ITASCA Consulting Group, Inc.

A Flat-Jointed Bonded-Particle Model for Rock

David Potyondy

52nd U.S. Rock Mechanics/Geomechanics Symposium
(Seattle, WA, 17-20 June 2018)

Microstructural Physics of Intact Rock

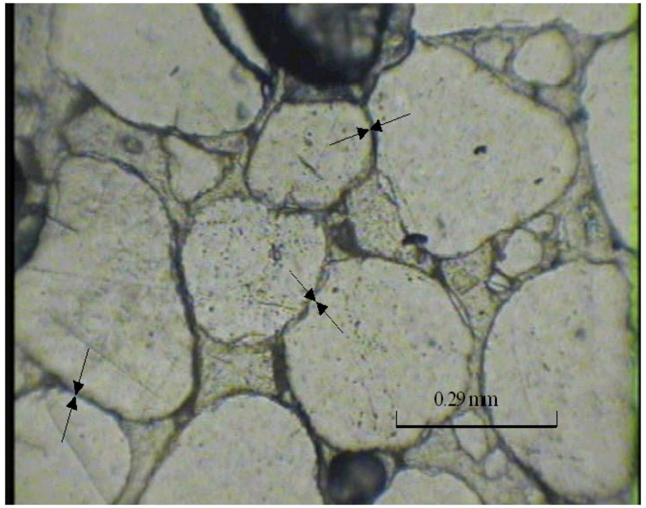
Intact rock can be viewed as an aggregate of crystals & amorphous particles joined by varying amounts of cementing materials.

Intact rock can be represented as…

Heterogeneous material comprised of cemented grains.

Much disorder in system:

grain size, shape & packing
grain & cement properties
degree of cementation
locked-in stresses



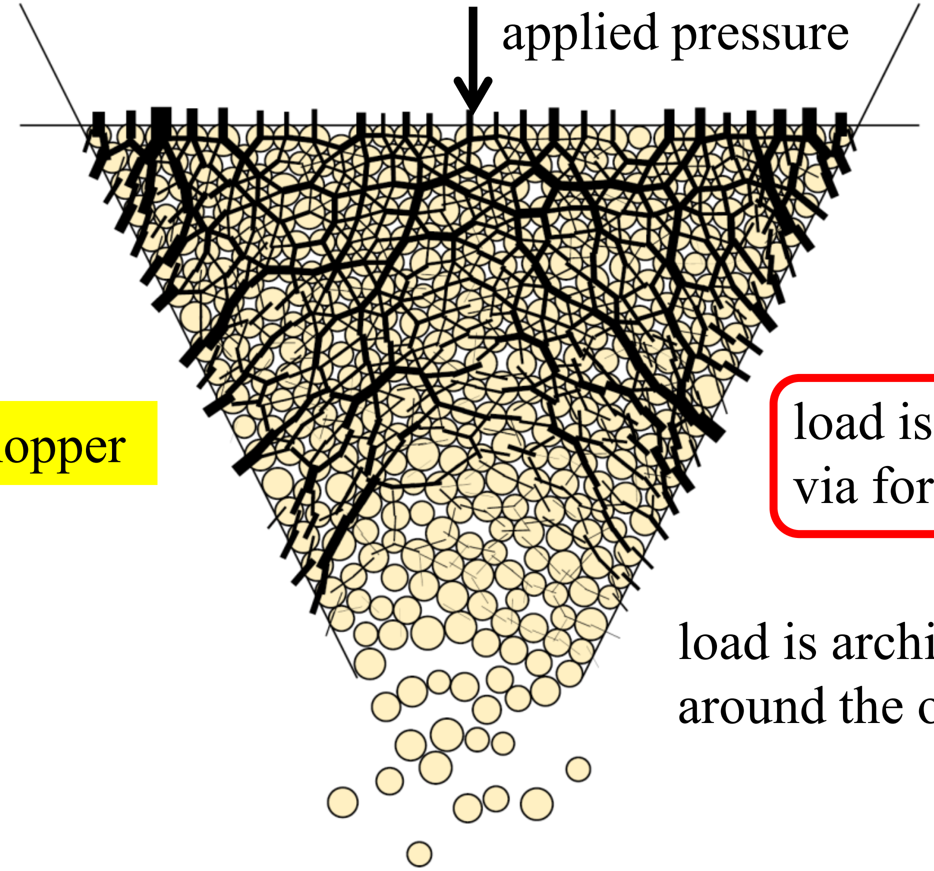
sandstone Dittes & Labuz (2002)

Each item influences mechanical behavior, and may evolve under load application.

Dittes, M., and J.F. Labuz (2002) "Field and Laboratory Testing of St. Peter Sandstone," *J. Geotech. Engr.*, ***128***(5), 372-380, May.

Essential Features of a BPM

Packed assembly of rigid grains joined by deformable and breakable cement.

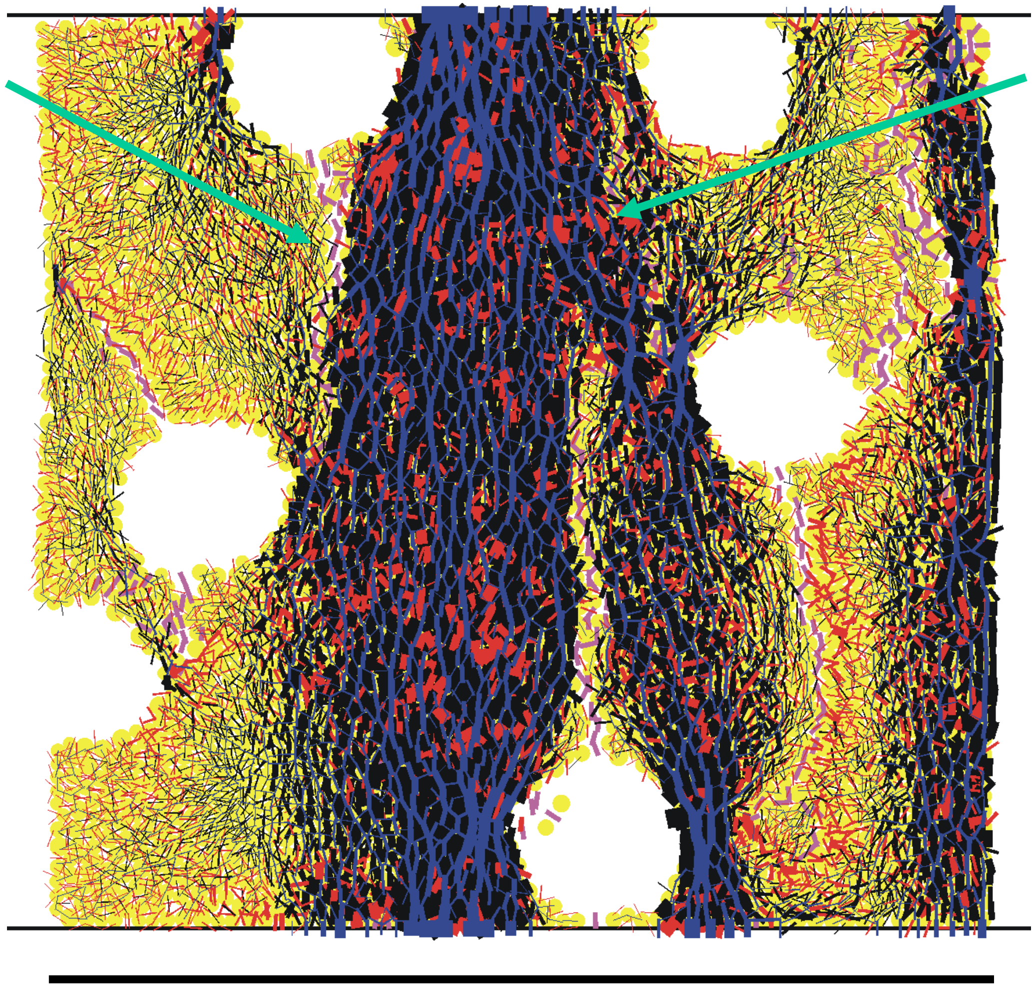


Flow from hopper

Simulate movement & interaction of grains via distinct-element method, which provides an explicit dynamic solution to Newton's laws of motion.

Essential Features of a BPM

broken bonds



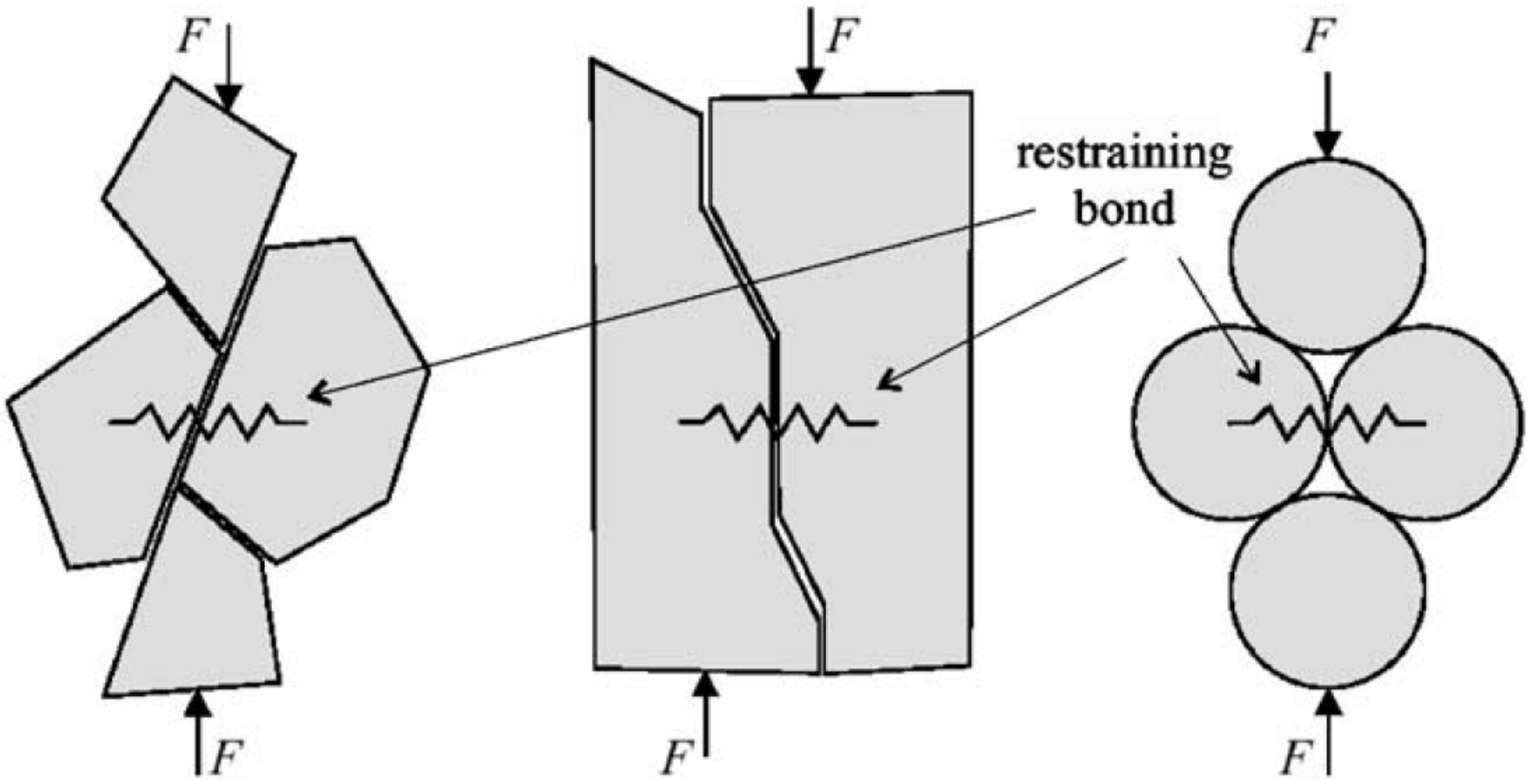
heterogeneous force transmission induces microtension

1 m (100 grains)

blue : compression between grains
black/red : compression/tension in cement

Packed assembly of rigid grains joined by deformable and breakable cement.

