Selective cell-based smoothed finite element method using 10-node tetrahedral elements for large deformation of nearly incompressible solids

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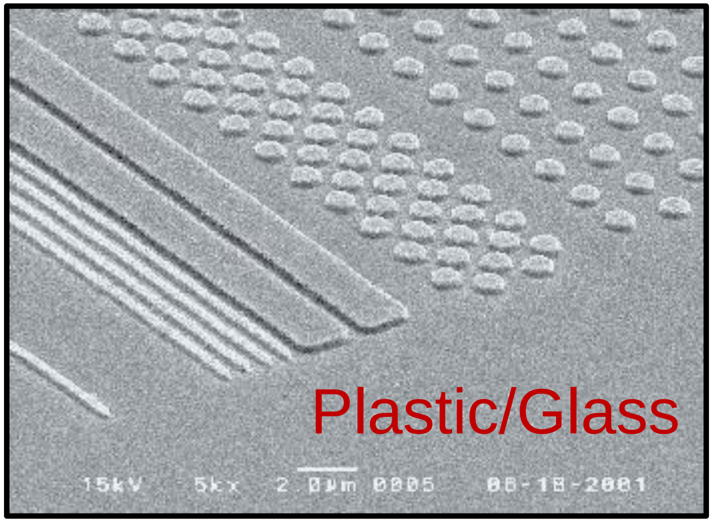
Motivation

What we want to do:

- Solve **hyper large deformation** analyses accurately and stably.
- Treat complex geometries with **tetrahedral meshes**.
- Consider **nearly incompressible materials** $(\nu \simeq 0.5)$.
- Support **contact** problems.
- Handle **auto re-meshing**.



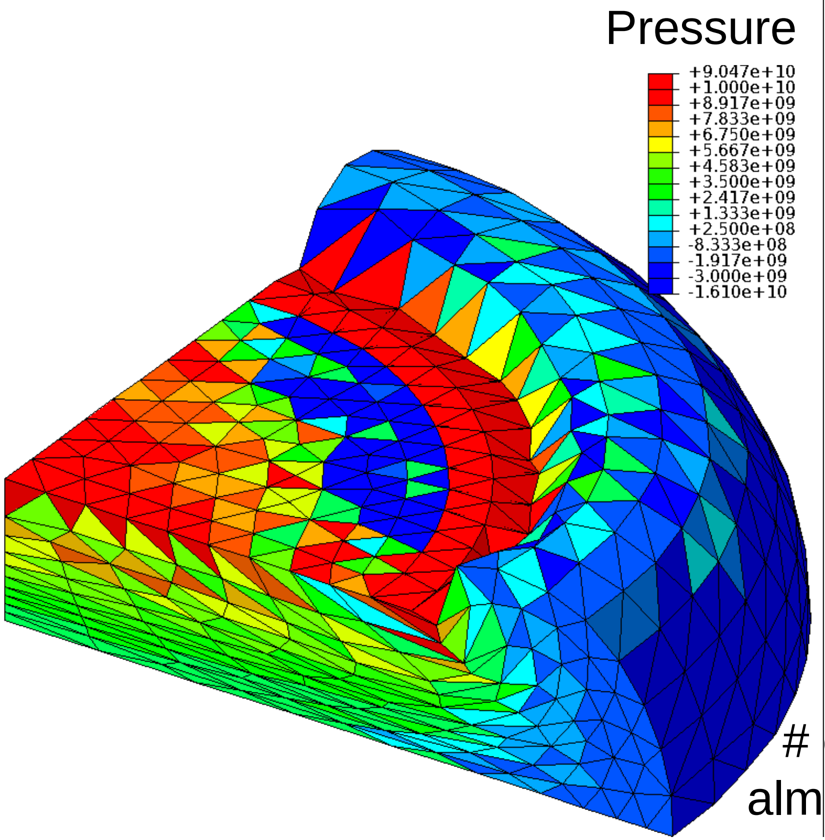
Issues

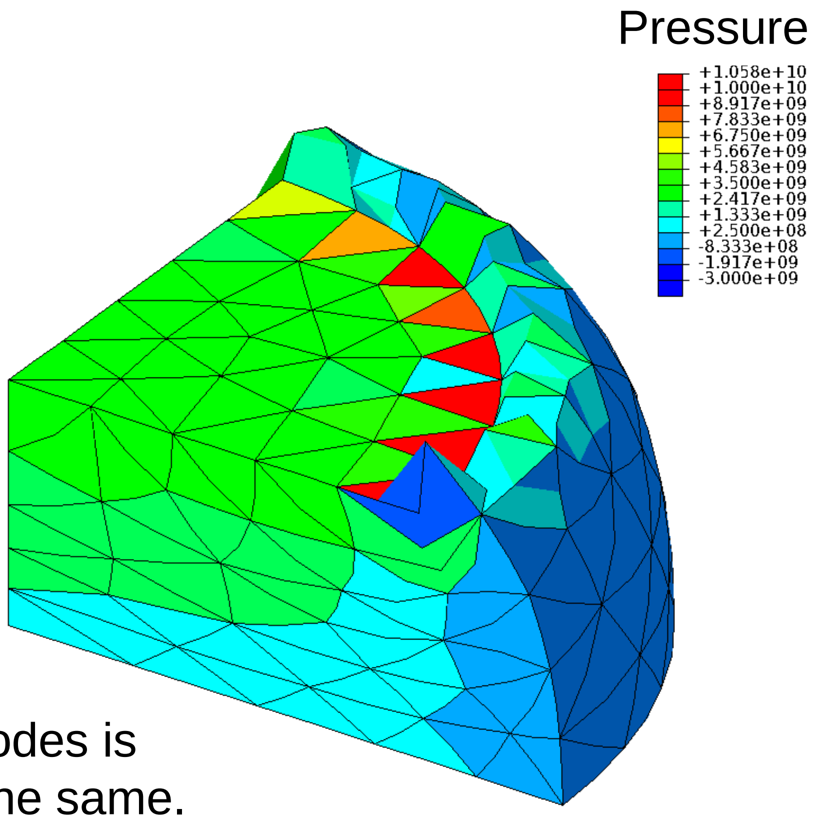
Conventional tetrahedral (T4/T10) FE formulations still have issues in accuracy or stability especially in nearly incompressible cases.

- 2nd or higher order elements:
  - ✗ Volumetric locking.
    Accuracy loss in large strain due to intermediate nodes.
- B-bar method, F-bar method, Selective reduced integration:
  - ✗ Not applicable to tetrahedral element directly.
- F-bar-Patch method:
  - ✗ Difficulty in building good-quality patches.
- **u/p mixed (hybrid) method:**
  (e.g., ABAQUS/Standard **C3D4H** and **C3D10MH**)
  - ✗ Pressure checkerboarding, Early convergence failure etc..
- **F-bar type smoothed FEM (F-barES-FEM-T4):**
  - ✓ Accurate & stable ✗ Hard to implement in FEM codes.

Issues (cont.)

E.g.) Compression of neo-Hookean ***hyperelastic*** body with $\nu_{\rm ini} = 0.49$





# of Nodes is almost the same.

1st order hybrid T4 (C3D4H)

✓ No volumetric locking

✗ Pressure checkerboarding

✗ Shear & corner locking

2nd order modified hybrid T10 (C3D10MH)

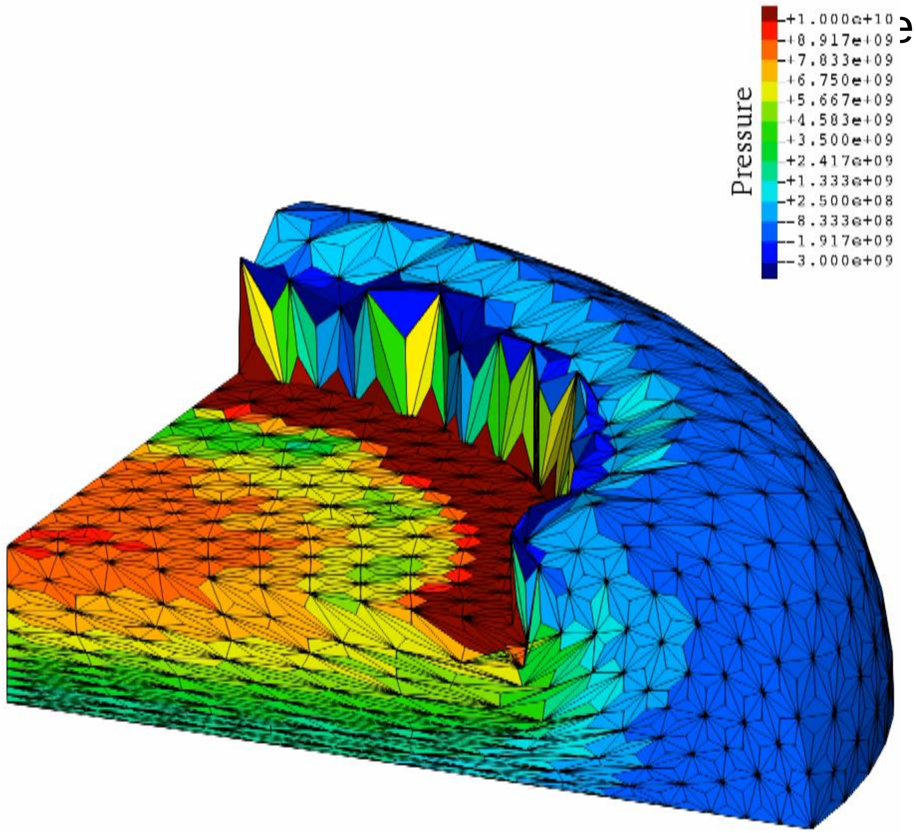
✓ No shear/volumetric locking

✗ Early convergence failure

✗ Low interpolation accuracy

Issues (cont.)

