gamma_{xy} = \ldots = \xi_x / l_x$ ➡ **ELFORM = -1, -2**

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Improved hexahedral elements

EQ.1	Constant stress solid element: default element type
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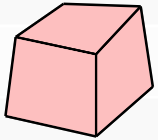
EQ.3	Fully integrated quadratic 8-node element with nodal rotations



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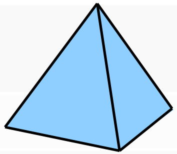

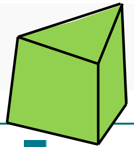

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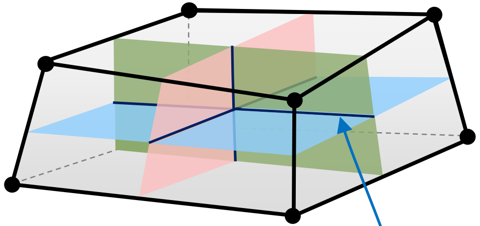
Solid element formulations -1 and -2

Thomas Borrvall: „A *heuristic attempt to reduce transverse shear locking in fully integrated hexahedra with poor aspect ratio*“, Salzburg 2009



Original Jacobian matrix

$$J_{\mathrm{ij}}^{\mathrm{orig}} = \frac{\partial x_i}{\partial \xi_j} = x_{Ii} \, \frac{1}{8} \left(\xi_j^I + \xi_{jk}^I \xi_k + \xi_{jl}^I \xi_l + \xi_{123}^I \, \xi_k \, \xi_l \right)$$

Modification of the Jacobian matrix

Reduction of spurious stiffness without affecting the true physical behavior of the element

$$J_{\mathrm{ij}}^{\mathrm{mod}} = x_{Ii} \, \frac{1}{8} \left(\xi_j^I + \xi_{jk}^I \xi_k \, \kappa_{jk} + \xi_{jl}^I \xi_l \, \kappa_{jl} + \xi_{123}^I \, \xi_k \, \kappa_{jk} \, \xi_l \, \kappa_{jl} \right)$$

aspect ratios between dimensions computed **efficiently**

- computed once at time zero
- with edge lengths through element center

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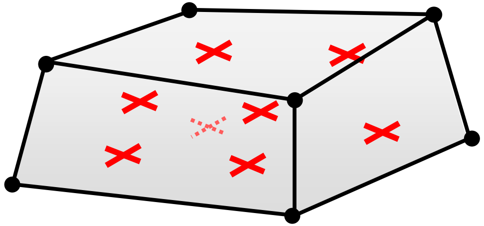
Improved hexahedral elements

Identical with ELFORM=2 but accounted for **poor aspect ratio** in order to reduce shear locking



ELFORM = -1

- **efficient** formulation
- sometimes hourglass tendencies

ELFORM = -2

- **accurate** formulation
- higher computational cost than type -1

CPU cost compared to ELFORM=2 for explicit analysis

≈1.2 (ELFORM=-1) ≈ 2.0 to 3.5 (ELFORM=-2)

… but implicit ELFORM -2 is a good choice!

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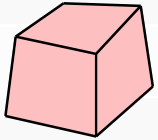

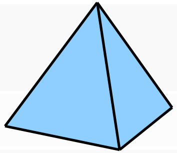

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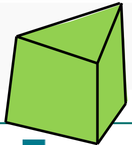
New hexahedral elements



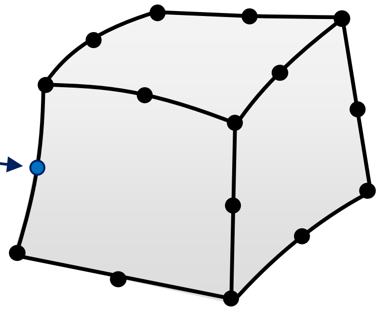
Quadratic hexahedron element formulations (use R10)

Good bending behaviour

ELFORM = 23

8 corner + 12 edge nodes

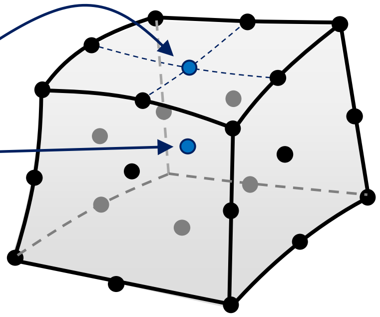
14 integration points



ELFORM = 24

8 corner + 12 edge
+ 6 surface
+ 1 center node

27 integration points (3×3×3)



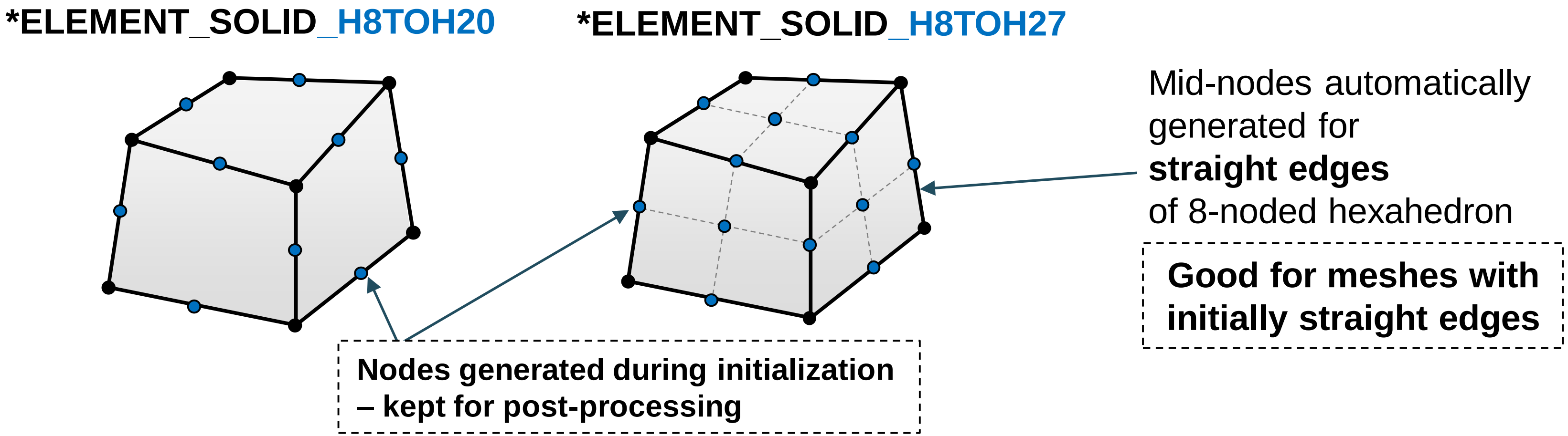
- Serendipity formulation – not fully quadratic
- Faster than ELFORM 24

- Fully quadratic displacement field
- 21 degrees of freedom more than ELFORM 23
- S/R integration

Compared to 8-node solid hexahedral "coarse meshes" often sufficient for convergence

Quadratic hexahedron element formulations (use R10)

Automatic node generation similar to *ELEMENT_SOLID_TET4TOTET10



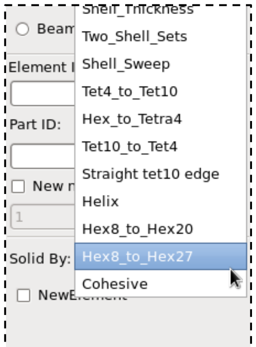
- Boundary conditions partly translated
- Size of time step getting smaller

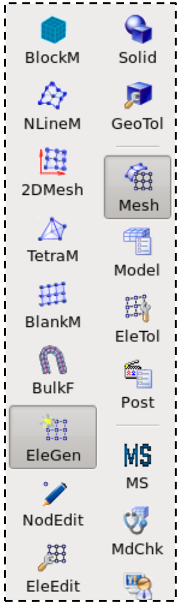
Quadratic hexahedron element formulations (use R10)

Define nodes a priori with mesh generator / LSPP

***ELEMENT_SOLID_H20**

***ELEMENT_SOLID_H27**





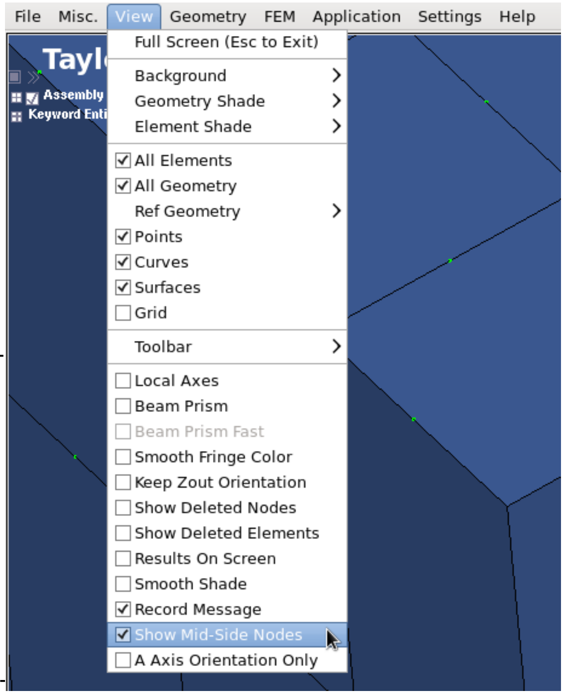

```
*ELEMENT_SOLID_H27
$#    eid       pid
        1         1
$#     n1        n2        n3        n4        n5        n6        n7        n8        n9       n10
        1         2         3         4         5         6         7         8         9        10
$#    n11       n12       n13       n14       n15       n16       n17       n18       n19       n20
       11        12        13        14        15        16        17        18        19        20
$#    n21       n22       n23       n24       n25       n26       n27
       21        22        23        24        25        26        27
```

Quadratic hexahedron element formulations (use R10)

Define nodes a priori with mesh generator / LSPP

Using *ELEMENT_SOLID_H20/_H27
all mid-side nodes may be directly accessed
e. g. for single point constraints

```
*ELEMENT_SOLID_H27
$#    eid       pid
        1         1
$#     n1        n2        n3        n4        n5        n6        n7        n8
        1         2         3         4         5         6         7         8
$#    n11       n12       n13       n14       n15       n16       n17       n18
       11        12        13        14        15        16        17        18
$#    n21       n22       n23       n24       n25       n26       n27
       21        22        23        24        25        26        27
```



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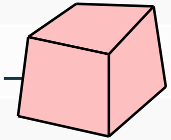

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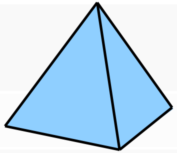
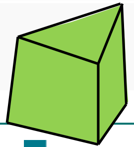
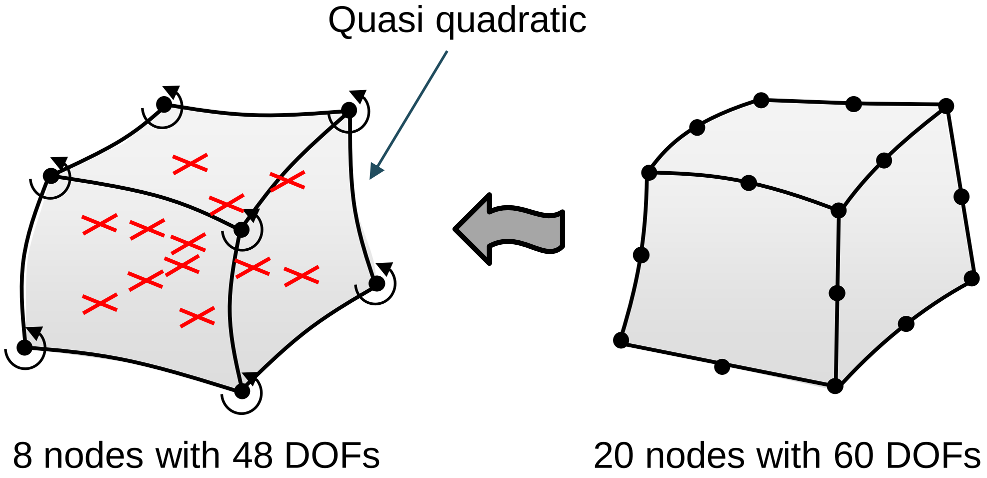




Quadratic solid element with nodal rotations

ELFORM = 3

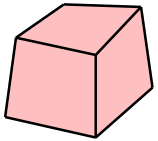
- Quadratic 8 node hexahedron with nodal rotations, i.e. 6 DOF per node
- Full integration (12 point)
- Well suited for connections to shells
- Good accuracy for small strains
- Tendency to volumetric locking – possible remedy: incompatible modes



Pawlak, TP and Yunus, SM: *Solid elements with rotational degrees of freedom: Part 1 – Hexahedron elements*, IJNME 1991

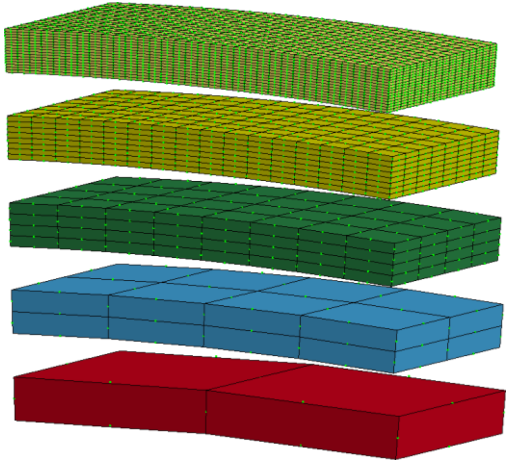
Teng, H: *Solid elements with Rotational Degree of Freedom for Grand Rotation Problems in LS-DYNA*, 11th International LS-DYNA Users Conference, 2010

Examples part 1



Implicit elastic bending

- clamped plate of dimensions 10x5x1 mm^3
- subjected to 1 Nm torque at the free end
- E = 210 GPa
- analytical solution for end tip deflection: 0.57143 mm
- convergence study with aspect ratio 5:1 kept constant

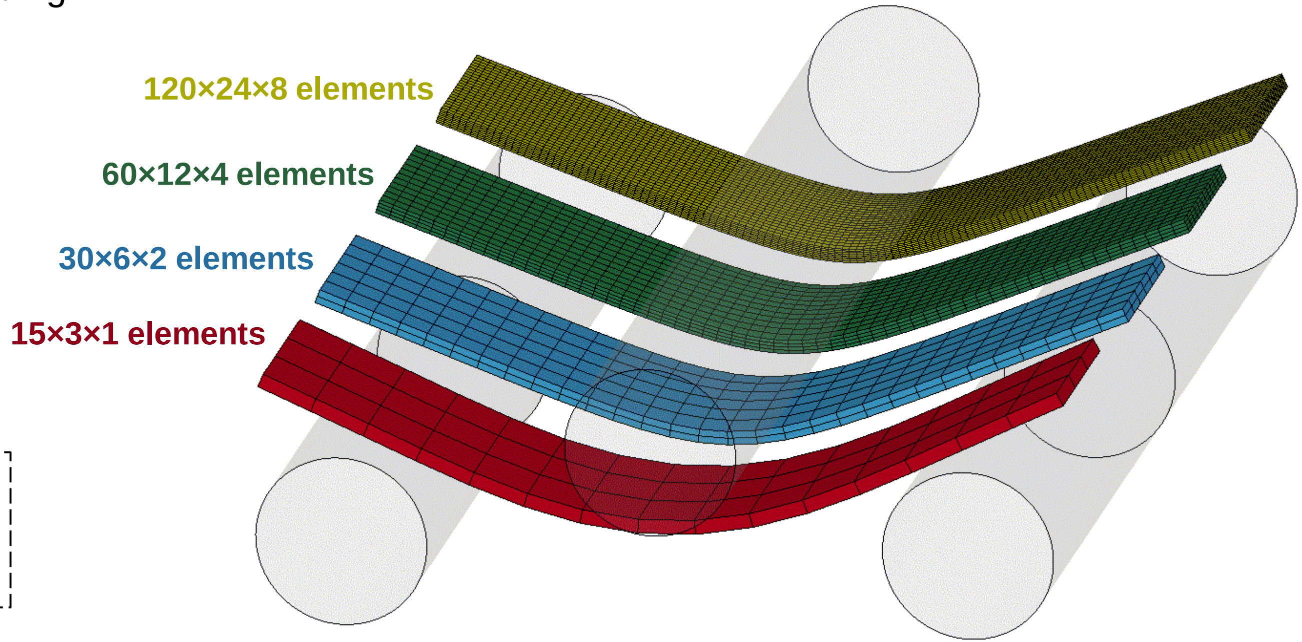


End tip deflection, different mesh discretizations and element types, error in parenthesis.