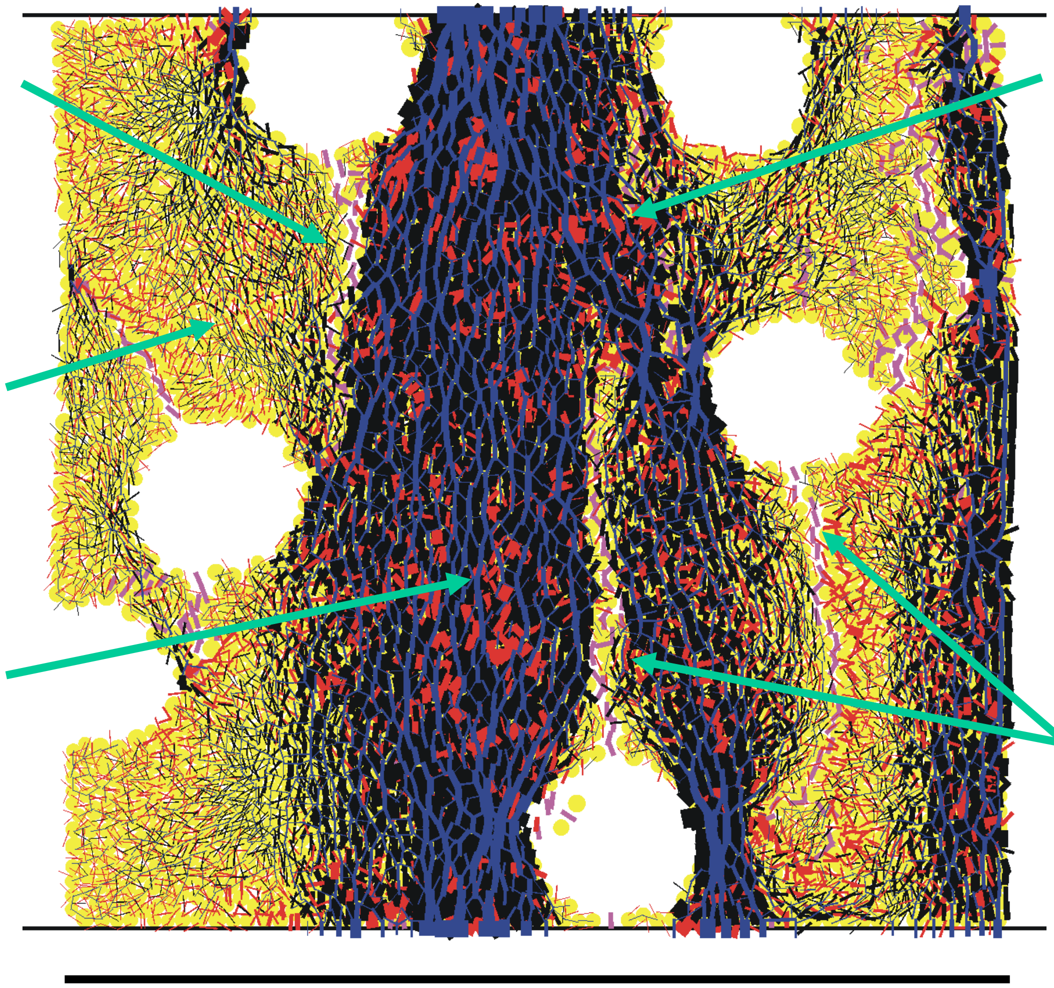
Essential Features of a BPM



Microstructural mechanisms in cemented granular material to induce microtension and bond breakage.

Essential Features of a BPM

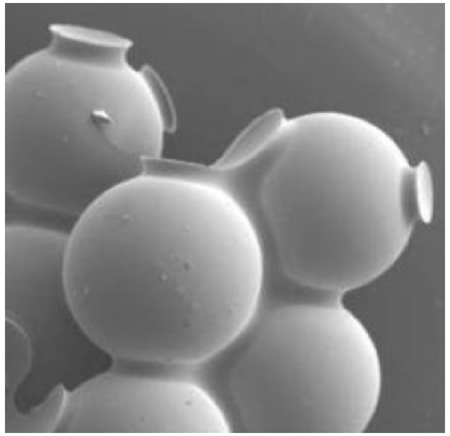
Packed assembly of rigid grains joined by deformable and breakable cement.

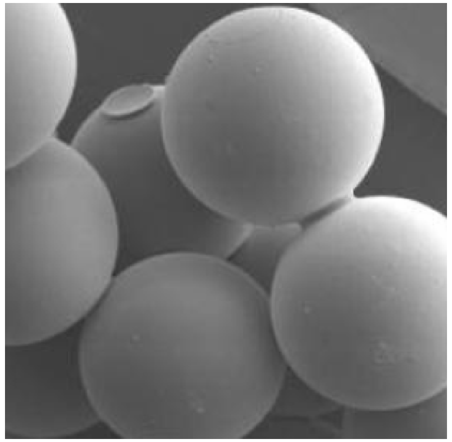


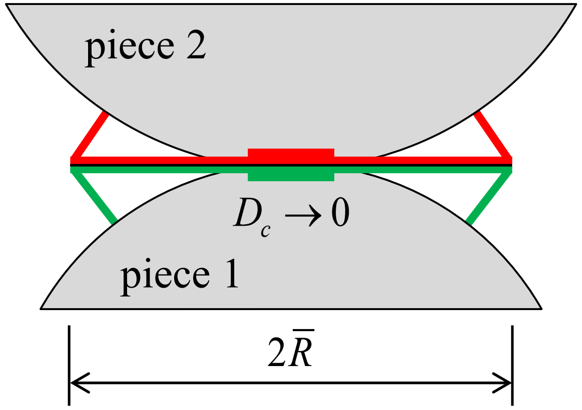
blue : compression between grains
black/red : compression/tension in cement

Parallel-bonded material (microstructure)

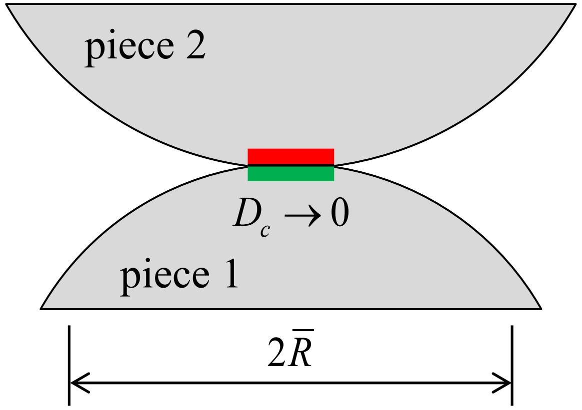
Glass beads
cemented with epoxy







bonded



unbonded

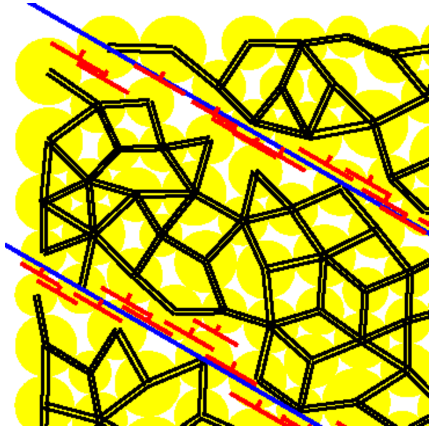
Bond breaks ➔ it is removed, no longer resists relative rotation.

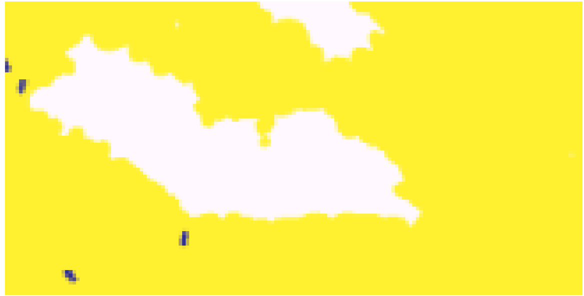
Holt et al. (2005) "Comparison Between Controlled Laboratory Experiments and Discrete Particle Simulations of the Mechanical Behaviour of Rock," *Int. J. Rock Mech. & Min. Sci.*, ***42***, 985-995.

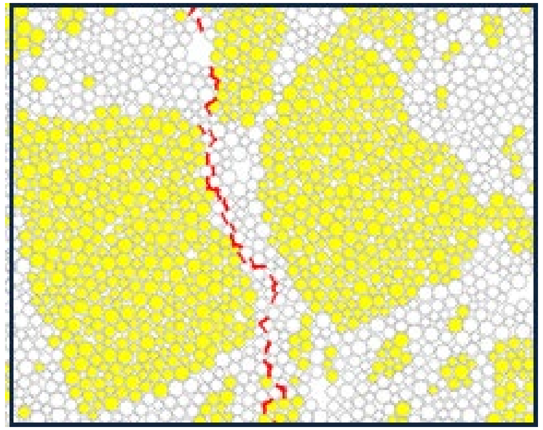
Microstructural Models Provided by BPM

Rich variety of models, described and classified

- base material itself (intact rock)
- overlay joints, voids & material regions







Provide wide range of rock behaviors that encompass

- compact & porous rock at both an intact and rock-mass scale

Potyondy, D.O. (2015) "The Bonded-Particle Model as a Tool for Rock Mechanics Research and Application: Current Trends and Future Directions," *Geosystem Engineering*, ***18**(1)*, 1–28.

Limitation (match uniaxial & tensile strengths)

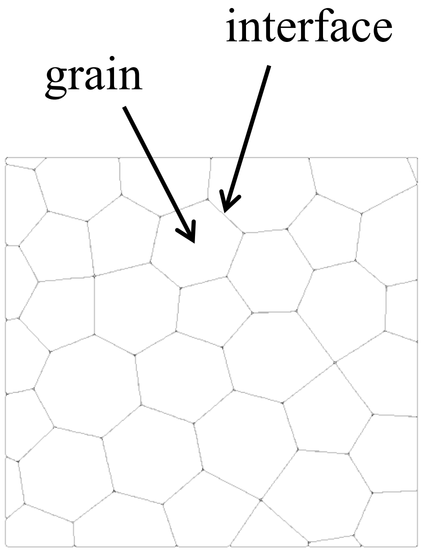
BPM of parallel-bonded disks or spheres cannot match both tensile and compressive strengths of typical compact rock.

This limitation is overcome by introducing intergranular interlock in the form of a well-connected grain structure with interfaces that are deformable, breakable and can sustain partial damage.

Partial interface damage with continued moment-resisting ability is an important microstructural feature of a BPM.

