DYNAmore Express Webinar, 03 June 2022

Solid element formulations in LS-DYNA

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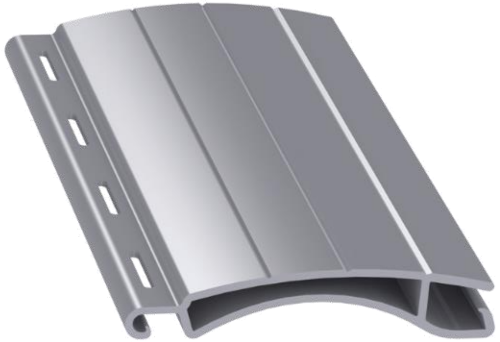
Motivation

Typical applications

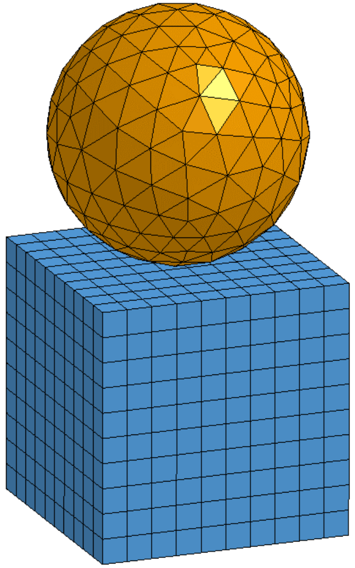


- Foam Structures
- Rubber components
- Cast iron parts
- Solid barriers
- Plastic parts
- Bulk forming
- Thick metal sheets
- Elastic tools
- Impact analysis
- Civil engineering
- … and more

Motivation

What are solid elements?

- Solid elements are three-dimensional finite elements that can model solid bodies and structures without any a priori geometric simplification
- Finite element mesh visually looks like the physical system
- Effective assembly of complicated geometries
- Boundary and loading conditions treated more realistically (compared to shells or beams)
- No constitutive assumptions required



But …

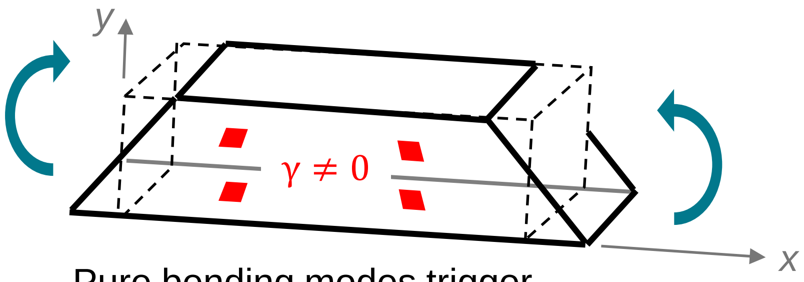
- Expensive mesh refinement: Curse of dimensionality
- Higher effort: mesh preparation, CPU time, post-processing, …
- Often poor performance for thin-walled structures and low-order formulations (locking problems)

Motivation

Requirements

Requirements

- No volumetric locking (rubber-like, elasto-plastic)
- Good bending performance (also for thin elements)
- No mesh distortion sensitivity (huge deformation)
- Coarse mesh accuracy
  - Size of real engineering application sometimes not allows to model with converged mesh
- **Robustness**
- **Efficiency**



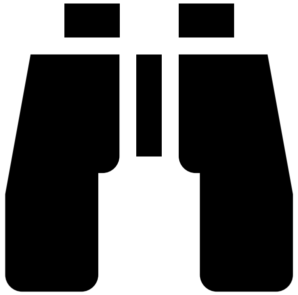
Pure bending modes trigger spurious shear energy

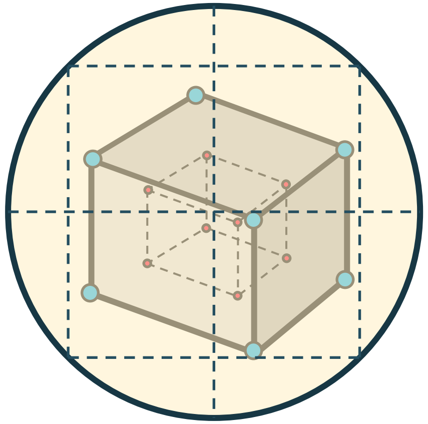
Element technology

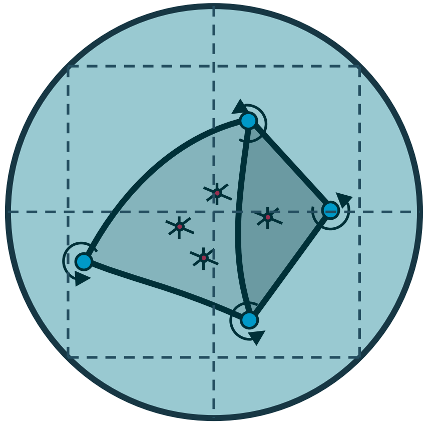
- Reduced integration with stabilization
- Selective reduced integration
- Mixed methods
- Nodally based formulations
- Composite (macro) formulations
- Cosserat point based
- Special interpolations

A first look

Safari of solid formulations







Solid element formulations

*SECTION_SOLID, ELFORM

EQ.-18: 8 point enhanced strain with 13 incompatible modes

EQ.-2: 8 point hexahedron intended for poor aspect ratios, accurate formulation

EQ.-1: 8 point hexahedron intended for poor aspect ratios, efficient formulation

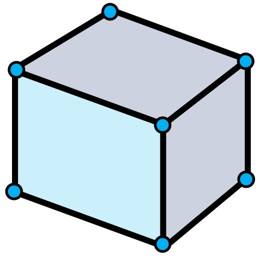
EQ.1: Constant stress solid element: default element type
Cosserat Point Element with hourglass type 10

EQ.2: 8 point hexahedron

EQ.3: Fully integrated quadratic 8 node element with nodal rotations

EQ.23: 20-node solid formulation

EQ.62: 8 point brick with incompatible modes by assumed strain



EQ.4: S/R quadratic tetrahedron element with nodal rotations

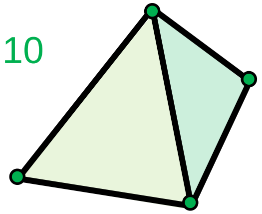
EQ.10: 1 point tetrahedron

EQ.13: 1 point nodal pressure tetrahedron

EQ.16: 4 or 5 point 10-noded tetrahedron
Cosserat Point Element with hourglass type 10