Mesh	ELFORM 2	ELFORM -2	ELFORM -1	ELFORM 3	**ELFORM23**	**ELFORM 24**
2×1×1	0.0564(90.1%)	0.6711(17.4%)	0.6751(18.1%)	0.4001(30.0%)	**0.5264(7.8%)**	**0.5525(3.3%)**
4×2×2	0.1699(70.3%)	0.5466(4.3%)	0.5522(3.4%)	0.4596(19.6%)	**0.5456(4.5%)**	**0.5534((3.1%)**
8×4×4	0.3469(39.3%)	0.5472(4.2%)	0.5500(3.8%)	0.5237(8.4%)	**0.5517(3.5%)**	**0.5541(3.0%)**
16×8×8	0.4820(15.7%)	0.5516(3.5%)	0.5527(3.3%)	0.5557(2.8%)	**0.5537(3.1%)**	**0.5543(3.0%)**
32×16×16	0.5340(6.6%)	0.5535(3.1%)	0.5540(3.1%)	0.5552(2.8%)	**0.5543(3.0%)**	**0.5545(3.0%)**

Plastic bending

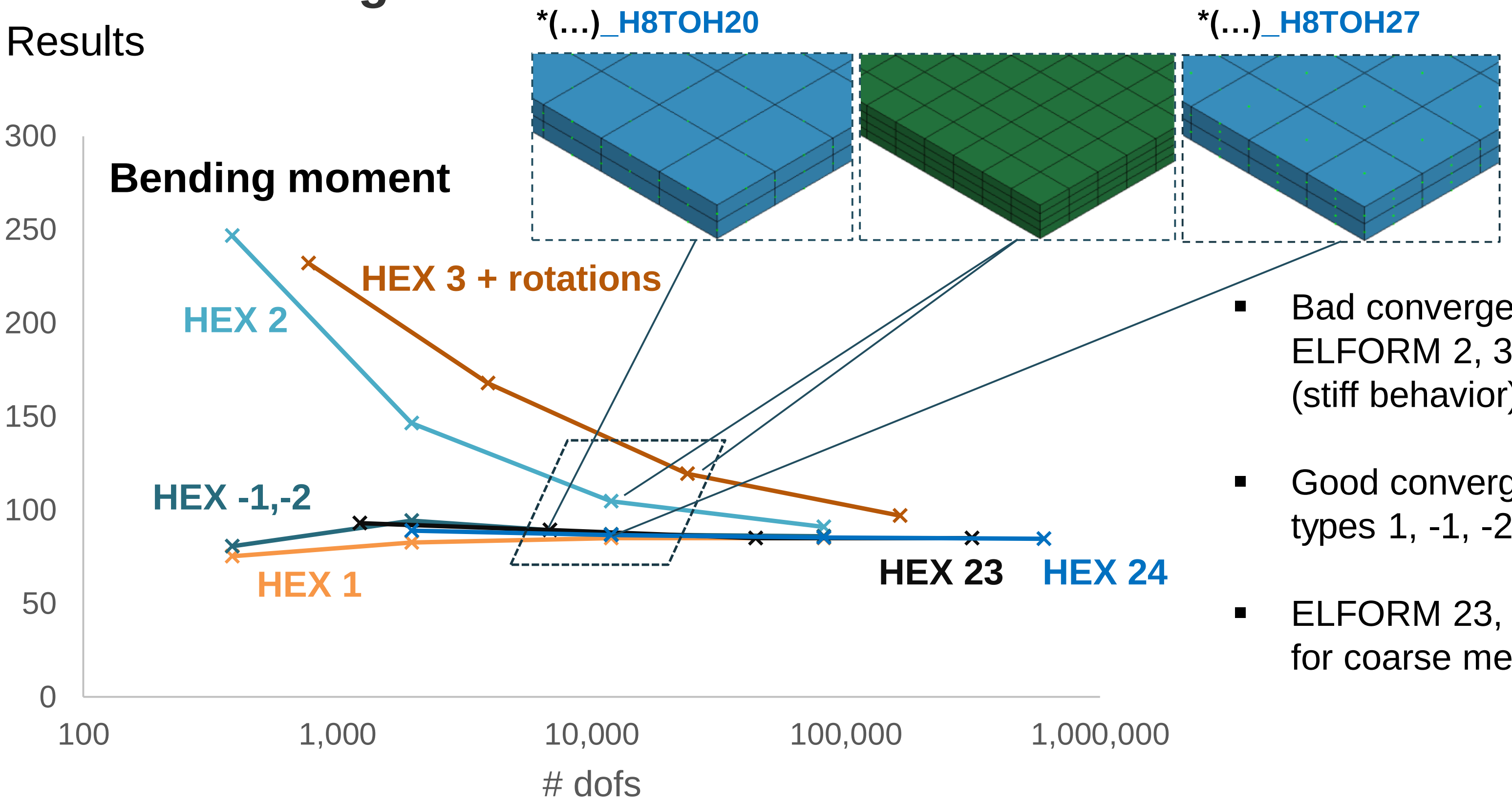
- Explicit plastic 3 point bending (prescribed motion)
- Plate of dimensions 300×60×5 mm^3
- *MAT_024 (Aluminum)



convergence study – aspect ratio 4:1 kept constant

Plastic bending

Results



- Bad convergence of ELFORM 2, 3 (stiff behavior)
- Good convergence with types 1, -1, -2
- ELFORM 23, 24 converged for coarse mesh

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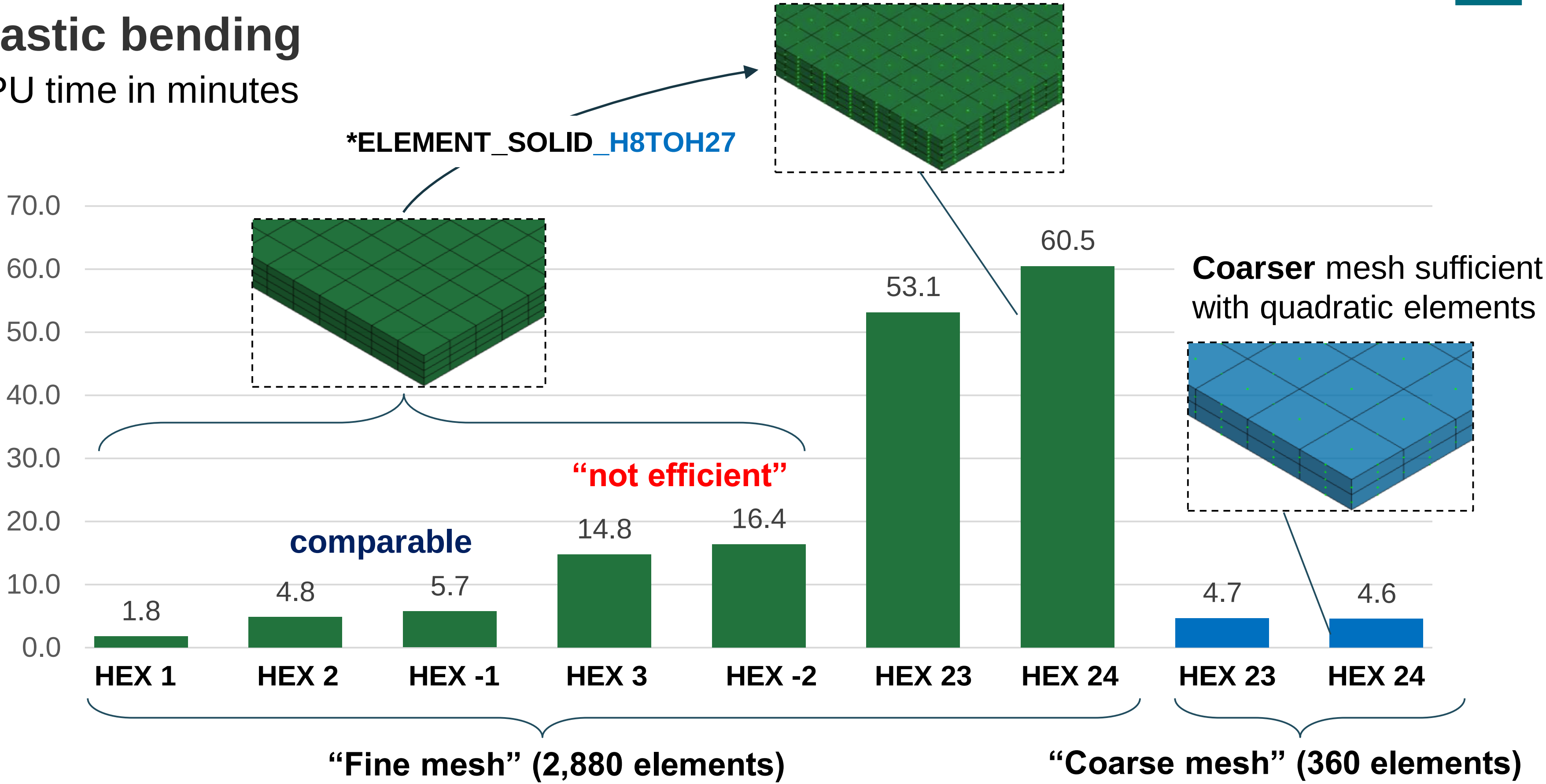
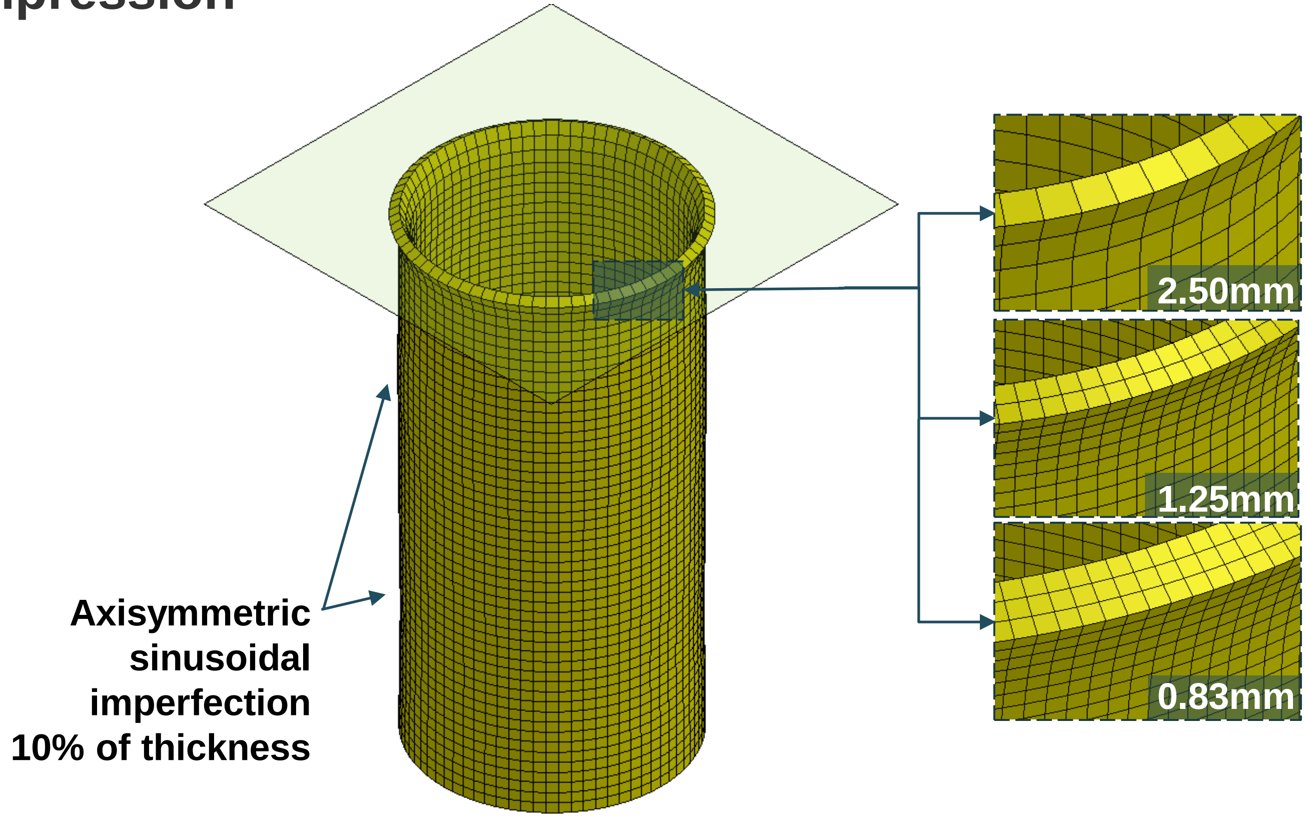
Plastic bending

CPU time in minutes



Circular tube compression

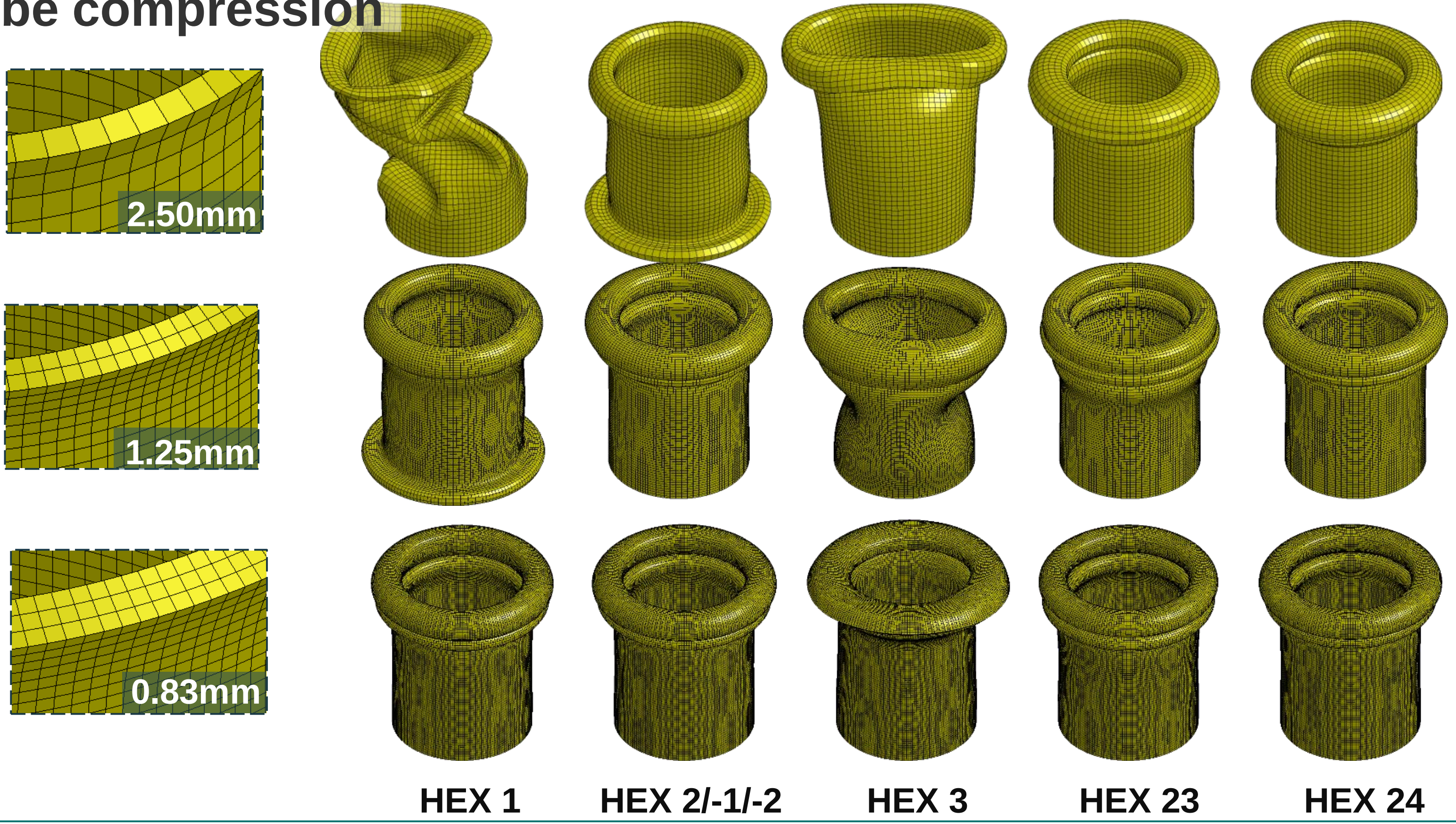
- *MAT_024 (Aluminium)
- Different mesh sizes: convergence study