E.g.) Compression of neo-Hookean ***hyperelastic*** body with $\nu_{\mathrm{ini}} = 0.49$



Same mesh as C3D4H case.

F-barES-FEM-T4

✓ No shear/volumetric locking
✓ No corner locking
✓ No pressure checkerboarding

Although F-barES-FEM-T4 is accurate and stable,
✗ it cannot be implemented in general-purpose FE software due to the adoption of ES-FEM.

⇩

Another approach adopting CS-FEM with T10 element would be effective.

Objective

To propose an accurate and stable CS-FEM-T10, "SelectiveCS-FEM-T10", and to implement it into general-purpose FE software.

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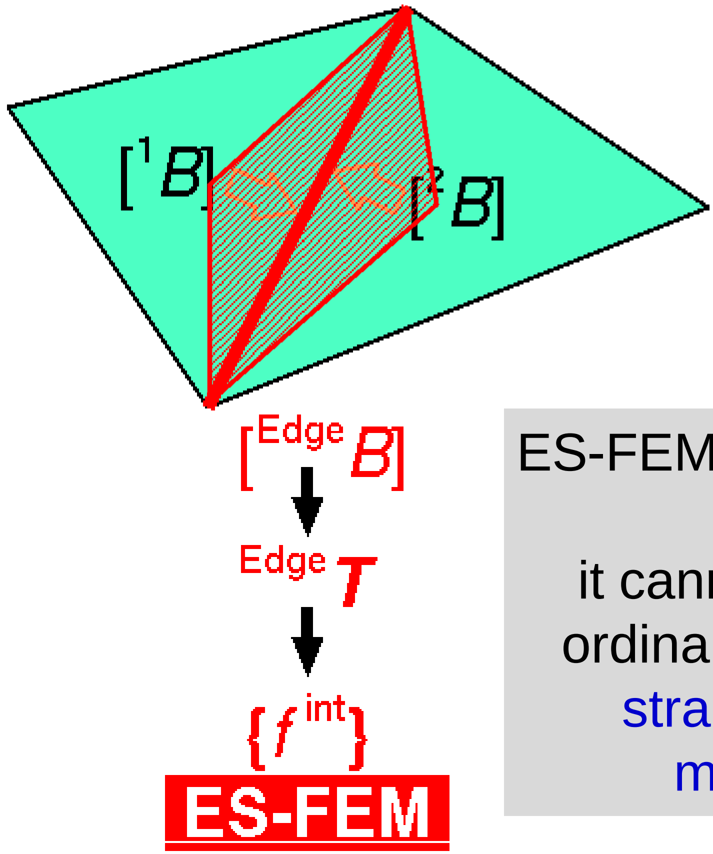
- Demonstrations of SelectiveCS-FEM-T10
- Implementation of SelectiveCS-FEM-T10 into ABAQUS
- Summary

Formulation of SelectiveCS-FEM-T10

Brief Review of Edge-based S-FEM (ES-FEM)

- Calculate $[B]$ at each element as usual.
- Distribute $[B]$ to the connecting edges with area weight and build $[\,^{\mathrm{Edge}}B]$.
- Calculate $\boldsymbol{F}, \boldsymbol{T}, \{f^{\mathrm{int}}\}$ etc. in each edge smoothing domain.

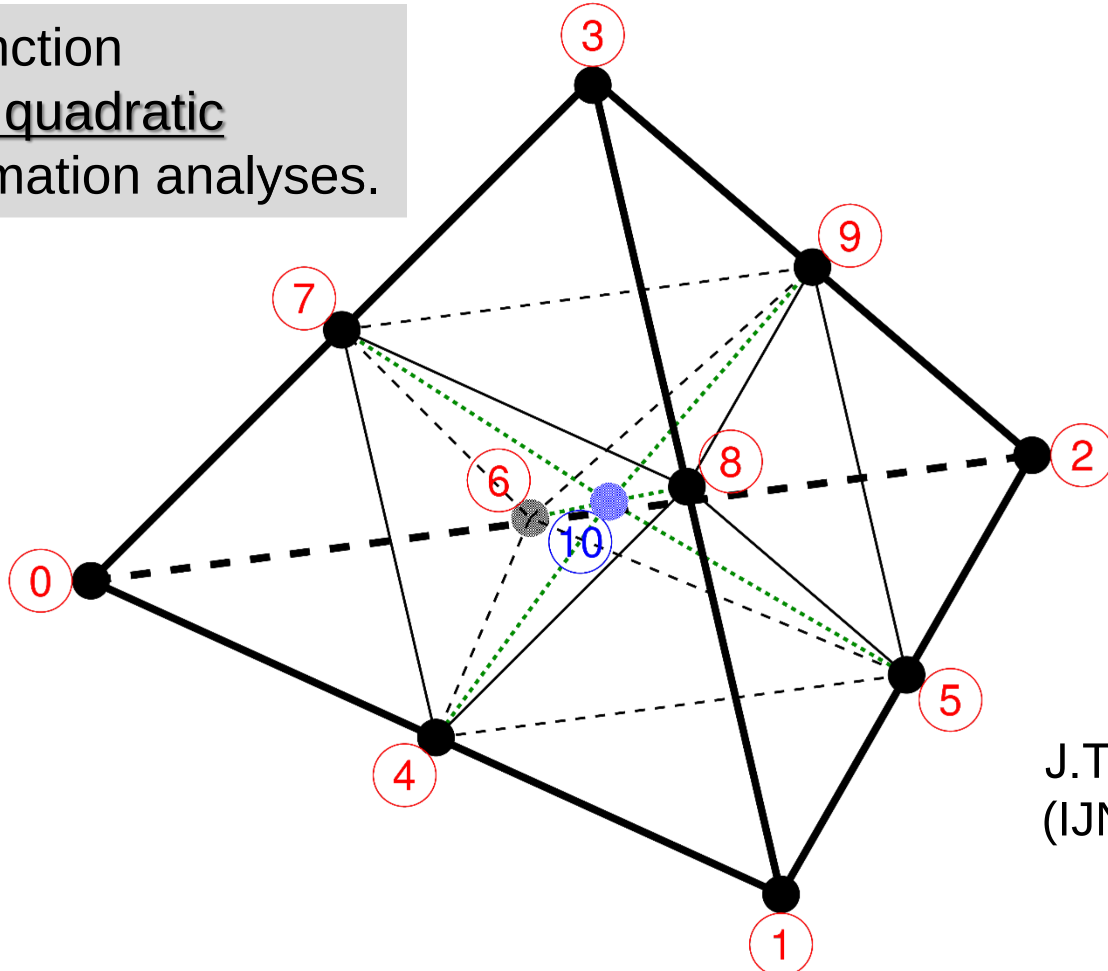
As if putting an integration point on each edge center



ES-FEM can avoid shear locking.
However,
it cannot be implemented in ordinary FE codes due to the strain smoothing across multiple elements...

(1) Subdivision into T4 Sub-elements

The shape function
<u>should not be quadratic</u>
in large deformation analyses.