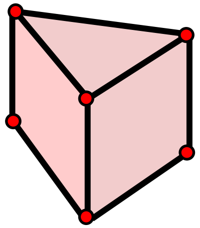
EQ.17: 10-noded composite tetrahedron

EQ.60: 1 point tetrahedron



EQ.15: 2 point pentahedron element

EQ.115: 1 point pentahedron element with hourglass control



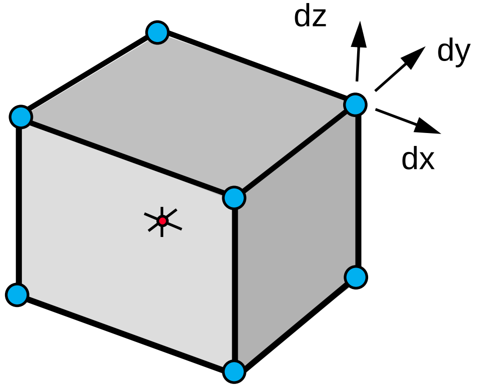
Not shown in this overview

- More higher order formulations
- Cohesive and gasket formulations
- Isogeometric element formulations
- ALE, EFG, SPG, …

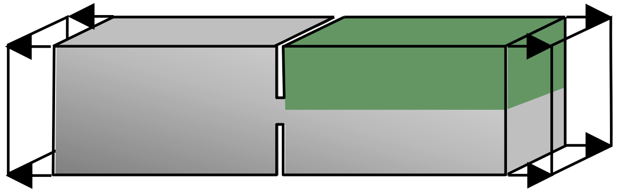
Constant stress solid

ELFORM = 1 (the default)

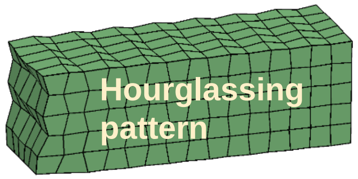
- Single point integration with hourglass control
- Efficient and accurate
- Can sustain largest nonlinear deformation
- Requires hourglass control
  - Choice of hourglass formulation
  - and values remains an issue

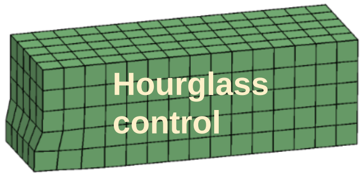


- Example for Hourglassing: Stretching of a notched steel specimen



Notched steel specimen

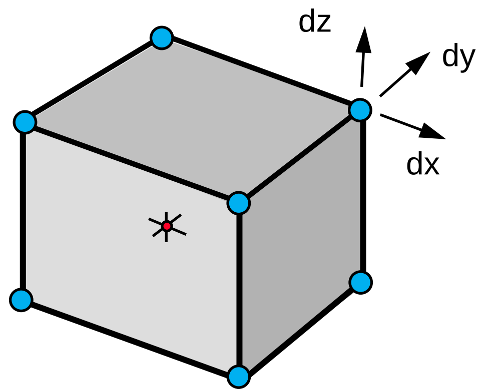




Constant stress solid

Hourglass control

- **IHQ = 1…5**
  - Viscous form (1,2,3) for higher velocities
  - Stiffness form (4,5) for lower velocities
  - Exact volume integration recommended (3,5)



- **IHQ = 6**
  - Recommended in most situations
  - The QBI (Quintessential Bending Incompressible) hourglass control by Belytschko and Bindeman
  - Hourglass stiffness uses elastic constants
  - Sometimes modified QM makes sense (watch hourglass energy)
  - Used in implicit analysis

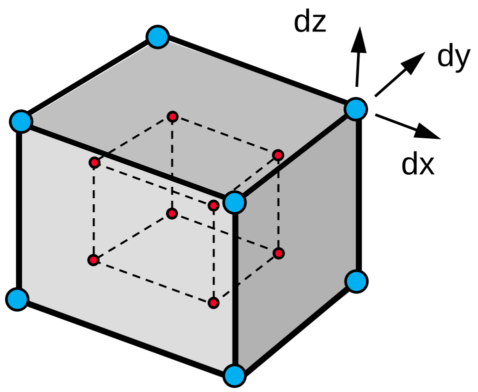
- **IHQ = 7**
  - Similar to type 6
  - Total deformation instead of incremental update

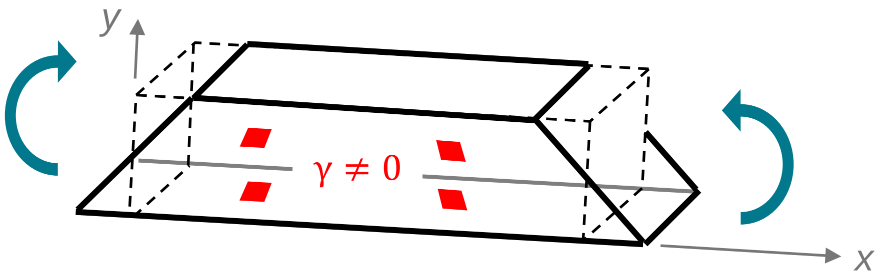
- **IHQ = 9**
  - More accurate results for distorted meshes
  - Hourglass stiffness can be based on current material properties for materials 3, 18 and 24

8 point hexahedron

ELFORM = 2

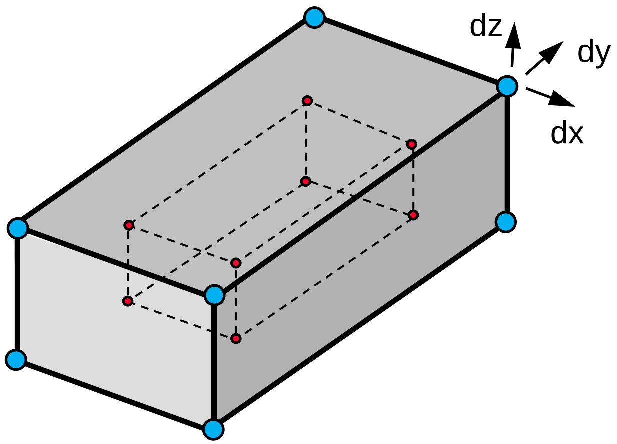
- Selective reduced integration (B-Bar method)
  - Alleviates volumetric locking assuming constant pressure
  - Some materials use full integration to better treat compressible behavior
- No hourglass stabilization needed
- Slower than ELFORM = 1
- More unstable in large deformation applications (negative Jacobian)
- Too stiff in many situation
  - Pure bending modes trigger spurious shear energy
  - Getting worse for poor aspect ratios
  - Counter measures
    - Reduced integration, ELFORM = 1
    - Modified/Enhanced strains, ELFORM = -2, -1, -18, 62
    - Higher order, ELFORM = 23, …