Circular tube compression

Deformation

Half way compressed



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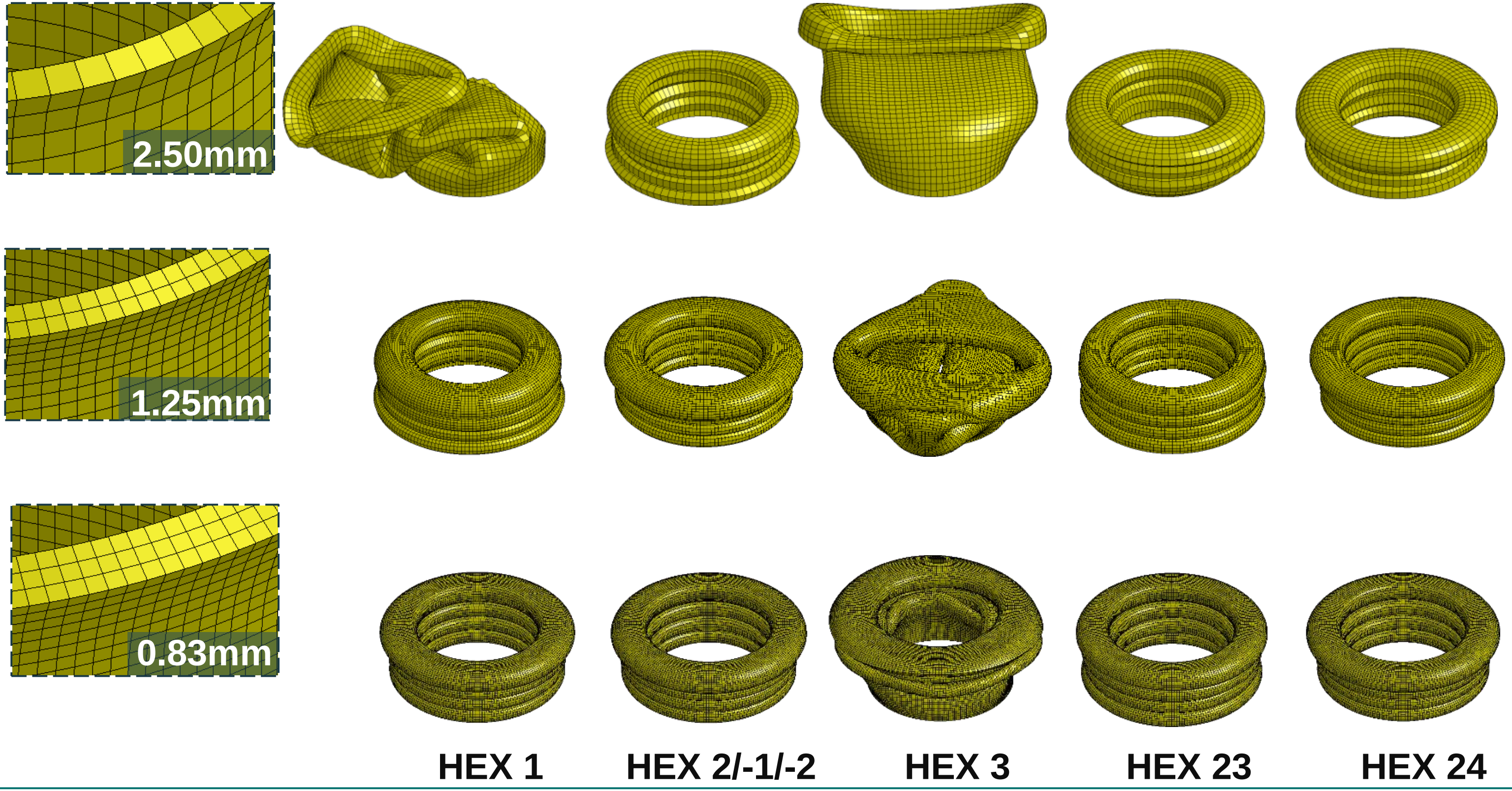
Circular tube compression

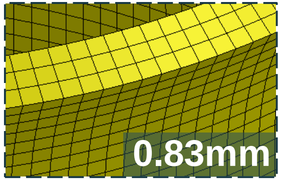
Deformation

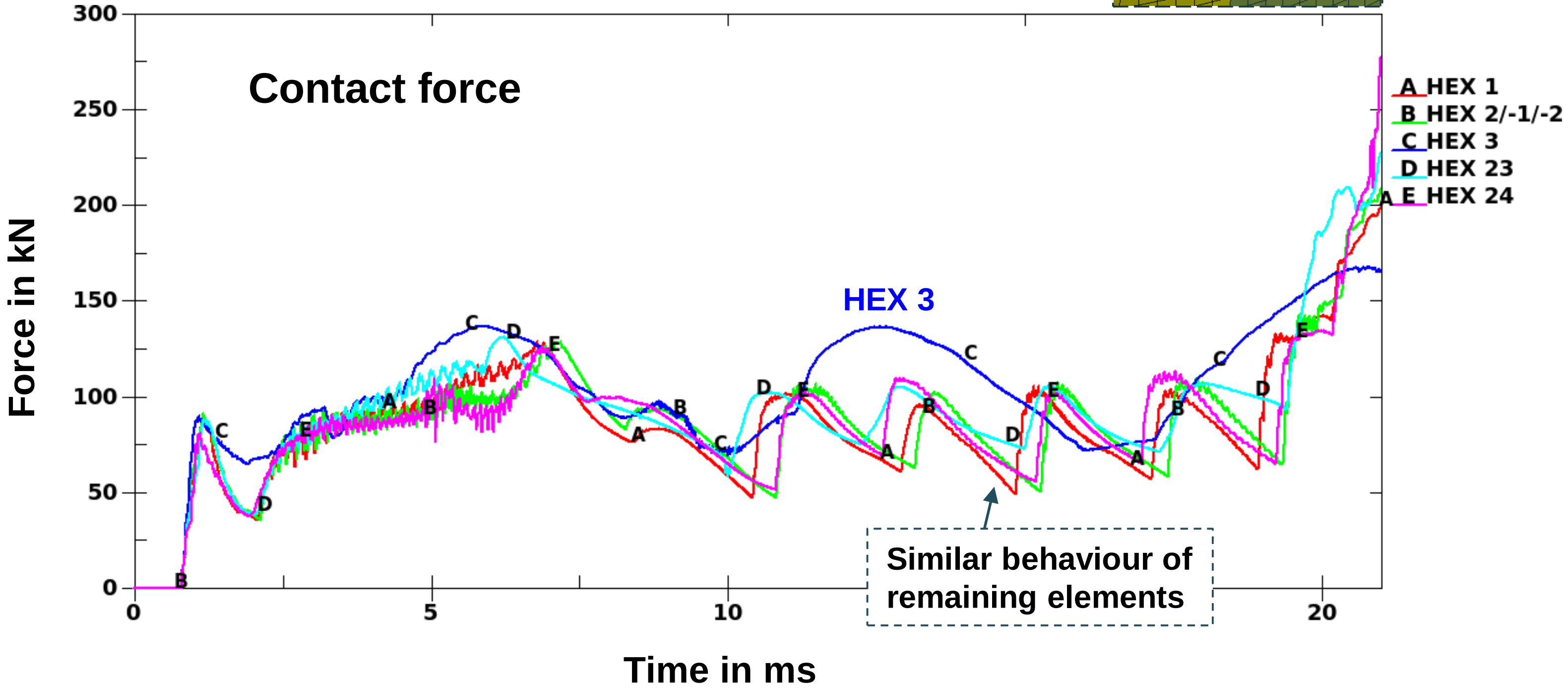
Fully compressed



Circular tube compression

Results

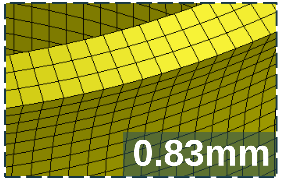


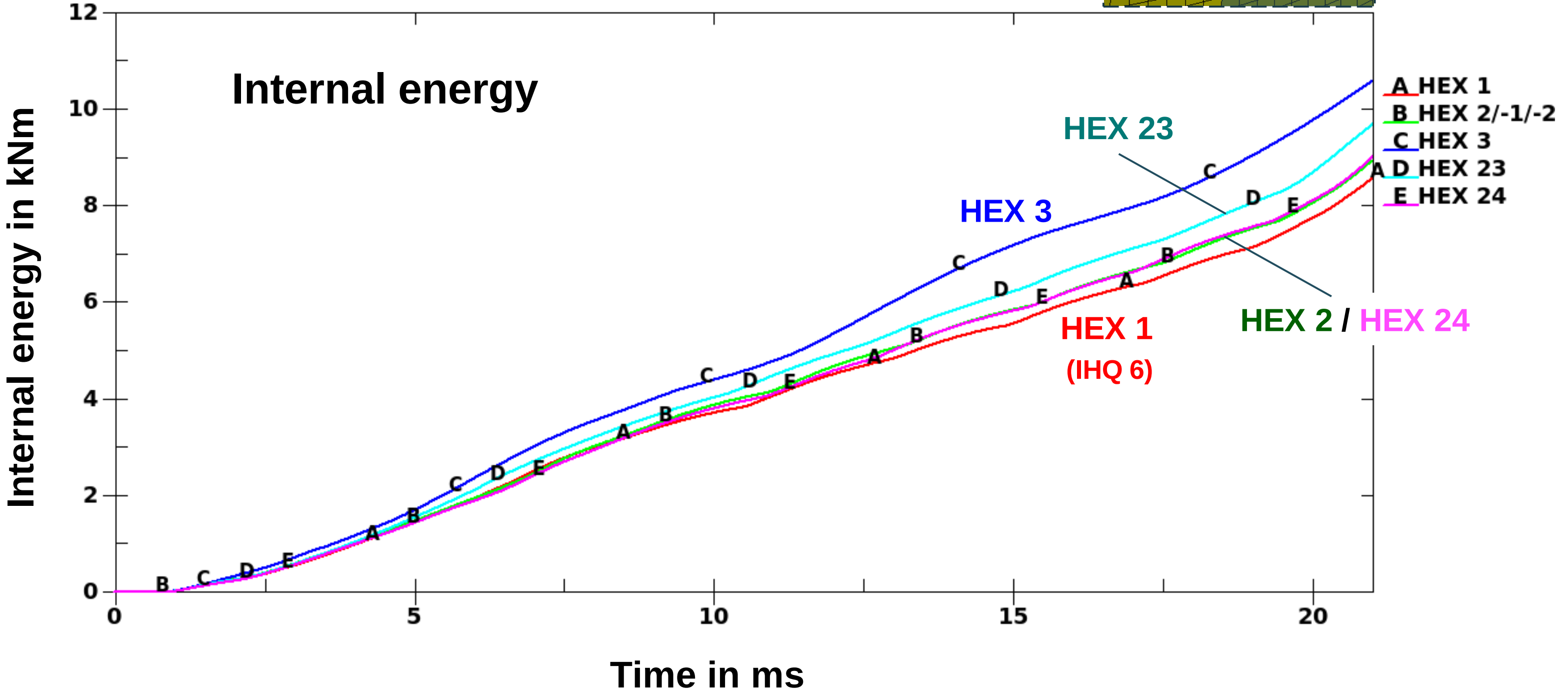


DYNA MORE

Circular tube compression

Results



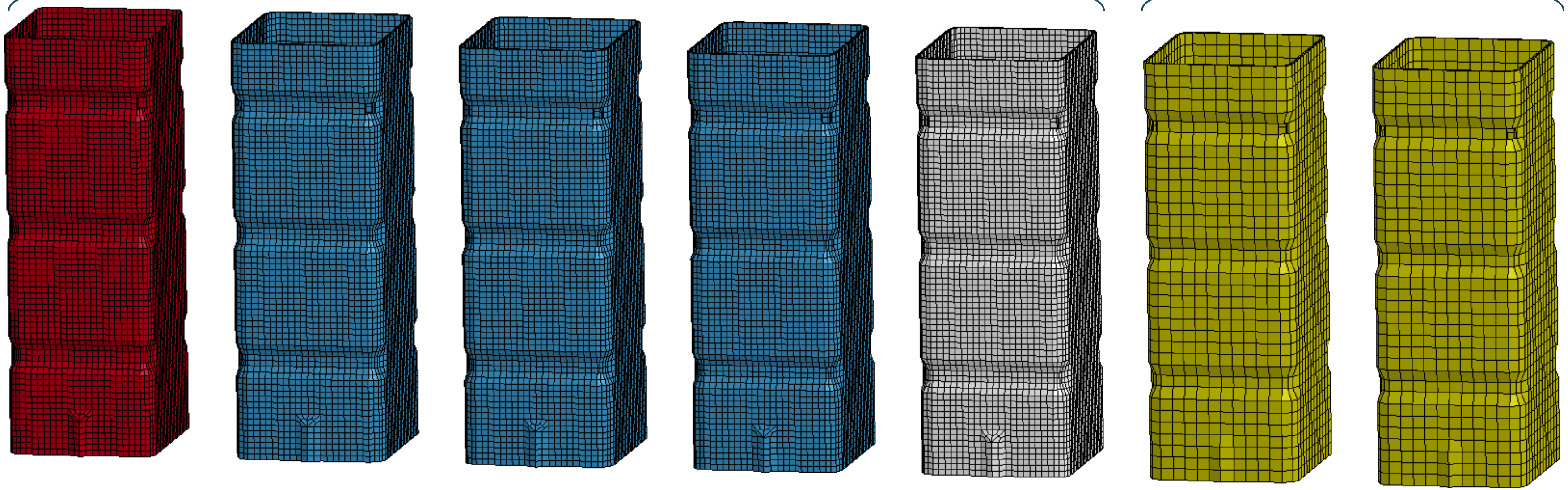


DYNA MORE

Tube crash

thickness: 2 mm (2 elements)
element size: 3.5 mm

element size: 7 mm



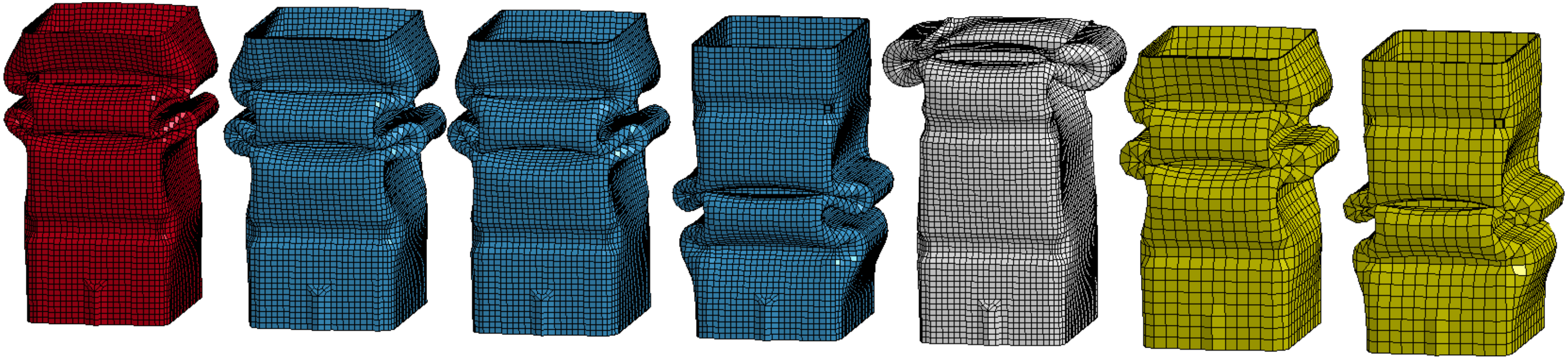
SHELL 16	HEX 1 (IHQ6)	HEX 2	HEX -1	HEX 3	HEX 23	HEX 24
	t_{CPU}=1.0	t_{CPU}=4.7	t_{CPU}=4.7	t_{CPU}=10.3	t_{CPU}= 3.6	t_{CPU}= 5.2
			HEX -2 (same pattern)		3.5mm mesh:	3.5mm mesh:
			t_{CPU}=7.6		t_{CPU}= 32.0	t_{CPU}= 43.2

