

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

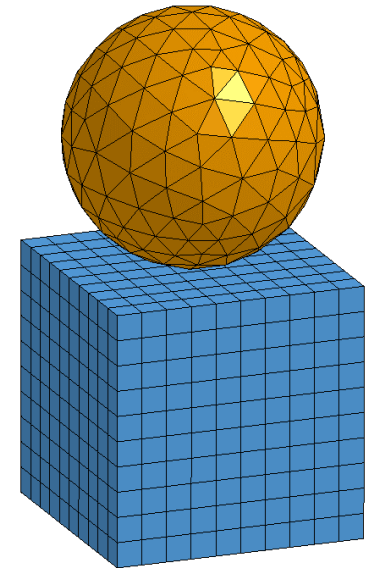
Motivation

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)

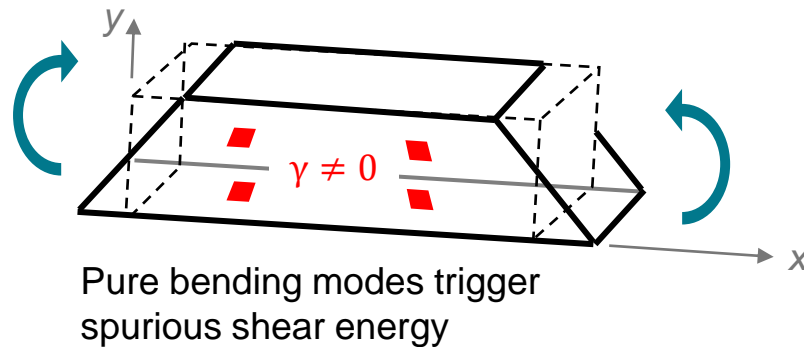


Motivation

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**

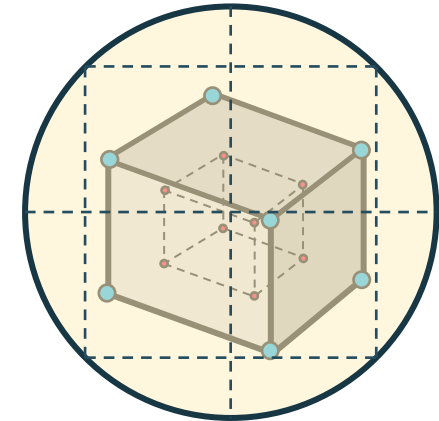
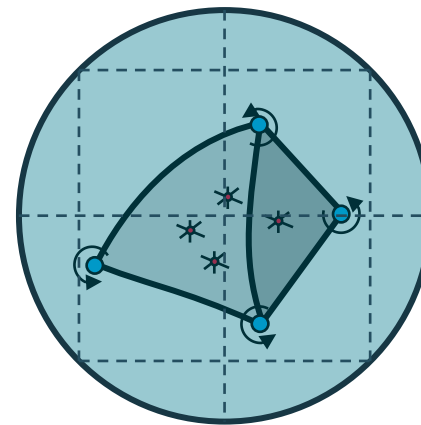
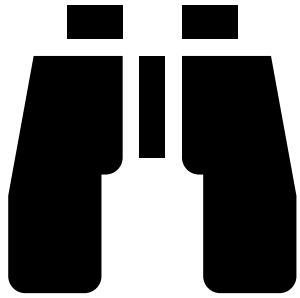


Element technology

- 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

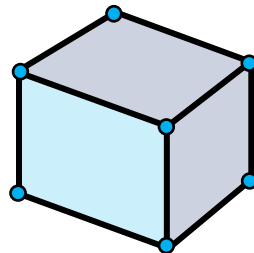
EQ.1: Constant stress solid element: default element type
Cosserat Point Element with hourglass type 10

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

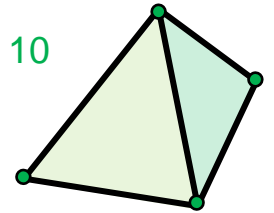
EQ.10: 1 point tetrahedron

EQ.13: 1 point nodal pressure tetrahedron

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

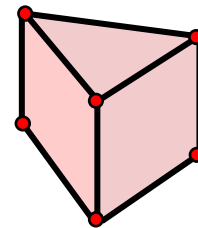
EQ.17: 10-noded composite tetrahedron

EQ.60: 1 point tetrahedron



EQ.15: 2 point pentahedron element

EQ.115: 1 point pentahedron element with hourglass control



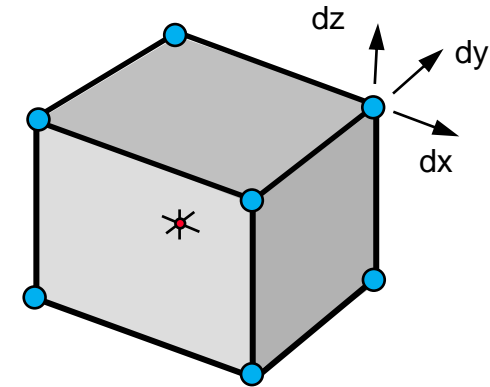
Not shown in this overview

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

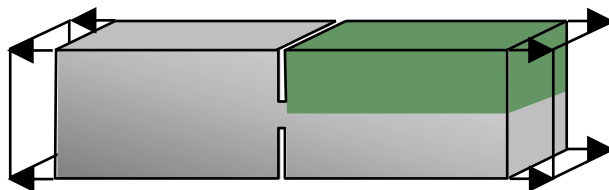
Constant stress solid

ELFORM = 1 (the default)