Improved solid

ELFORM = -1 and -2



ELFORM = -2

- Like ELFORM = 2 but intended for poor aspect ratios
- Assumed strain approach reduces spurious stiffness without affecting the true physical behavior of the element
- **Accurate** formulation, about 2 to 3.5 times slower than ELFORM = 2

ELFORM = -1

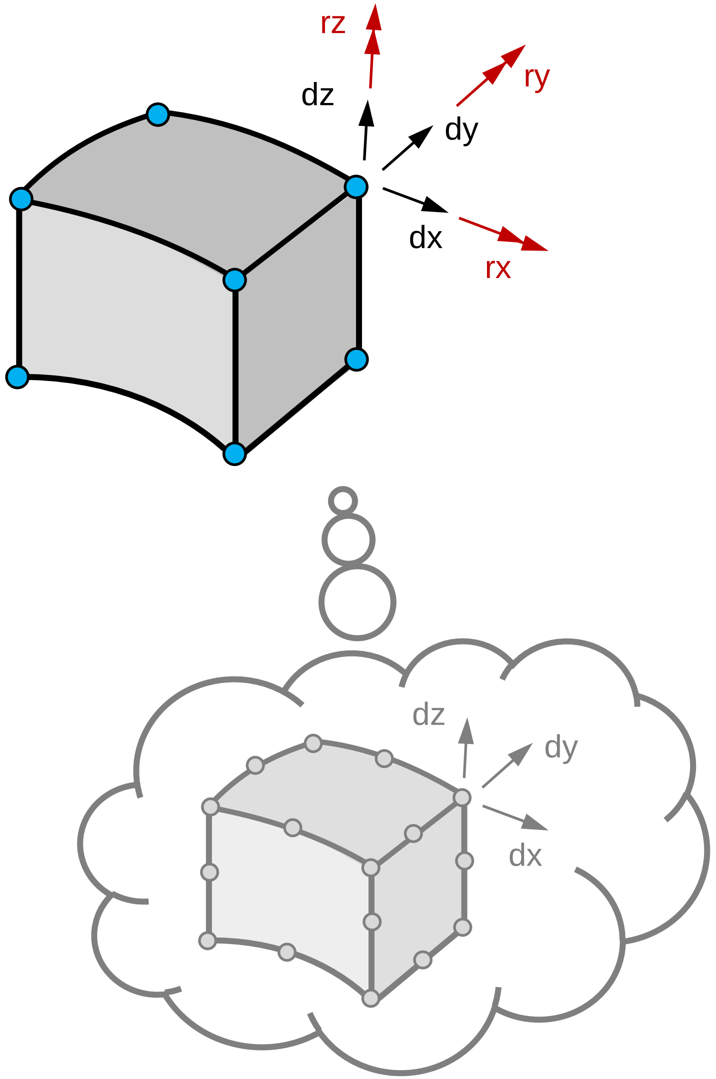
- More **efficient** implementation of ELFORM = -2
- About 1.2 times slower than ELFORM = 2
- Side effect: Weak deformation mode similar to hourglass mode, but not truly hourglassing, hence no stabilization
- But often sufficient

www.dynalook.com
Thomas Borrvall: *A heuristic attempt to reduce transverse shear locking in fully integrated hexahedra with poor aspect ratio*
Salzburg 2009

Nodal rotation solid

ELFORM = 3

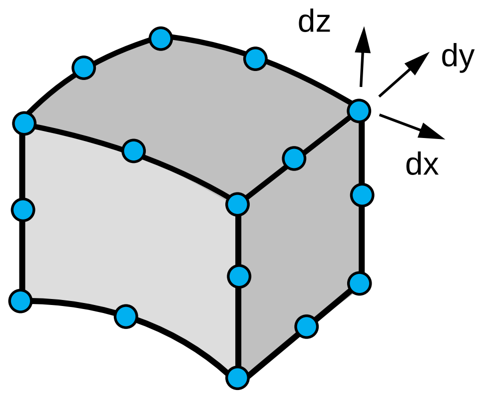
- Quadratic 8 node hexahedron with nodal rotations, 6 DOF per node
- Derived from 20 node hexahedron
- Full integration with 14 points
- Well suited for connections to shells
- Good accuracy for small strains
- Slower than ELFORM = 2
- Tendency to volumetric locking
- References
  - Teng, H: *Solid elements 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 1 – Hexahedron elements*, IJNME 1991



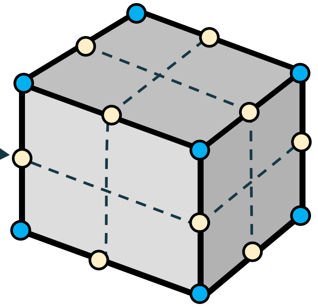
20-node hexahedron

ELFORM = 23

- 8 corner + 12 edge nodes
- Serendipity formulation (without mid-face nodes) faster than 27 node hexahedron (Lagrange)
- 14 integration points
- Improved bending performance and reduced volumetric locking
- Often “coarser” meshes sufficient



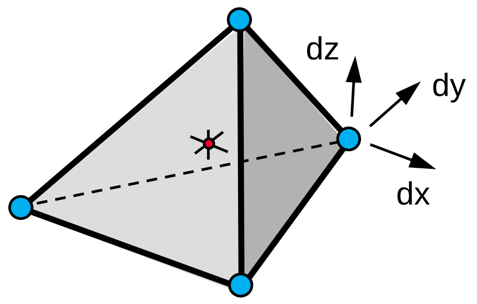
- Easy conversion of 8-noded hexahedra
  - Append _H8TOH20 to *ELEMENT_SOLID
  - Mid-side nodes automatically generated
  - Ideal if edges are initially straight



Standard tetrahedron

ELFORM = 10

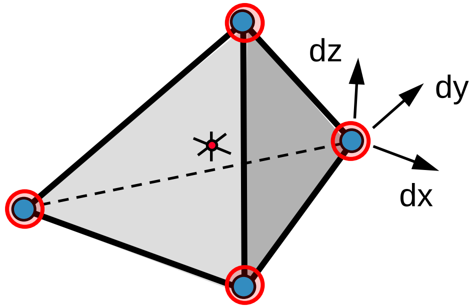
- 1-point constant stress element
- No hourglass stabilization needed (valid for all tetrahedra)
- Usually too stiff
  - Volumetric locking
  - Only applicable for foams with $\nu = 0$
  - Not recommended in general
- Often used for transitions in meshes *CONTROL_SOLID, ESORT=1
- Better than degenerated hex element