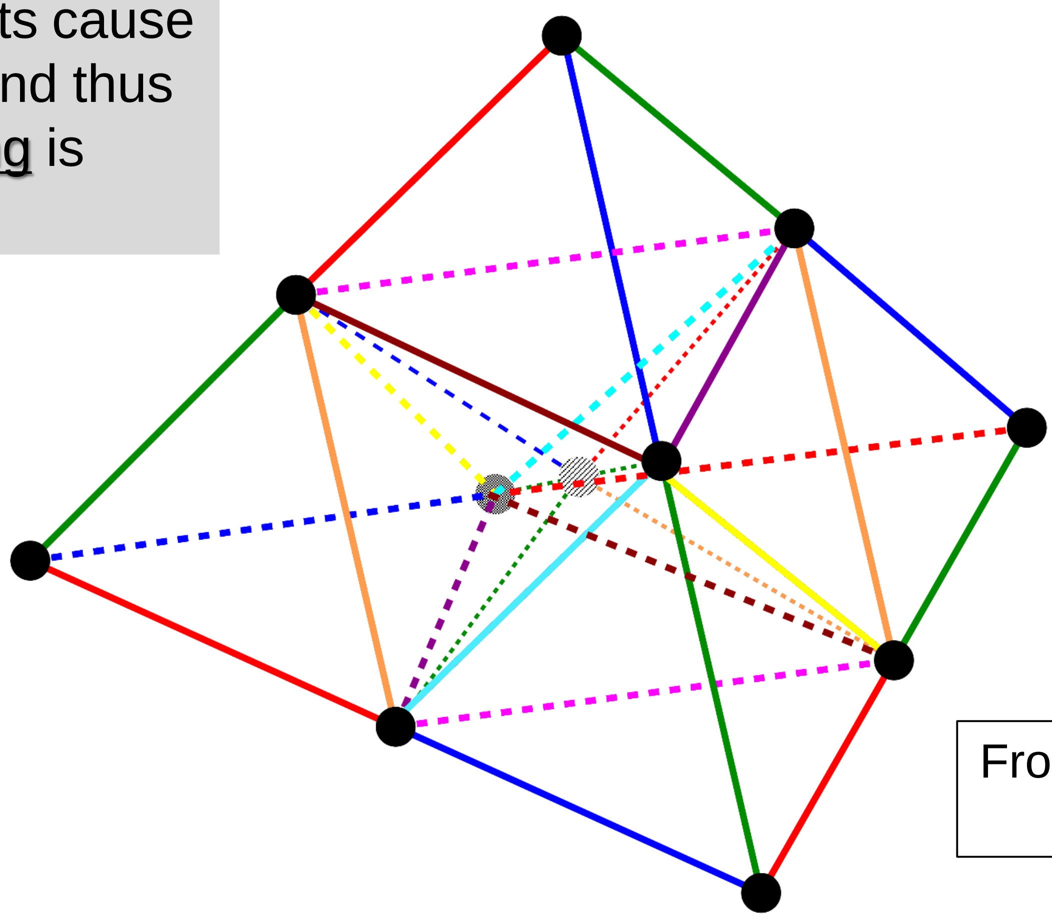


Same as
J.T.Ostien's method.
(IJNME, v107, 2016)

- Put a dummy node (10) at the mean location of 6 mid-nodes.
- Subdivide a T10 element into <u>twelve T4 sub-elements</u> and calculate their *B*-matrices and strains.

(2) Deviatoric Strain Smoothing

T4 sub-elements cause shear locking and thus strain smoothing is necessary.

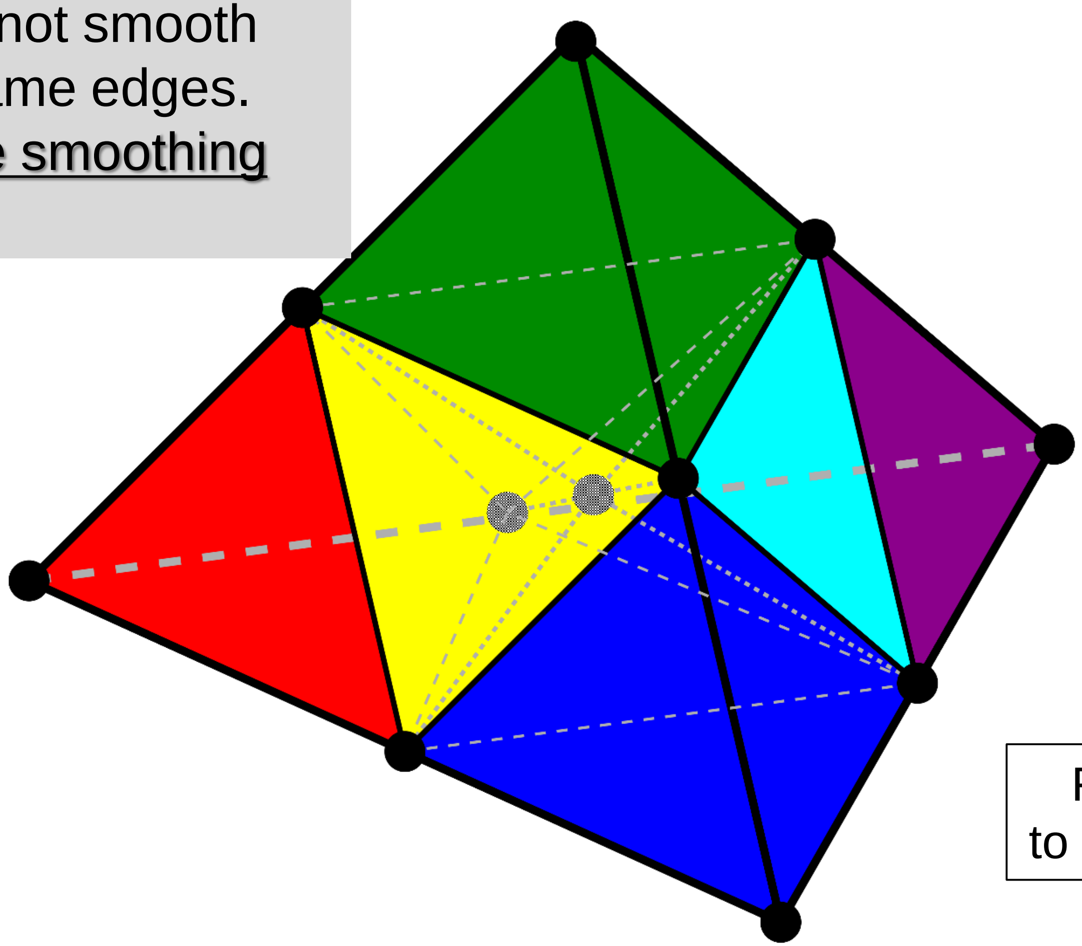


From 12 sub-elements to 30 edges

- Perform strain smoothing in the manner of ES-FEM (i.e., average dev. strains of sub-elements at edges). Then…

(2) Deviatoric Strain Smoothing (cont.)

ES-FEM does not smooth the strain at frame edges. Thus <u>one more smoothing</u> is necessary.

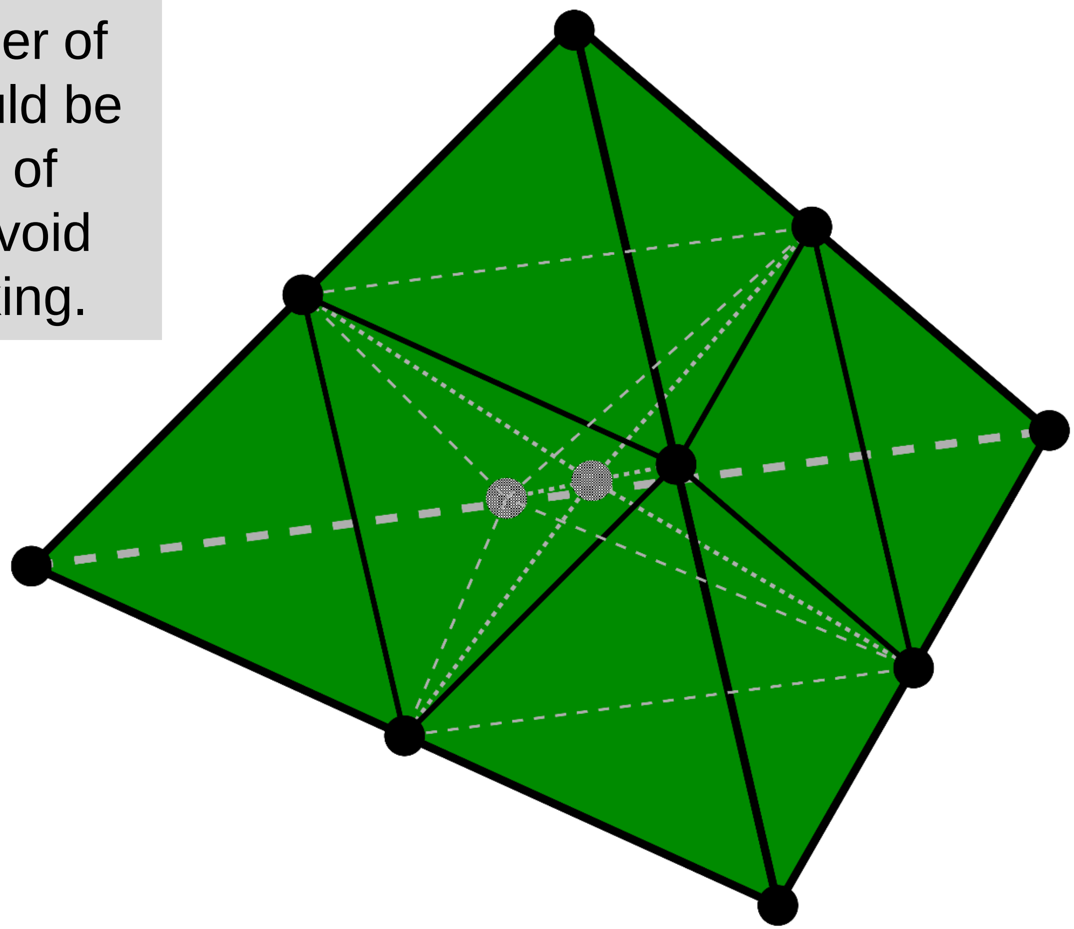


From 30 edges to 12 sub-elements

- Perform one more strain smoothing in the reverse direction (i.e., average dev. strains of edges at sub-elements), which is so to speak (ES-FEM)$^{-1}$.

