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Using Rigid Block / *FLAC3D* Coupling in Mine-Scale Simulations

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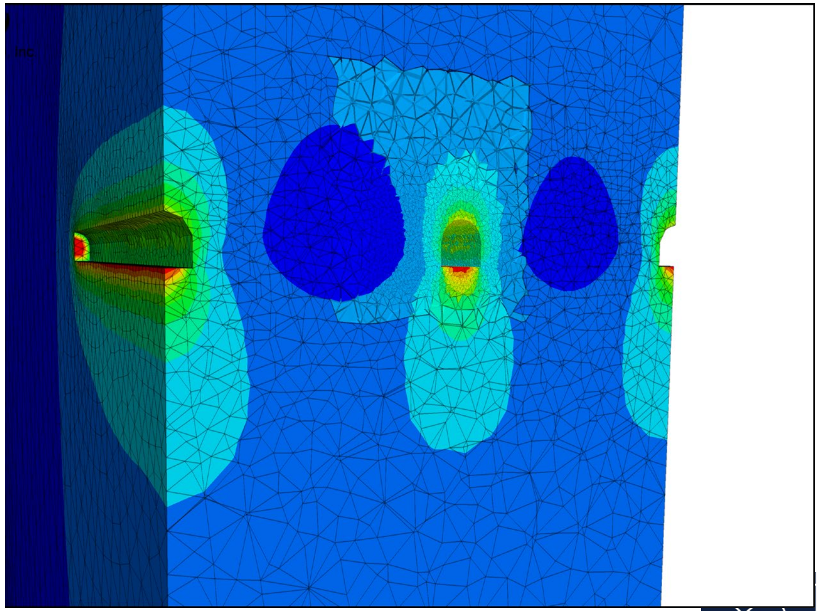
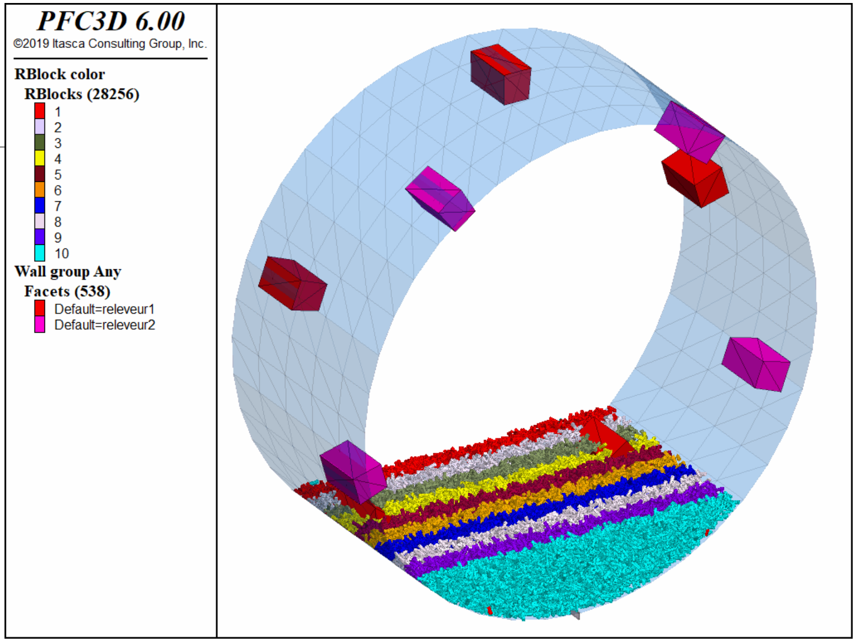
Outline

- **Introduce rigid blocks (rblocks) in *PFC 6***
- Discuss specifics of bonded block modeling (BBM) using rblocks
- Compare *PFC* BBM with rigid and deformable *3DEC* BBM
- Describe the mine-scale caving model
- Mine-scale modeling results
- Conclusions



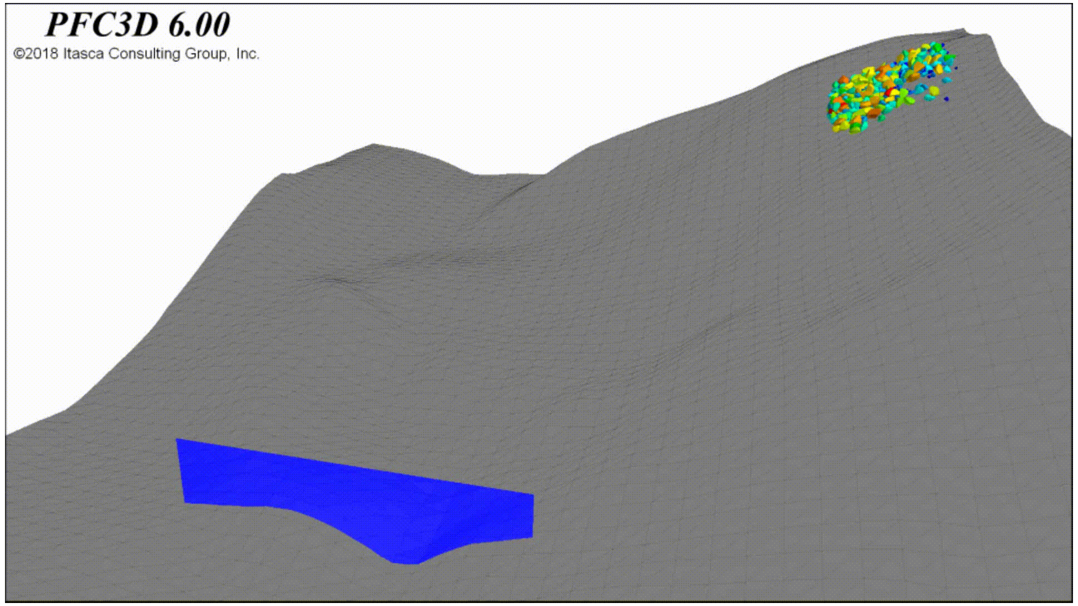
Rigid Blocks (RBlocks) in *PFC* 6



- Convex, rigid {polygons in 2D; polyhedra in 3D}
- Surfaces are {linear segments in 2D; triangles in 3D}
  - Surfaces are computed via Qhull for economical discretization and to ensure closed/convex surfaces
  - Connectivity is stored and utilized for contact resolution
- The full inertia tensor is used for dynamic rotational EOM
- Contact detection/resolution starts with optimized GJK + EPA to detect overlap efficiently and determine minimum penetration direction and depth (i.e., gap)
- Unlike in *3DEC*, no subcontacts exist between rblocks and other pieces when they overlap, with the single contact position/normal updated as:
  - Unbonded: position at the centroid of the overlap region, normal in minimum penetration direction
  - Bonded: position and normal computed for configuration first then incrementally updated using relative piece velocities until bond failure

Rigid Blocks (RBlocks) in *PFC* 6 contd.

- Contact detection/resolution times depend directly on the number of vertices discretizing the rblocks
- Periodic space support
- Direct coupling with *FLAC3D* zones and structural elements
- Fragment tracking
- Planned rblock additions in *PFC* 7:
  - Face data (groups with *FISH* and command access)
  - Apply conditions for faces and rblocks
  - Hide/select
  - Clump to make concave rblocks
  - Zonking via command
  - Reaction forces
  - MPI support