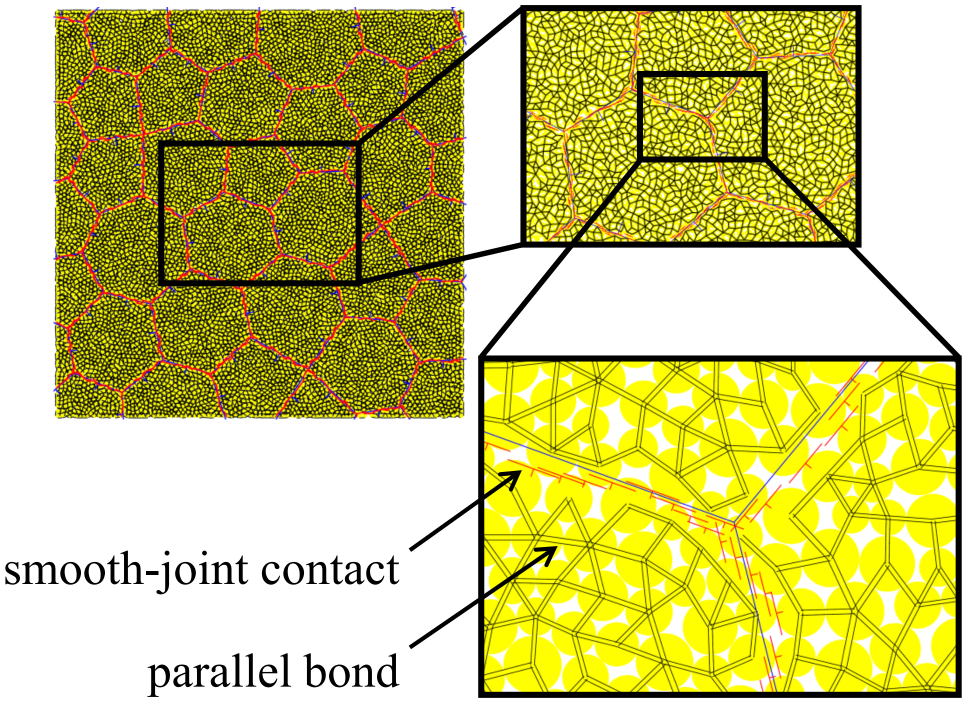
WHY?

Grain-based material (Matches strength ratio)



grain structure

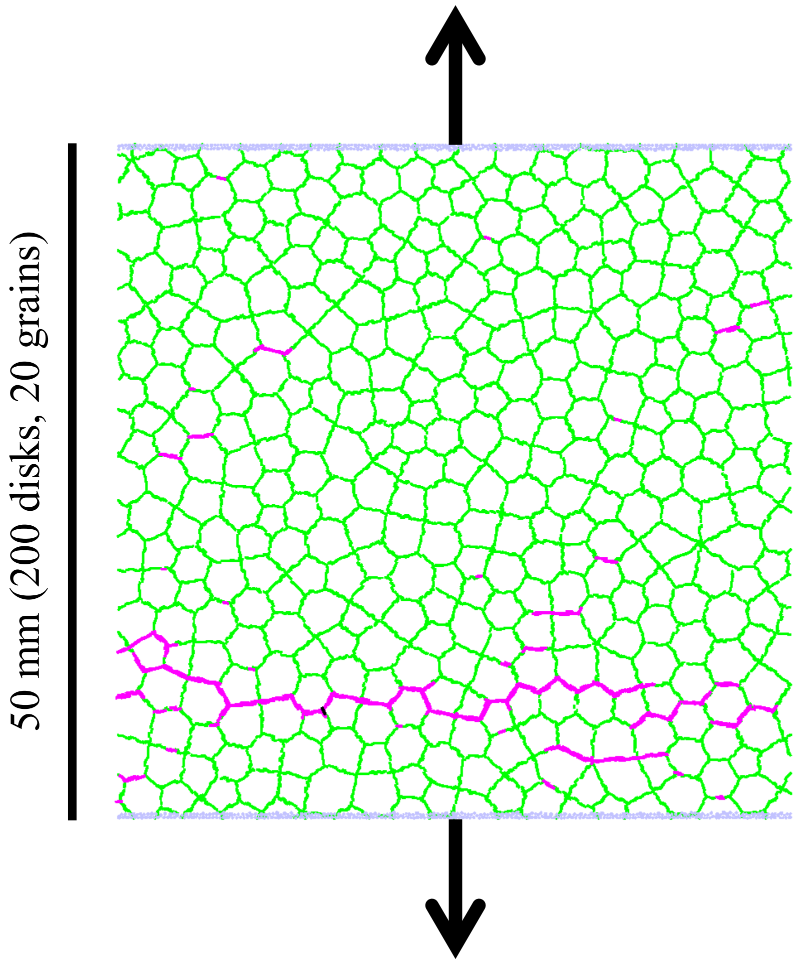
Grain Based Model (GBM)



GBMs are used to represent intact compact rock, allow partial interface damage and grain breakage.

Potyondy (2010) "A Grain-Based Model for Rock: Approaching the True Microstructure," in *Rock Mechanics in the Nordic Countries 2010*, pp. 225–234, C.C. Li, et al., Eds., ISBN: 978-82-8208-017-0, Kongsberg: Norwegian Group for Rock Mechanics.

Grain-based material (Matches strength ratio)



Failure consists of micro-tensile breakages.
➔ Can choose micro tensile strength to match sig_t.

Potyondy (2010) "A Grain-Based Model for Rock: Approaching the True Microstructure," in *Rock Mechanics in the Nordic Countries 2010*, pp. 225–234, C.C. Li, et al., Eds., ISBN: 978-82-8208-017-0, Kongsberg: Norwegian Group for Rock Mechanics.

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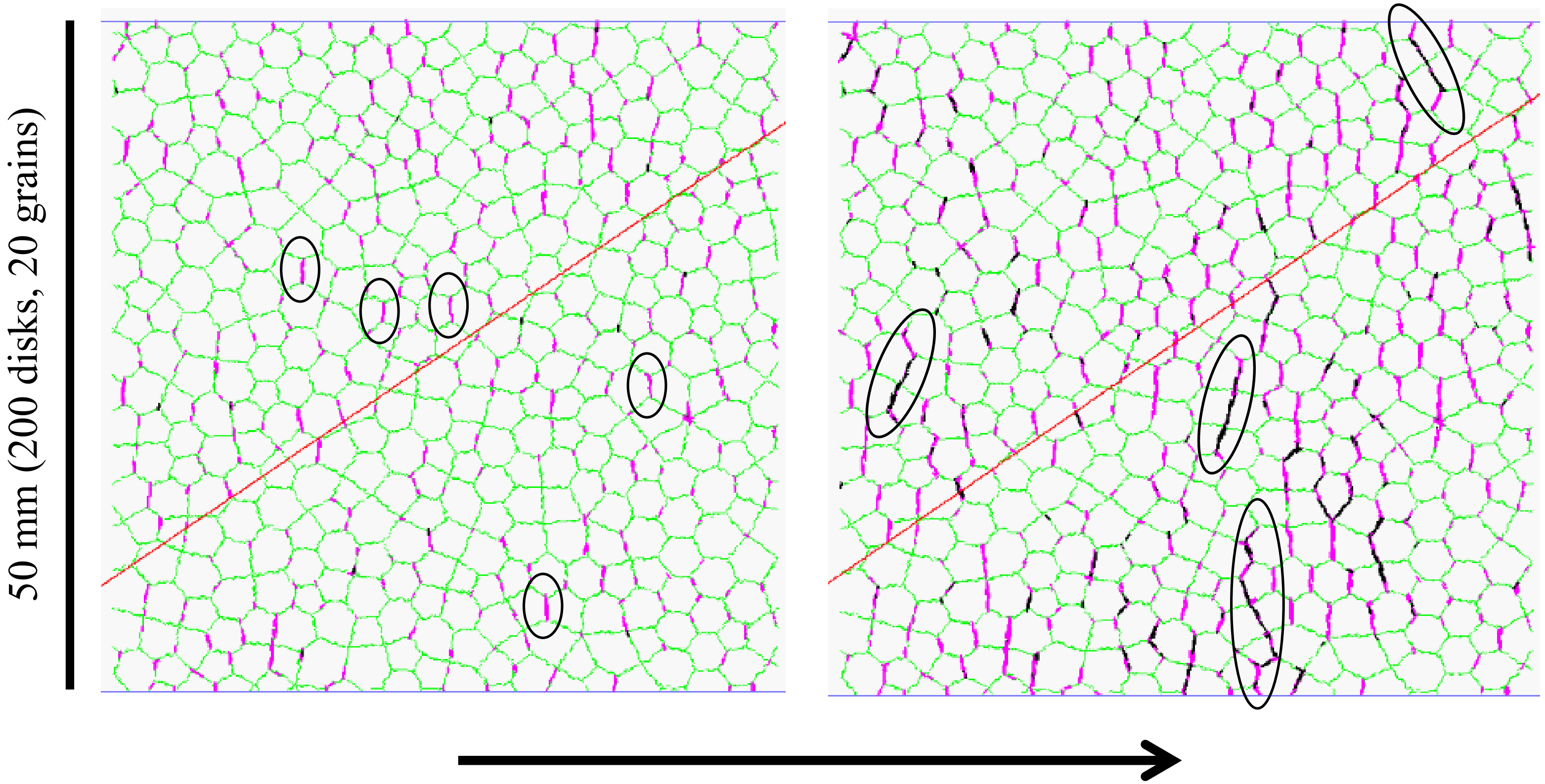
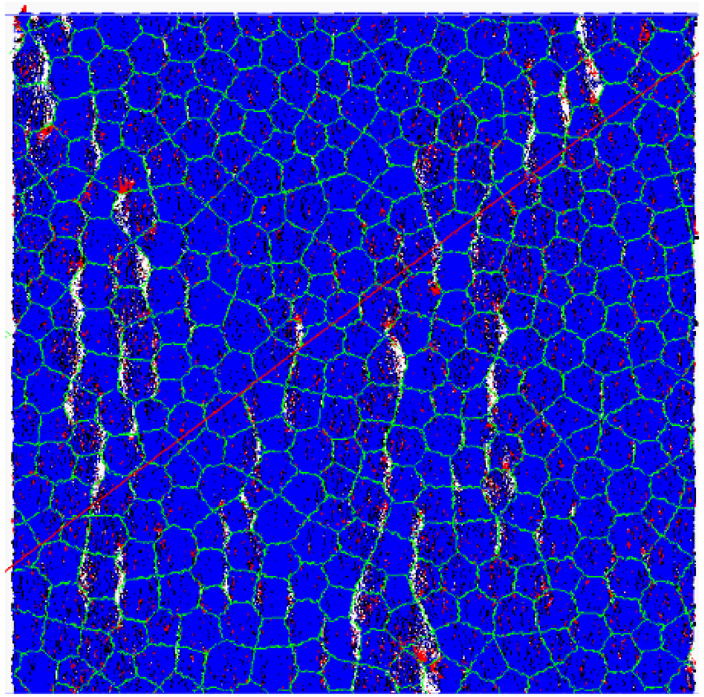


axial splitting

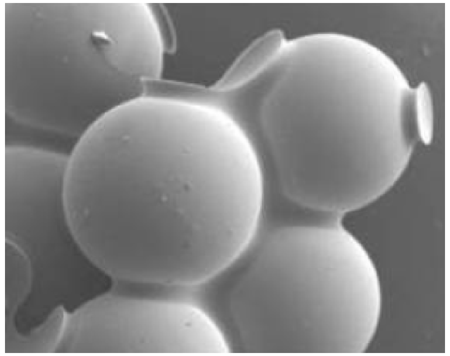


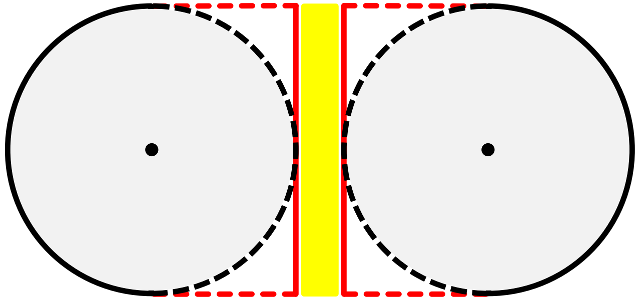
Failure at peak load coincides with a few micro-shear breakages.
➔ Can choose shear strength to match UCS.