Nodal pressure tetrahedron

ELFORM = 13

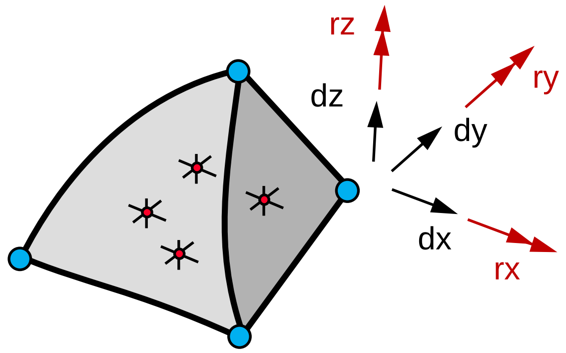
- 1-point constant stress plus nodal pressure averaging
- Materials
  - Common models supported for explicit
  - All models supported for implicit
- Parts with different materials should not share nodes
  - nodal pressure averaging will cause spurious energy
  - exception if the same bulk modulus
- Better performance than ELFORM = 10 if $\nu > 0$ (metals, rubber, …)
  - Significantly less volumetric locking
  - Well suited for (nearly) incompressible material behavior

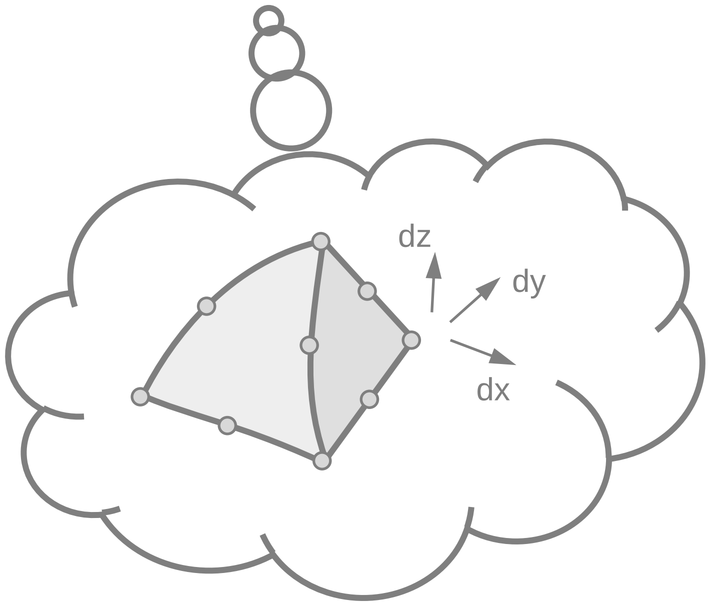


Nodal rotation tetrahedron

ELFORM = 4

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



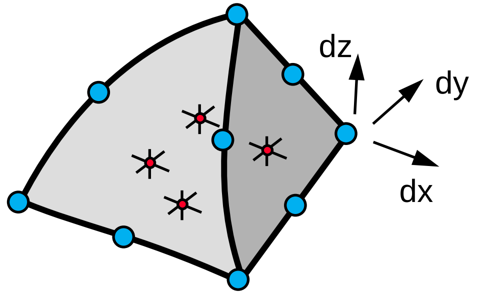


Higher order tetrahedra

ELFORM = 16 and 17

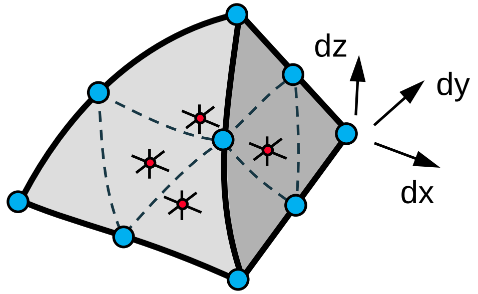
ELFORM = 16

- 4 or 5-point integration
- Good accuracy for moderate strains
- High CPU cost
- Use part definition in contacts – correct segment generation
- Easy conversion of 4 noded tets via *ELEMENT_SOLID_TET4TOTET10
- Full output of midside nodes with *CONTROL_OUTPUT, TET10=1



ELFORM = 17

- composed of 12 linear sub-tetrahedrons
- Properties like ELFORM = 16

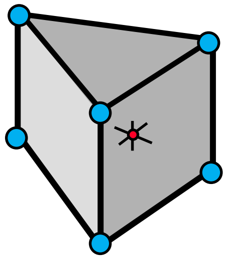


Pentahedra

ELFORM = 15 and 115

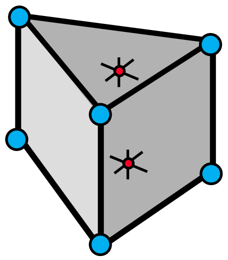
ELFORM = 15

- 2-point selective reduced integration
- Needs hourglass stabilization for twist mode
- Often used as transition element (ESORT=1)



ELFORM = 115

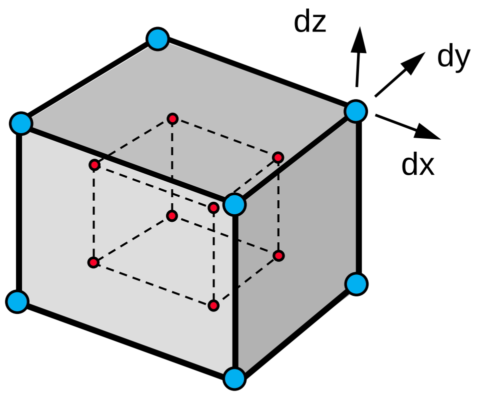
- 1-point reduced integration
- Hourglass stabilization needed
- Analogue to hexahedron ELFORM = 1 with Flanagan-Belytschko hourglass formulation



Enhanced strain solid

ELFORM = -18

- **New in R13**
- 13 incompatible modes
  - 9 improve bending
  - 4 alleviate volumetric locking
  - Requires the solution of a compatibility equation in each element
- Expensive for explicit
  - 2 to 5 times slower than ELFORM = 2
  - Depends on severity of element deformation and/ or nonlinear effects in materials
- Element cost relative for implicit
  - Compared to global linear algebra element expense becomes insignificant
  - Increased accuracy seems to compensate for the cost

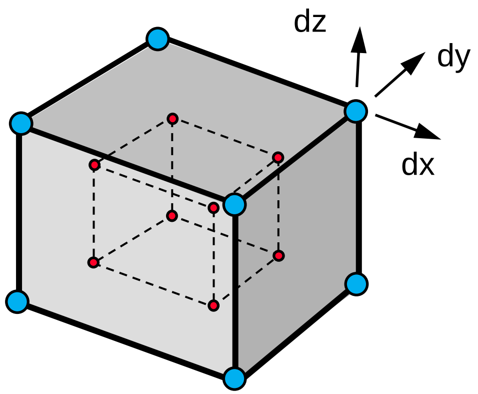


- Version for linear implicit analysis with 12 incompatible modes: ELFORM = 18 (available since at least R7)