Tube crash

thickness: 2 mm (2 elements)
element size: 3.5 mm

element size: 7 mm

Different folding sequences



SHELL 16

HEX 1 (IHQ6)
t_{CPU}=1.0

HEX 2
t_{CPU}=4.7

HEX -1
t_{CPU}=4.7

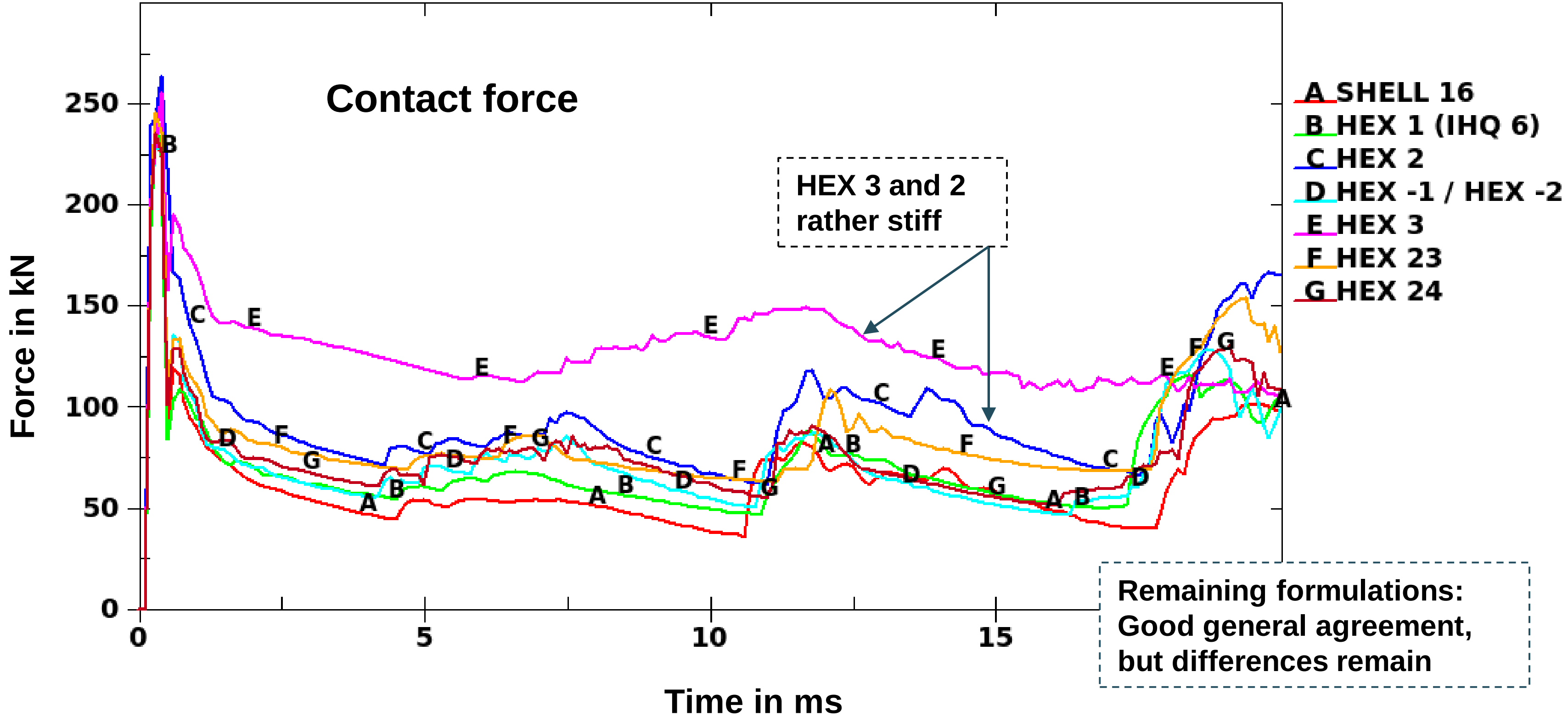
HEX -2 (same pattern)
t_{CPU}=7.6

HEX 3
t_{CPU}=10.3

HEX 23
t_{CPU}= 3.6
3.5mm mesh:
t_{CPU}= 32.0

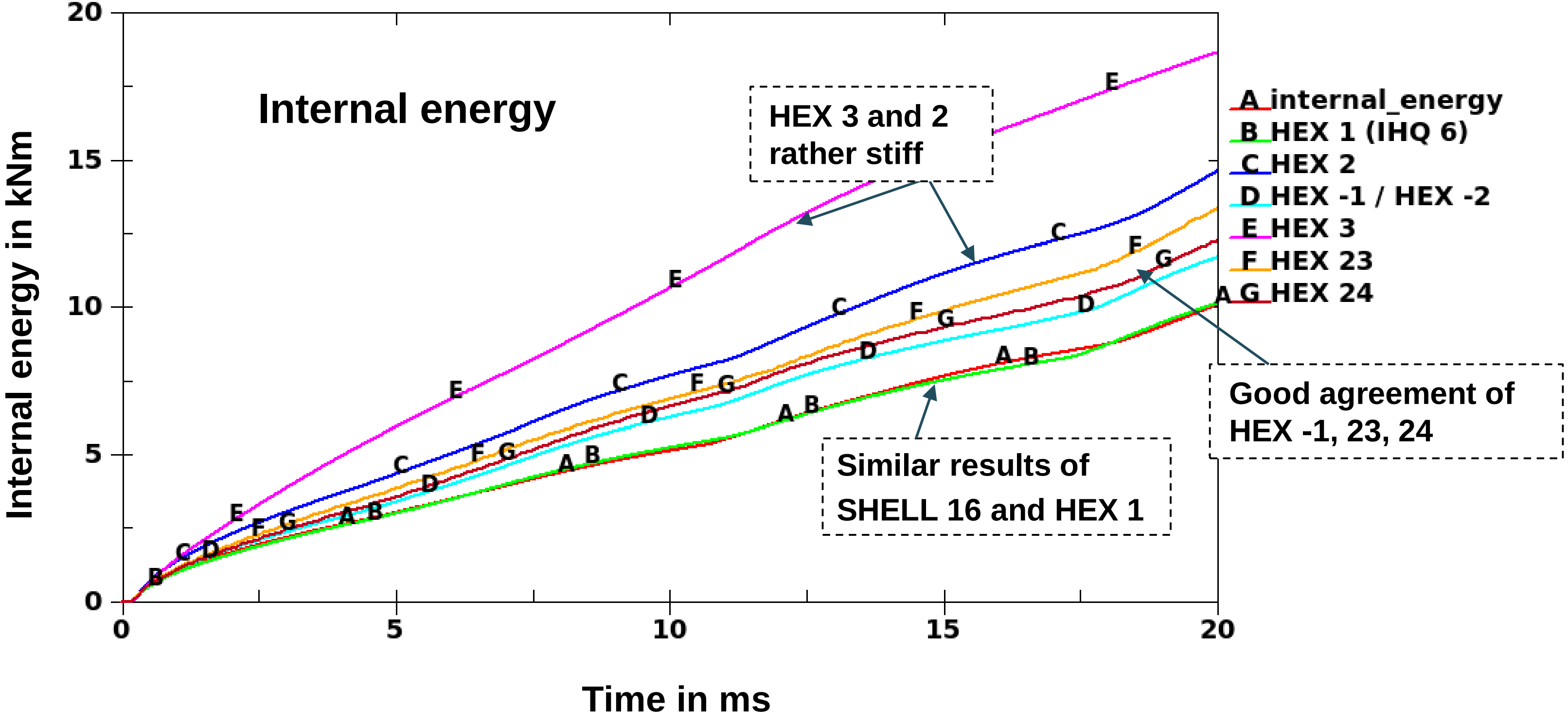
HEX 24
t_{CPU}= 5.2
3.5mm mesh:
t_{CPU}= 43.2

Tube crash



Remaining formulations:
Good general agreement,
but differences remain

Tube crash

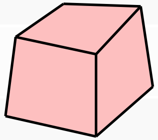


Internal energy
HEX 3 and 2 rather stiff
Similar results of SHELL 16 and HEX 1
Good agreement of HEX -1, 23, 24
A internal_energy
B HEX 1 (IHQ 6)
C HEX 2
D HEX -1 / HEX -2
E HEX 3
F HEX 23
G HEX 24
Internal energy in kNm
Time in ms
0
5
10
15
20

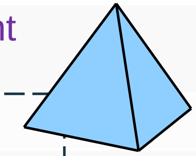
Overview

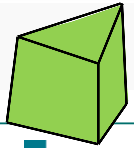
LS-DYNA User‘s manual: *SECTION_SOLID, parameter ELFORM

EQ.-2	Fully integrated S/R solid intended for elements with poor aspect ratio, accurate formulation
EQ.-1	Fully integrated S/R solid intended for elements with poor aspect ratio, efficient formulation
EQ.1	Constant stress solid element: default element type
EQ.2	Fully integrated S/R solid.
EQ.3	Fully integrated quadratic 8-node element with nodal rotations



EQ.4	S/R quadratic tetrahedron element with nodal rotations
EQ.10	**1 point tetrahedron**
EQ.13	**1 point nodal pressure tetrahedron**
Linear tetrahedral elements	element
EQ.16	4 or 5 point 10-noded tetrahedron
EQ.17	10-noded composite tetrahedron
EQ.23	20-node solid formulation
EQ.24	27-noded, fully integrated S/R quadratic solid element
EQ.115	1 point pentahedron element with hourglass control

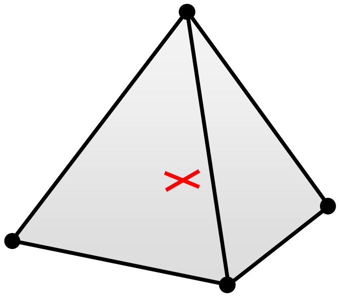




DYNA MORE

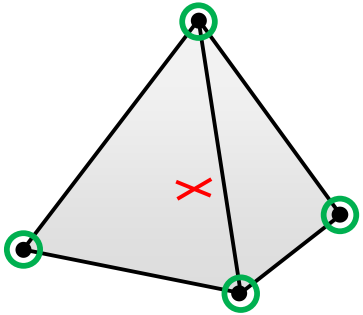
Linear tetrahedral elements in LS-DYNA

ELFORM = 10



- 1-point constant stress
- Volumetric locking – stiff behavior
- Only applicable for foams with $\nu = 0$ (not recommended in general)
- Often used for transitions in meshes *CONTROL_SOLID, ESORT=1

ELFORM = 13



- 1-point constant stress with nodal pressure averaging to alleviate volumetric locking
- Better performance than ELFORM=10 if Poisson‘s ratio $\nu > 0$ (metals, rubber, …)
- Supported materials for explicit *MAT_001, 003, 006, 007, 015, 024, 027, 077, 081, 082, 091, 092, 098, 103, 106, 120, 123, 124, 128, 129, 181, 183, 187, 224, 225, 244
- Implicit: all materials supported

DYNA MORE

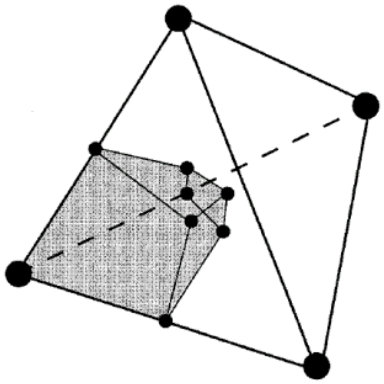
Linear tetrahedra elements in LS-DYNA

Theoretical background

Bonet J, Burton, AJ: *A simple average nodal pressure tetrahedral element for incompressible dynamic explicit applications*. Comm. Num. Meth. Engrg. 14: 437-449, 1998

*"(...) the element **prevents volumetric locking** by defining nodal volumes and evaluating average nodal pressures in terms of these volumes (...)"*

*"(...) it can be used in explicit dynamic applications involving (nearly) **incompressible material behavior** (e.g. rubber, ductile elastoplastic metals) (...)"*



Speed penalty of max. 25% compared to TET#10

➡ **TET 13 = TET 10 + averaging nodal pressures**

= TET 10 – volumetric locking

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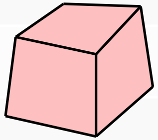
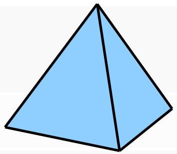
EQ.2	Fully integrated S/R solid.
EQ.3	Fully integrated quadratic 8-node element with nodal rotations

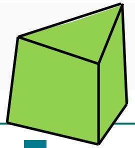


EQ.4	S/R quadratic tetrahedron element with nodal rotations
EQ.10	1 point tetrahedron
EQ.13	1 point nodal pressure tetrahedron



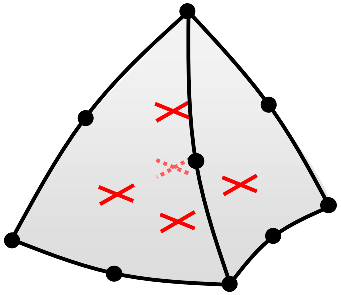
Higher order tetrahedral elements

EQ.16	**4 or 5 point 10-noded tetrahedron**
EQ.17	**10-noded composite tetrahedron**
EQ.23	20-node solid formulation
EQ.24	27-noded, fully integrated S/R quadratic solid element
EQ.115	1 point pentahedron element with hourglass control



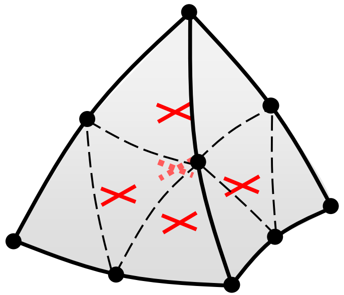
Higher order tetrahedral elements

ELFORM = 16



- 4(5) point 10-noded tetrahedron
- Good accuracy for moderate strains
- High cpu cost
- Observe the node numbering
- Use *CONTACT_AUTOMATIC_... with PID
- Easy conversion of 4-noded tets via *ELEMENT_SOLID_TET4TOTET10
- Midside nodes: *CONTROL_OUTPUT, TET10=1

ELFORM = 17



- 4(5) point 10-noded „composite“ tetrahedron (12 linear sub-tetrahedrons)
- Properties similar to type 16
- Correct external force distribution

Automatic node generation
*ELEMENT_SOLID_TET4TOTET10
Similar to *ELEMENT_SOLID_H8TOH20/_H8TOH27

Overview

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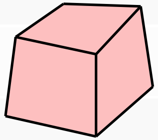
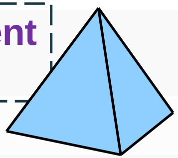
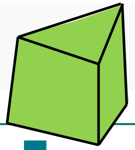


EQ.4	**S/R quadratic tetrahedron element with nodal rotations**
EQ.13	1 point nodal pressure tetrahedron
EQ.15	2 point pentahedron element
EQ.16	4 or 5 point 10-noded tetrahedron
EQ.17	10-noded composite tetrahedron
EQ.23	20-node solid formulation
EQ.24	27-noded, fully integrated S/R quadratic solid element
EQ.115	1 point pentahedron element with hourglass control

Nodal rotation tetrahedral element

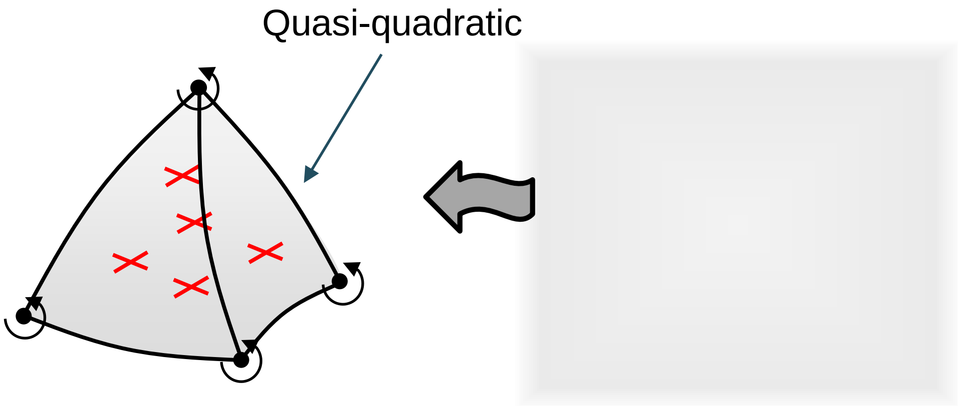




Quadratic tetrahedron with nodal rotations

ELFORM = 4

- Quadratic 4 node tetrahedron with nodal rotations, i.e. 6 DOF per node
- Derived from 10 node tetrahedron
- S/R integration (5-point)
- Well suited for connections to shells
- Good accuracy for small strains
- Tendency to volumetric locking