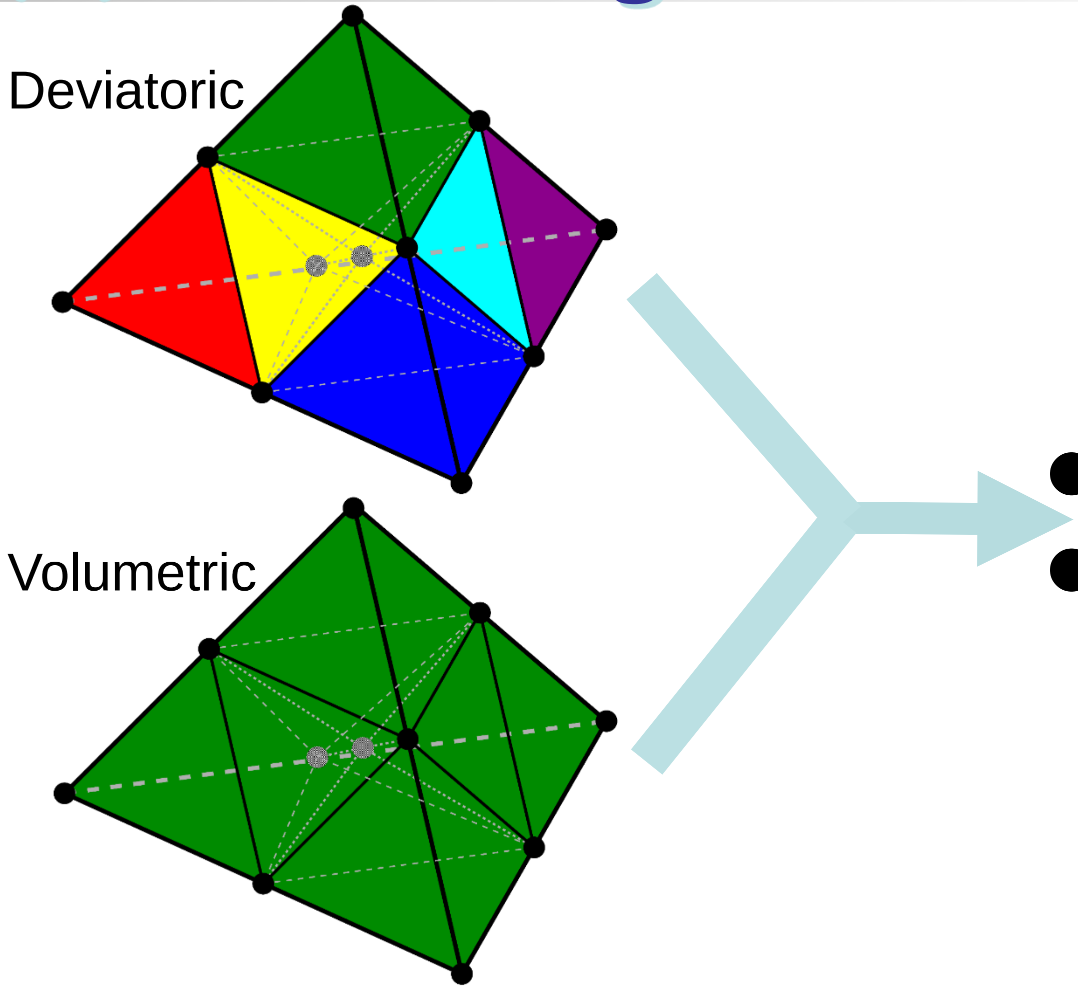
(3) Volumetric Strain Smoothing

The spatial order of vol. strain should be lower than that of dev. strain to avoid volumetric locking.



- Treat the overall mean vol. strain of all sub-elements as the uniform element vol. strain (i.e., same approach as SRI elements).

(4) Combining with SRI Method

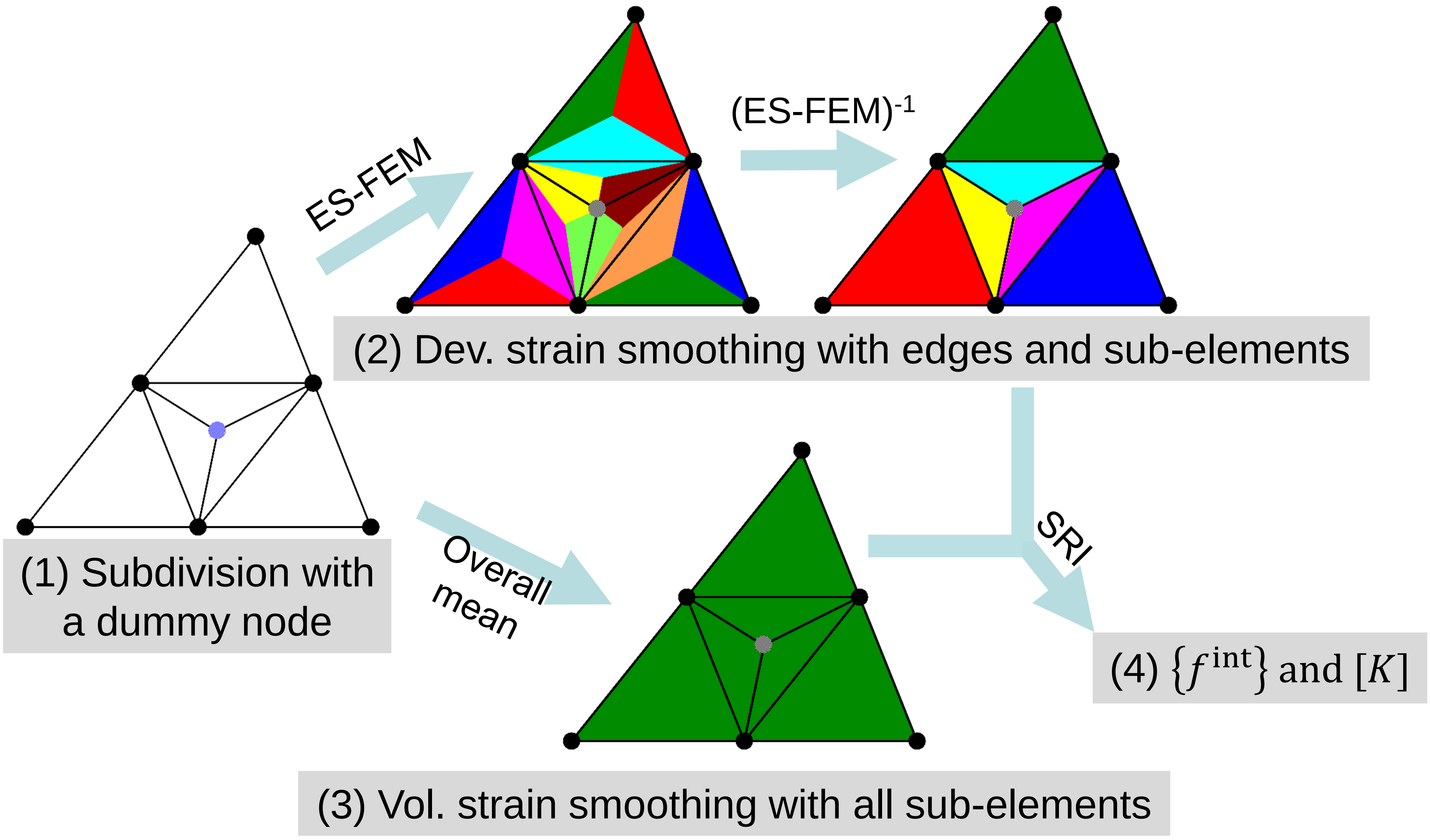


- Internal force $\{f^{\mathrm{int}}\}$
- Stiffness $[K]$

■ Apply SRI method to combine the Dev. & Vol. parts and obtain $\{f^{\mathrm{int}}\}$ and $[K]$.