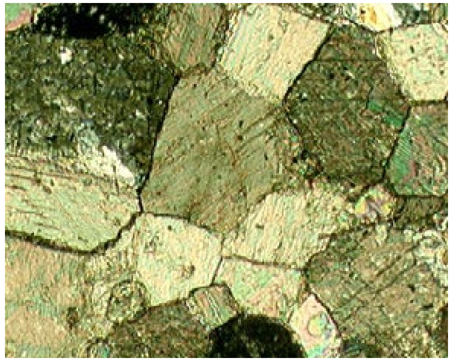
Potyondy (2010) "A Grain-Based Model for Rock: Approaching the True Microstructure," in *Rock Mechanics in the Nordic Countries 2010*, pp. 225–234, C.C. Li, et al., Eds., ISBN: 978-82-8208-017-0, Kongsberg: Norwegian Group for Rock Mechanics.

Flat-jointed material (Differs from parallel bond)

intact parallel bond



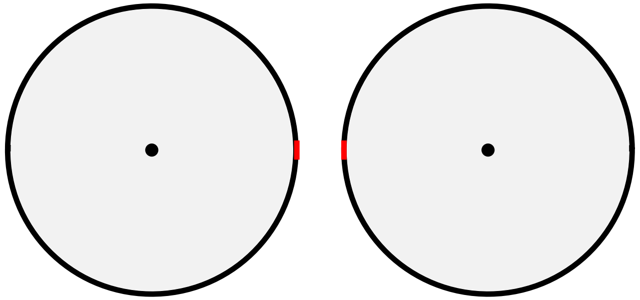


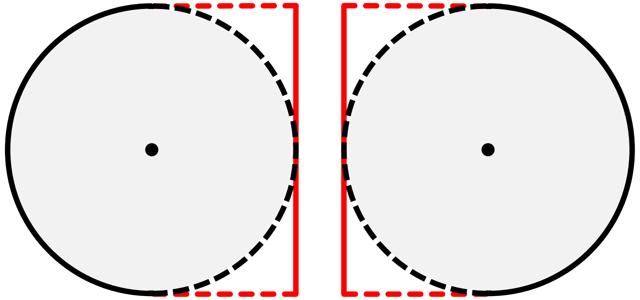


bonded finite-length interface

broken parallel bond

fully broken flat joint



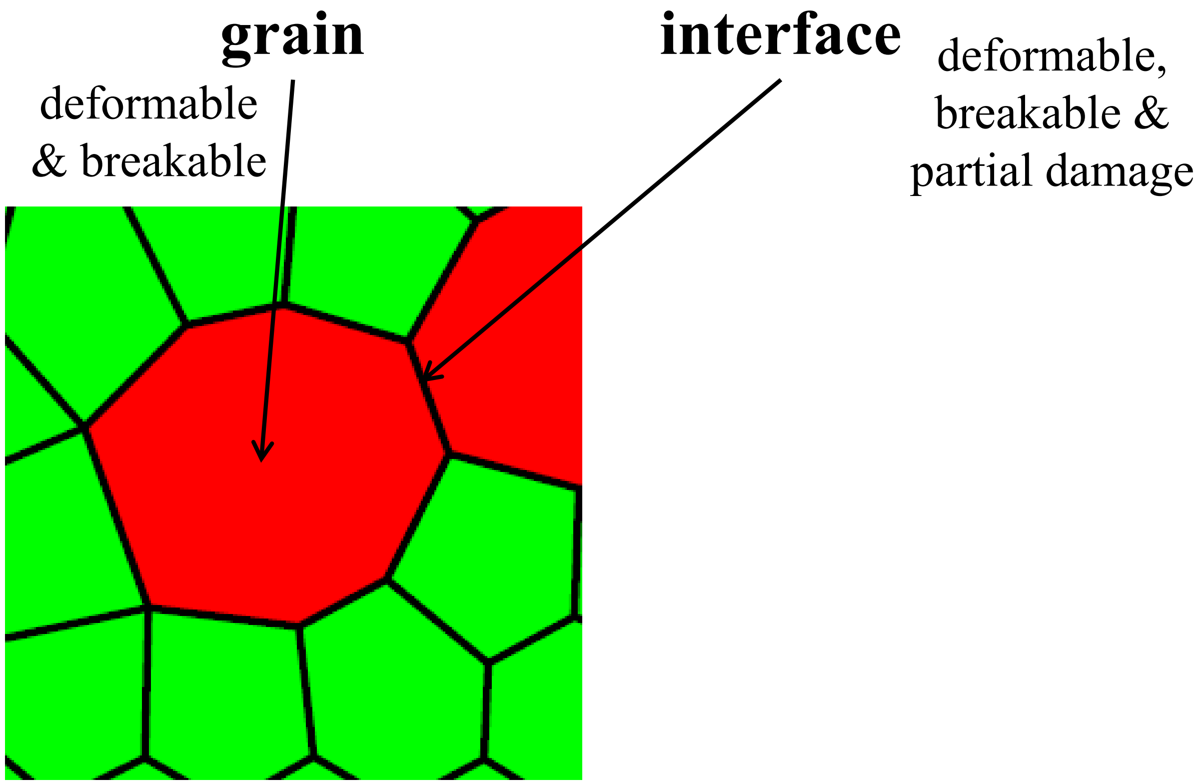


frictional zero-length interface

frictional finite-length interface

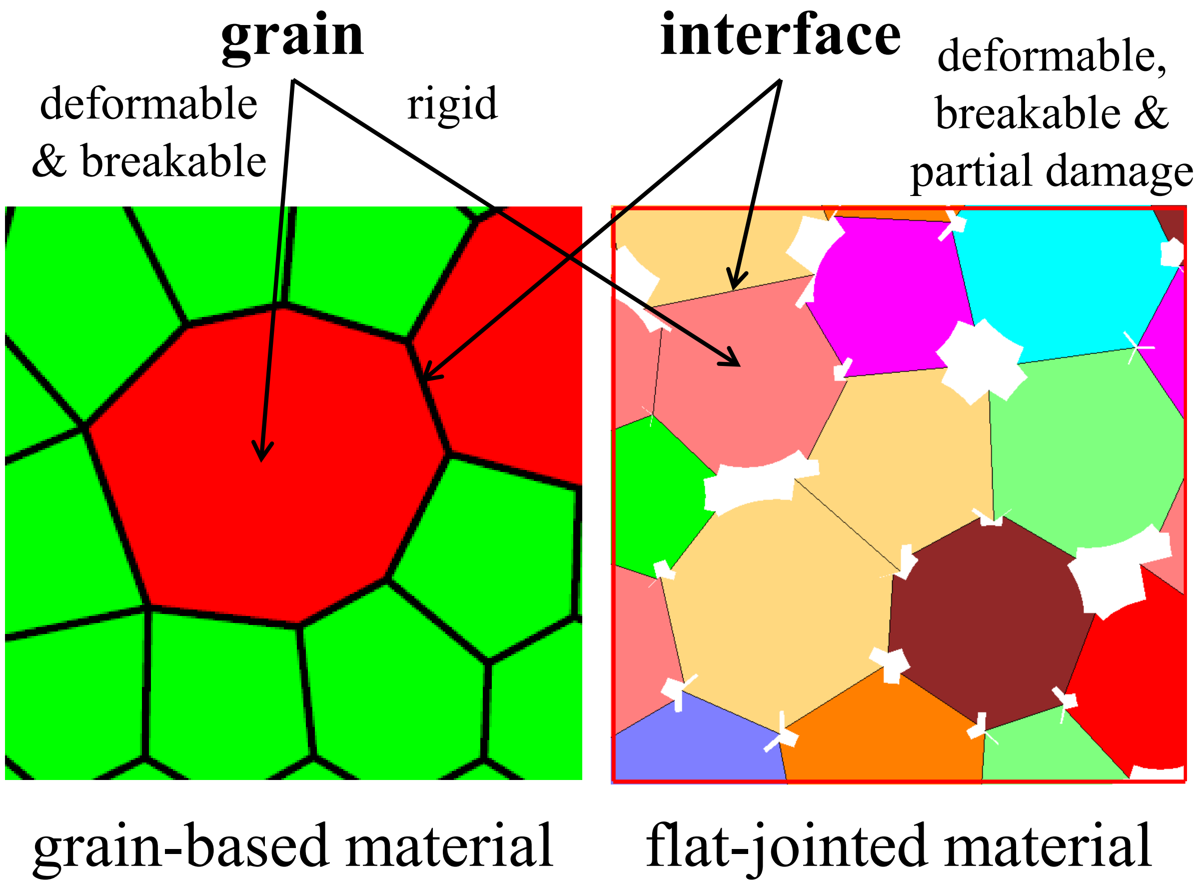
Bandini et al. (2012) "Effects of Intra-Crystalline Microcracks on the Mechanical Behavior of a Marble Under Indentation," *Int. J. Rock Mech. & Min. Sci.*, ***54***, 47-55.

Two Materials (match uniaxial & tensile strengths)



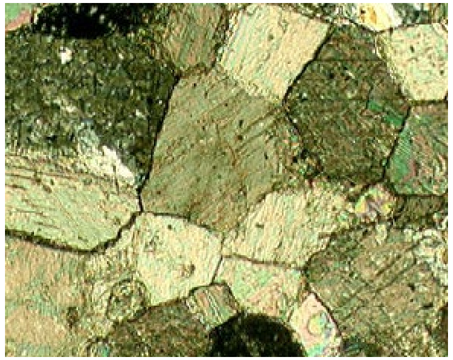
grain-based material

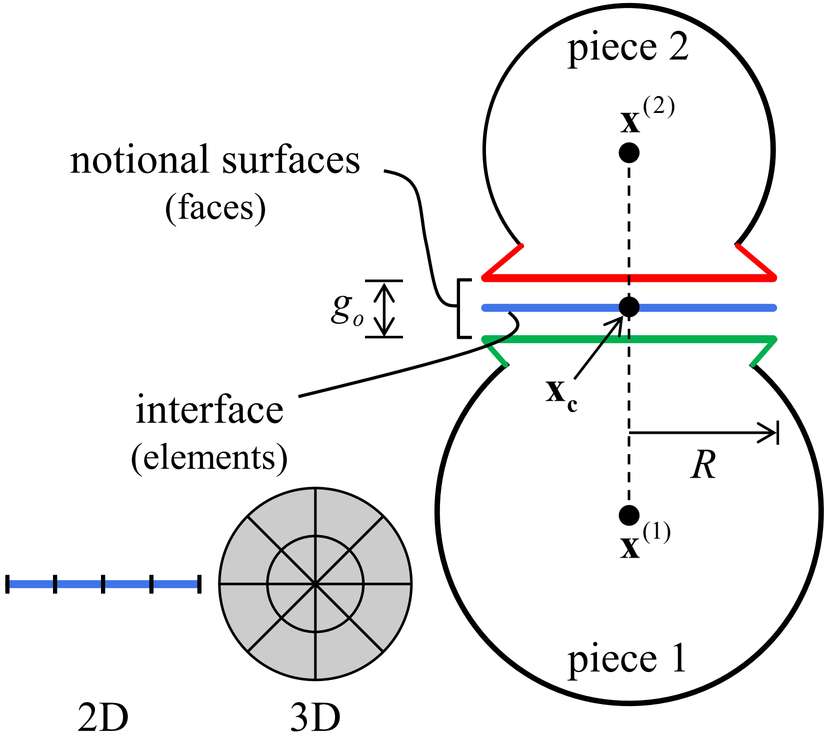
Two Materials (match uniaxial & tensile strengths)



Flat-jointed material (microstructure)