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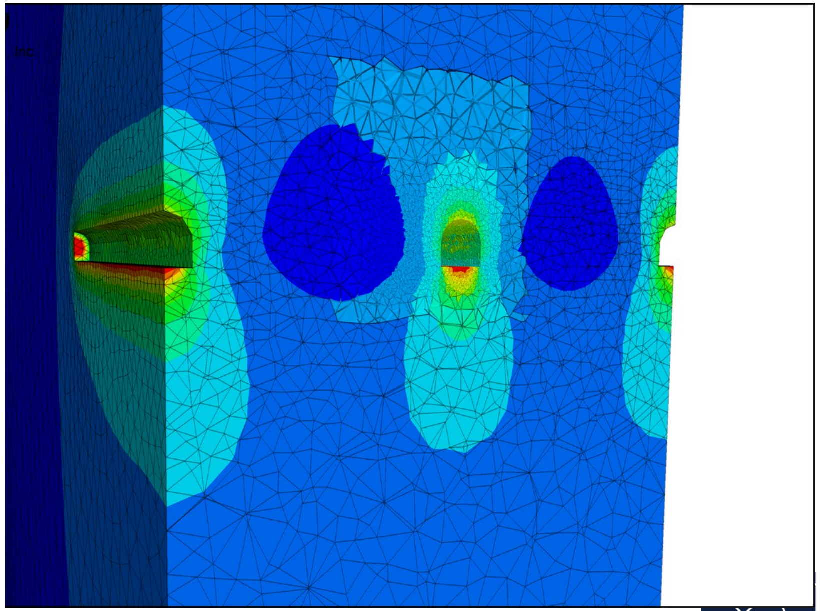
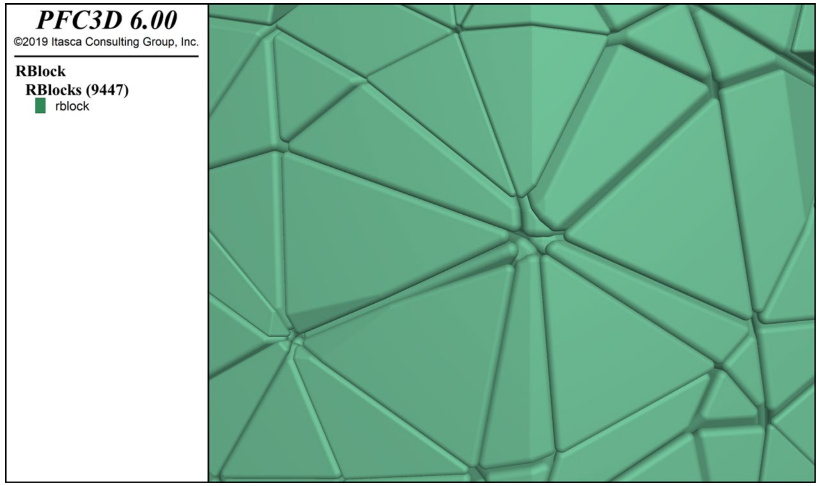
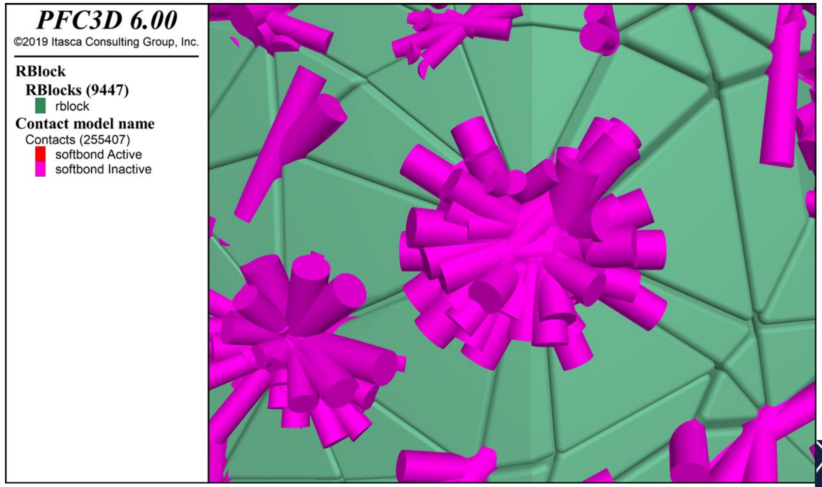


Working With RBlock BBMs

- Mesh volumes in *PFC* to create zero porosity packings via commands in 2D and 3D
- Cut (using throughgoing specification and sliver removal)
- Manage contact inhibiting via command
  - ❖ Skip inhibited contact computations, periodically checking if they should be re-activated
- RBlock rounding and inhibiting vertex/edge contacts can be used to significantly speed up BBM simulations





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Working With RBlock BBMs contd.

- Stress visualization and installation (in contacts) via command
- Some initial rblock overlap is required for contact creation for BBM
- Can use uniform density scaling to speed up simulations
- Direct coupling with *FLAC3D* zones (via wall-zone coupling) to provide stress boundaries
- Direct coupling with *FLAC3D* structural elements (via wall-structure coupling and via structural node links)
- Since single contact need to think about moment accumulation …

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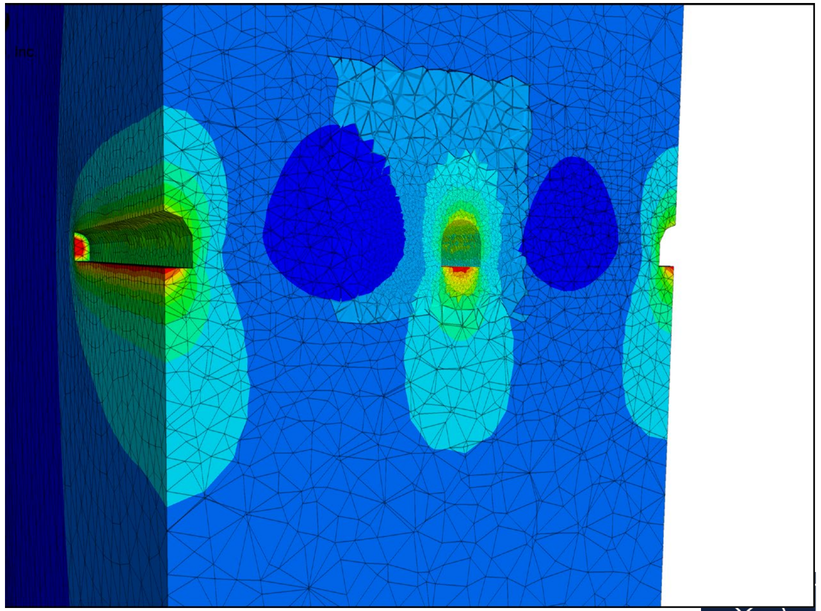
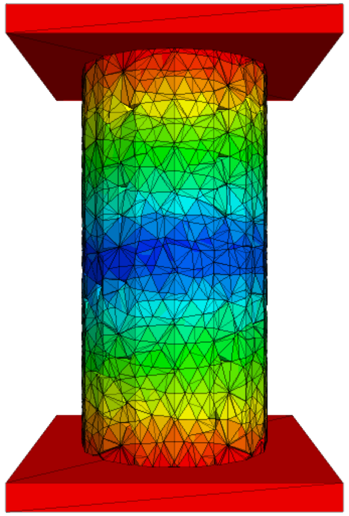


PFC – 3DEC Comparison: Simple Tests

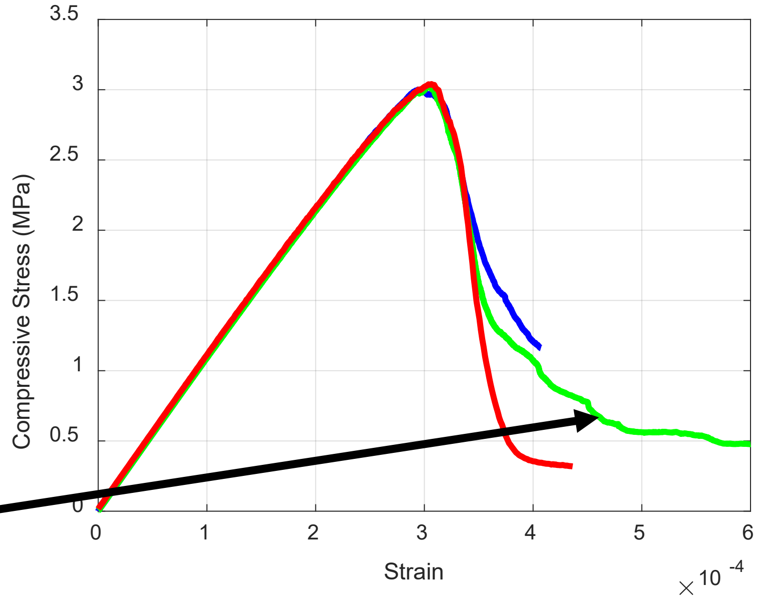


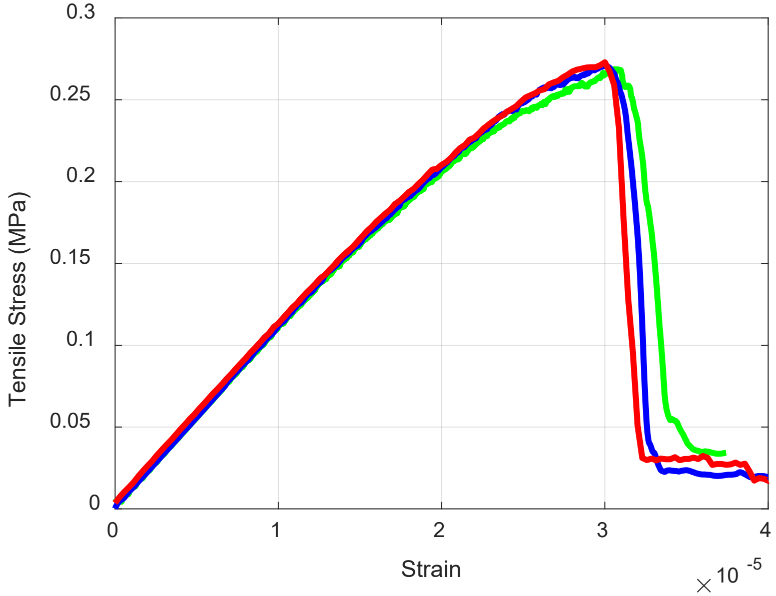
- Sliding wedge and falling wedge
  - *3DEC* and *PFC* give very similar results
- UCS/direct tension tests with material similar to Garza-Cruz et al. (2014)
  - 11 GPa Young's modulus, 0.25 Poisson's ratio
  - 3 MPa UCS strength
  - 40 degree peak and residual friction
  - No dilation (10 degrees in that study)
  - Tensile and cohesive strength drawn from Gaussian distribution (slightly different from that study)
  - Large strain
- Create rblock and *3DEC* rigid block BBMs and *3DEC* deformable BBM (~6,000 blocks)
  - Calibrate UCS and tensile strength for exactly the same initial tetrahedral models
  - Triaxial tests