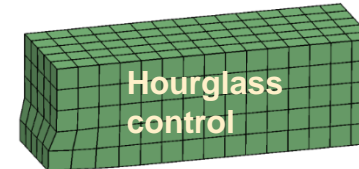
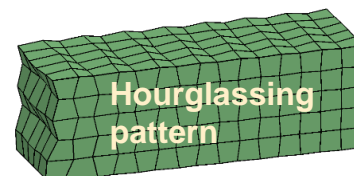
- Single point integration with hourglass control
- Efficient and accurate
- Can sustain largest nonlinear deformation
- Requires hourglass control
 - Choice of hourglass formulation
 - and values remains an issue



- Example for Hourglassing: Stretching of a notched steel specimen



Notched steel specimen



Constant stress solid

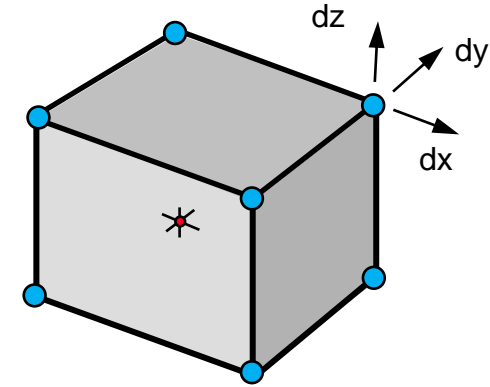
Hourglass control

■ 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

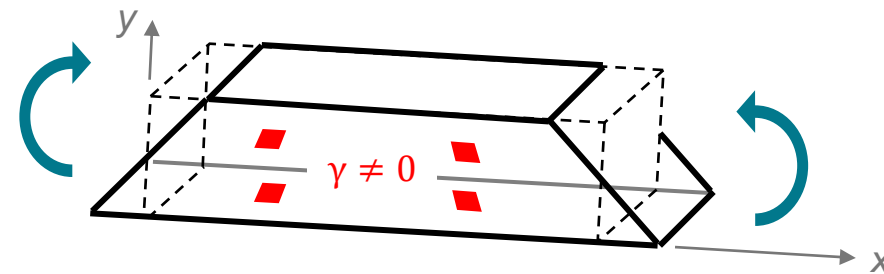
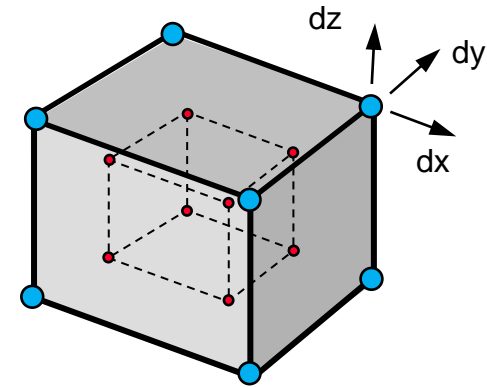
■ IHQ = 9

- 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

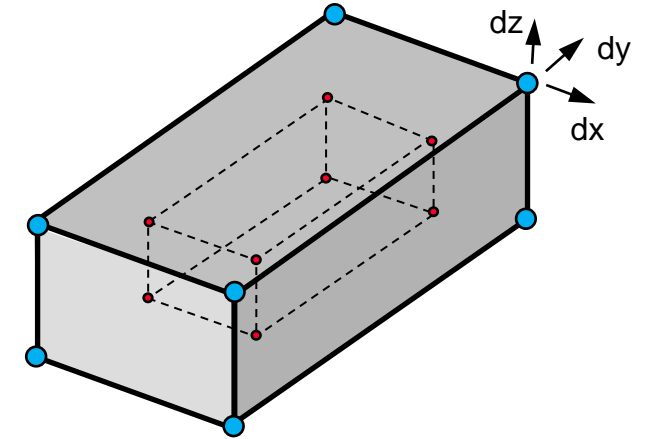
ELFORM = -1 and -2

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



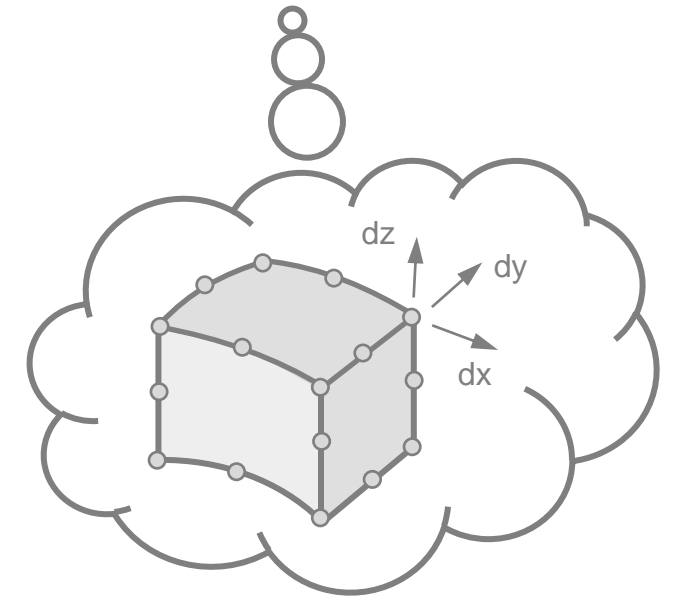
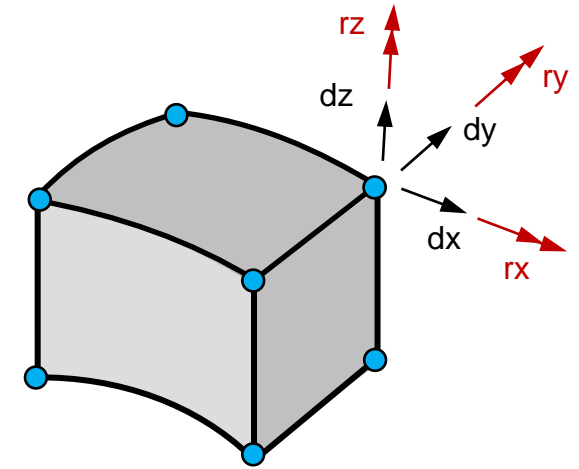
www.dynalook.com