Marble with angular, interlocked grains



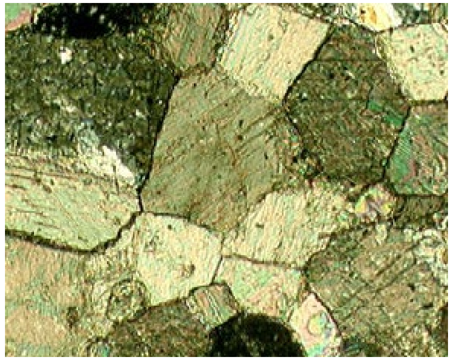


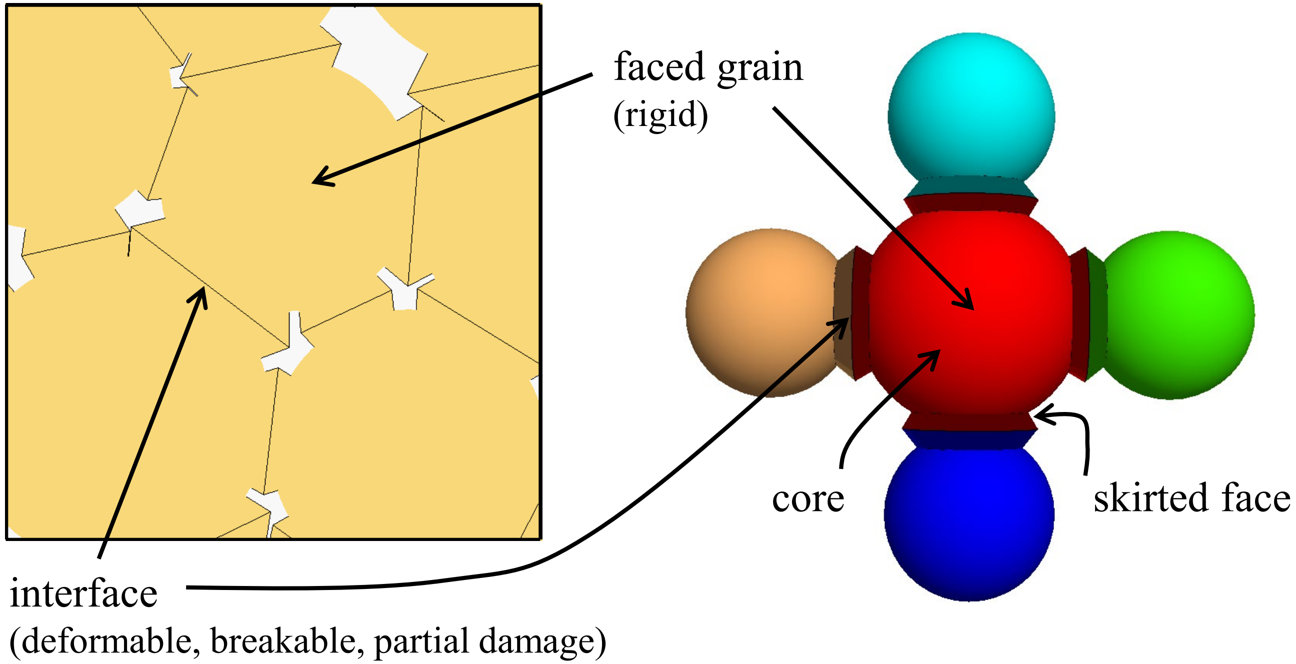
flat-joint contact

Each interface is discretized into elements that may be initially bonded, after breakage they are frictional.

Flat-jointed material (microstructure)

Marble with angular, interlocked grains

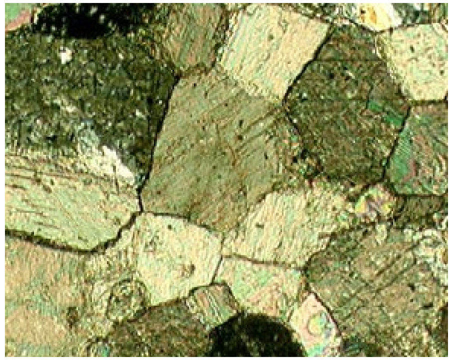




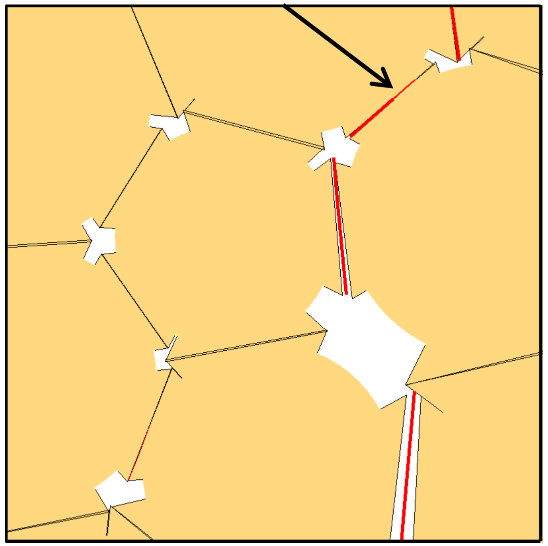
flat-jointed material consists of faced grains

Flat-jointed material (microstructure)

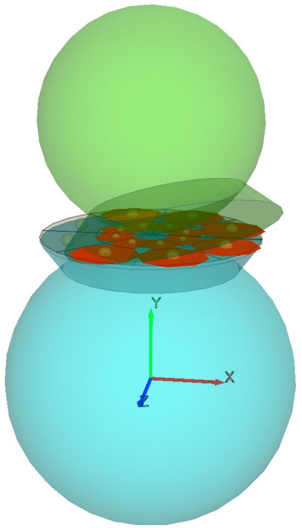
Marble with angular, interlocked grains



Bending failure with 3 of the 4 elements cracked.

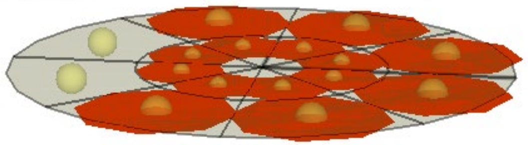


Crack thickness is proportional to gap.



14 of the 16 elements cracked.

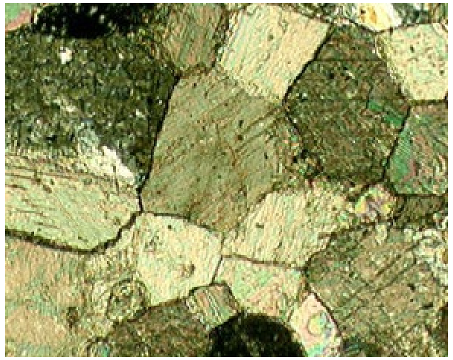
interface with cracks

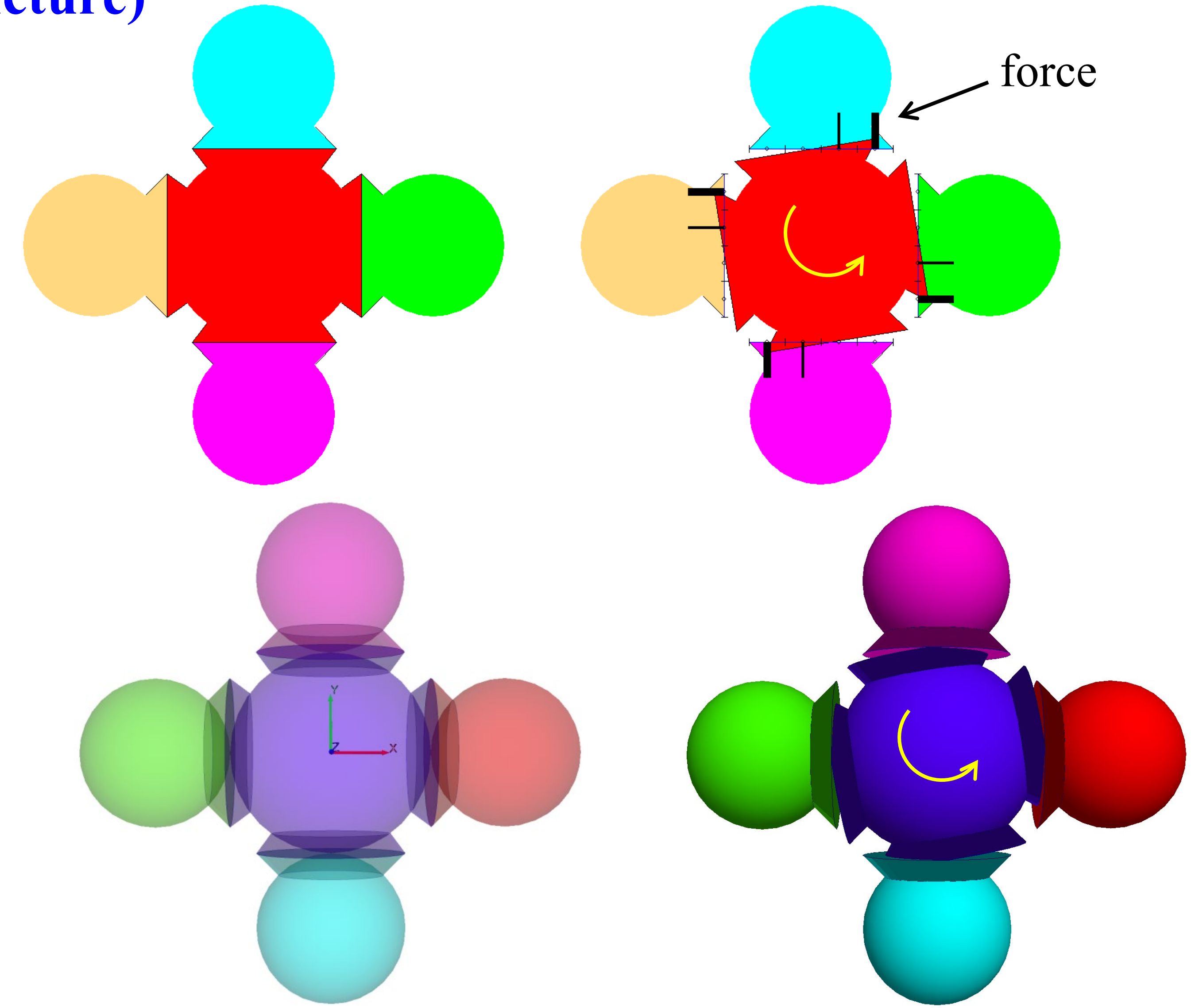


The interface can sustain partial damage.

Flat-jointed material (microstructure)

Marble with angular, interlocked grains



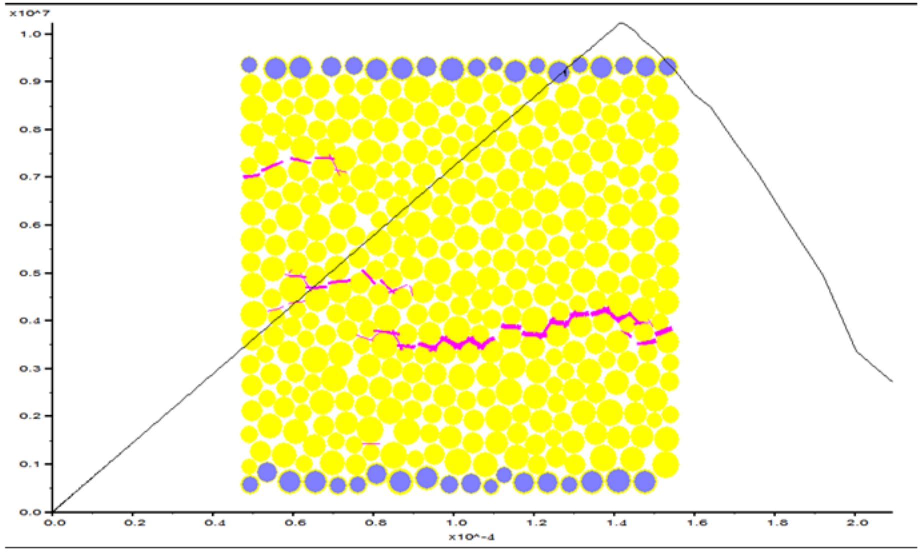


Even a fully broken interface continues to resist relative rotation.