QBI solid

ELFORM = 62

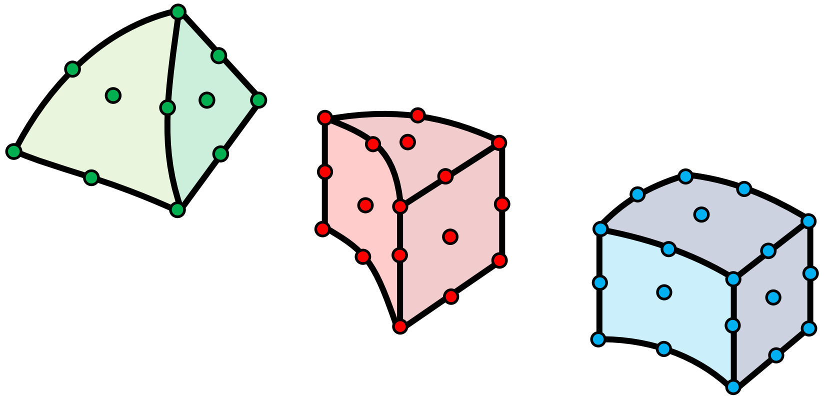
- **New in R13**
- The fully integrated QBI - Quintessential Bending Incompressible - element by Belytschko and Bindeman
- No hourglass stabilization needed
- Assumed strain field alleviates shear and volumetric locking
- Enhanced bending performance
- Only 10% slower than ELFORM = 2
- Reference
  - Belytschko, T. and Bindeman, L. P. *Assumed Strain Stabilization of the Eight Node Hexahedral Element*, Comp. Meth. Appl. Mech. Eng. 105, 225-260 (1993)



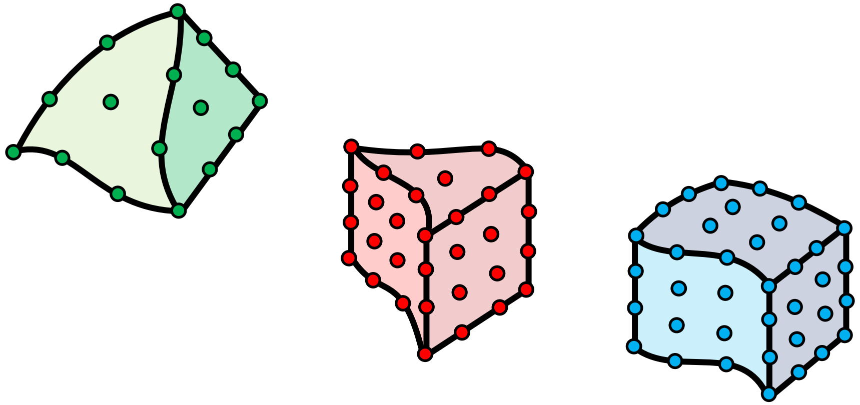
Higher order solids

ELFORM = 24 … 29

- Quadratic family
  - ELFORM = 24, *ELEMENT_SOLID_H27
  - ELFORM = 25, *ELEMENT_SOLID _P21
  - ELFORM = 26, *ELEMENT_SOLID _T15



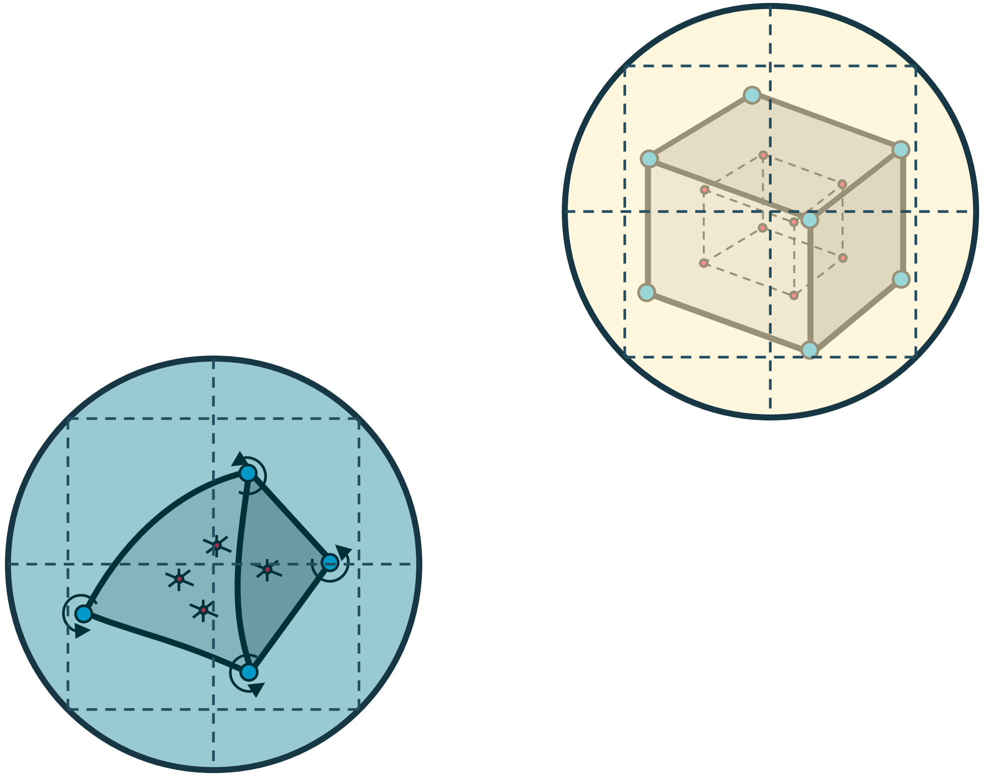
- Cubic family
  - ELFORM = 27, *ELEMENT_SOLID _T20
  - ELFORM = 28, *ELEMENT_SOLID _P40
  - ELFORM = 29, *ELEMENT_SOLID _H64