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

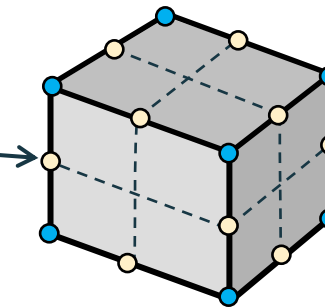
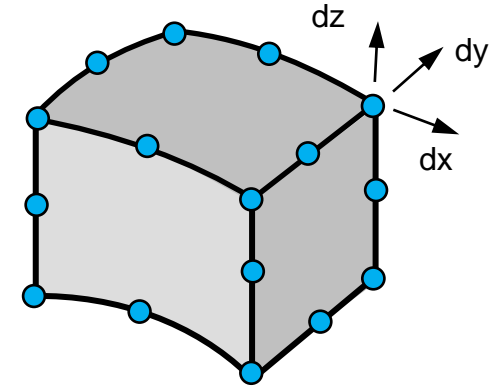


20-node hexahedron

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

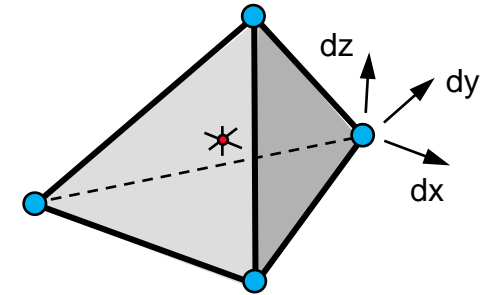
- Easy conversion of 8-noded hexahedra
 - Append `_H8TOH20` to `*ELEMENT_SOLID`
 - Mid-side nodes automatically generated
 - Ideal if edges are initially straight



Standard tetrahedron

ELFORM = 10

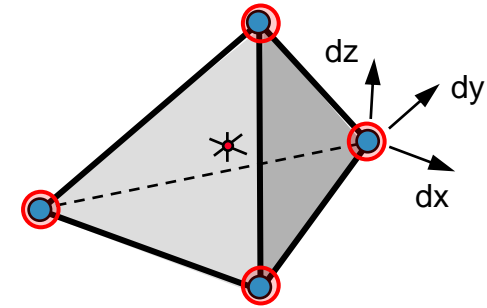
- 1-point constant stress element
- No hourglass stabilization needed (valid for all tetrahedra)
- Usually too stiff
 - Volumetric locking
 - Only applicable for foams with $\nu = 0$
 - Not recommended in general
- Often used for transitions in meshes *CONTROL_SOLID, ESORT=1
- Better than degenerated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



Nodal pressure tetrahedron

ELFORM = 13

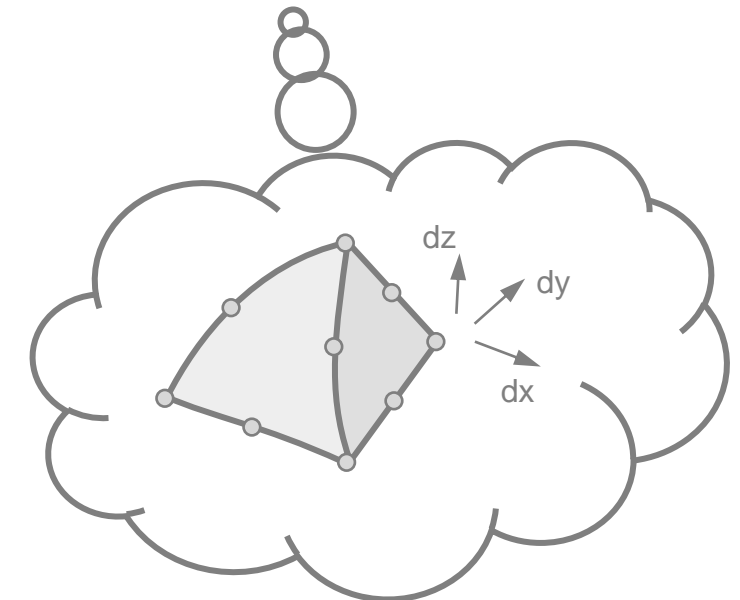
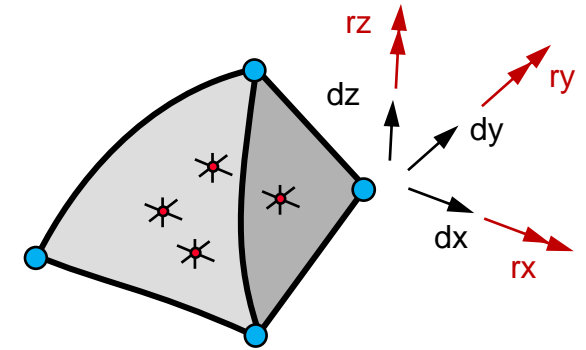
- 1-point constant stress plus nodal pressure averaging
- Materials
 - Common models supported for explicit
 - All models supported for implicit
- Parts with different materials should not share nodes
 - nodal pressure averaging will cause spurious energy
 - exception if the same bulk modulus
- Better 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