UCS and Direct Tension – Softbond and Mohr

- Softbond model in *PFC*
  - No softening (parallel bond without separate linear stiffness)
  - Incremental normal force accumulation with contacts remaining active if compressive normal forces remain, even if rblocks no longer overlap
  - To approximate the emergent behavior of *3DEC* subcontacts need to have moment accumulation when unbonded, meaning that contact position update isn't adequate to represent the flat surfaces

PFC rblock (red)
3DEC rigid (green)
3DEC deformable (blue)

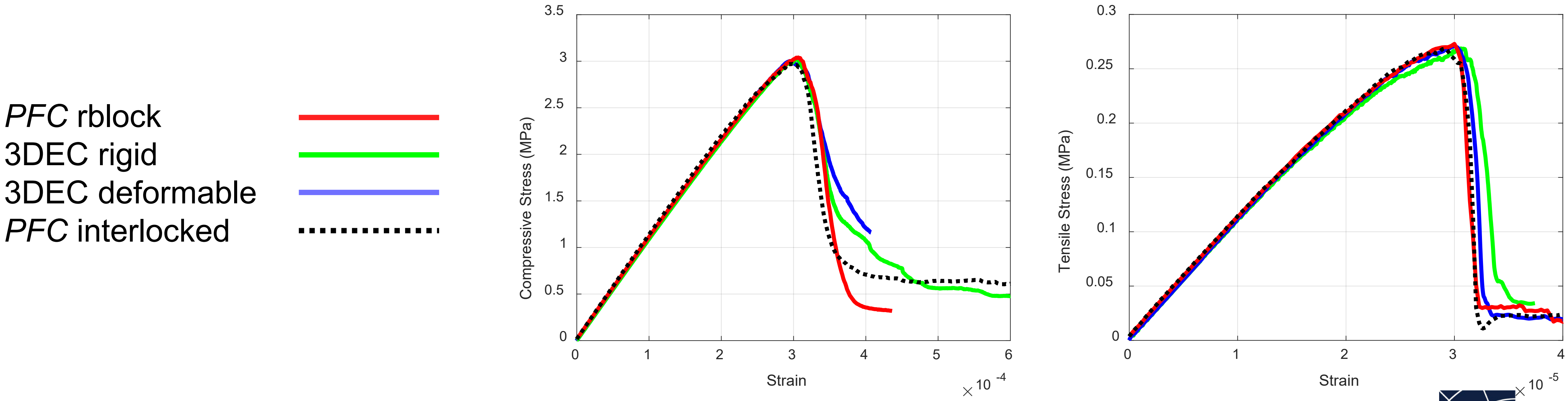




3DEC shows more interlock … why does this happen?

Interlock in *PFC*

- Face-face contacts active, resisting moment, with rounding inhibiting edge-edge and vertex-vertex contacts
- What happens if you randomly bond some of the other contacts?
- 5% of edge-edge and vertex-vertex contacts randomly bonded initially



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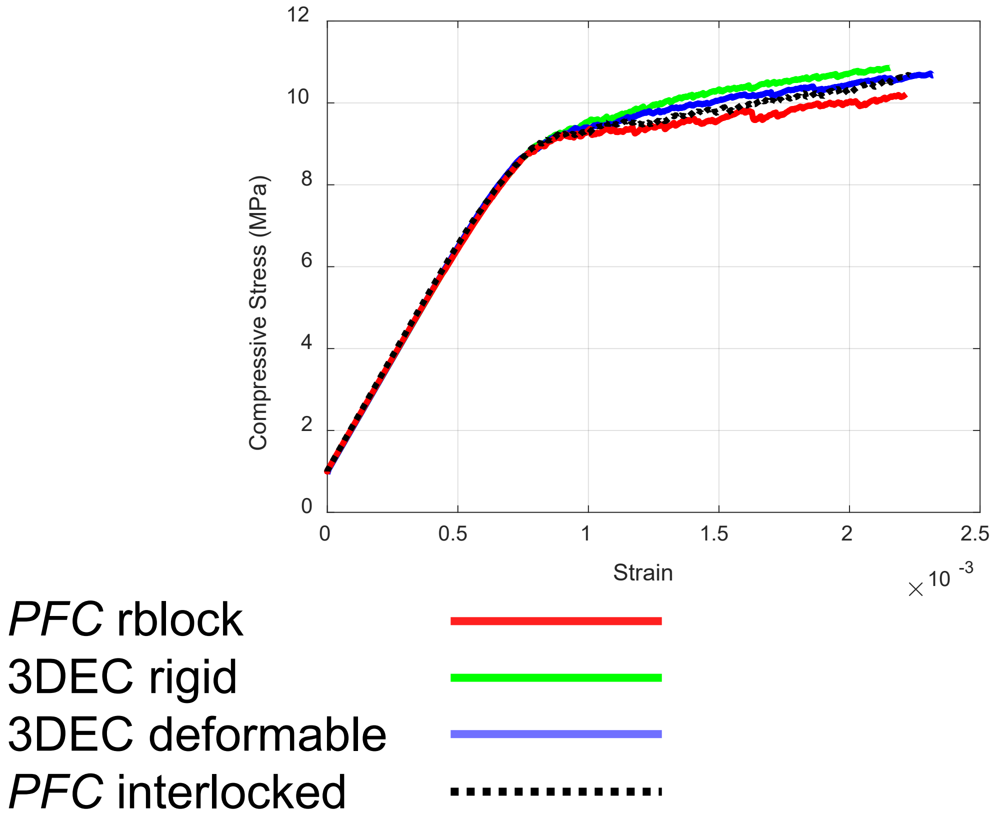
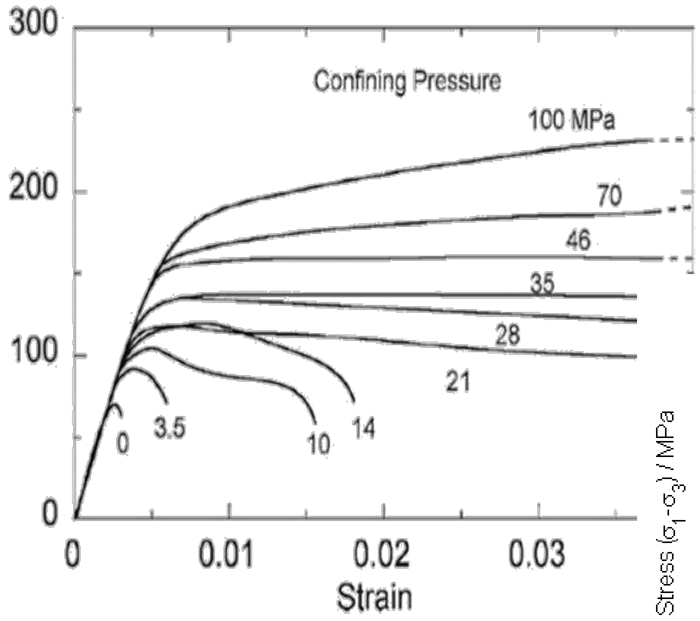
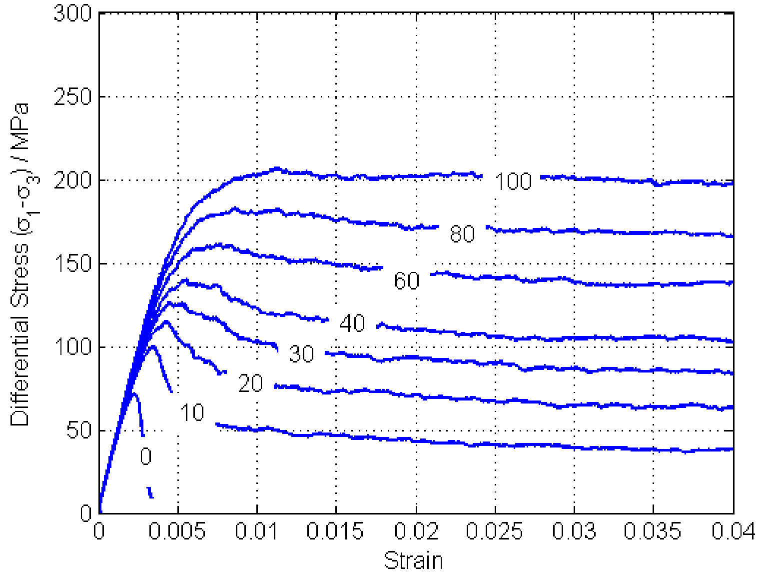
Triaxial Results – 1MPa Confinement