Remain under development

A closer look

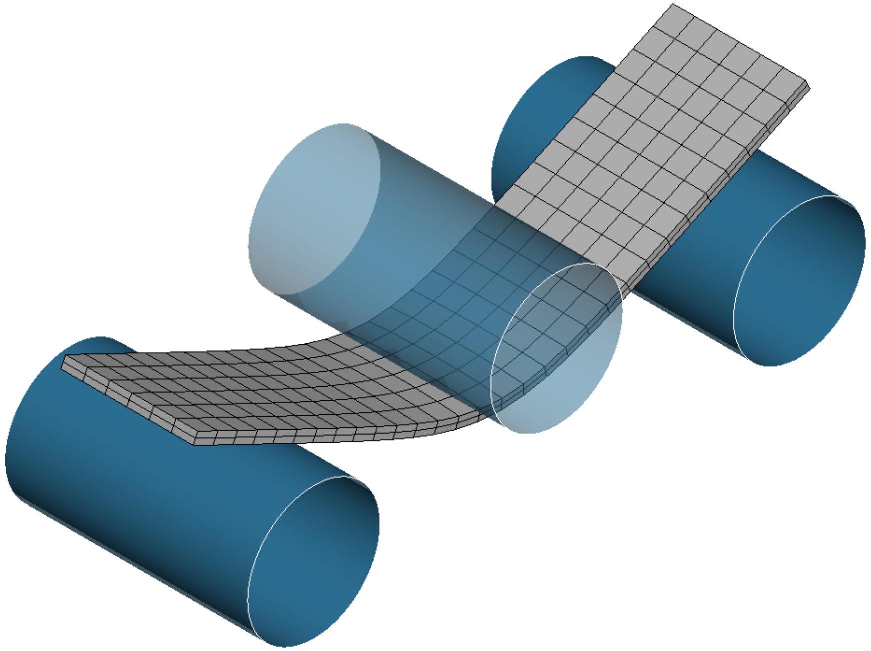
Comparisons, statistics, …



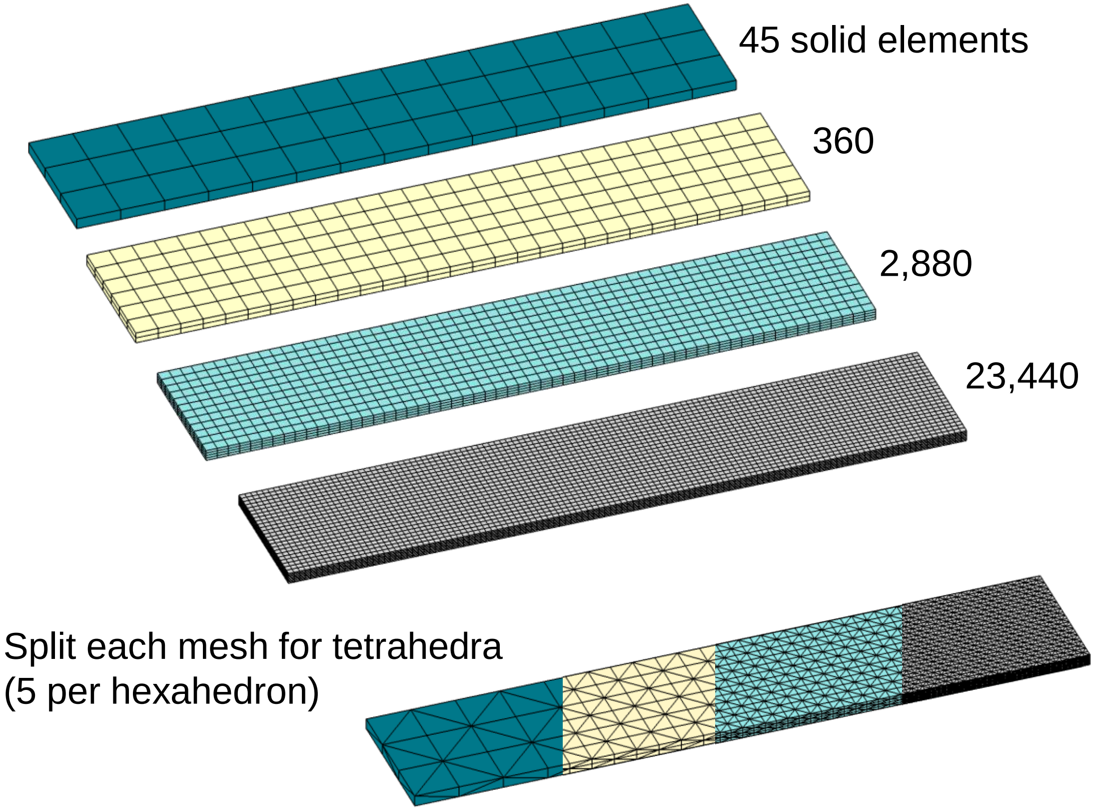
Bending performance

Shear locking ?