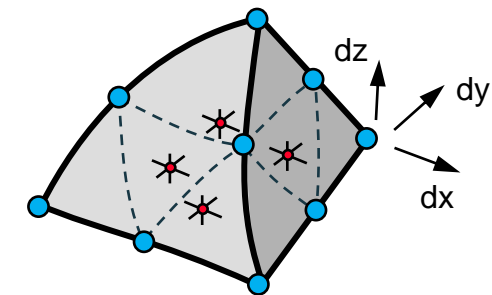
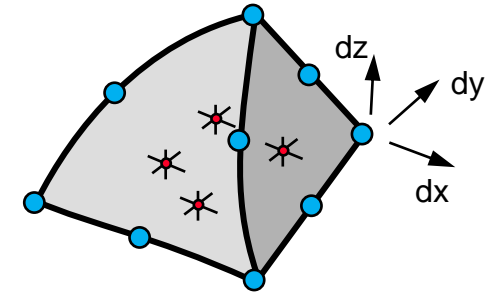


Higher order tetrahedra

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

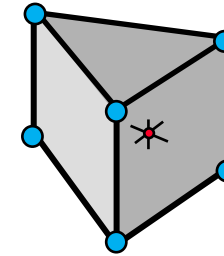
- composed of 12 linear sub-tetrahedrons
- Properties like ELFORM = 16

Pentahedra

ELFORM = 15 and 115

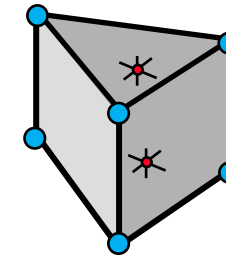
ELFORM = 15

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



ELFORM = 115

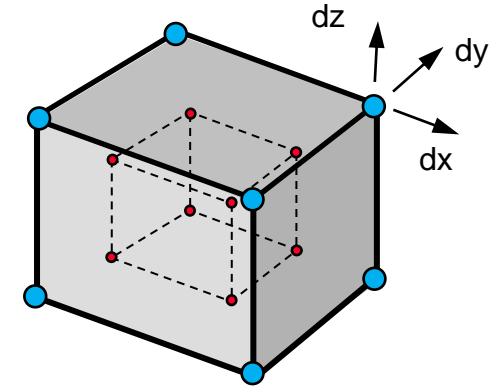
- 1-point reduced integration
- Hourglass stabilization needed
- Analogue to hexahedron ELFORM = 1 with Flanagan-Belytschko hourglass formulation



Enhanced strain solid

ELFORM = -18

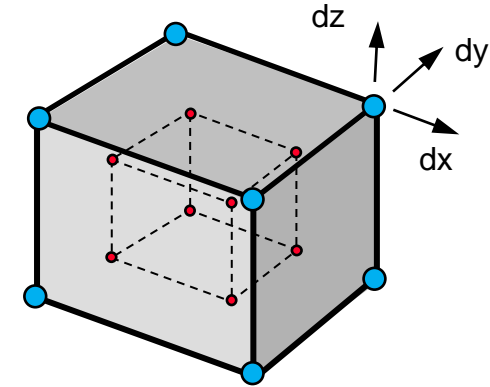
- **New in R13**
- 13 incompatible modes
 - 9 improve bending
 - 4 alleviate volumetric locking
 - Requires the solution of a compatibility equation in each element
- Expensive for explicit
 - 2 to 5 times slower than ELFORM = 2
 - Depends on severity of element deformation and/ or nonlinear effects 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)