Flat-jointed material (Matches strength ratio)

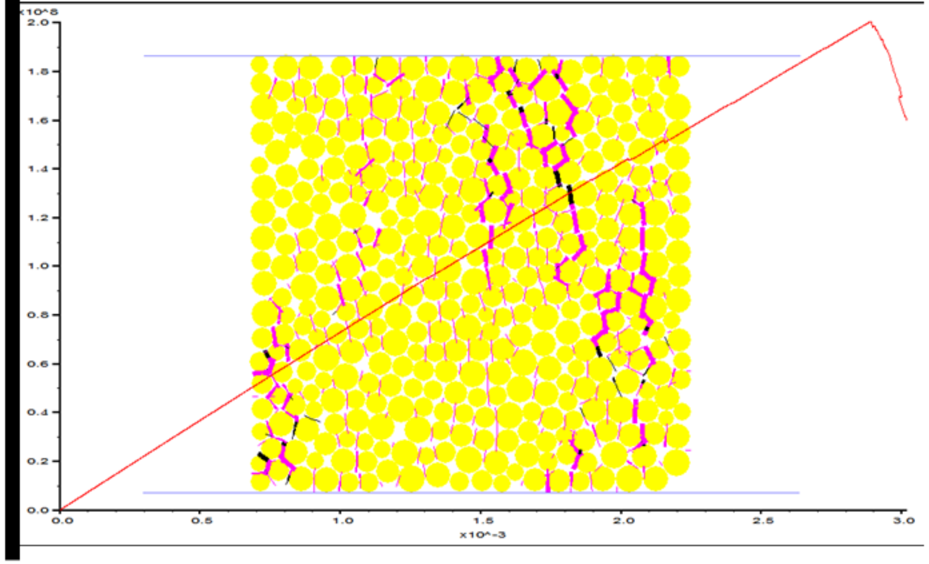
We can construct a 2D flat-jointed material that provides a reasonable match to the laboratory-test response (direct tension, unconfined & confined compression) of Äspö diorite.

$\sigma_t = 10.2$ MPa



direct-tension test

$q_u = 201$ MPa

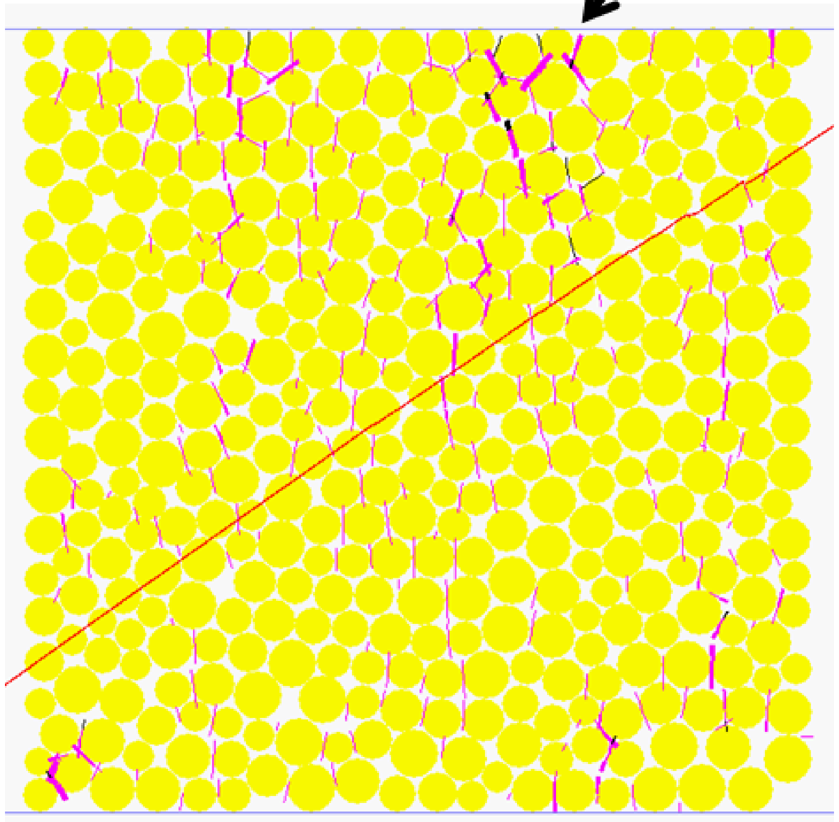


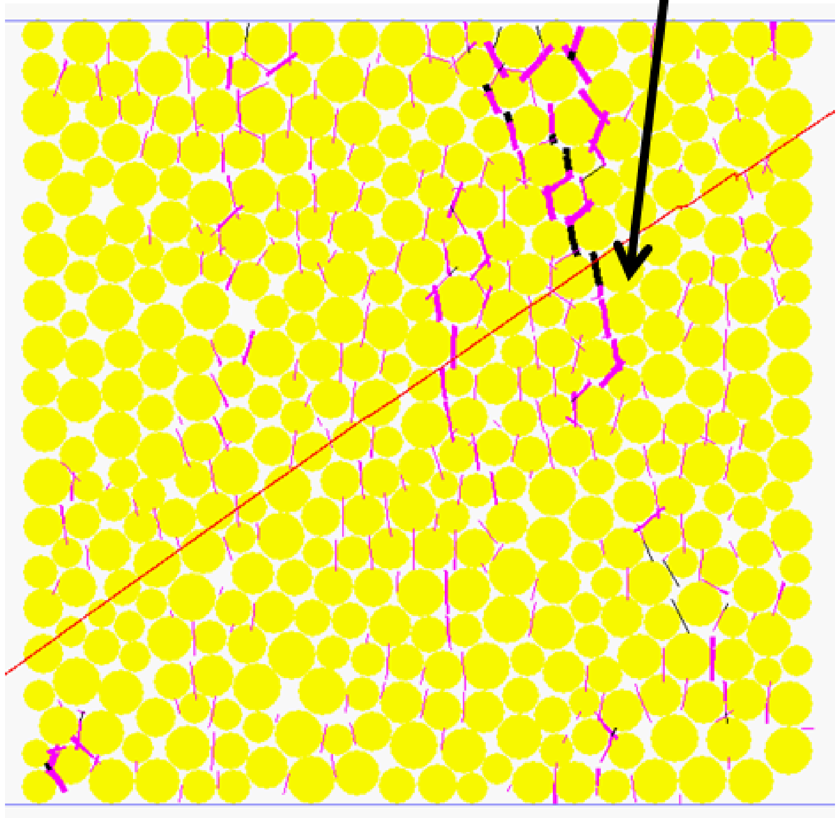
UCS test

Failure consists of micro-tensile breakages.

➔ Can choose micro tensile strength to match sig_t.

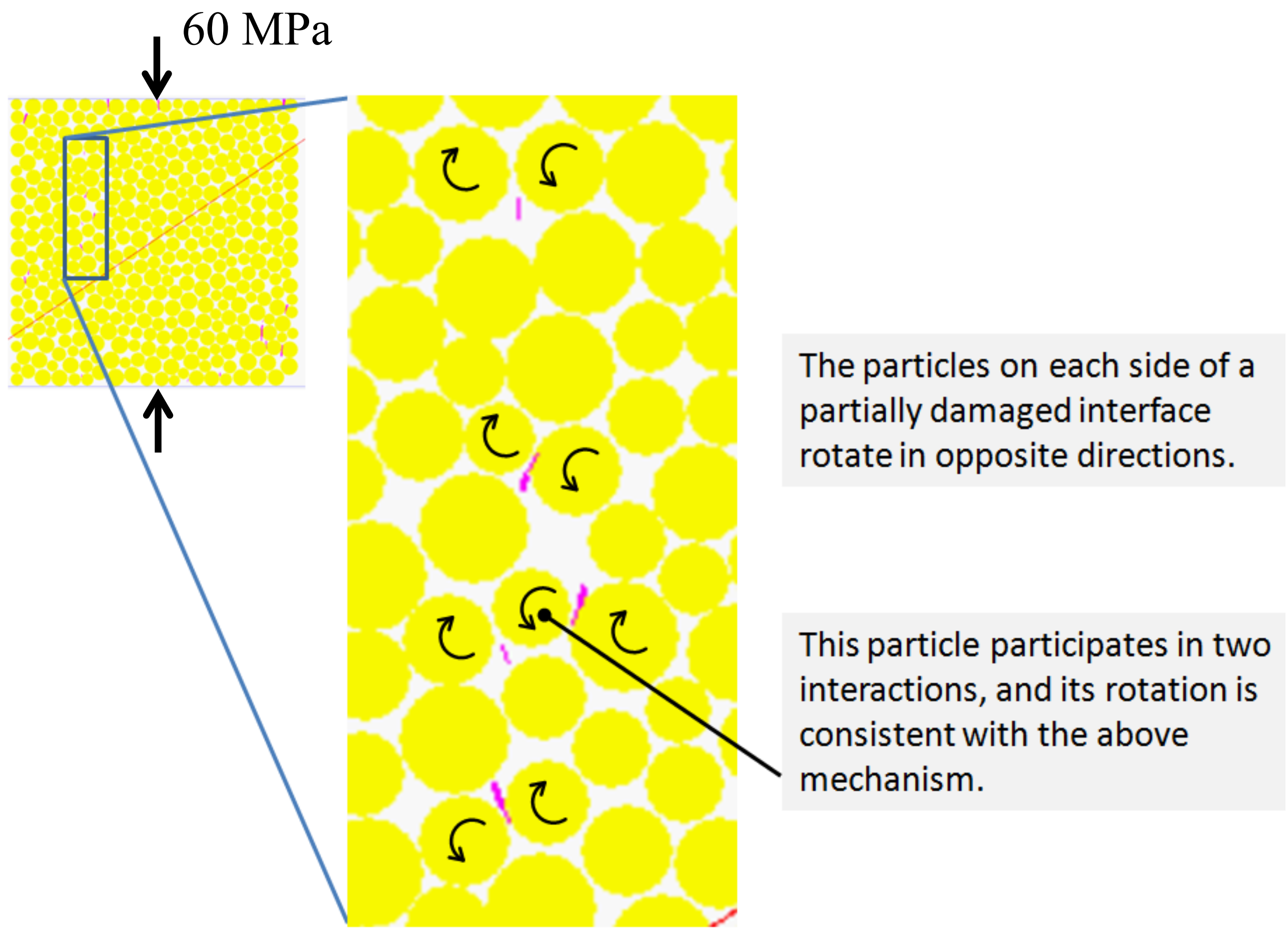
Flat-jointed material (Matches strength ratio)





Failure at peak load coincides with a few micro-shear breakages.
➔ Can choose shear strength to match UCS.

Flat-jointed material (Matches strength ratio)

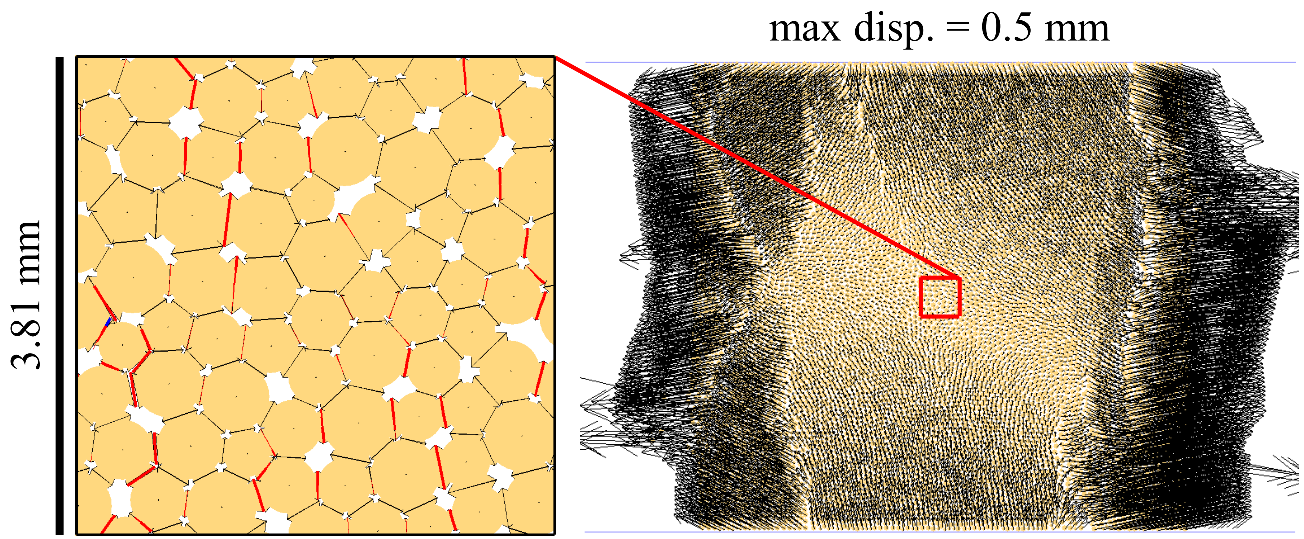


Substantial partial damage continues to resist micro-moments without triggering complete failure. Equivalent parallel-bonded material would have already failed via particle rolling.