- 3 point bending of aluminium strip
  - Dimension: 300×60×5 mm^3

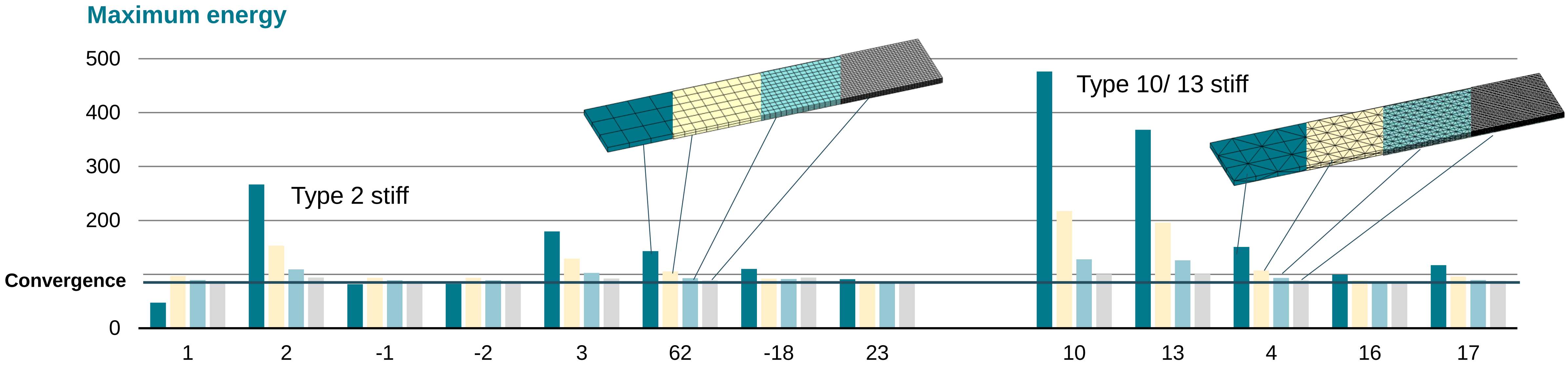


- Convergence study, aspect ratio of 4:1
  - Up to 8 plys in thickness direction



Bending test

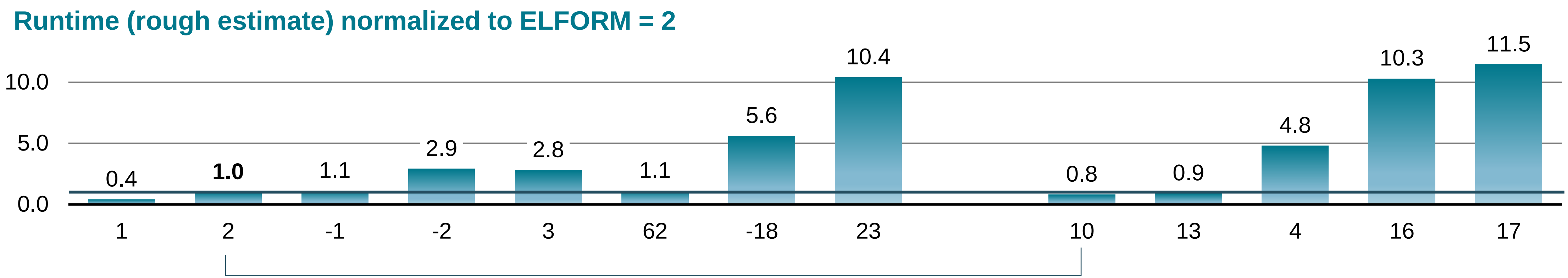
Convergence and runtime



- Good convergence of most element formulations
- ELFORM = 2, 3, 10, 13 are (as expected) stiff
- Quadratic formulations expensive but “coarser meshes” would be sufficient

Bending test

Convergence and runtime

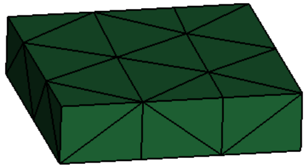


- How to compare between hexahedron and terahedron

1 Hexahedron

Split into 5 tetrahedra

More common tetrahedron mesh (not shown here)



8 nodes × 3 dofs
1 × 8 integration points

8 nodes × 3 dofs
5 × 1 integration points

29 nodes × 3 dofs
48 × 1 integration points

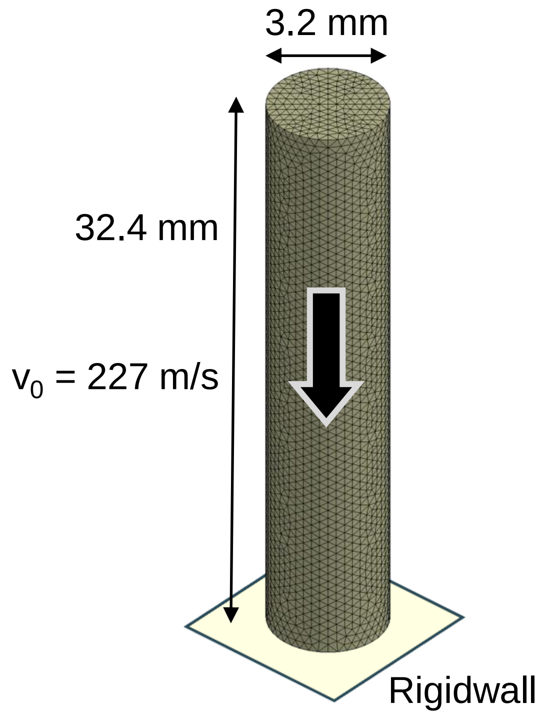
Comparable time step size ➔ similar runtimes

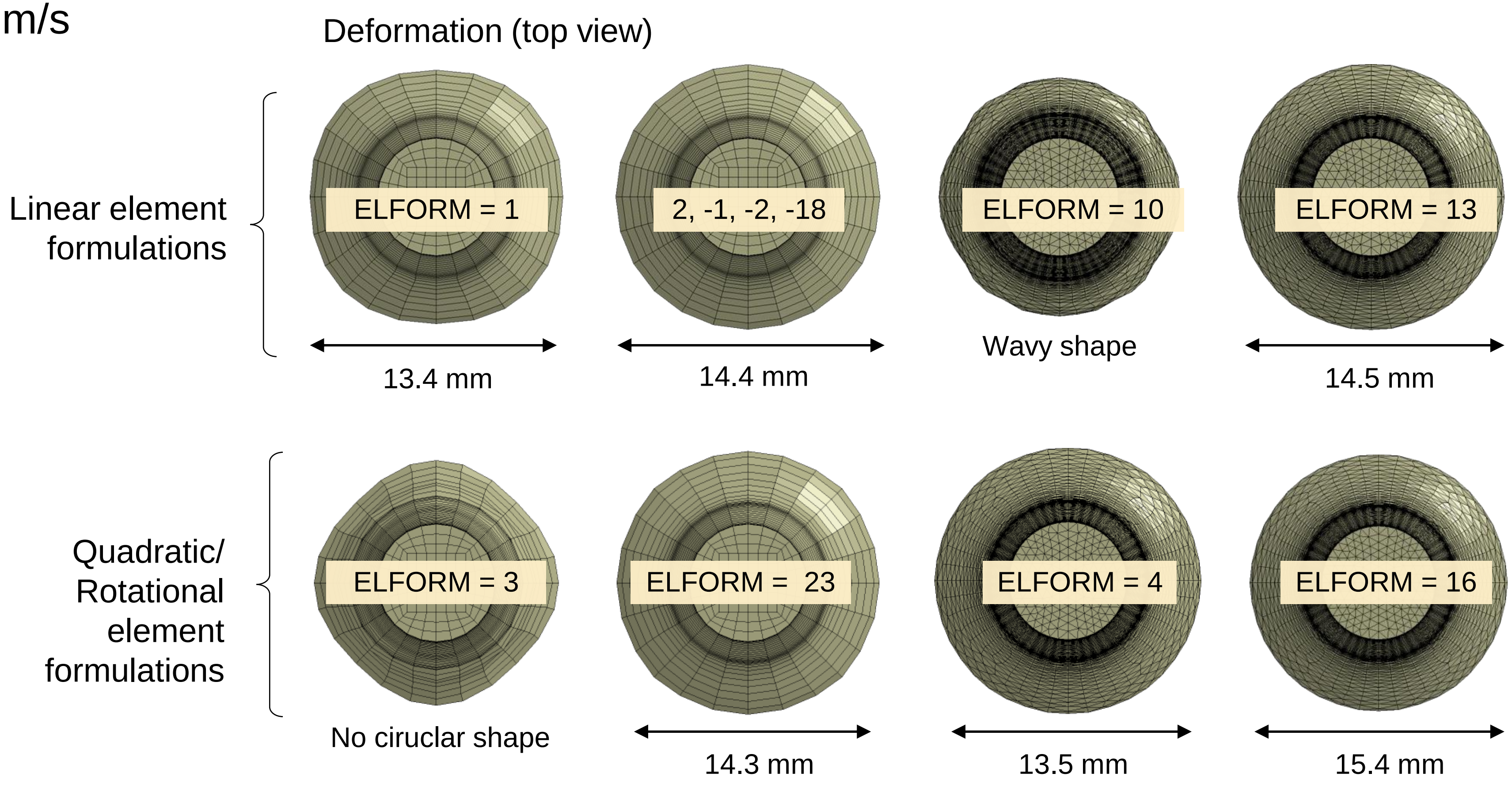
Plus smaller step size ➔ more expensive

Taylor bar impact

Volumetric locking ?