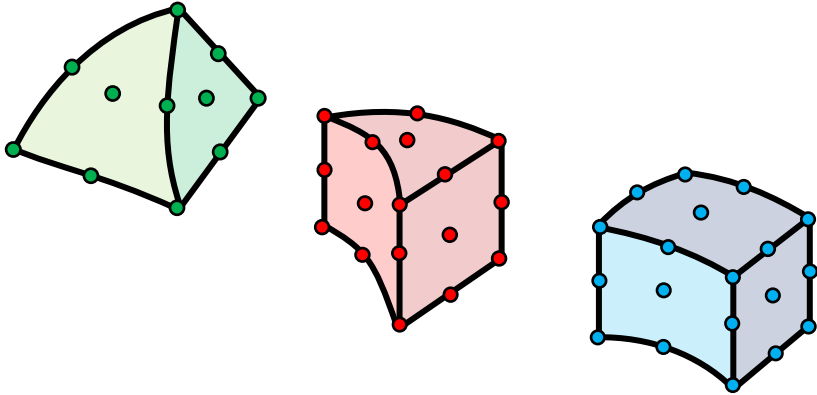


Higher order solids

ELFORM = 24 ... 29

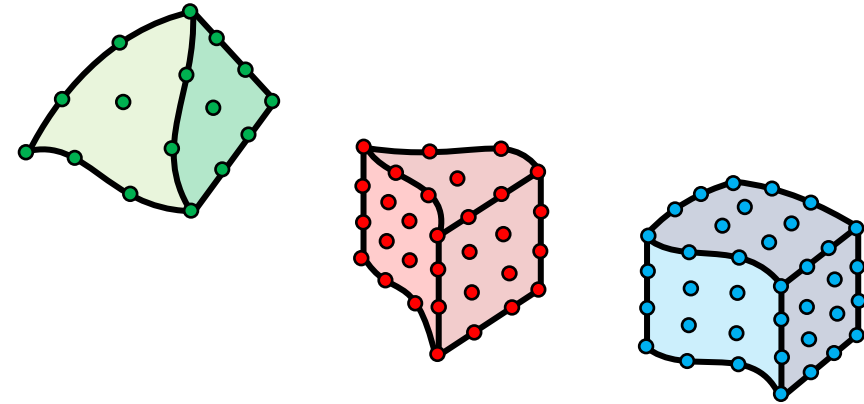
■ Quadratic family

- **ELFORM = 24**, *ELEMENT_SOLID_H27
- **ELFORM = 25**, *ELEMENT_SOLID_P21
- **ELFORM = 26**, *ELEMENT_SOLID_T15



■ Cubic family

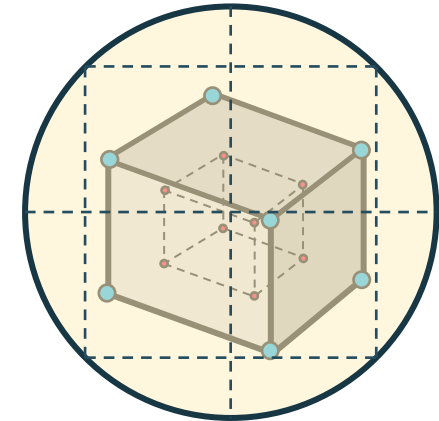
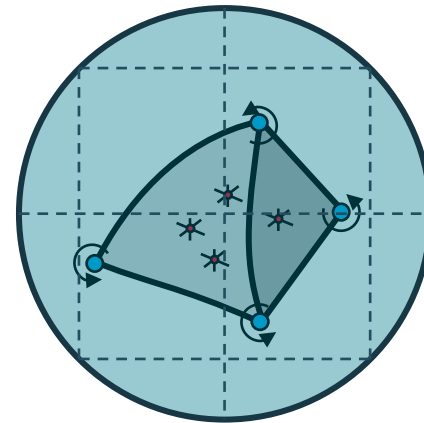
- **ELFORM = 27**, *ELEMENT_SOLID_T20
- **ELFORM = 28**, *ELEMENT_SOLID_P40
- **ELFORM = 29**, *ELEMENT_SOLID_H64



Remain under development

A closer look

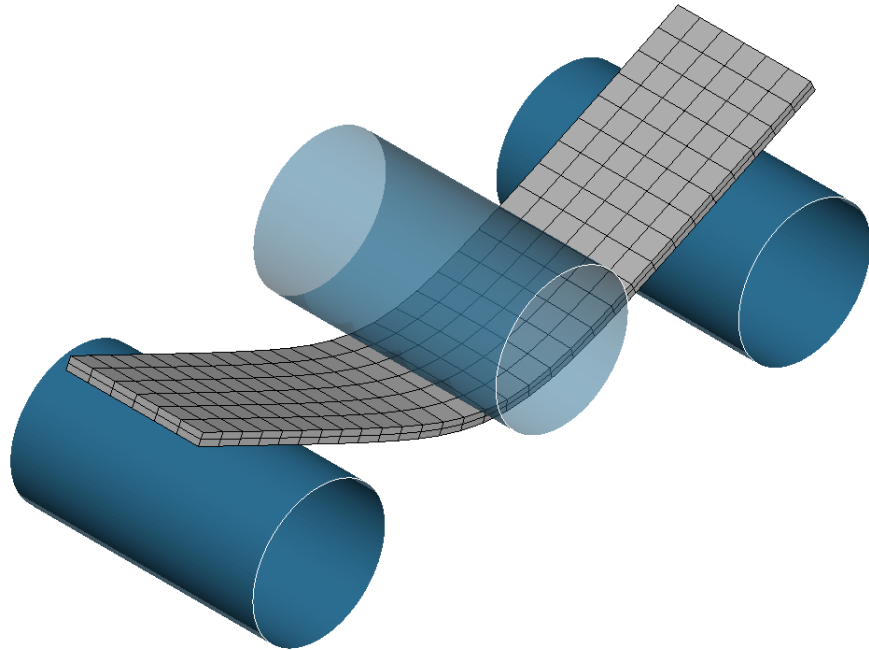
Comparisons, statistics, ...