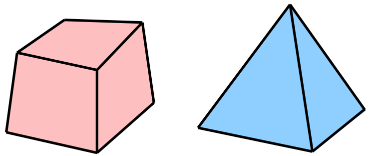
4 nodes with 24 DOF

10 nodes with 30 DOF

Teng, H: *Solid elements with Rotational Degree of Freedom for Grand Rotation Problems in LS-DYNA,* 11th International LS-DYNA Users Conference, 2010

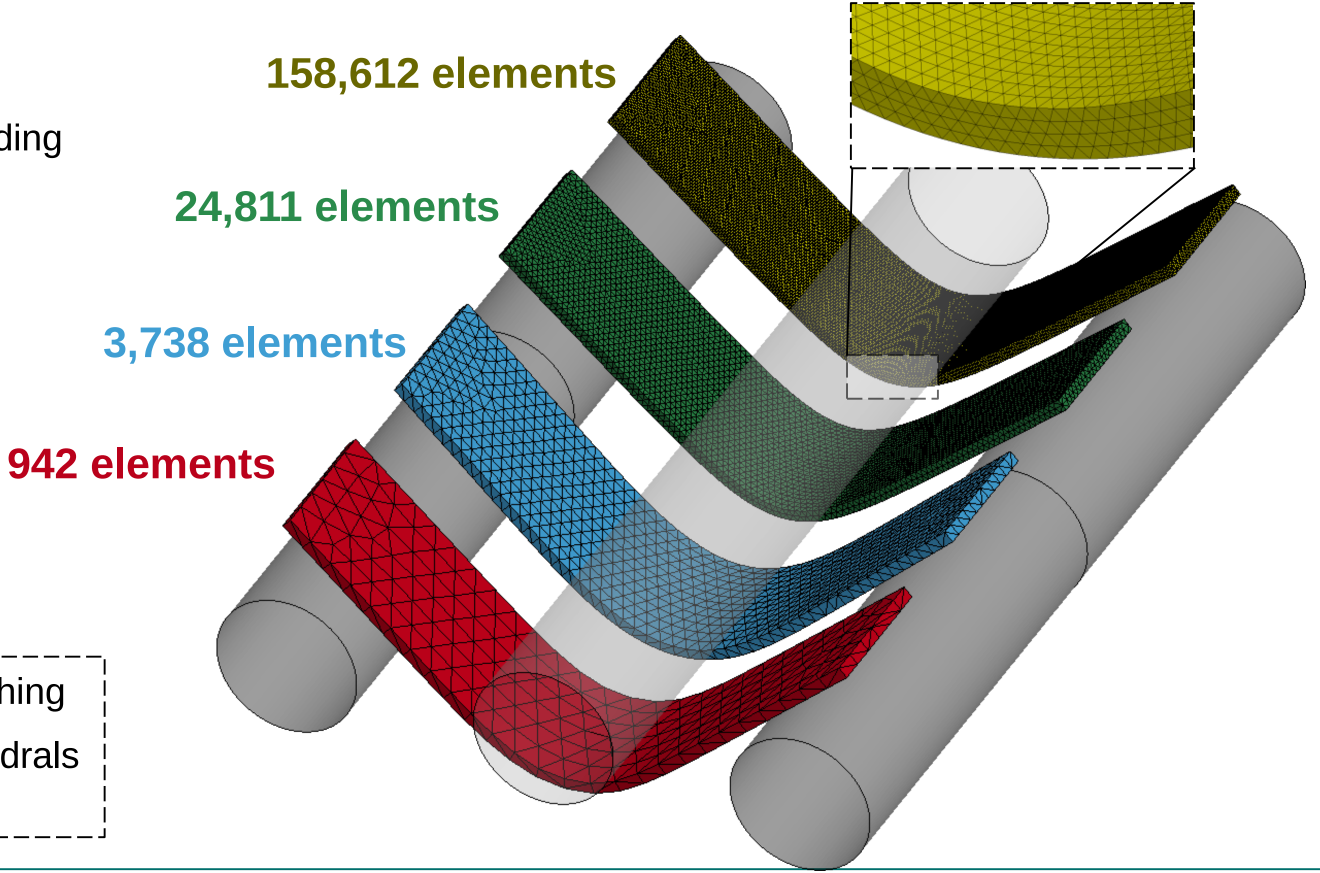
Pawlak, TP and Yunus, SM: *Solid elements with rotational degrees of freedom: Part 2 – Tetrahedron elements*, IJNME 1991

Examples part 2



Plastic bending

- Explicit plastic 3 point bending (prescribed motion)
- plate of dimensions $300 \times 60 \times 5\ \text{mm}^3$
- *MAT_024 (aluminum)



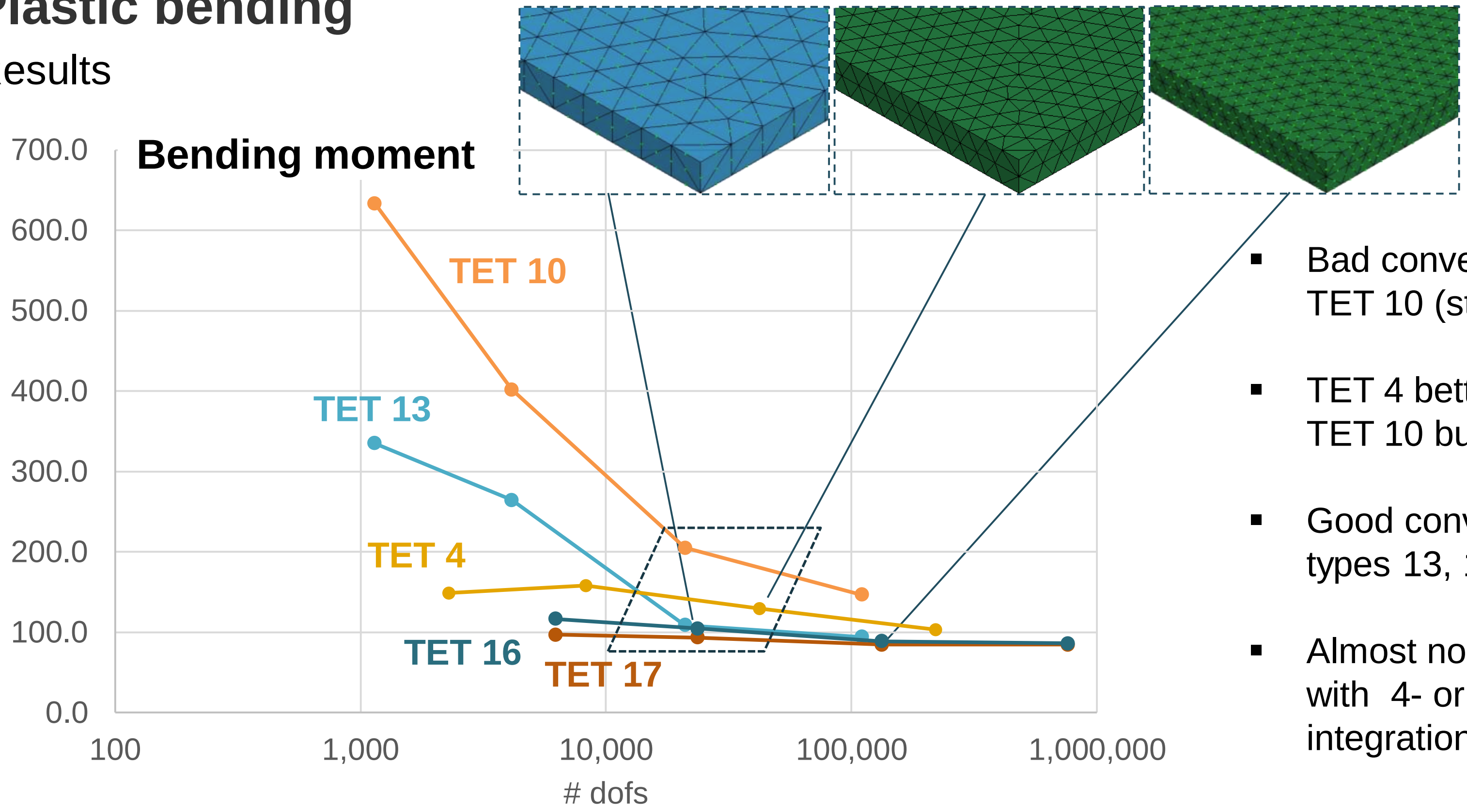
Free tetrahedral meshing

(no split of hexaedehedrals into tetrahedrals)

DYNA MORE

Plastic bending

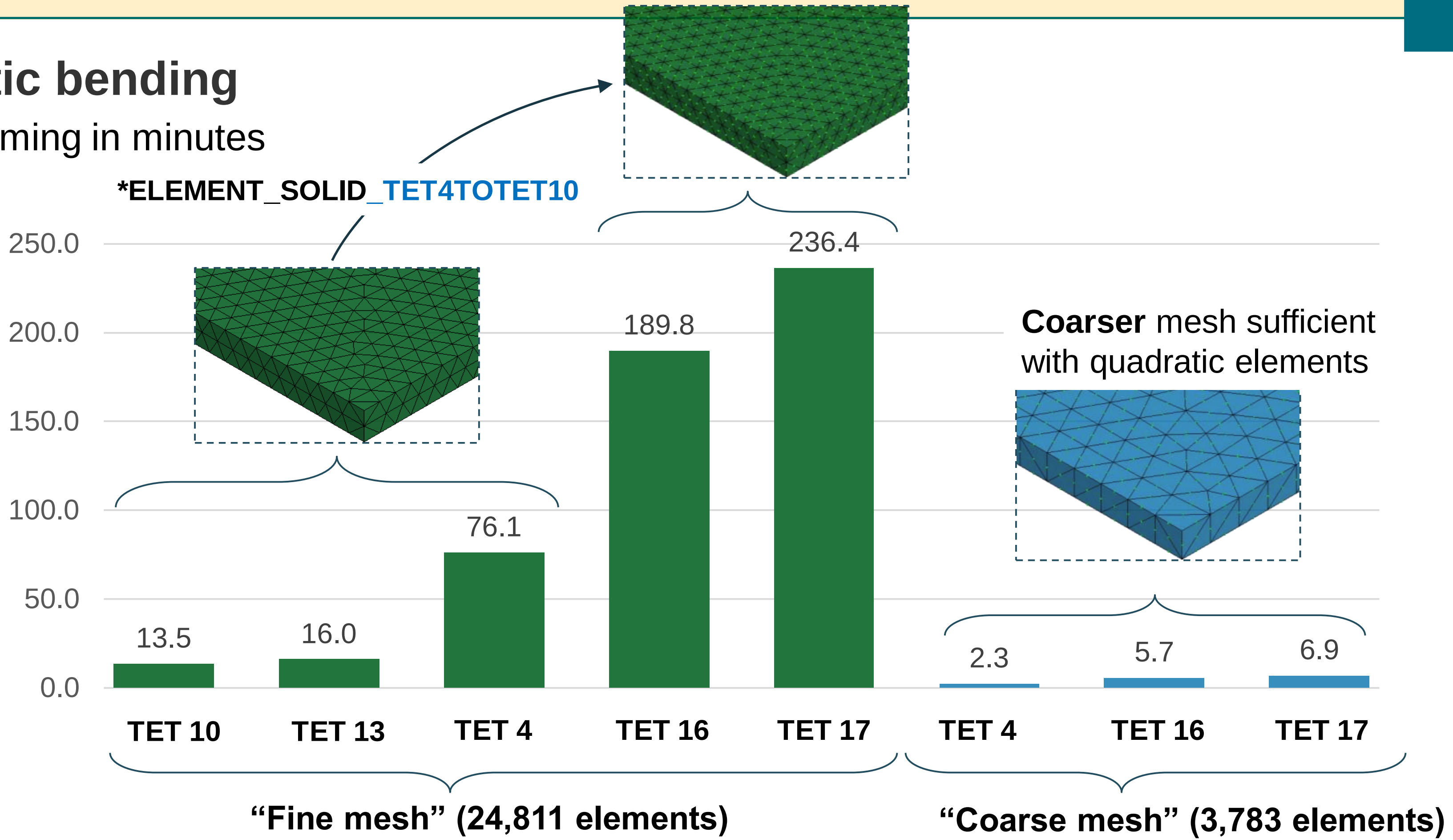
Results



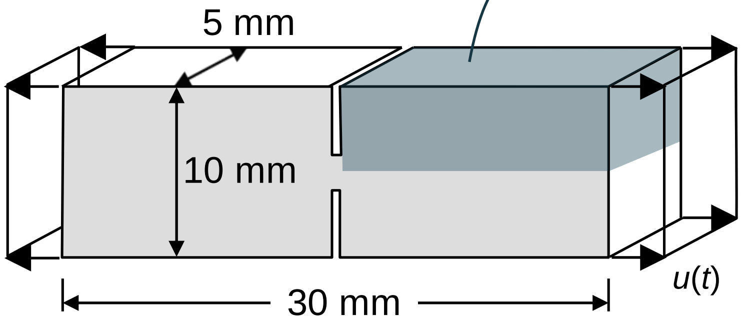
- Bad convergence of TET 10 (stiff behavior)
- TET 4 better than TET 10 but still too stiff
- Good convergence with types 13, 16, 17
- Almost no difference with 4- or 5-point-integration

Plastic bending

CPU timing in minutes

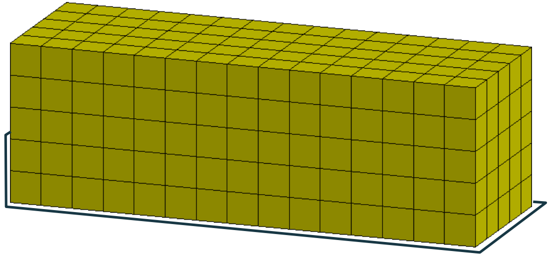


Notched steel specimen

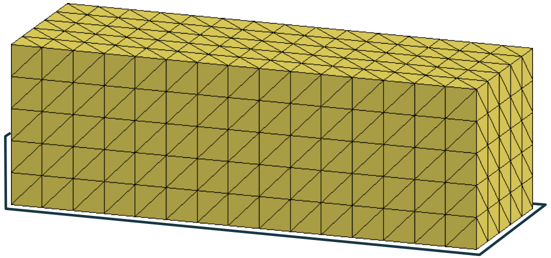


Discretized quarter system

Hexahedral mesh



Tetrahedral mesh



***MAT_PIECEWISE_LINEAR_PLASTICITY**

E = 206.9 kN/mm²

ν = 0.29

σ_y = 0.45 kN/mm²

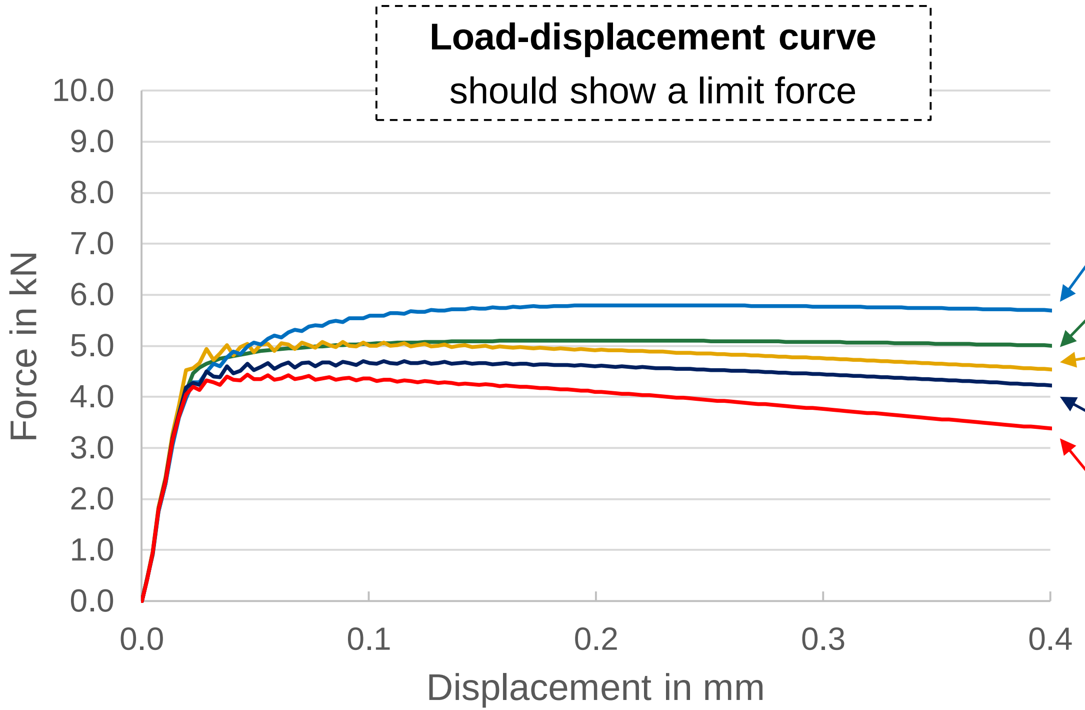
E_t = 0.02 kN/mm² (nearly ideal plastic)