Demonstrate good behavior in 2D. . .

Flat-jointed material **(Good behavior)**

Unconfined-compression test

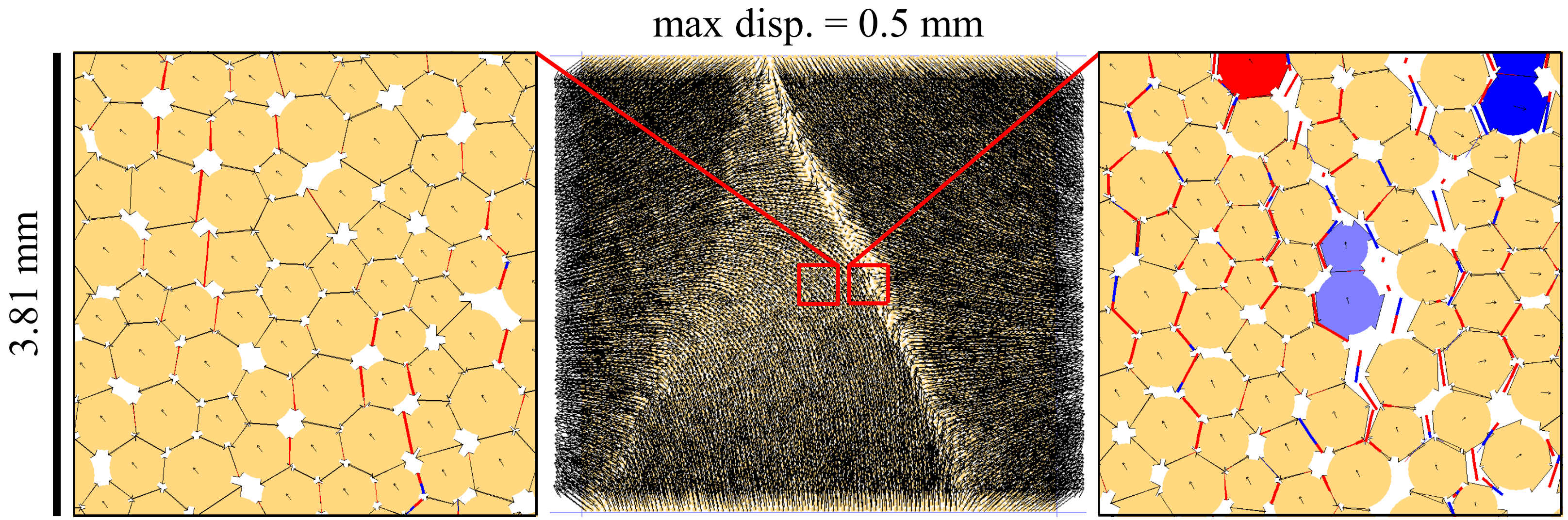


damaged microstructure
at post-peak state

axial splitting

Flat-jointed material (Good behavior)

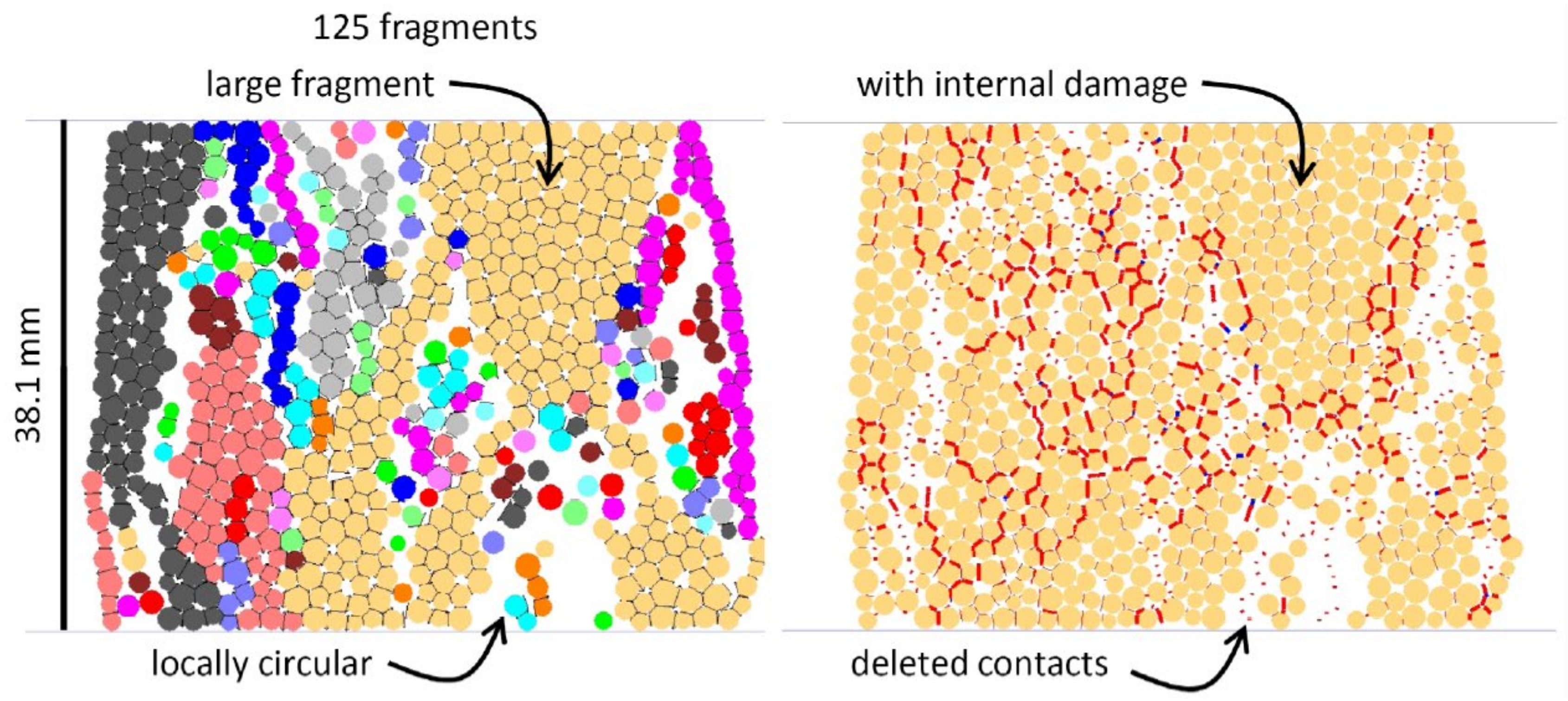
Confined-compression test



damaged microstructure
at post-peak state

shear fracture

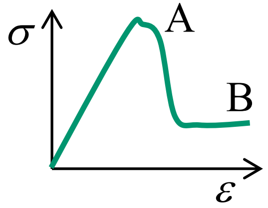
Flat-jointed material (Good behavior)



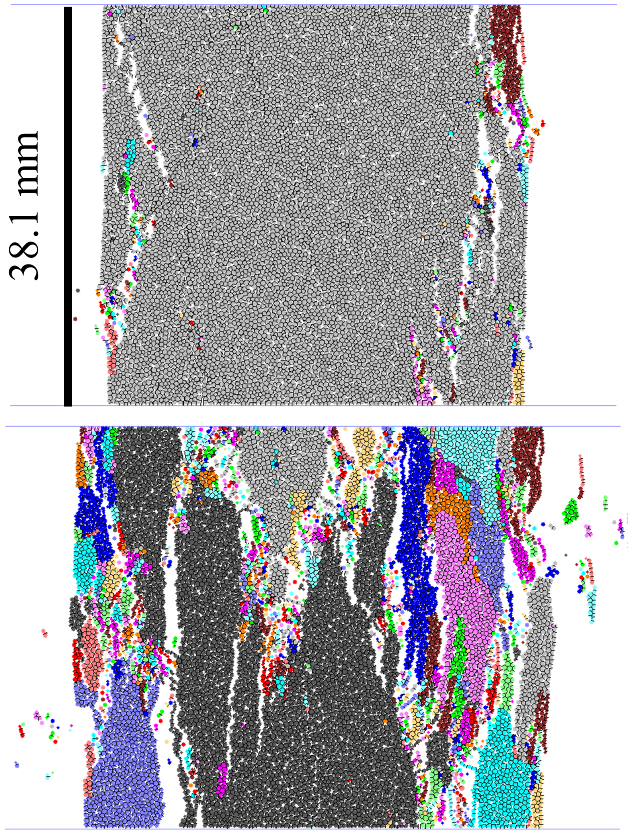
damaged microstructure
at residual state

axial splitting

Flat-jointed material (Good behavior)



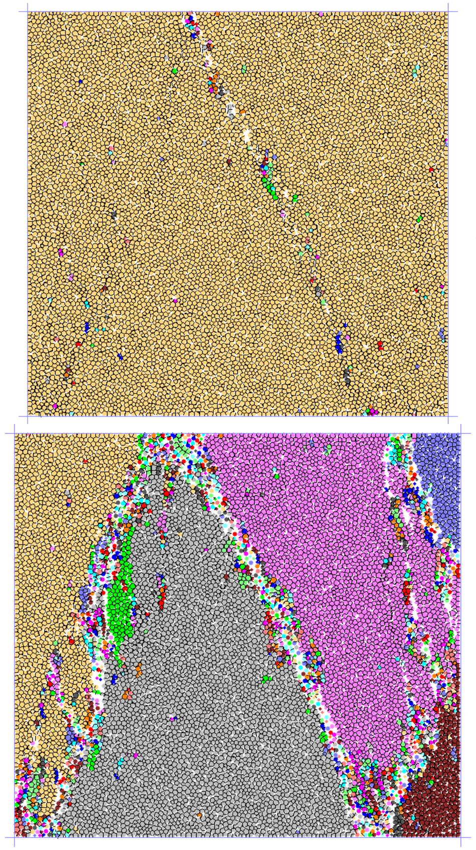
Compression tests



$P_c = 0$

unconfined

axial splitting



$P_c = 2.41$ MPa

confined

shear fracture

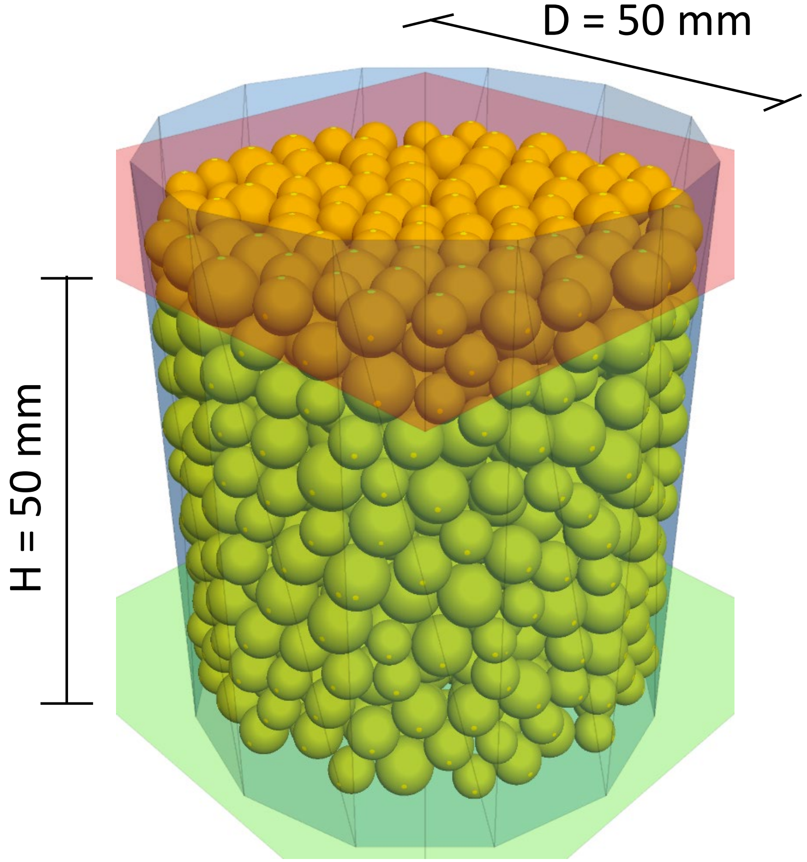
post-peak (A)

residual (B)

This paper demonstrates good behavior in 3D. . .