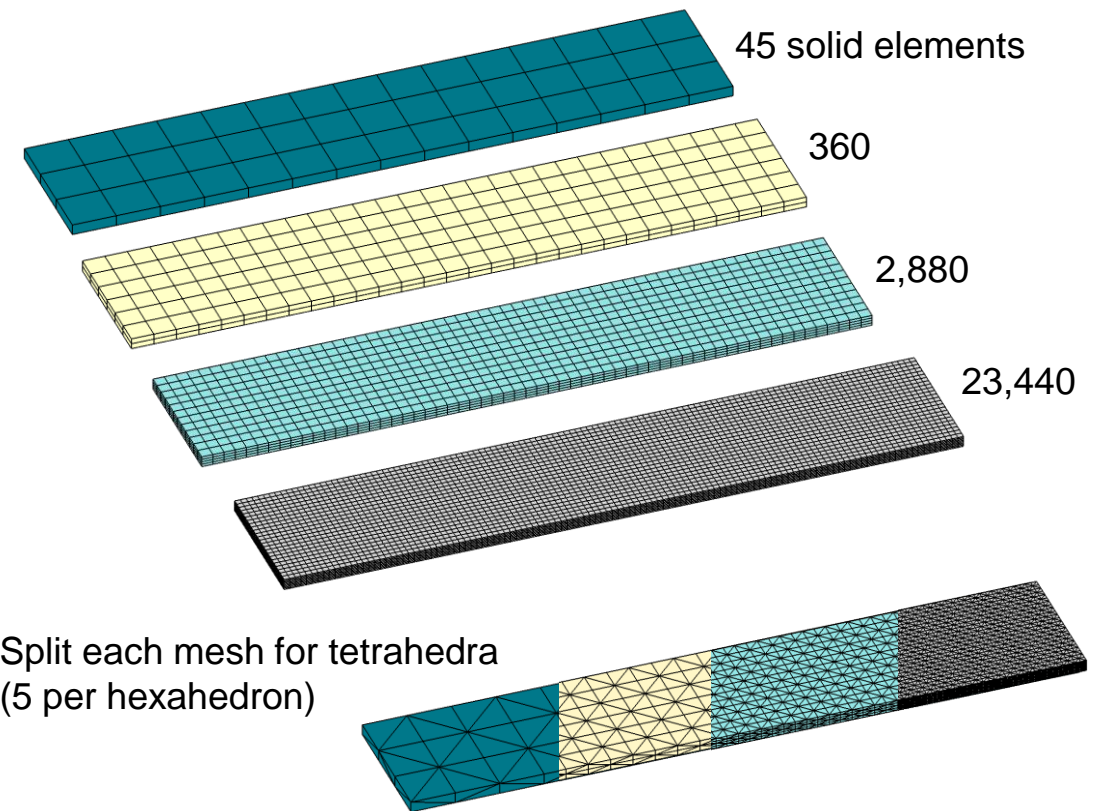
Bending performance

Shear locking ?

- 3 point bending of aluminium strip
 - Dimension: 300x60x5 mm³

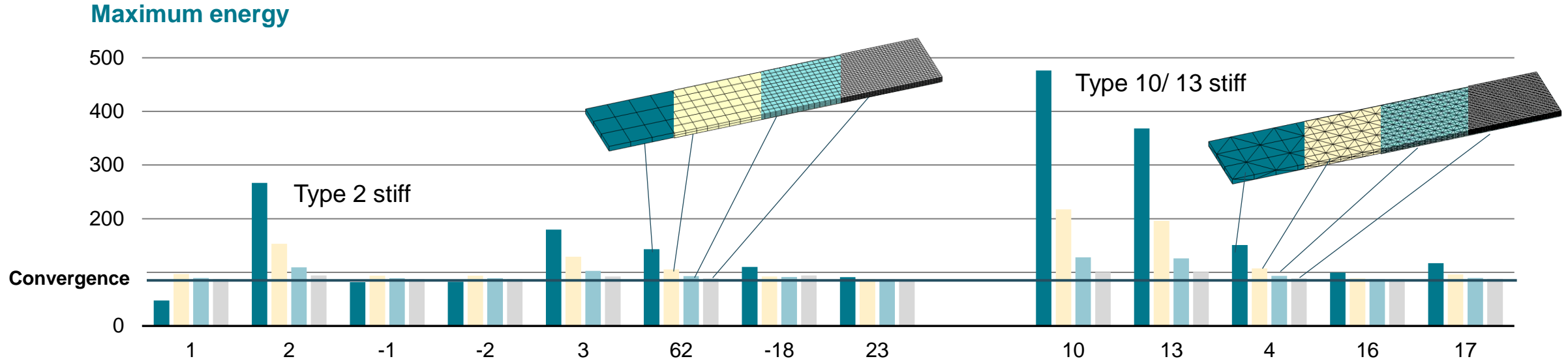


- Convergence study, aspect ratio of 4:1
 - Up to 8 plys in thickness direction



Bending test

Convergence and runtime

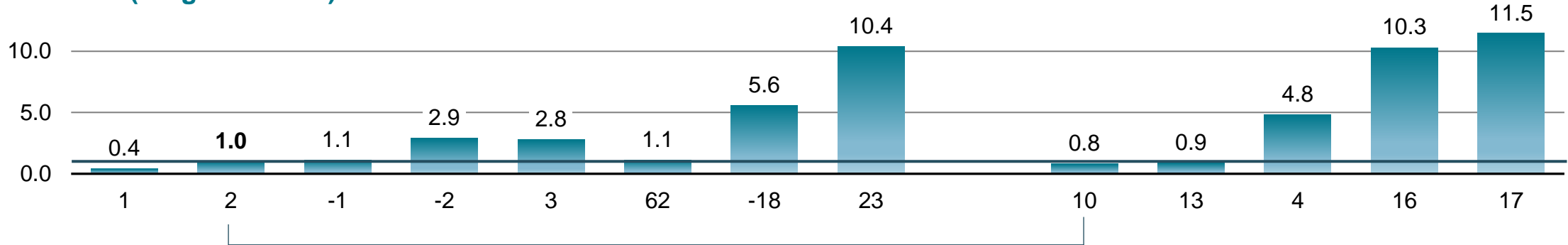


- Good convergence of most element formulations
- ELFORM = 2, 3, 10, 13 are (as expected) stiff
- Quadratic formulations expensive but “coarser meshes” would be sufficient