Flowchart of SelectiveCS-FEM

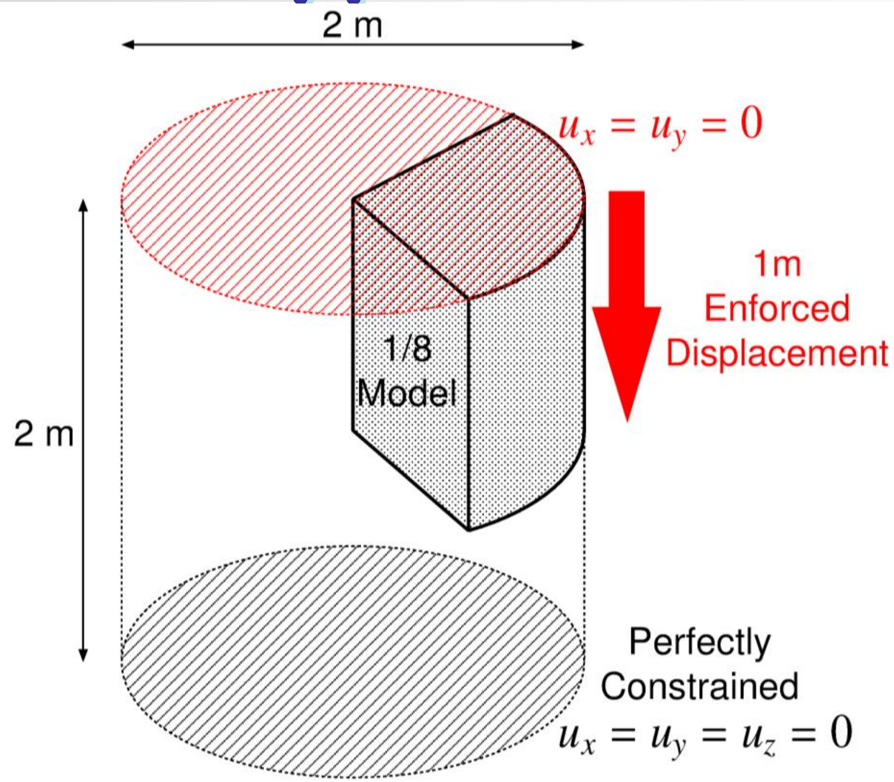
Explanation in 2D (6-node triangular element) for simplicity



Demonstration of SelectiveCS-FEM-T10

Barreling of Hyperelastic Cylinder

Outline

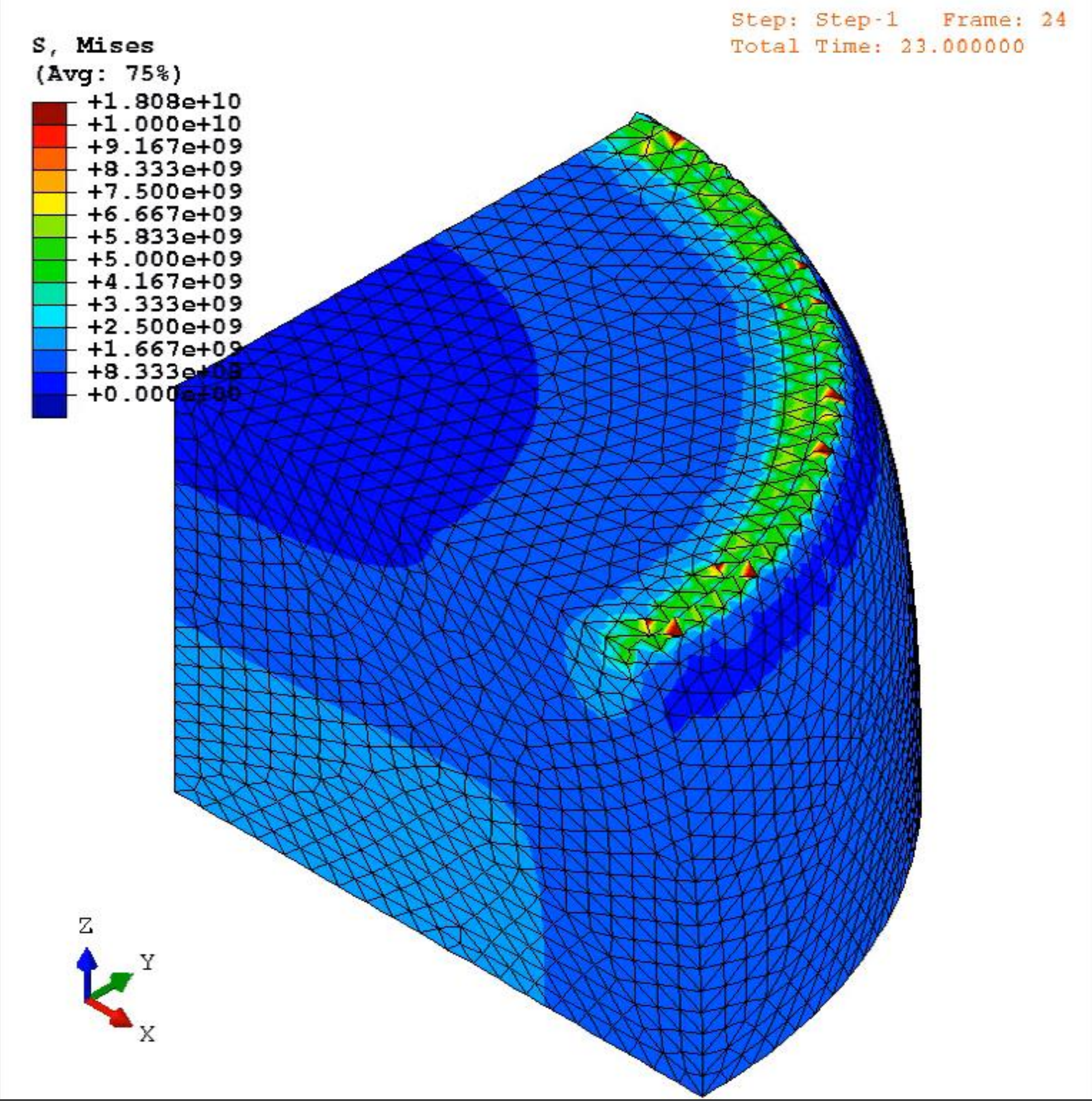


- Enforce axial displacement on the top face.
- Neo-Hookean body with $\nu_{\text{ini}} = 0.49$.
- Compare results with ABAQUS T10 hybrid elements (C3D10H, C3D10MH, C3D10HS) using the same mesh.

Barreling of Hyperelastic Cylinder

Animation of Mises stress (ABAQUS C3D10MH)