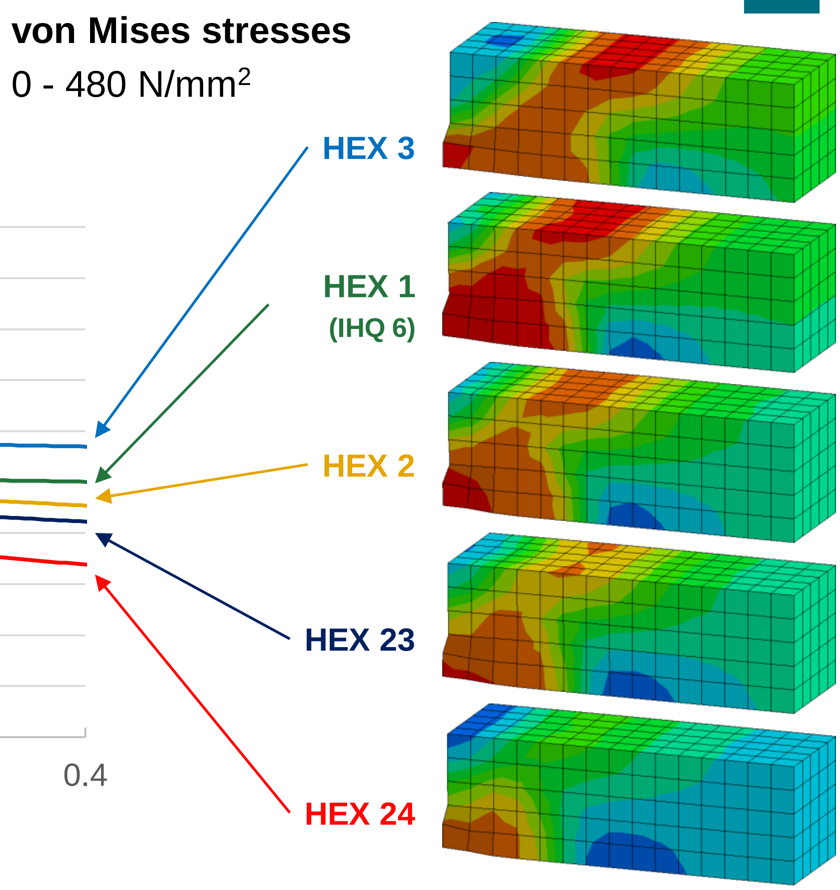
→ **Isochoric plastic flow** → **Load-displacement curve** should show a limit force

DYNA MORE

Notched steel specimen

Hexahedral results





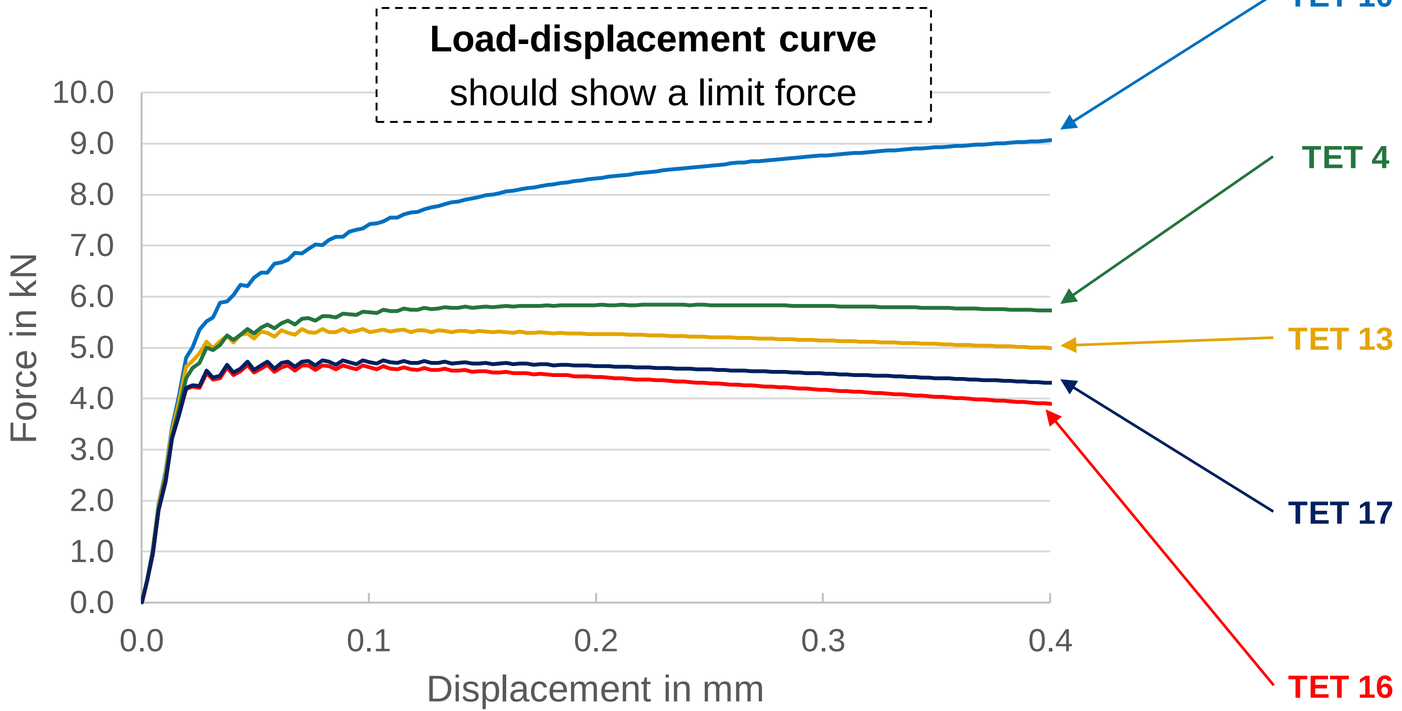
DYNA MORE

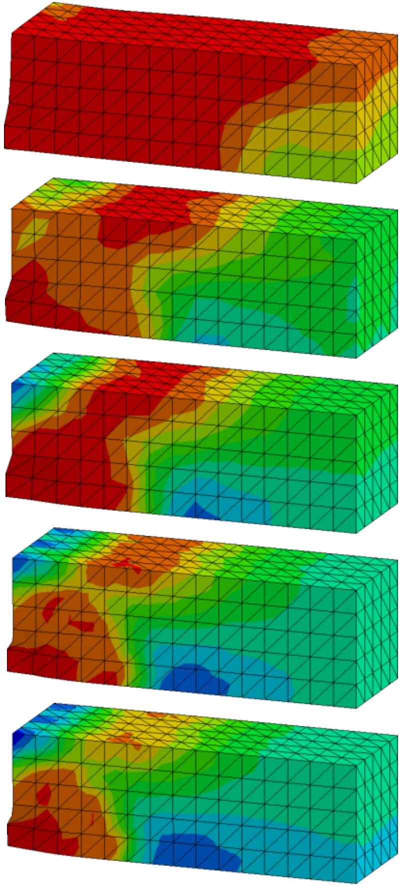
Notched steel specimen

Tetrahedral results

von Mises stresses

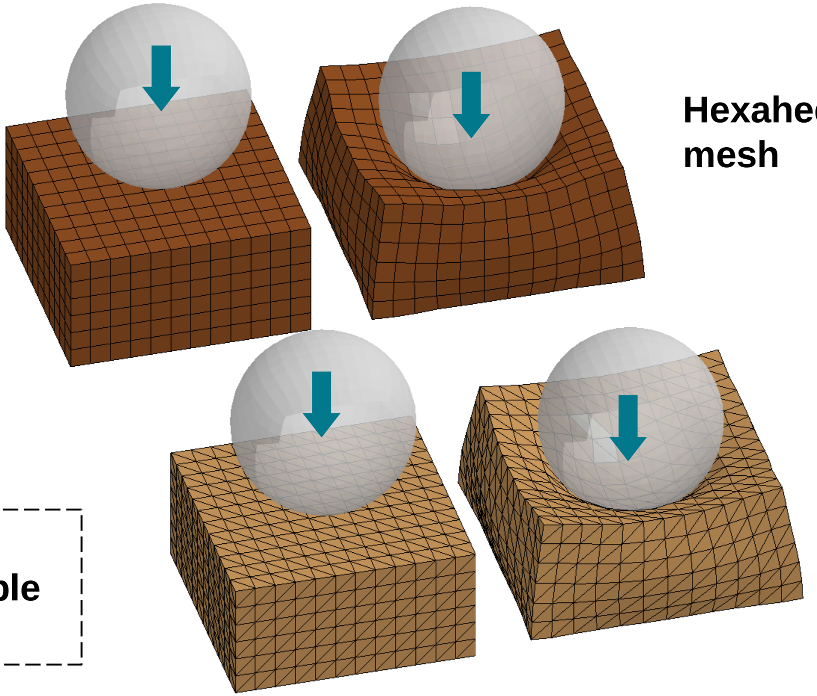
0 - 480 N/mm^2





Rubber block compression

Sphere pushed into rubber block



Hexahedral mesh

Tetrahedral mesh

*MAT_MOONEY-RIVLIN_RUBBER

A = 4.0 N/mm^2

B = 2.4 N/mm^2

v = 0.499 → **nearly incompressible material**

ρ = 1.5E-06 kg/mm^3

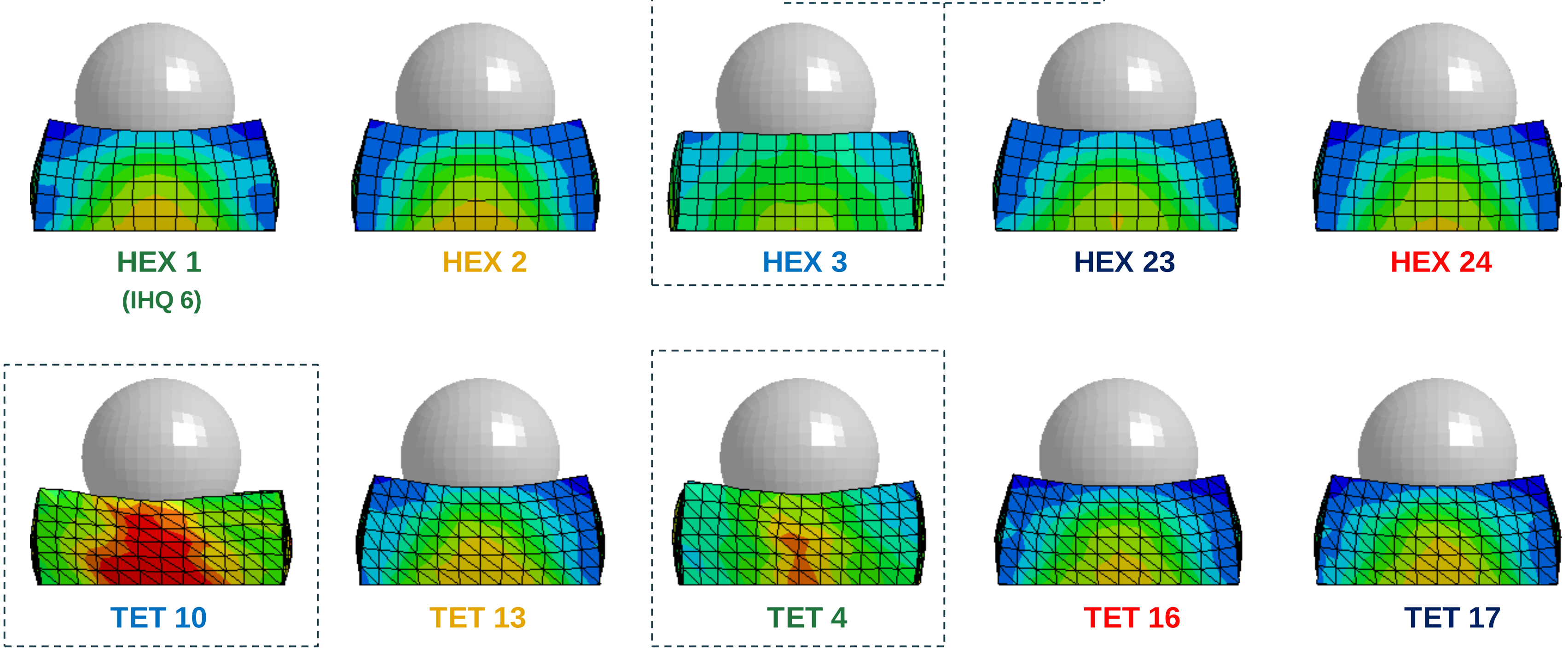
Rubber block compression

Results

No alleviation of volumetric locking

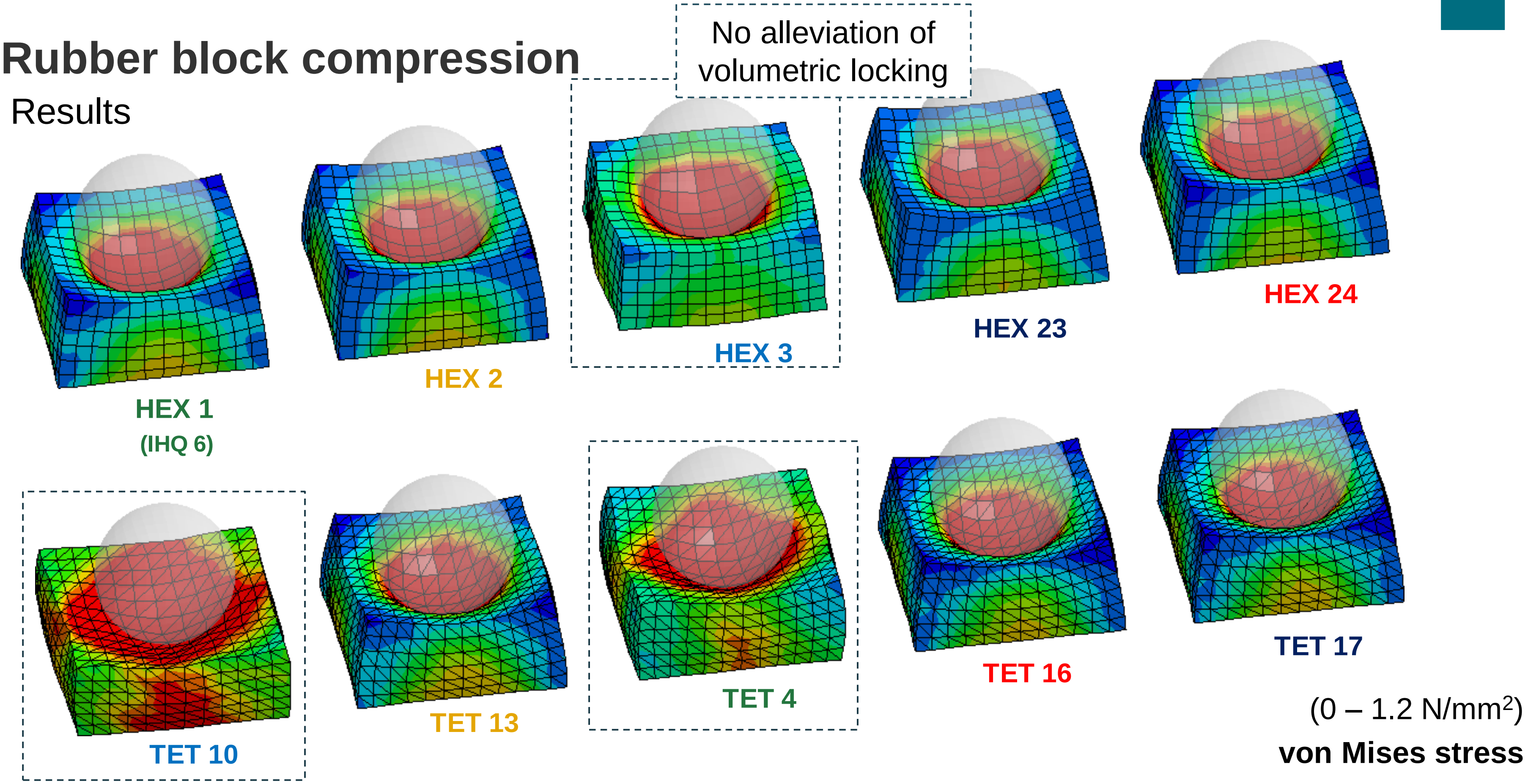
von Mises stress

(0 – 1.2 N/mm^2)