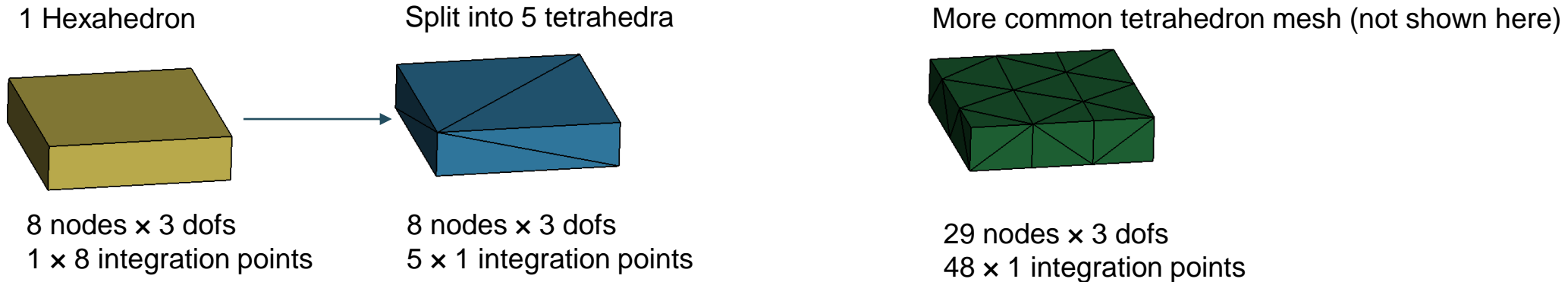
Bending test

Convergence and runtime

Runtime (rough estimate) normalized to ELFORM = 2



How to compare between hexahedron and tetrahedron



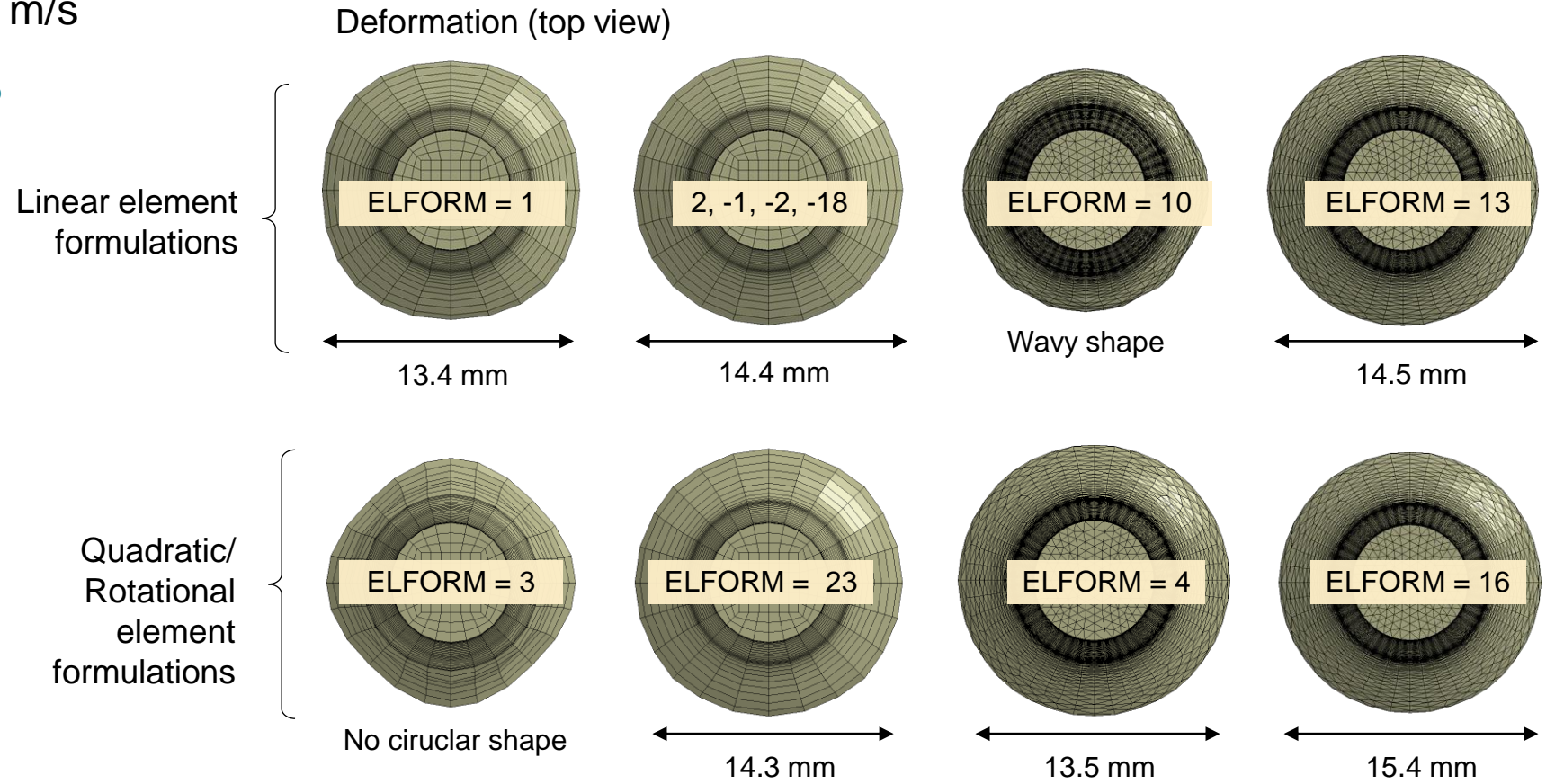
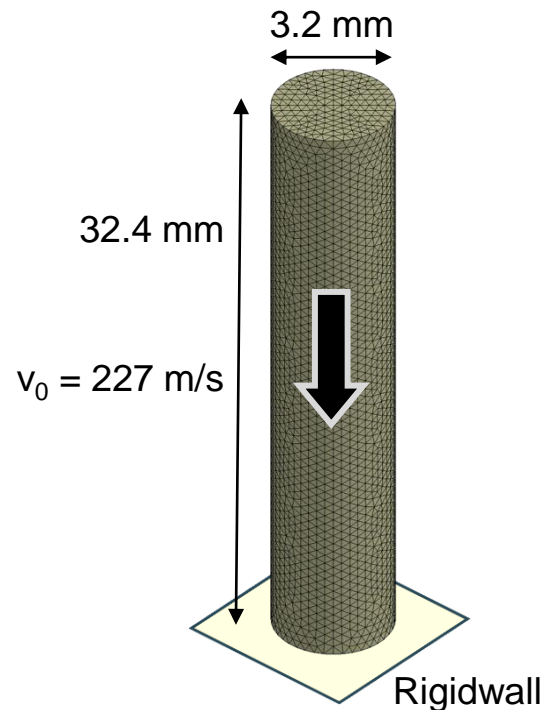
Comparable time step size → similar runtimes