Convergence failure at **24%** compression

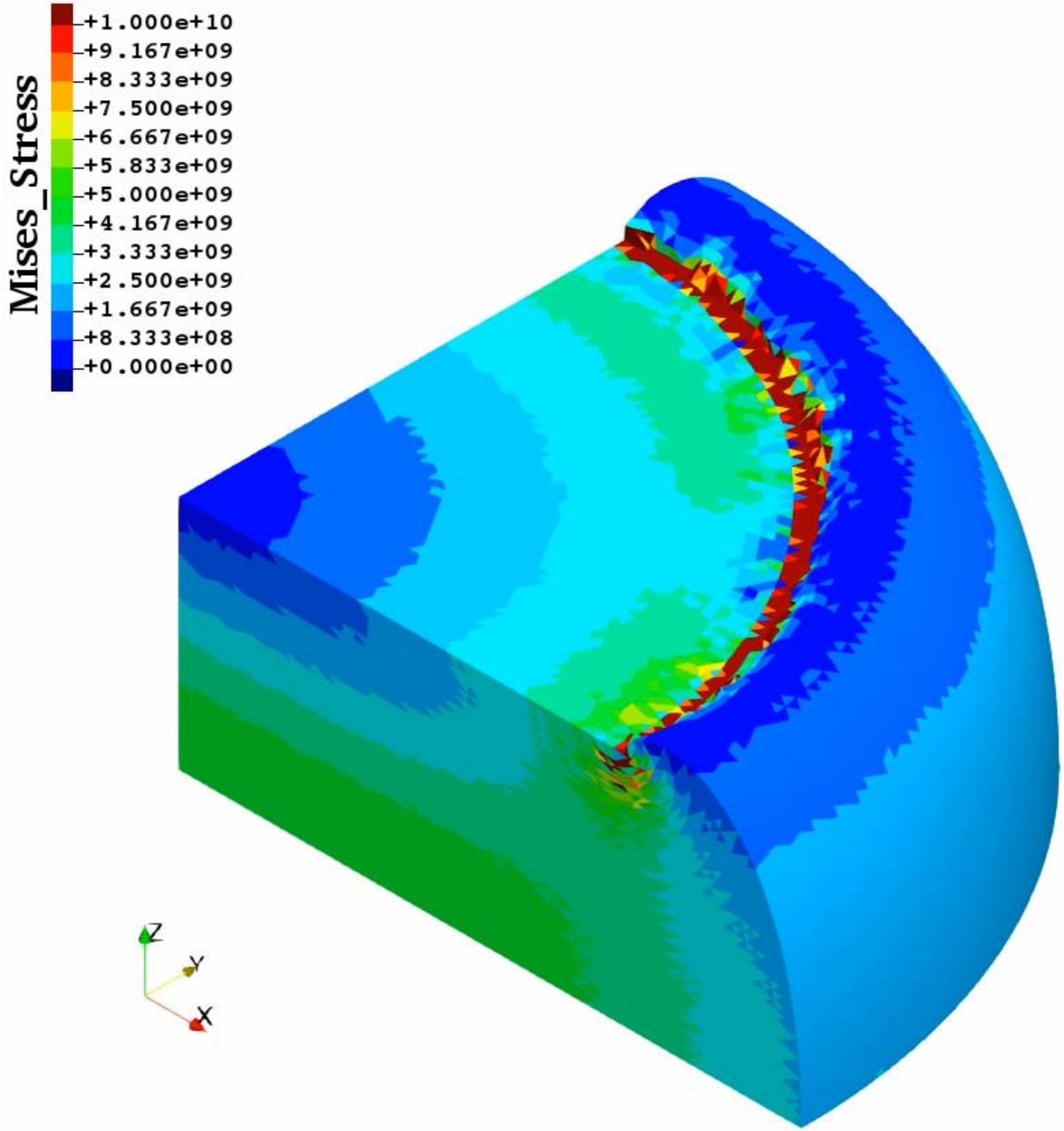


Unnaturally oscillating distributions are obtained around the rim.

Barreling of Hyperelastic Cylinder

Animation of Mises stress (Selective CS-FEM-T10)

Convergence failure at **47%** compression

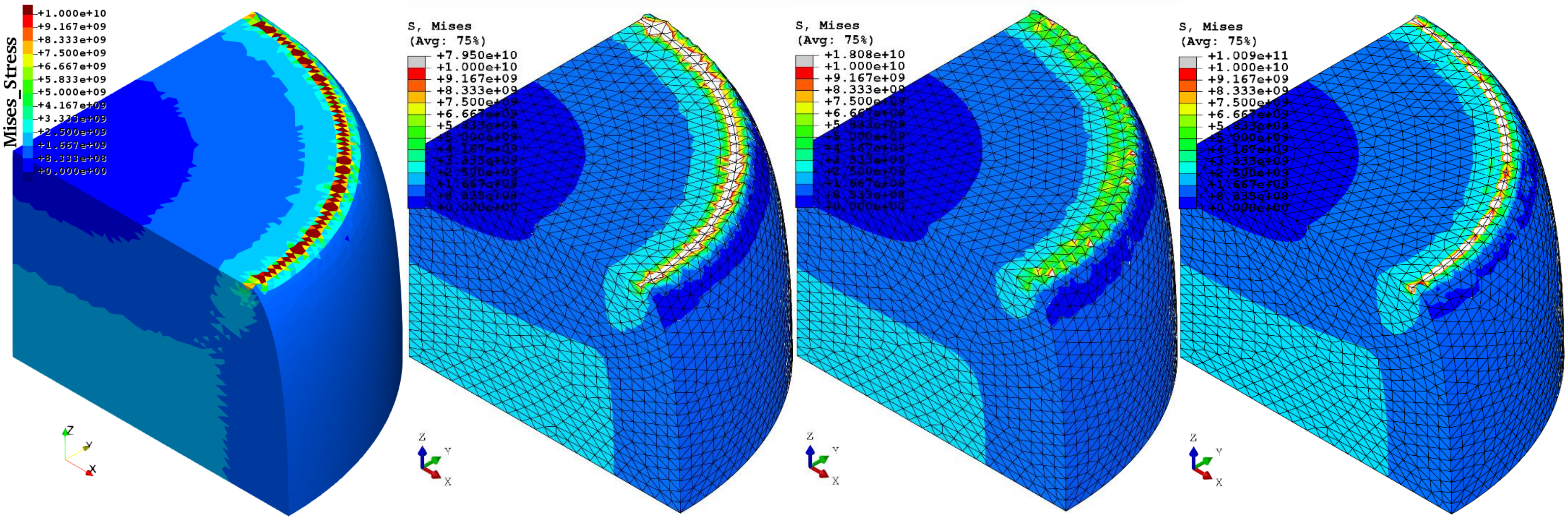


Smooth distributions are obtained except around the rim.

The present element is more **stable** than ABAQUS C3D10MH

Barreling of Hyperelastic Cylinder

Comparison of Mises stress at 24% comp.

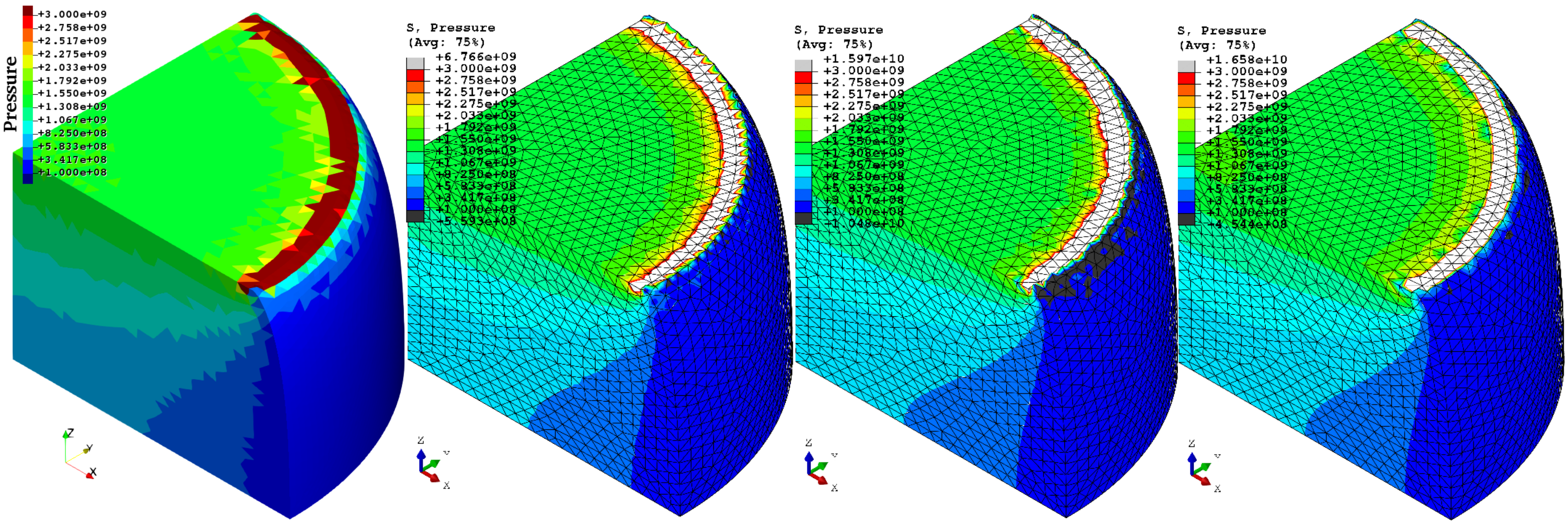


Selective CS-FEM-T10	ABAQUS C3D10H	ABAQUS C3D10MH	ABAQUS C3D10HS

All results are similar to each other
except around the rim having stress singularity.

Barreling of Hyperelastic Cylinder

Comparison of pressure at 24% comp.

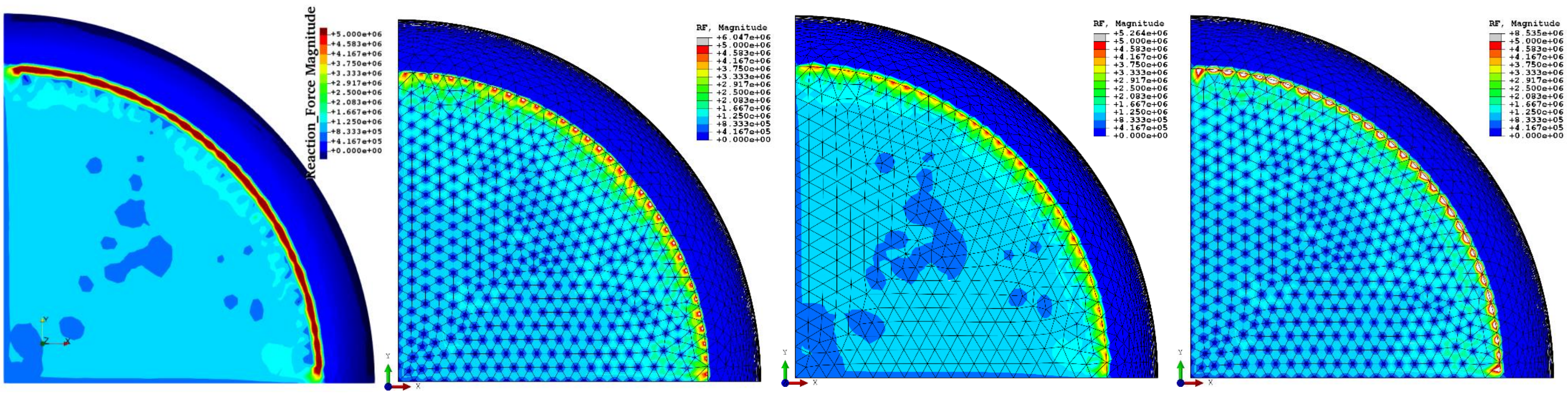


Selective CS-FEM-T10	ABAQUS C3D10H	ABAQUS C3D10MH	ABAQUS C3D10HS

All results are similar to each other
except around the rim having stress singularity.