- Small friction on platens since a stress confinement on the boundaries
  - ❖ Can get slight drift otherwise
  - ❖ Responsible for increase in compressive stress with continued strain

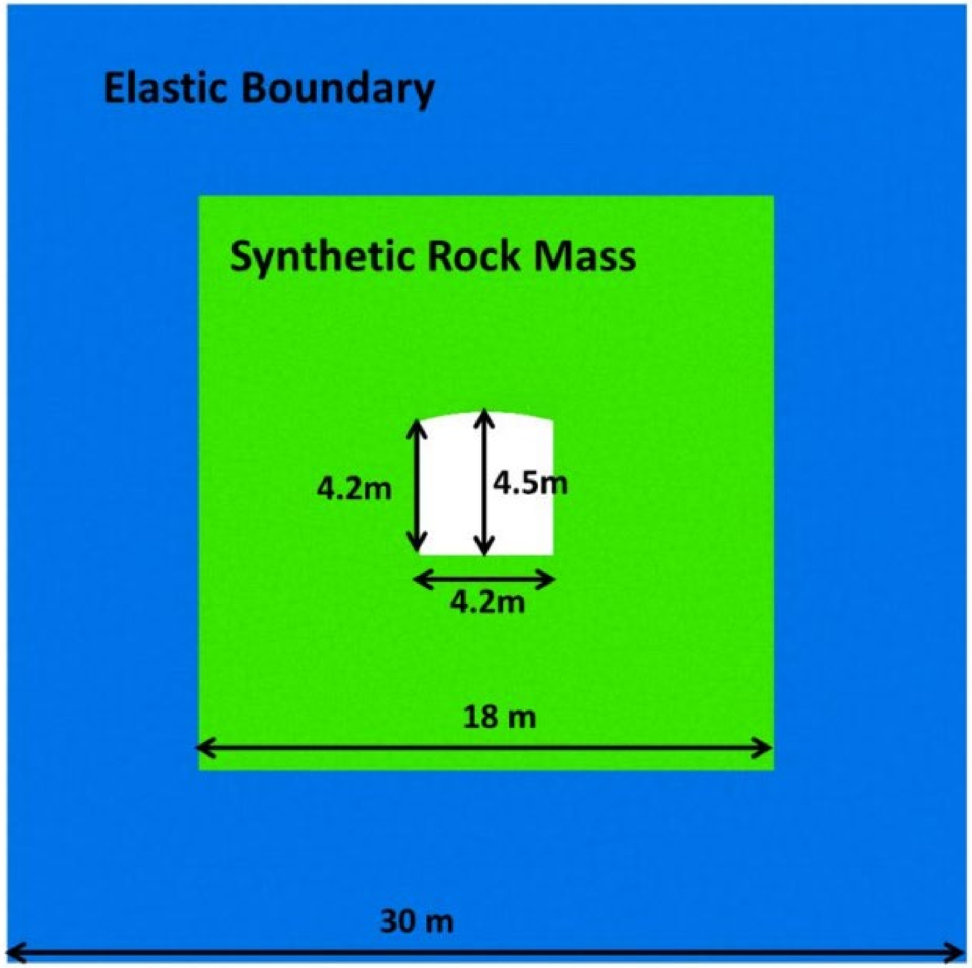






More Complex Comparison: Tunnel

- Quasi 2D tunnel excavation models using: rblocks, rigid blocks in *3DEC*, and deformable blocks in *3DEC* (Garza Cruz et al. 2014)
- Elastic boundaries outside the BBM (*FLAC3D* zones in *PFC*, deformable blocks in *3DEC*) with roller boundaries
- Apply an anisotropic stress state
  - σ_{xx} = -93 MPa (perpendicular to the tunnel)
  - σ_{yy} = -50 MPa (parallel to the tunnel)
  - σ_{zz} = -31 MPa (vertical)



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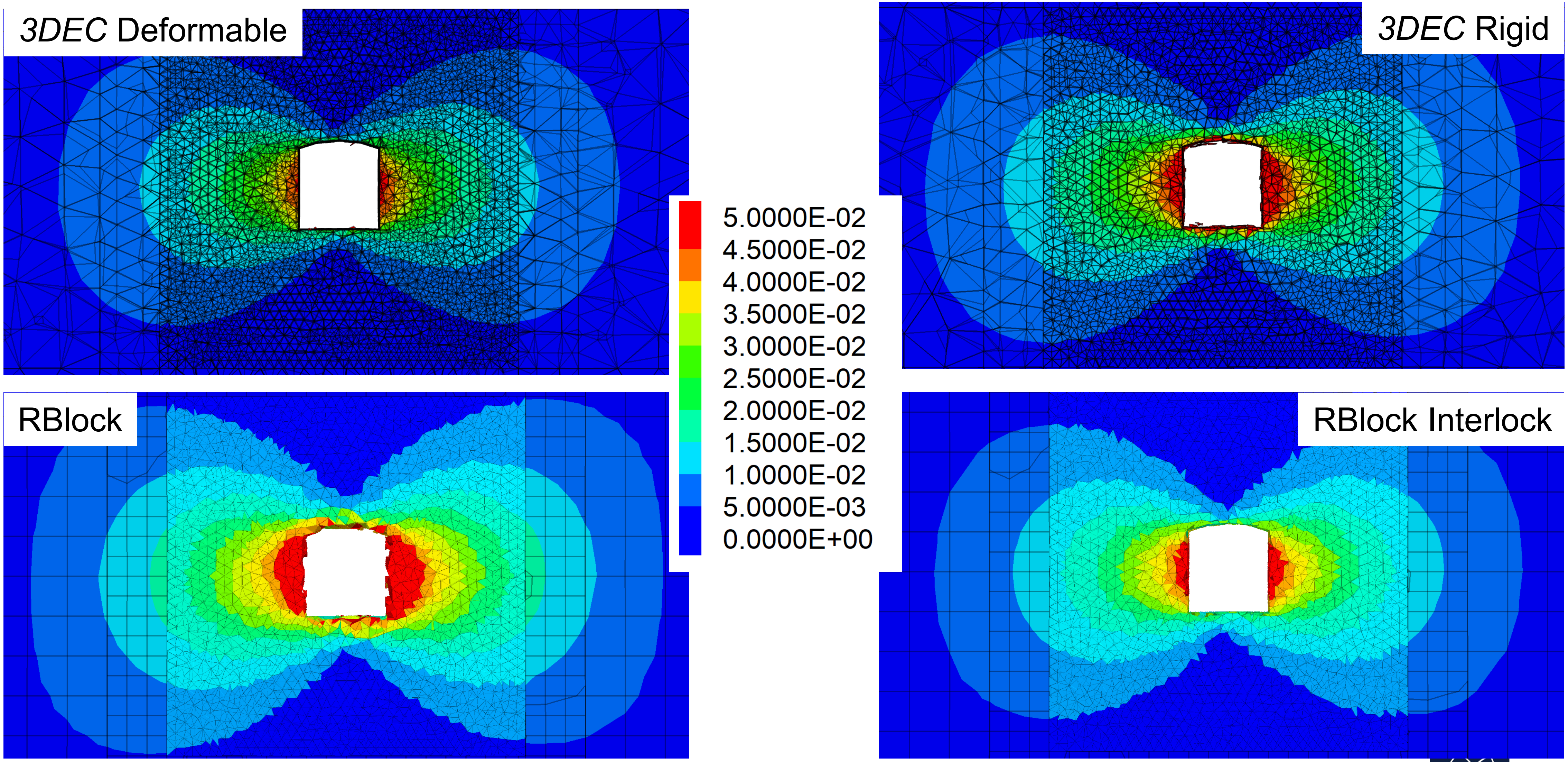
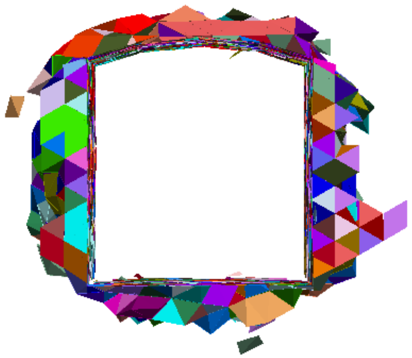
Displacements