Rubber block compression

Results



Taylor bar impact

***MAT_PIECEWISE_LINEAR_PLASTICITY**

ρ = 8930 kg/m^3,

E = 117 kN/mm^2,

v = 0.35,

σ_y = 0.4 kN/mm^2,

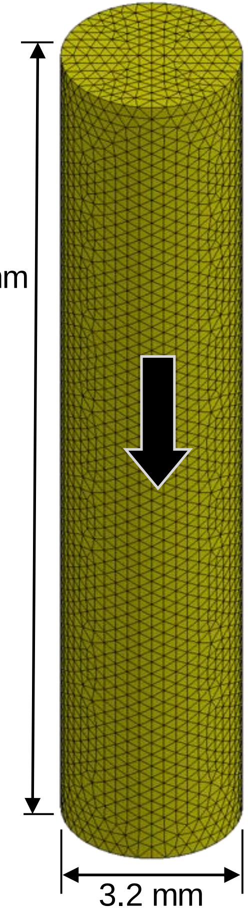
E_t = 0.1 kN/mm^2

Wilkins, ML et al.
"Impact of cylinders on
a rigid boundary"
Journal of Applied Physics, 1973

large strains > 300%

32.4 mm

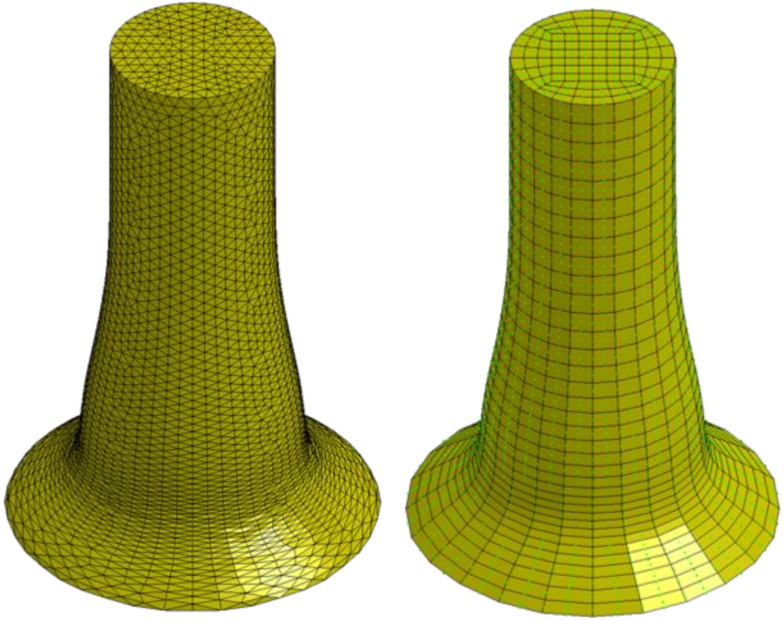
v_0 = 227 m/s



3.2 mm

Final deformation

Tetrahedrons | Hexahedrons

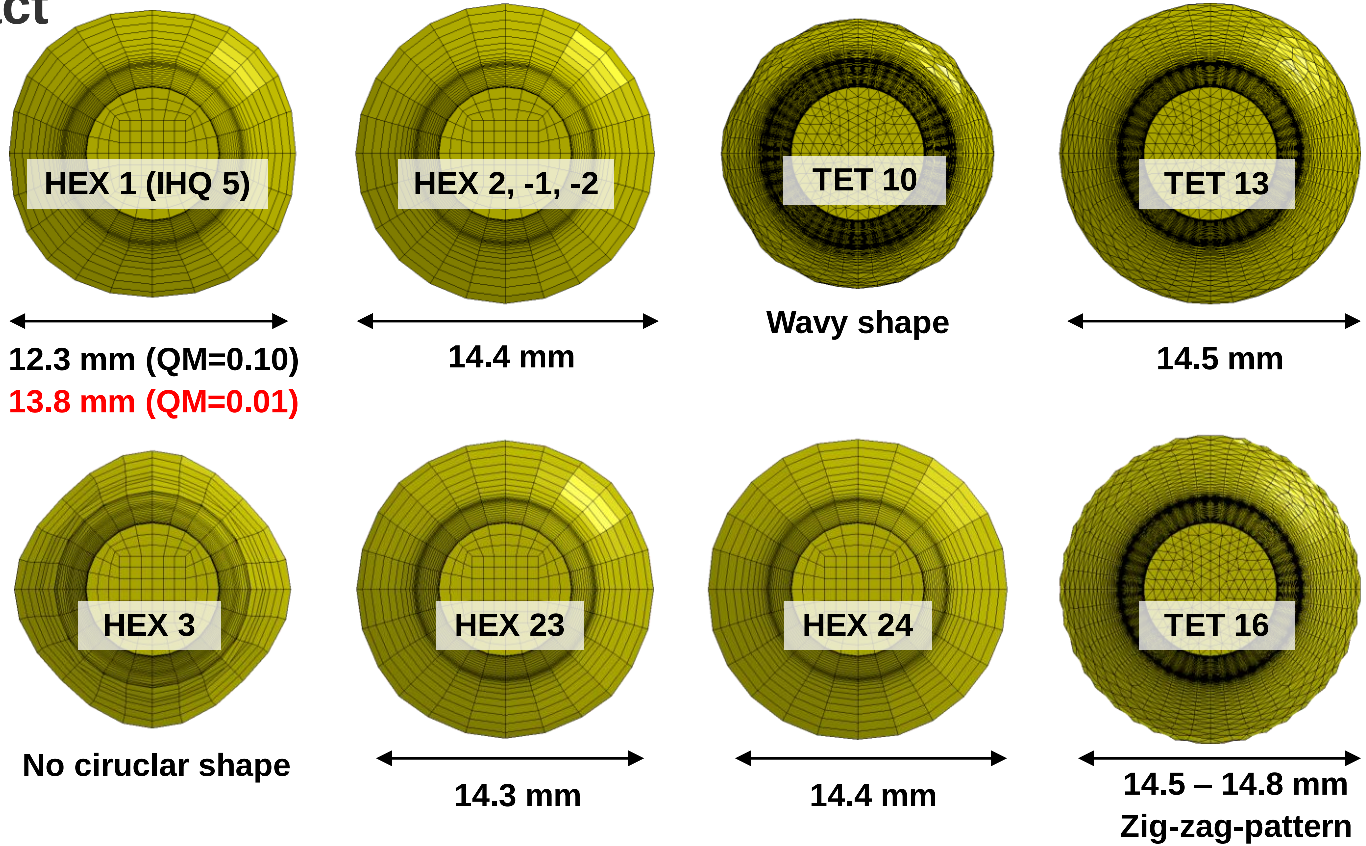


Taylor bar impact

Deformation (top view)