Barreling of Hyperelastic Cylinder

Comparison of nodal reaction force at 24% comp.



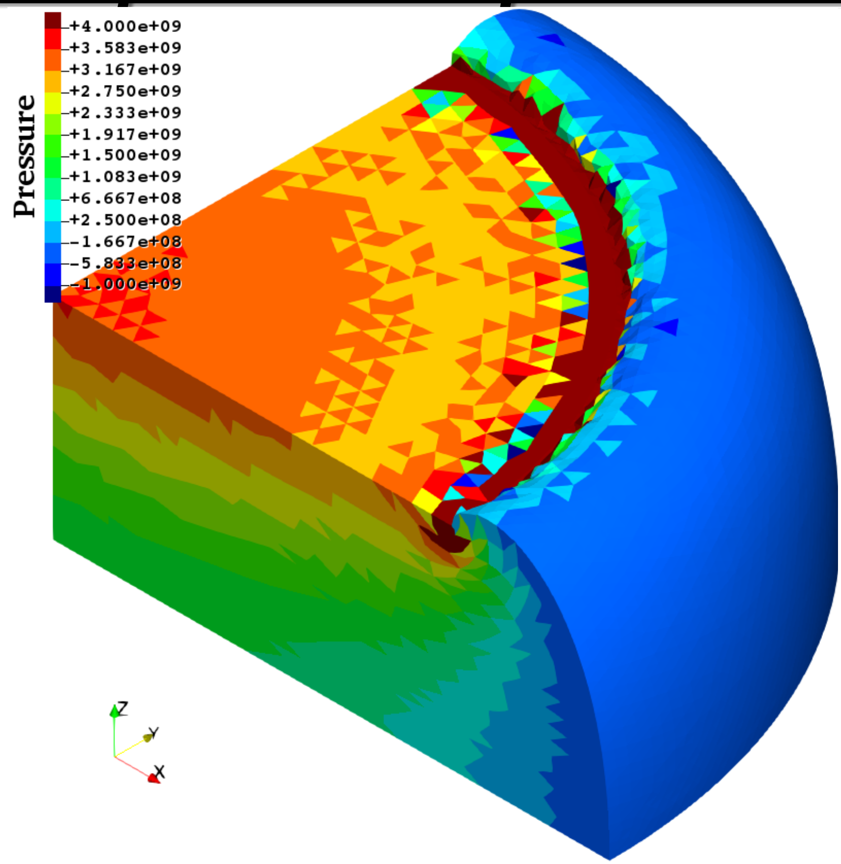
Selective CS-FEM-T10	ABAQUS C3D10H	ABAQUS C3D10MH	ABAQUS C3D10HS

ABAQUS C3D10H and C3D10HS suffer from nodal force oscillation.

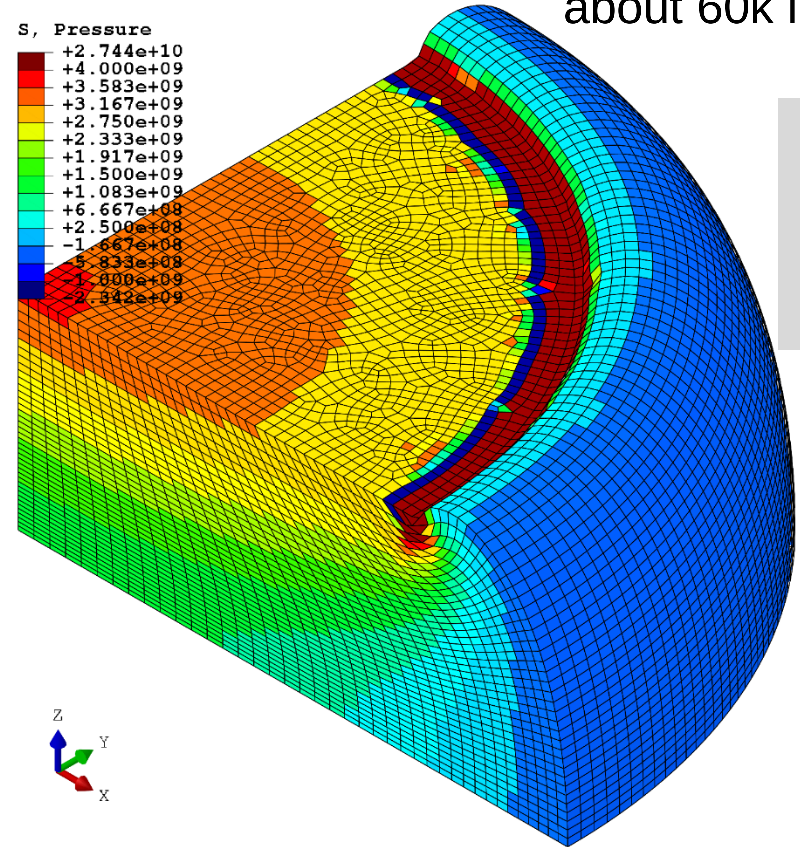
Barreling of Hyperelastic Cylinder

Comparison of pressure at 47% comp.

of nodes are about 60k in both.



SelectiveCS-FEM-T10



ABAQUS C3D8

Conv. failure at 50% comp.

The present element has competitive accuracy and stability as much as H8-SRI element.

Implementation of SelectiveCS-FEM-T10 into ABAQUS

Brief of ABAQUS UEL

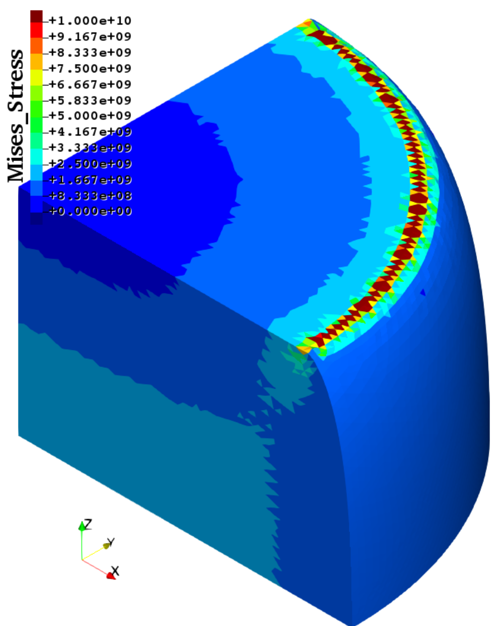
- ABAQUS has functionality of "user-defined element" (simply called "UEL").
- UEL is usually written in Fortran77, but in fact it can be written in Fortran90.
- Coding a subroutine named "UEL" and compiling it, one can execute ABAQUS using one's own element:

```
% abaqus job=test user=my_uel.o
```