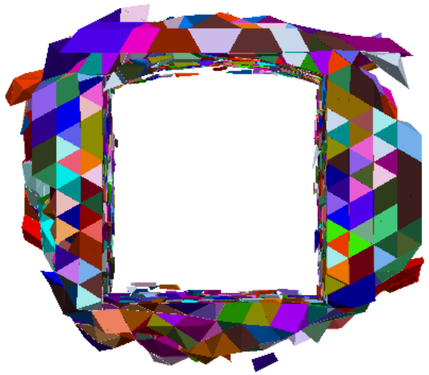


Fragments

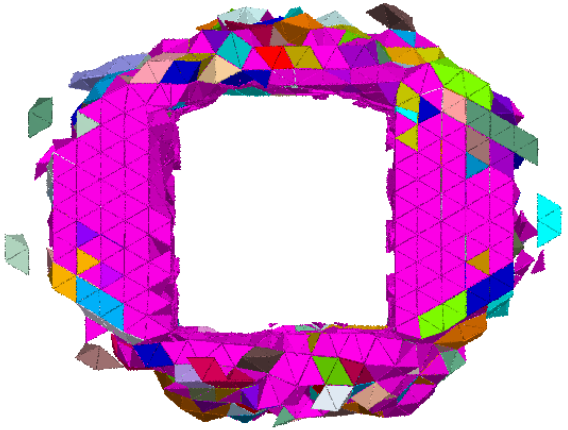
3DEC Deformable



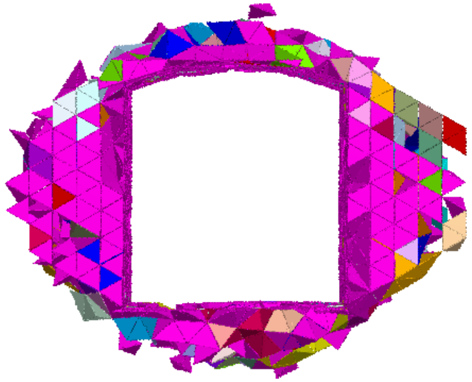
3DEC Rigid



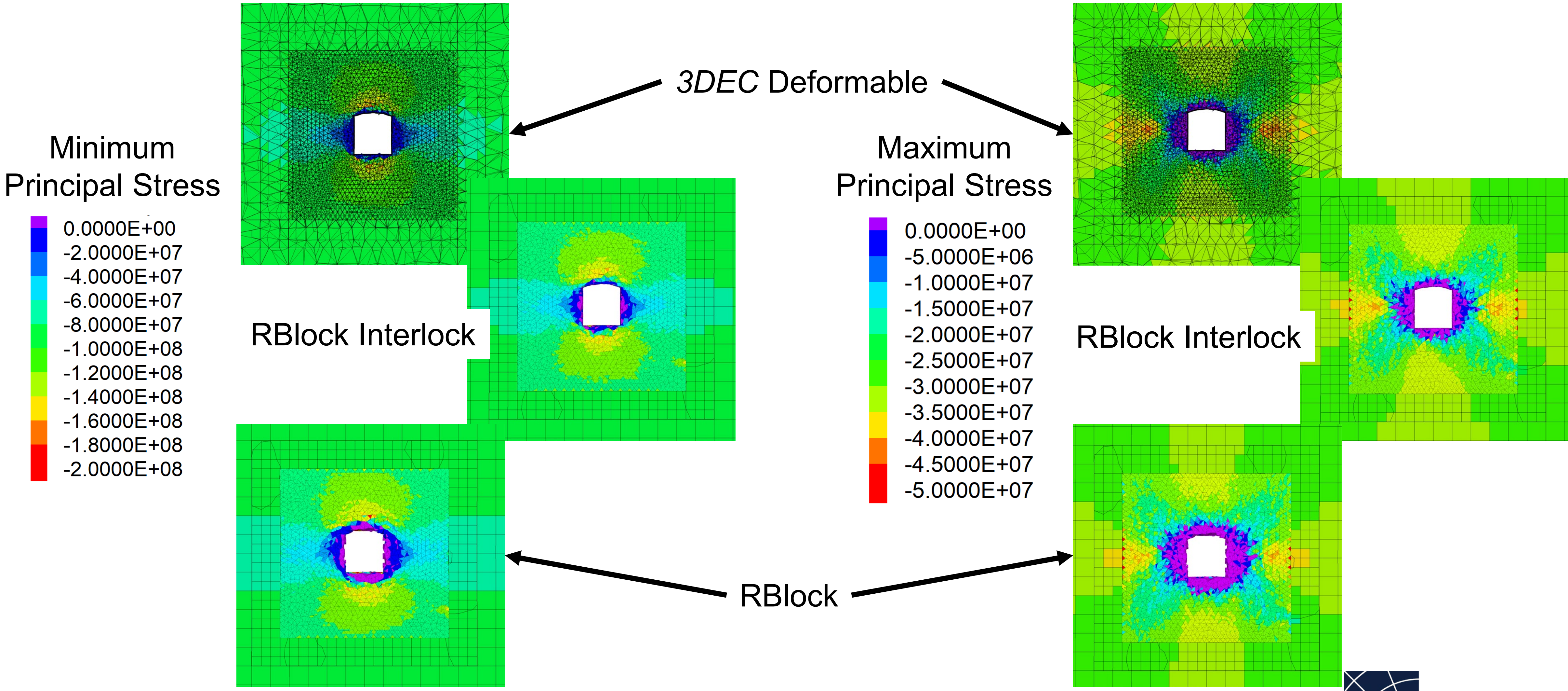
RBlock



RBlock Interlock



Min and Max Principal Stresses



Tunnel Runtime Comparison – i9 9900 K (8 core, 16 thread)

- Zonking time, 1% reduction each step, solve to average ratio 5e-5 at each step
  - RBlock with density scaling: 26 minutes (32,781 zonking cycles or ~ 4.8e-2 s/cycle or ~20 cycle/s)
  - RBlock interlock: 23 minutes (19,927 zonking cycles or ~ 6.9e-2 s/cycle or ~ 14 cycles/s)
  - *3DEC* deformable blocks: 146 minutes (20,664 zonking cycles or ~ 4.2e-01 s/cycle or ~ 2.4 cycles/s)
- *3DEC* rigid blocks – since mixed with deformable can't really compare solve time but 56 minutes for 10,000 cycles (~3.4e-01 s/cycle or ~2.9 cycles/s)