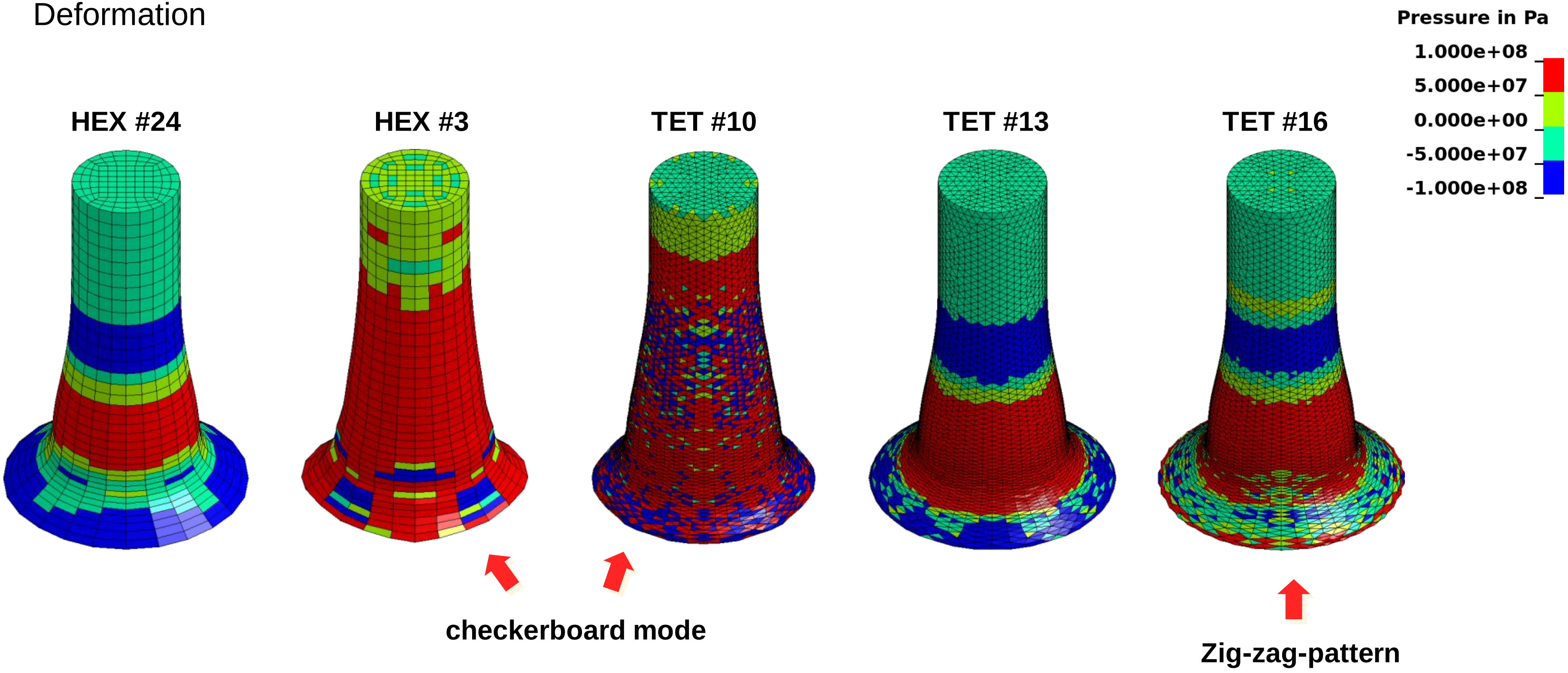
Linear element formulations

Quadratic/ Rotational element formulations

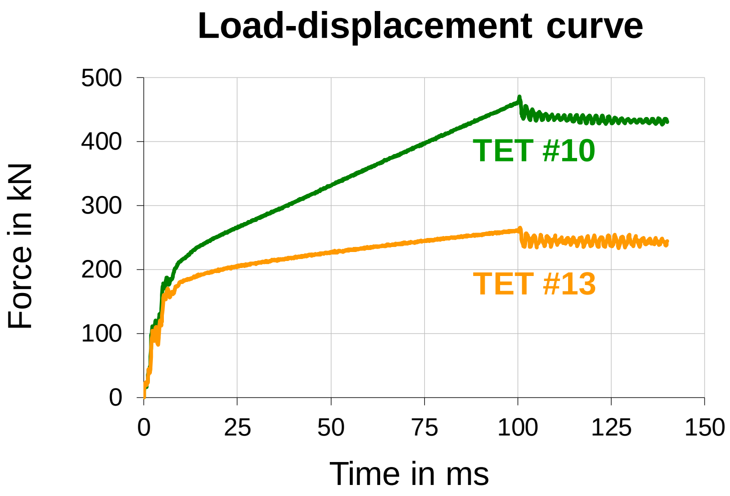


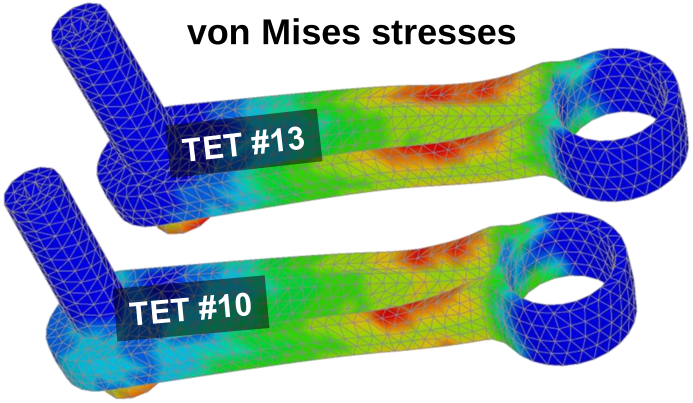
Taylor bar impact

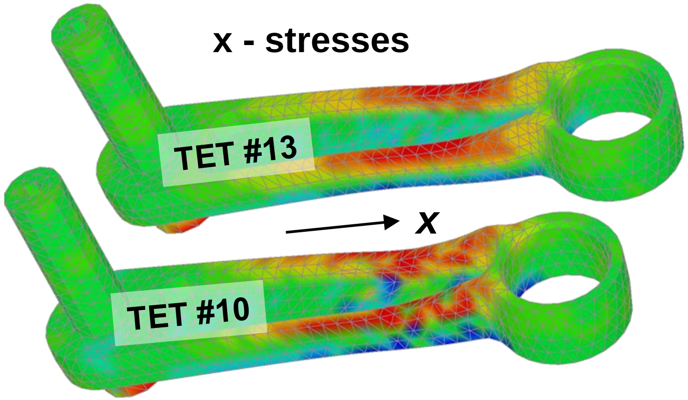
Deformation



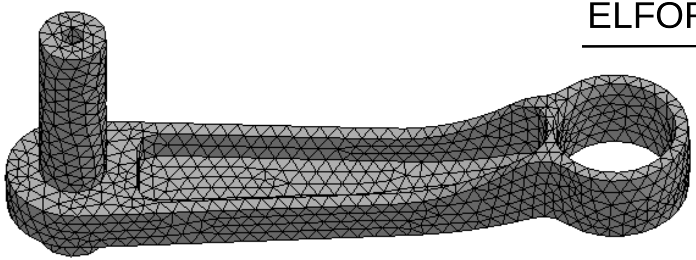
Structural component

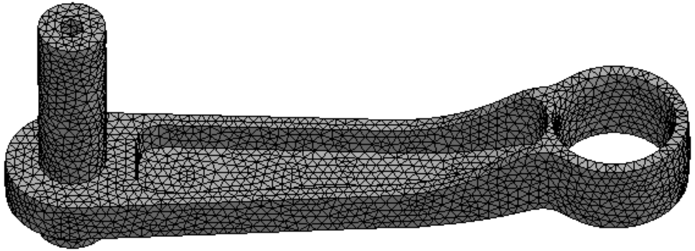


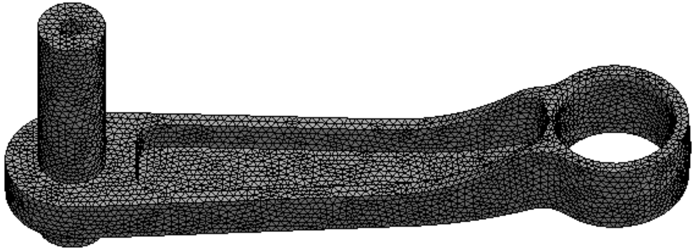




Structural component





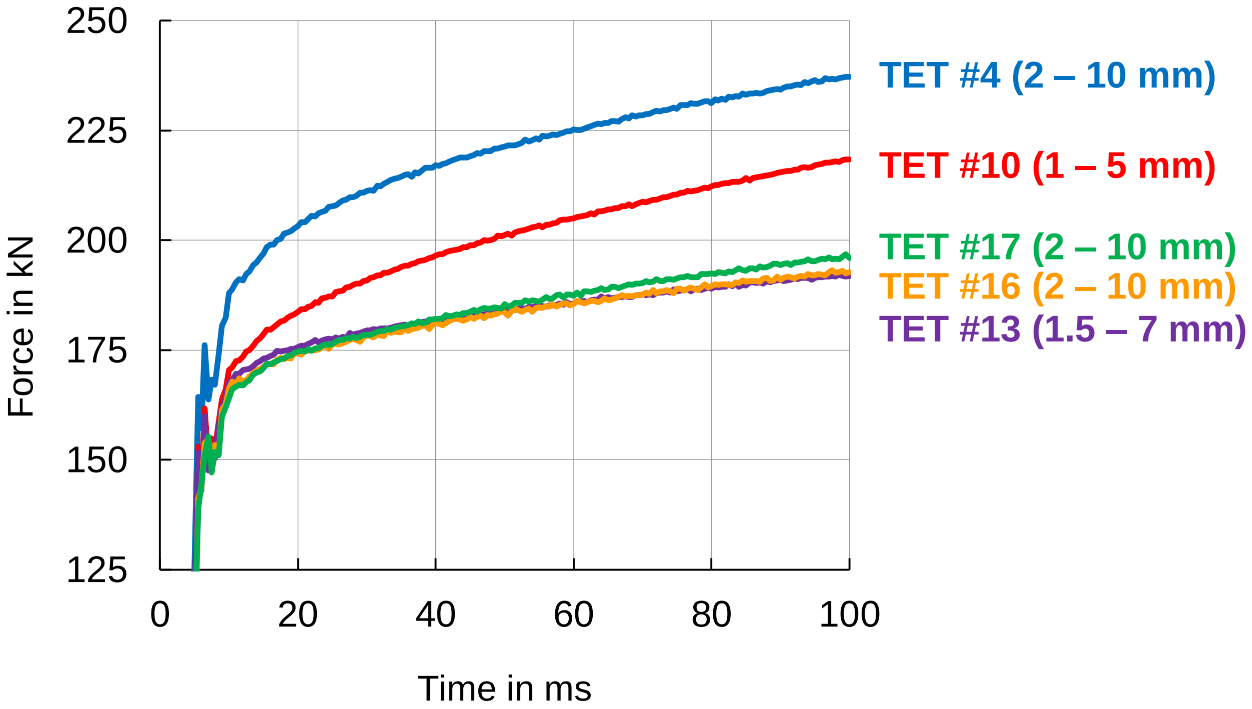


CPU time in minutes

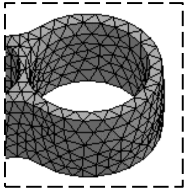
ELFORM =	4	10	13	16	17
7,500 elements 2-10 mm	**18**	3	4	**39**	**66**
27,000 elements 1.5-7 mm	97	14	**22**	212	344
77,000 elements 1-5 mm	403	**64**	98	945	1529

Structural component

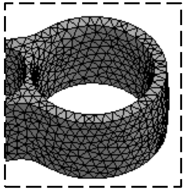
Load-displacement curve



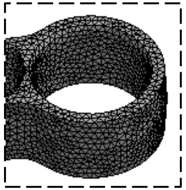
2 – 10 mm



1.5 – 7 mm



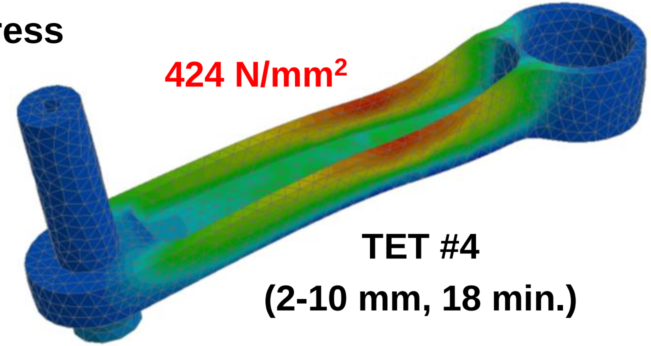
1 – 5 mm

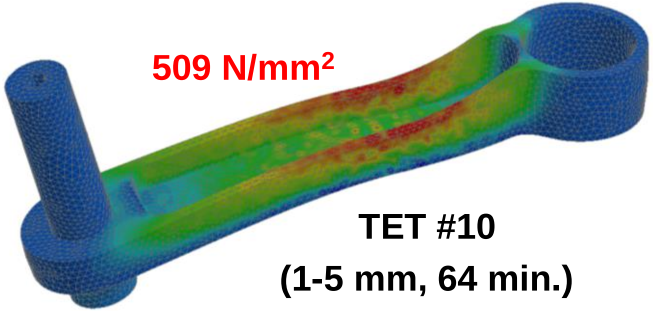


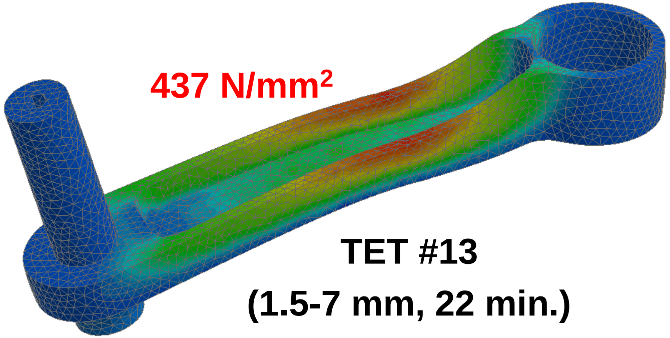
Structural component

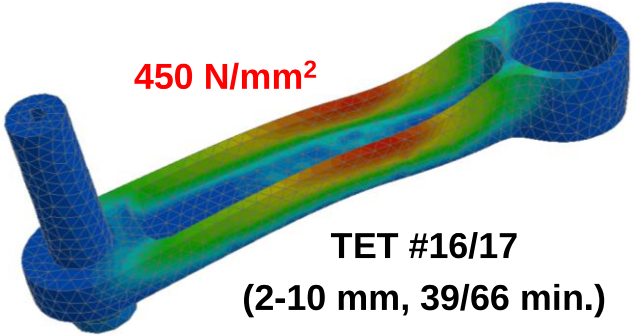
Maximum principal stress

-50.0 – 450.0 N/mm^2





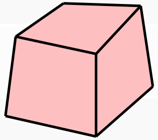




Overview

LS-DYNA User‘s manual: *SECTION_SOLID, parameter ELFORM

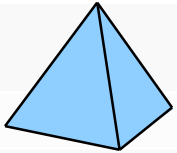
EQ.-2	Fully integrated S/R solid intended for elements with poor aspect ratio, accurate formulation
EQ.-1	Fully integrated S/R solid intended for elements with poor aspect ratio, efficient formulation
EQ.1	Constant stress solid element: default element type
EQ.2	Fully integrated S/R solid.
EQ.3	Fully integrated quadratic 8-node element with nodal rotations

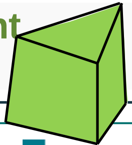


EQ.4	S/R quadratic tetrahedron element with nodal rotations
EQ.10	1 point tetrahedron
EQ.13	1 point nodal pressure tetrahedron
EQ.15	**2 point pentahedron element**
	d tetrahedron
EQ.17	10-noded composite tetrahedron
EQ.23	20-node solid formulation
EQ.24	27-noded, fully integrated S/R ent
EQ.115	**1 point pentahedron element with hourglass control**

Pentahedron element

Pentahedron element

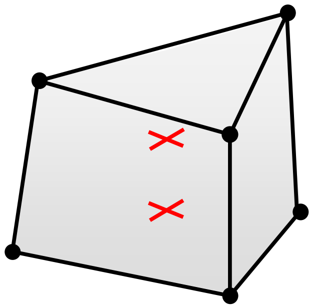




DYNA MORE

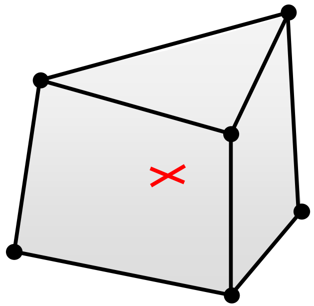
Pentahedra elements in LS-DYNA

ELFORM = 15



- 2-point selective reduced integration
- needs hourglass stabilization for twist mode (recent improvement → next official versions)
- often used as transition element (ESORT=1)

ELFORM = 115



- 1-point reduced integration
- needs hourglass stabilization (analogue to hexahedron element type 1 with Flanagan-Belytschko hourglass formulation)

should in general be avoided – better: pure hexahedral or tetrahedral meshes

Time step control

Critical time step

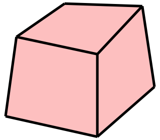
$$\Delta t_e = \frac{L_e}{Q + (Q^2 + c^2)^{1/2}} \approx \frac{L_e}{c}$$

L_e = main information from element formulation

Adiabatic sound speed

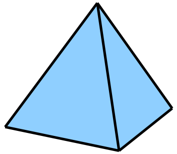
$$c = \sqrt{\frac{E(1-\nu)}{(1+\nu)(1-2\nu)\rho}} = \sqrt{\frac{K + \frac{4}{3}G}{\rho}}$$

Characteristic element length



ELFORM = 1, 2, 3, -1, -2: $L_e = V/A_{max}$

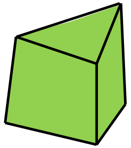
ELFORM = 4: $L_e = 0.85\ h_{min}$



ELFORM = 10 / 13: $L_e = h_{min}$

ELFORM = 16: $L_e = 0.3889\ h_{min}$

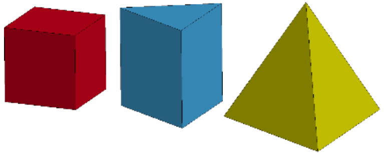
ELFORM = 17: $L_e = V/A_{max}$

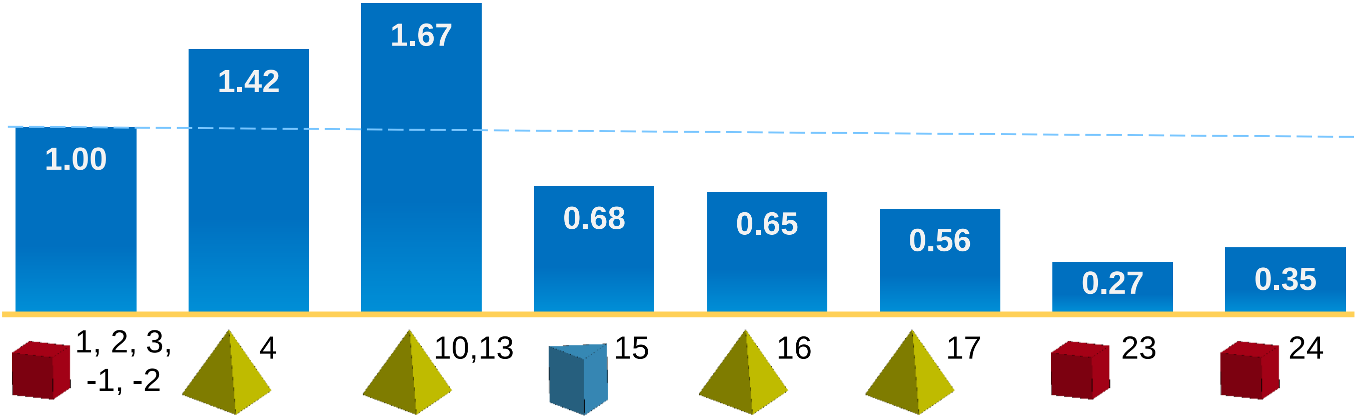


ELFORM = 15: $L_e = 1/\sqrt{B_{ij}B_{ij}}$

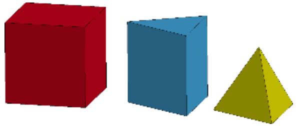
Time step control

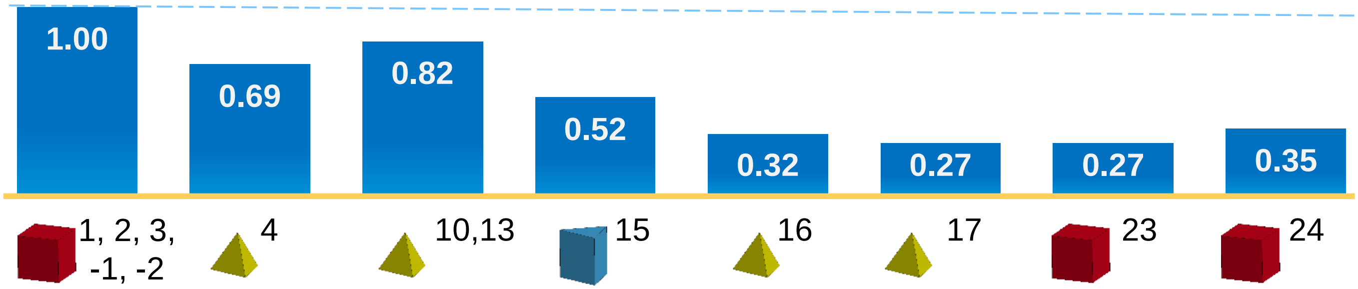
Example 1
Time step size for
same volume



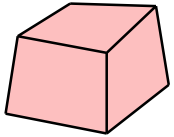


Example 2
Time step size for
same edge length





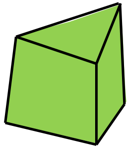
Conclusions and remarks



- Use hexahedron elements if possible (regular solid bodies)
  - ELFORM = 1 with IHQ = 6 or ELFORM = 2, 3
  - ELFORM = -1 or -2 for „flat“ hexas

- Quadratic ELFORM 23, 24 show good coarse mesh accuracy
- But for large strains linear elements in general more robust

use R10

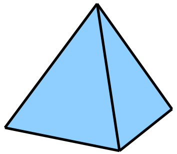


- Pentahedrons 15/115 should be avoided or only be used as transition elements, pure tetrahedral mesh is better choice

General remarks

- In implicit analysis: costly element formulations may be used – not as significant for speed as in explicit analysis
- Always set ESORT = 1 on *CONTROL_SOLID

Conclusions and remarks



- For complex solid structures, use tet type 4, 13, 16, or 17
  - ELFORM = 16/17 are the most accurate tets, but not suited for large strains
  - ELFORM = 13 needs finer mesh, well suited even for large strains (check if your material is supported)
- For metals or plastics (moderate strains), use tet type 4, 13, 16, or 17
- For rubber materials (incompressible, large strains) use tet type 13
- For bulk forming problems (large strains!), use ELFORM = 13 and r-adaptivity

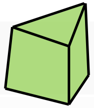
General remarks

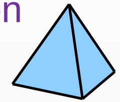
- In implicit analysis: costly element formulations may be used – not as significant for speed as in explicit analysis
- Always set ESORT = 1 on *CONTROL_SOLID

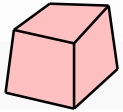
Conclusions and remarks

***SECTION_SOLID, parameter ELFORM**

EQ.25	21-noded quadratic pentahedron
EQ.26	15-noded quadratic tetrahedron
EQ.27	20-noded cubic tetrahedron
EQ.28	40-noded cubic pentahedron
EQ.29	64-noded cubic hexahedron







Further quadratic and cubic element types available in more recent versions of LS-DYNA

www.dynalook.com

Teng, H: “Recent Advances on Higher-Order 27-node Hexahedral Element in LS-DYNA”, 14th International LS-DYNA Users Conference 2016.

Borrvall, T, Benson, D, Teng, H: “An Implicit Study of High Order Elements in LS-DYNA”, 11th European LS-DYNA Conference 2017.