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

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

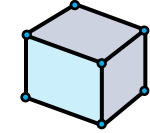
main information from element formulation

- Adiabatic sound speed

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

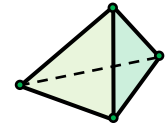
- Characteristic element length

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



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

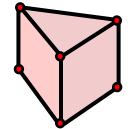
ELFORM = 10, 13: $L_e = h_{min}$



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

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

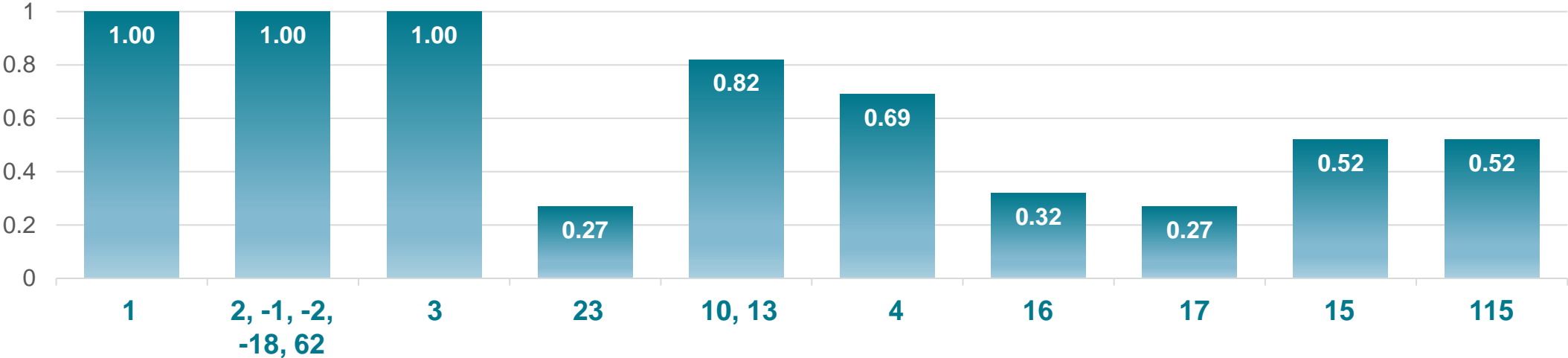
ELFORM = 15: $L_e = 1/\sqrt{B_{ij}B_{ij}}$



Some statistics

Timestep control, points and nodes

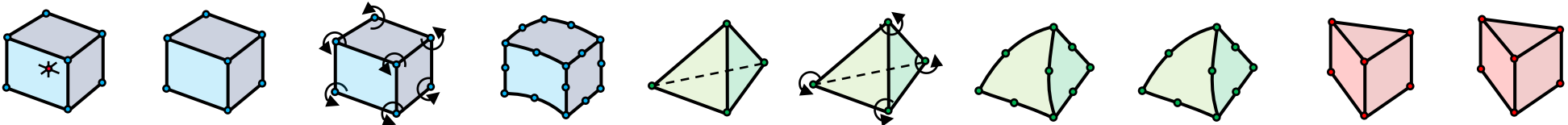
Timestep size for solid elements with same edge length



Integration points

Degrees of freedom

1	8	14	14	1	4 or 5	4 or 5	4 or 5	1	2
8×3	8×3	8×6	20×3	4×3	8×3	10×3	10×3	6×3	6×3

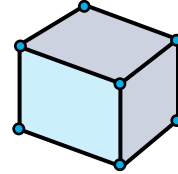


Conclusions and remarks

.... never final

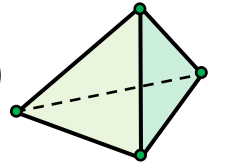
- Use hexahedron elements if possible

- 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

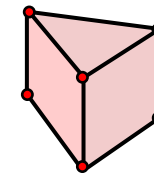


- For complex solid structures, use tetrahedron elements

- 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

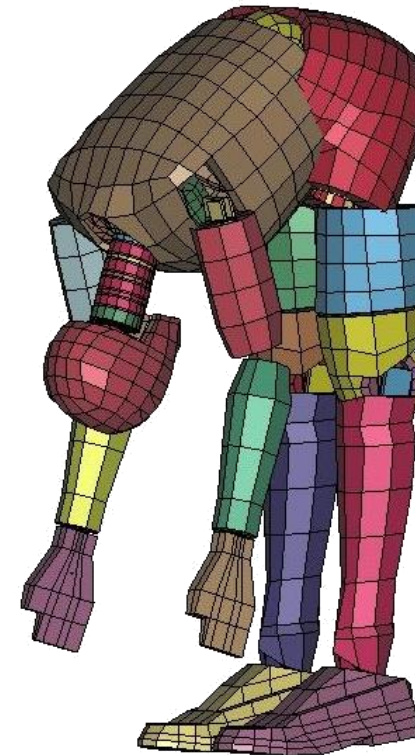


- Pentahedron elements 15, 115 should only be used as transition elements



- In implicit analysis costly element formulations may be used – not as significant for speed as in explicit analysis

Thank You



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