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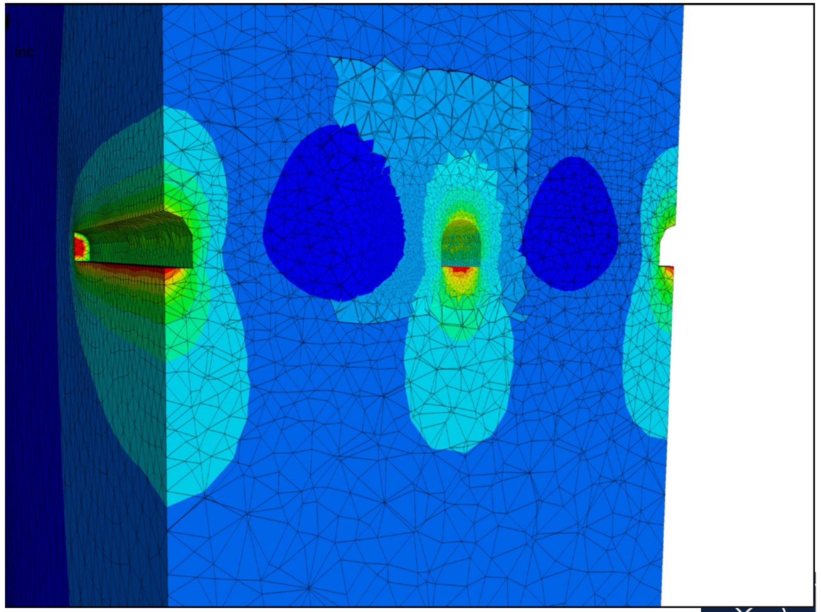
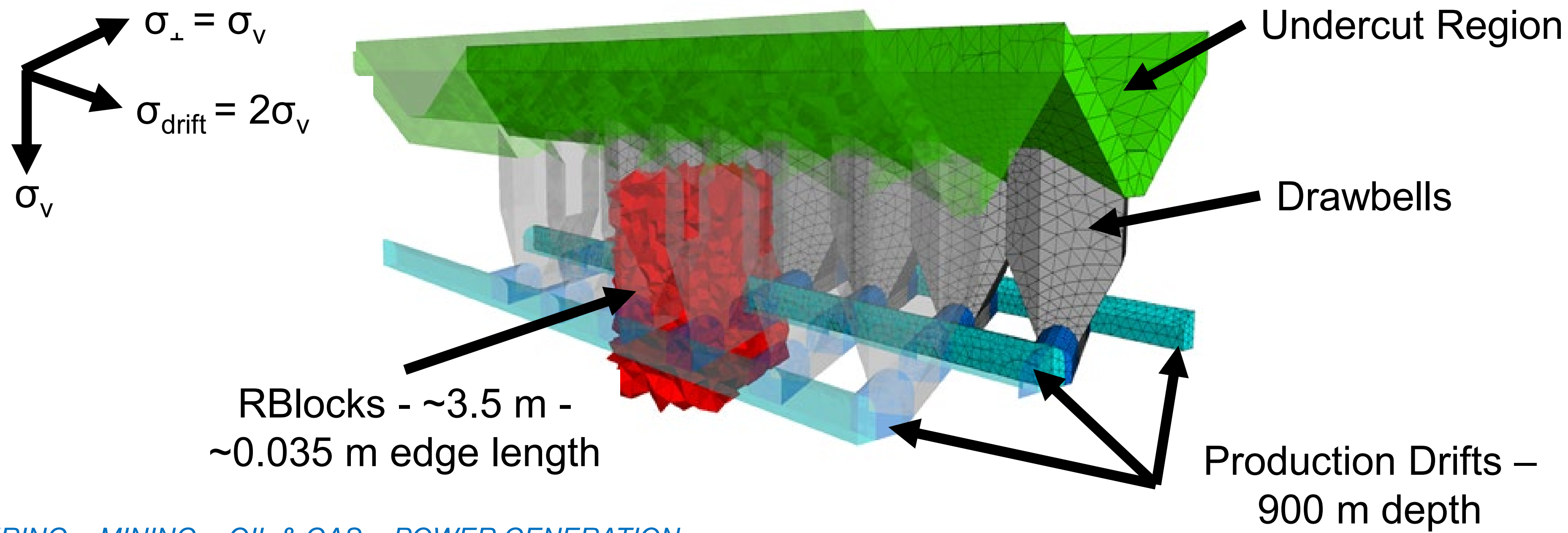


Mine-Scale Model of Block/Panel Cave Mining at Depth

- 14 GPa Young's modulus, 0.25 Poisson's ratio, 42.5 MPa UCS, 30 degree initial and residual friction angle
- The resulting model consists of ~261,000 rblocks, ~2,900 wall facets, ~528,000 active contacts, ~8,700,000 inhibited contacts, and ~656,000 zones
- Simulations do not have interlock nor contact activity if compressive forces remain



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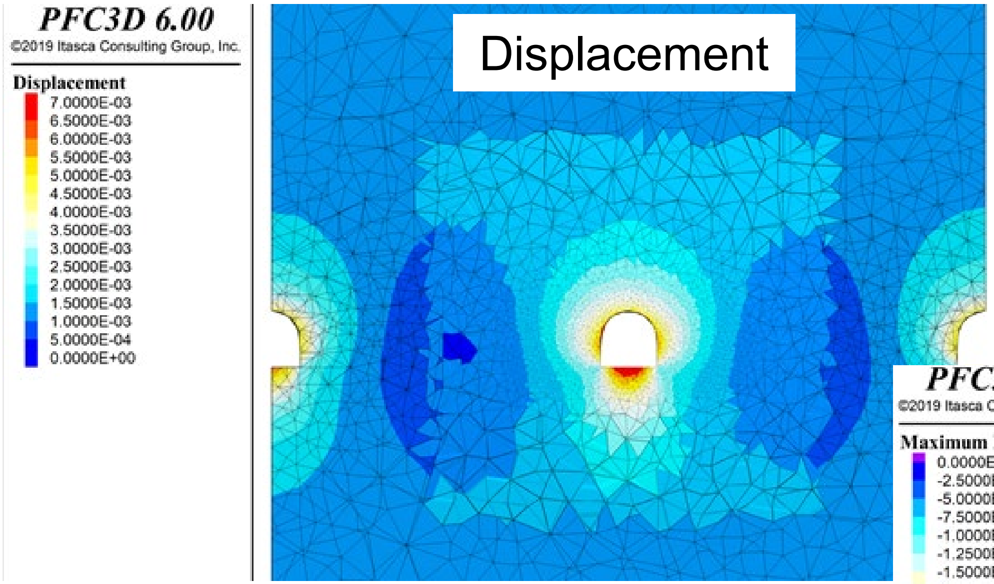
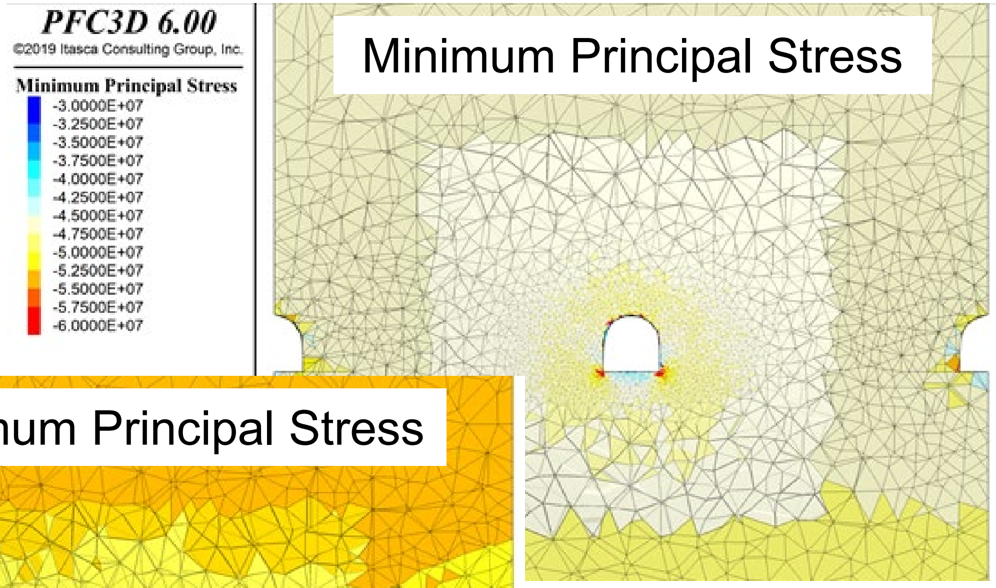
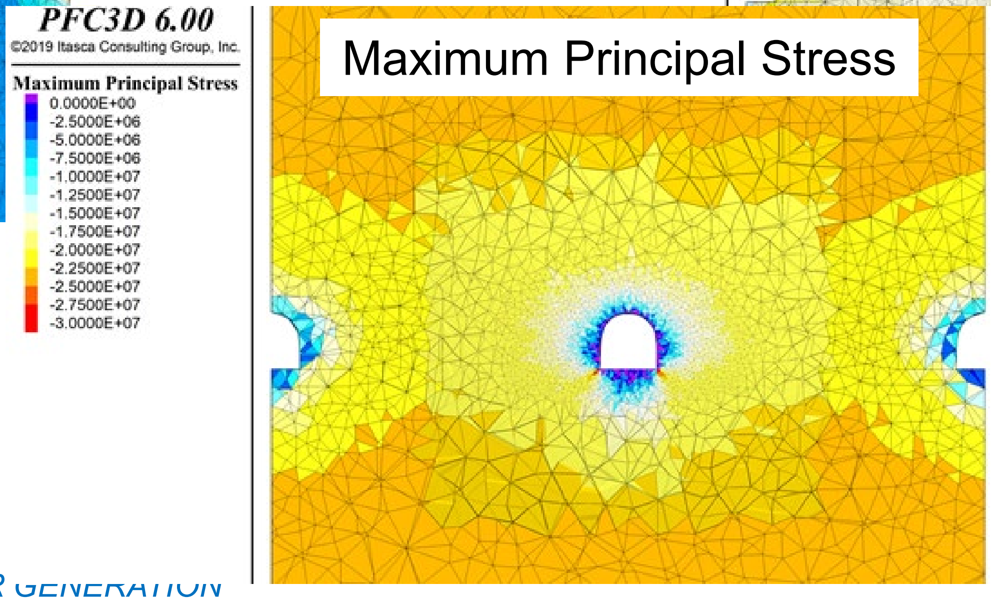
Drift Excavation