- Copper bar impact with v_0 = 227 m/s
- Generates large strains, > 300%





- Reference, Wilkins, ML et al.: *Impact of cylinders on a rigid boundary*, Journal of Applied Physics,1973

Some statistics

Timestep control

- Critical time step

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

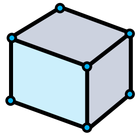
main information from element formulation

- 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: $L_e = V/A_{max}$

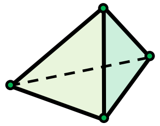


ELFORM = 4: $L_e = 0.85\, h_{min}$

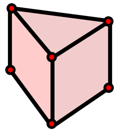
ELFORM = 10, 13: $L_e = h_{min}$

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

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

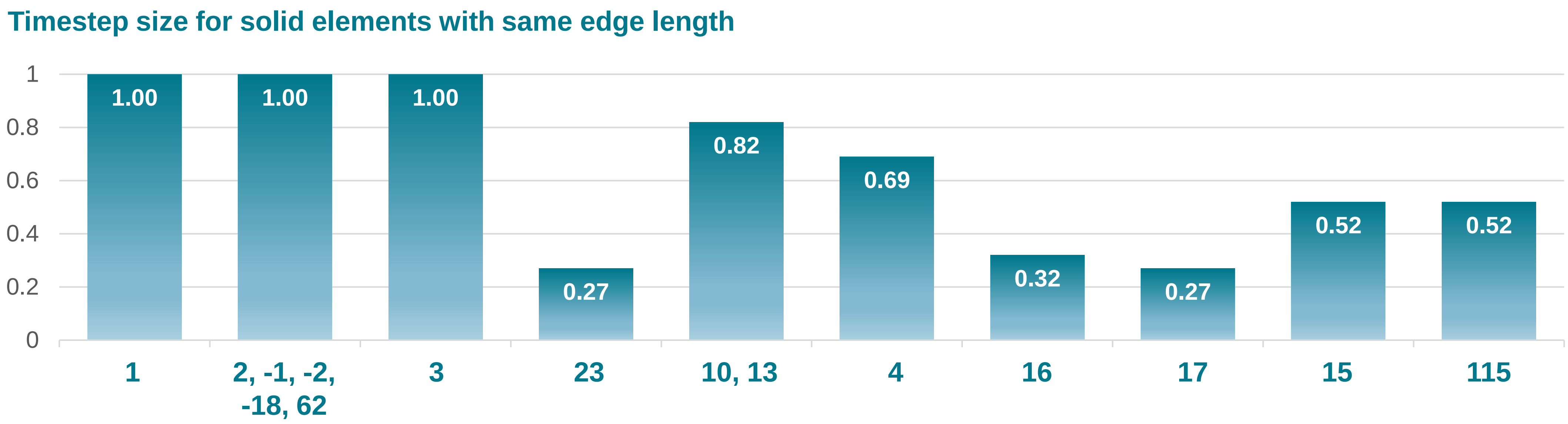


ELFORM = 15: $L_e = 1/\sqrt{B_{ij}B_{ij}}$

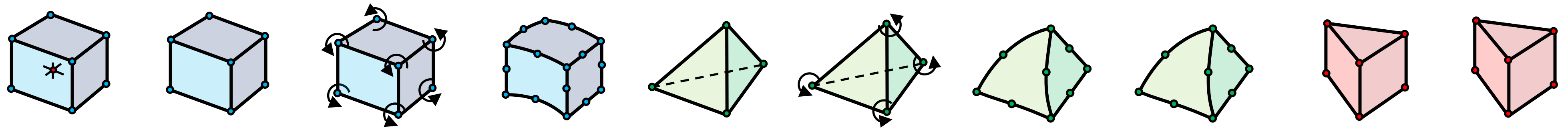


Some statistics

Timestep control, points and nodes



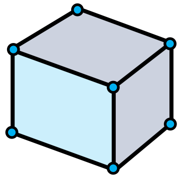
Integration points	1	8	14	14	1	4 or 5	4 or 5	4 or 5	1	2
Degrees of freedom	8×3	8×3	8×6	20×3	4×3	8×3	10×3	10×3	6×3	6×3



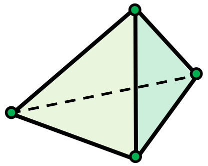
Conclusions and remarks

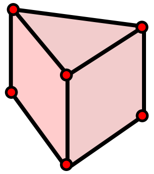
…. never final

- Use hexahedron elements if possible
  - ELFORM = 1 with hourglass type 6 or ELFORM = 2, 3
  - ELFORM = -1, -2 for “flat” hexas
  - ELFORM = 23 shows good coarse mesh accuracy, but in general linear elements more robust
  - ELFORM = -18 and 62 promising new candidates



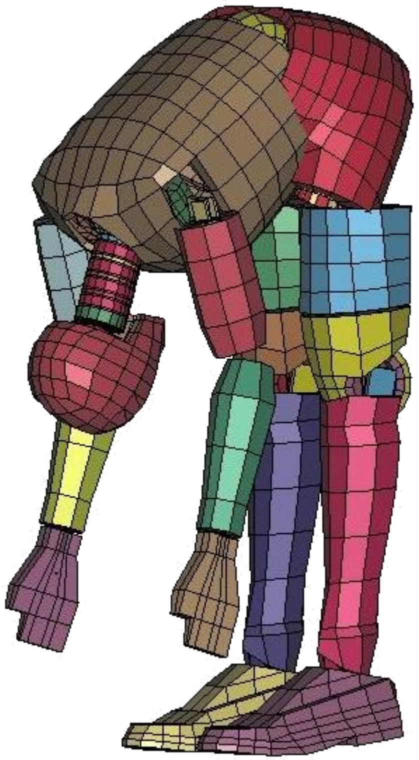
- For complex solid structures, use tetrahedron elements
  - ELFORM = 16/17 are the most accurate tets, but might not be suited for large strains
  - ELFORM = 13 needs finer mesh, well suited even for large strains (check if material is supported)
  - For metals or plastics (moderate strains), use ELFORM 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





- Pentahedron elements 15, 115 should only be used as transition elements
- In implicit analysis costly element formulations may be used – not as significant for speed as in explicit analysis

Thank You



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