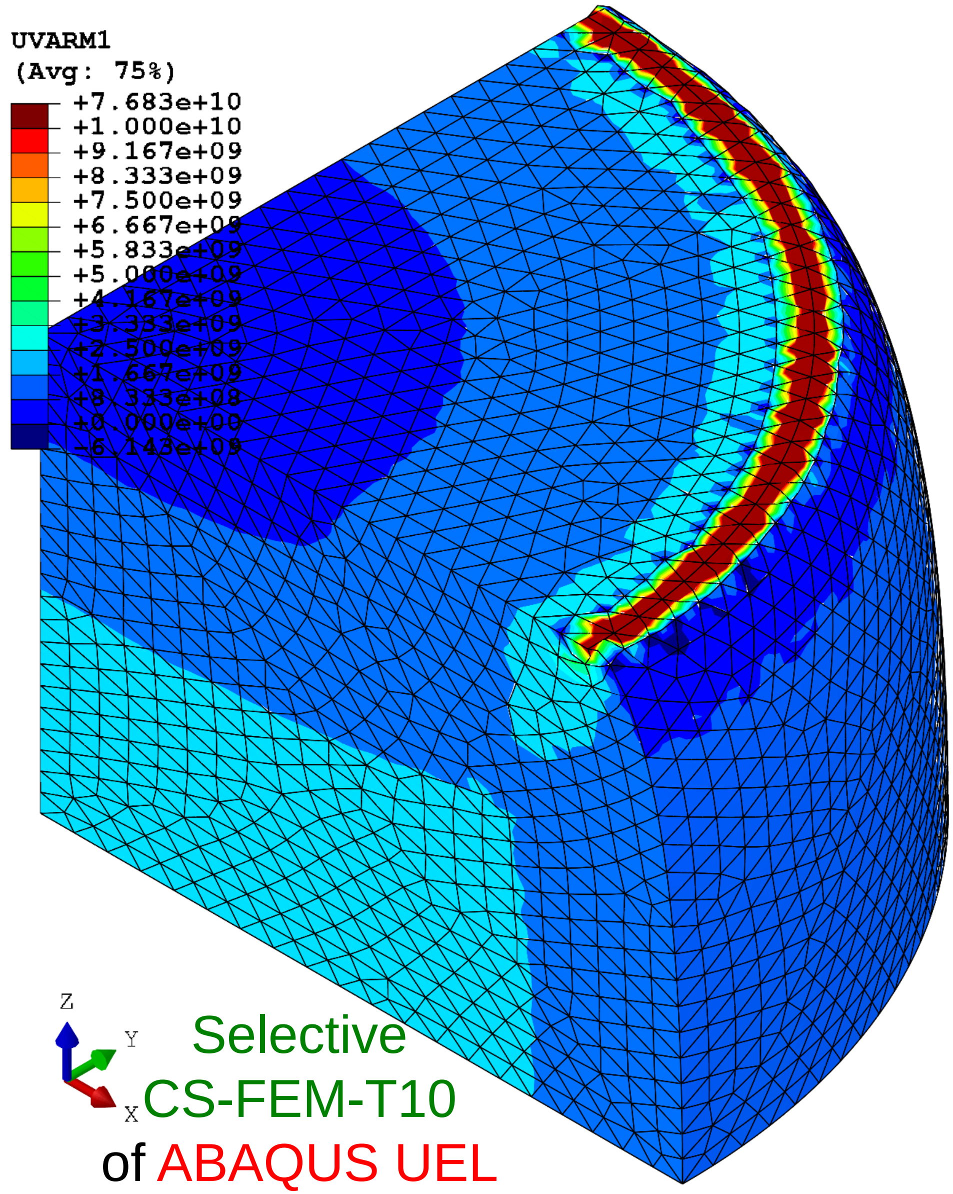
- Analysis results can be visualized on ABAQUS Viewer by defining overlap elements with zero stiffness in the "inp" file.

Results of ABAQUS UEL

Comparison of Mises stress (24% comp.)



Selective
CS-FEM-T10
of in-house code



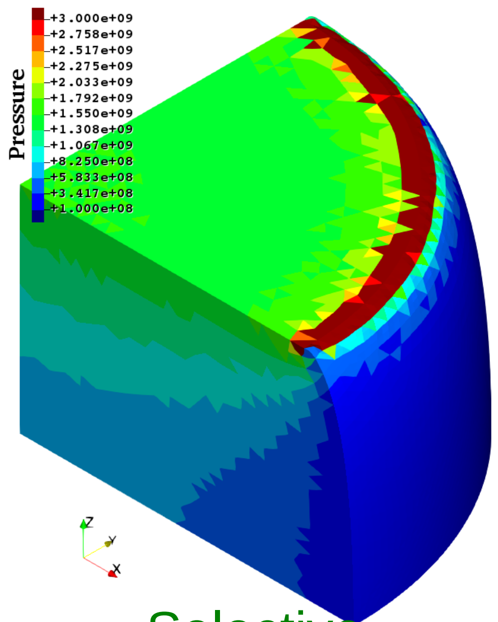
Selective
CS-FEM-T10
of ABAQUS UEL

Well agreed with in-house code.

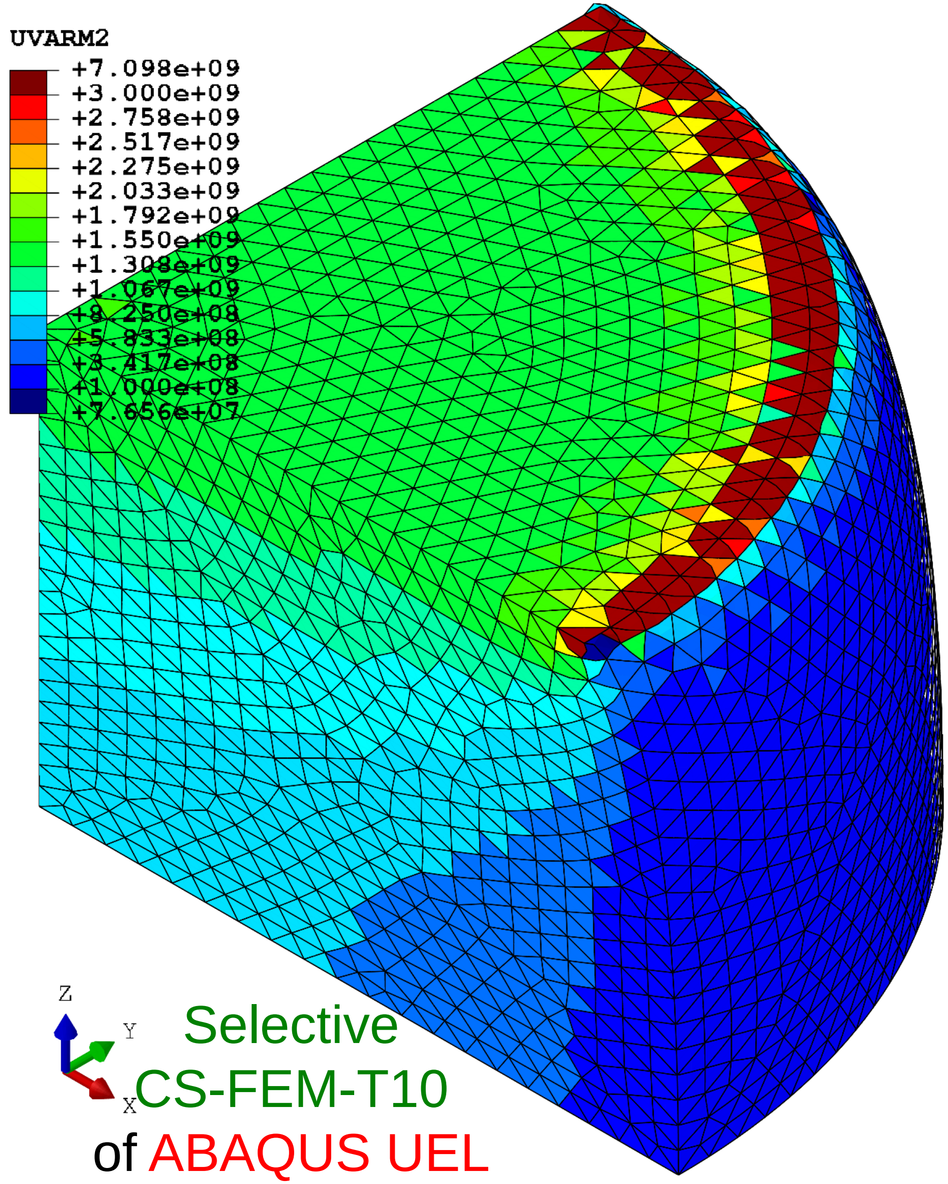
Small difference comes form the difference of mapping calculation.

Results of ABAQUS UEL

Comparison of pressure (24% comp.)



Selective CS-FEM-T10 of in-house code



Selective CS-FEM-T10 of ABAQUS UEL

Well agreed with in-house code.

Small difference comes form the difference of mapping calculation.

Issues in ABAQUS UEL

- We have to define the overlap elements
  - to visualize the results with ABAQUS Viewer.
  - to define element-based surface
    for pressure loading, contact pair definition etc..
- The overlap elements cause convergence failure in large deformation analysis.
  i.e., the cylinder barreling analysis stops at 24% compression when the overset elements are defined.

⇩

Native implementation is essential for the full use of SelectiveCS-FEM-T10, unfortunately…

Summary

Summary of SelectiveCS-FEM-T10

Benefits

- ✓ Locking-free.
- ✓ No pressure checkerboarding.
- ✓ No nodal force oscillation.
- ✓ No increase in DOF.
- ✓ Long lasting in large deformation.
- ✓ Same CPU cost as the standard T10 elements.

Drawbacks

- ✗ No longer a T4 formulation.

Take-home message

Please consider implementing SelectiveCS-FEM-T10 to your in-house code. It's supremely useful & easy to code!!

Thank you for your kind attention!