- Excavate the main production drifts
  - ❖ 0.5% reduction in support pressure per step, solving to average ratio 1e-5

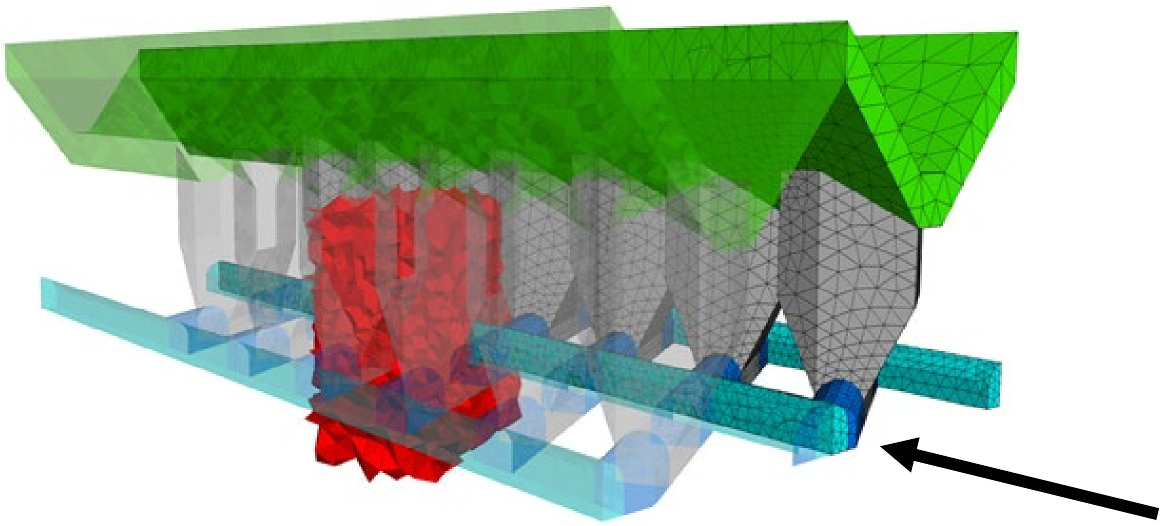






Approximate Caving via Bulking Algorithm

- Apply bulking algorithm to undercut region and then scheduled zones sequentially
  - Fix everything but scheduled zones, reducing zone stresses incrementally
  - Modify cavehoek model properties to simulate increase in porosity to 30%
  - Solve to average ratio of 1e-5 between reduction steps
  - Produce from front of model with ellipsoidal Isolated Movement Zones (IMZ's) above drawpoints based on a tonnage schedule



Production Direction Drifts – 900 m depth

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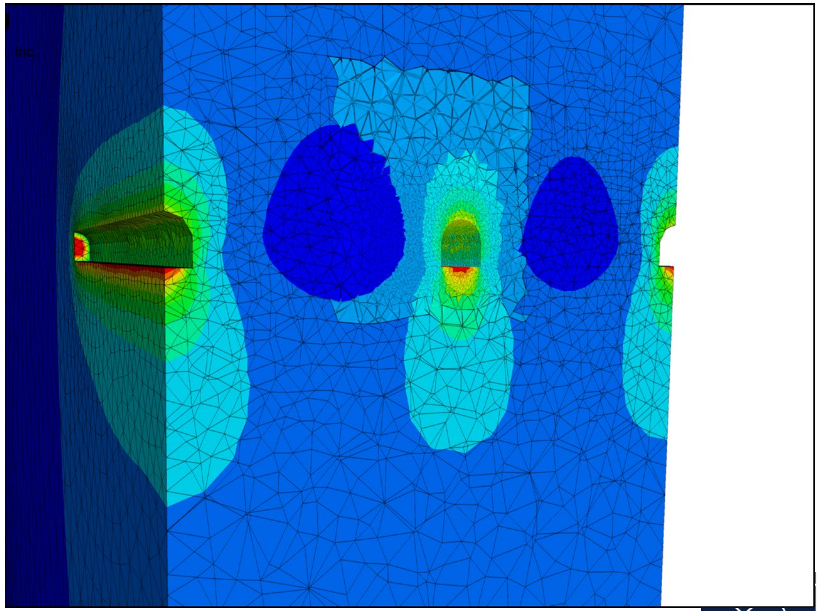
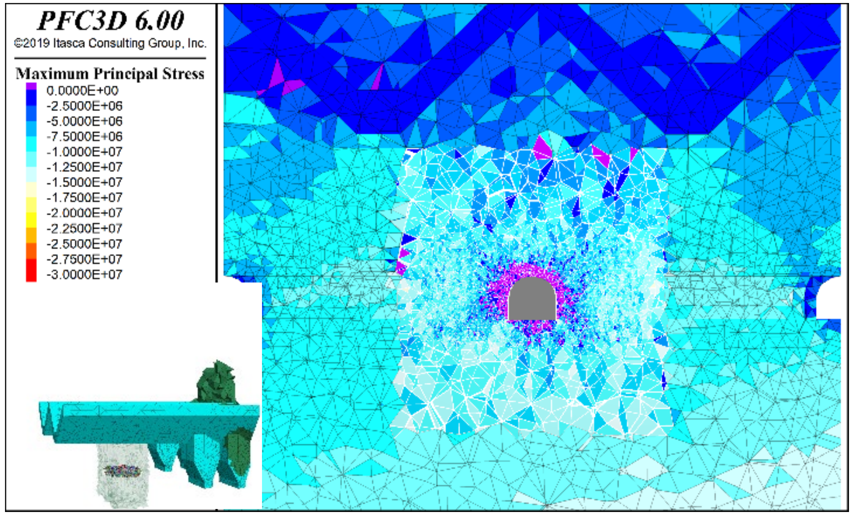
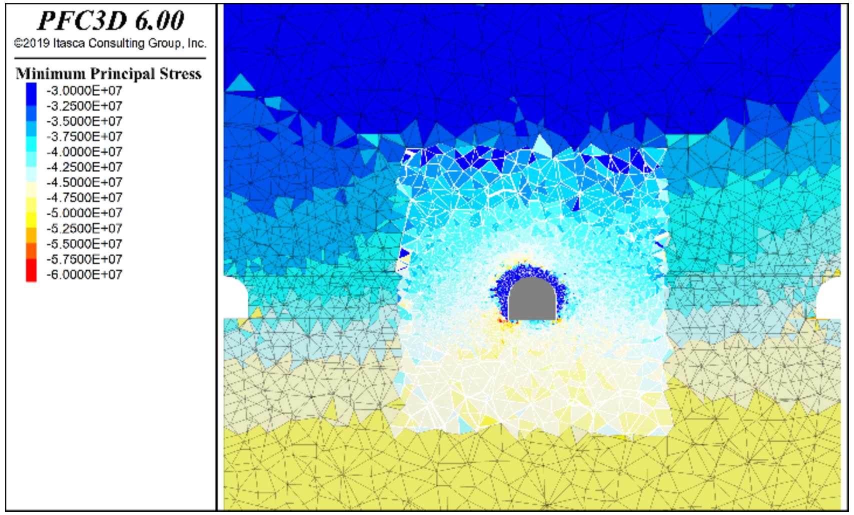


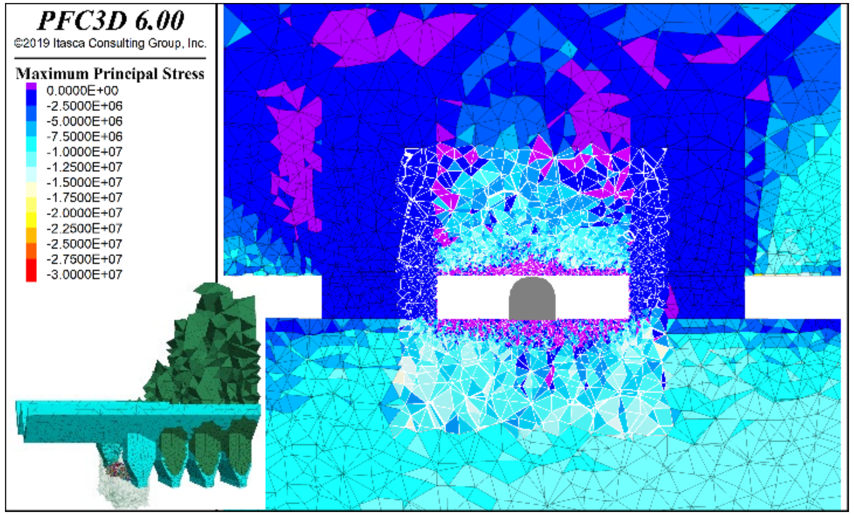
Production to RBlock Region

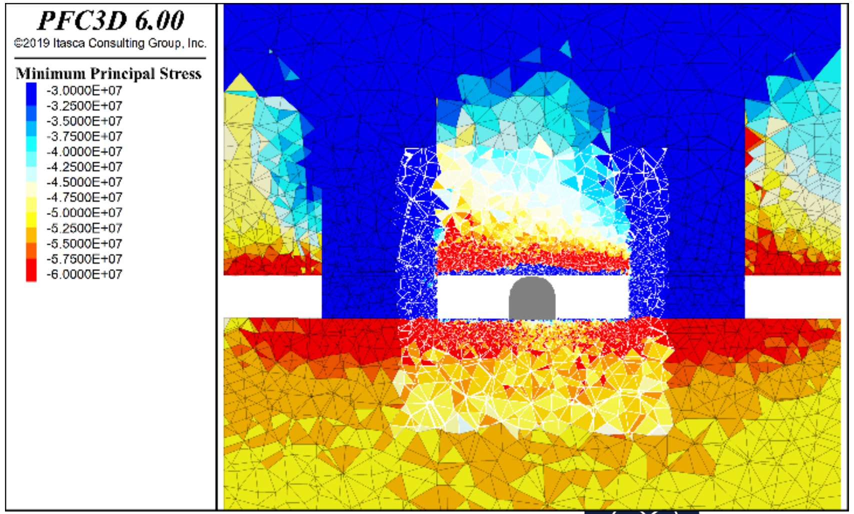
- ~3,000 fragments to ~1m from drift roof and walls
- Maximum principal stress from 20 to 10 MPa





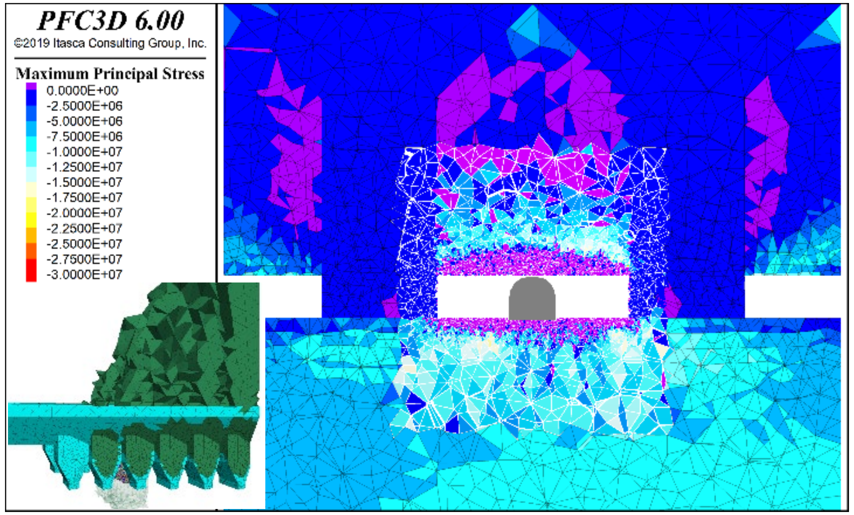
- ~5,500 fragments with added fragmentation around the exterior of the stub production drift

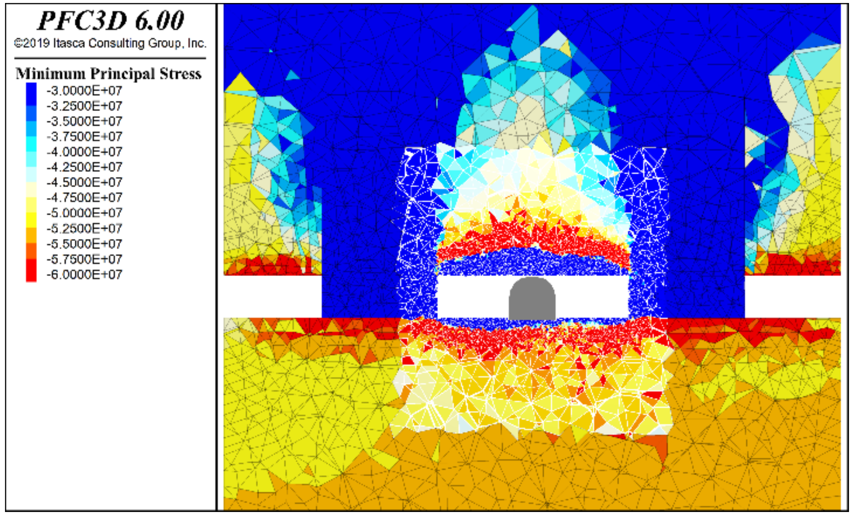




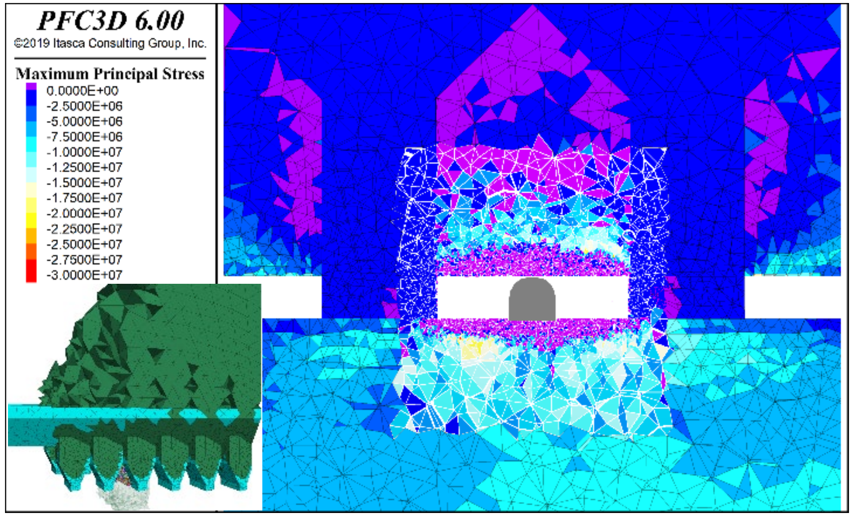
Production Past RBlock Region

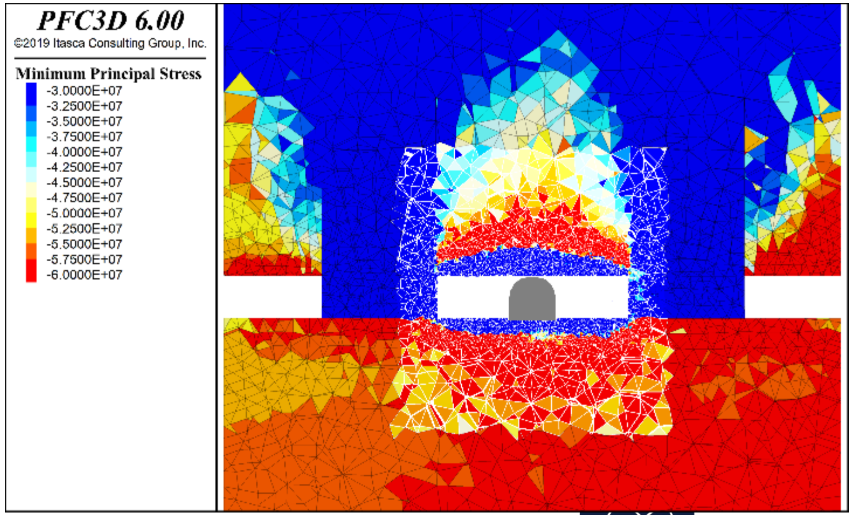
- Doubled fragments, roughly doubling volume of fragmented rock
- ~2 m above and ~0.5 m below





- ~13,000 fragments
- ~2.5 m above and ~1.0 m below





Conclusions

- *PFC* rblocks can be used for large-scale BBM simulations
- Large efficiency gain for BBM simulations using rblocks compared with *3DEC*
- Can couple with *FLAC3D* to provide stress boundaries and structural element support
- Need to think about moment accumulation, contact activity, and interlocking contacts
- Planned developments will make it easier to do BBM simulations, especially apply, face, reaction forces and zonking with commands