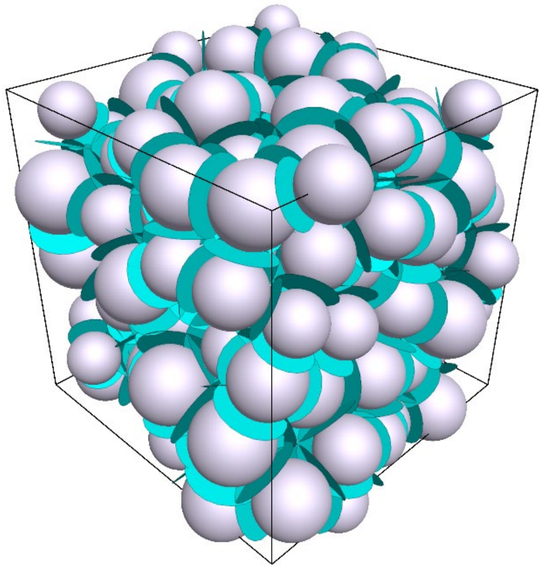
Create 3D FJ model for Lac du Bonnet granite.

3D FJ Model for Granite (microstructure)

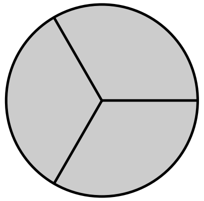


936 grains

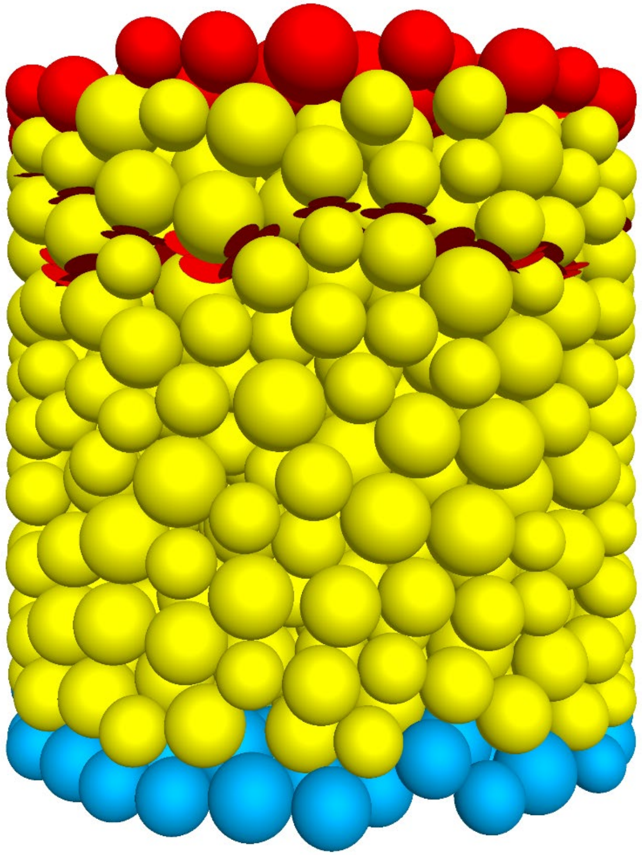
cube, s = 25 mm



flat-jointed interfaces
(blue, full size)



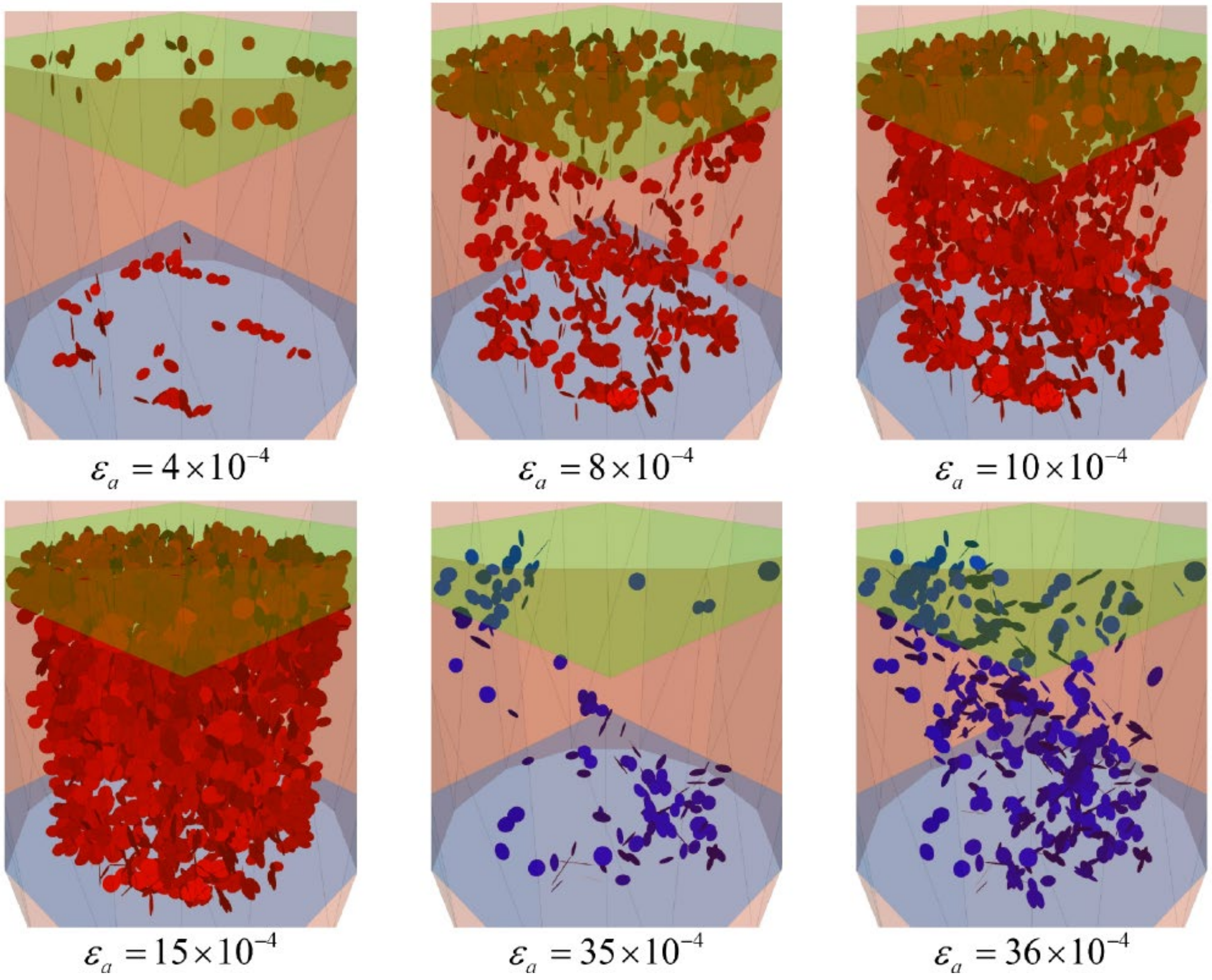
3D FJ Model for Granite (matches tensile strength)



411 tensile cracks

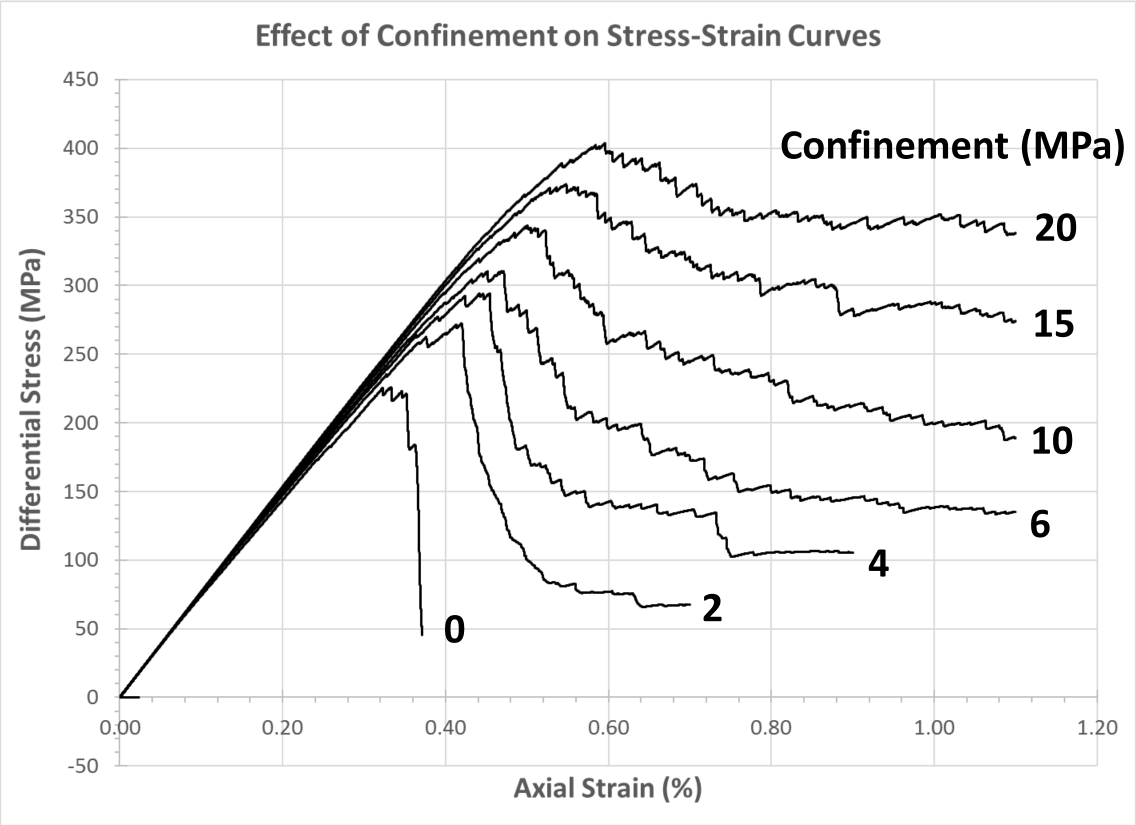
Failure consists of micro-tensile breakages.
➔ Can choose micro tensile strength to match sig_t.

3D FJ Model for Granite (matches compressive strength)

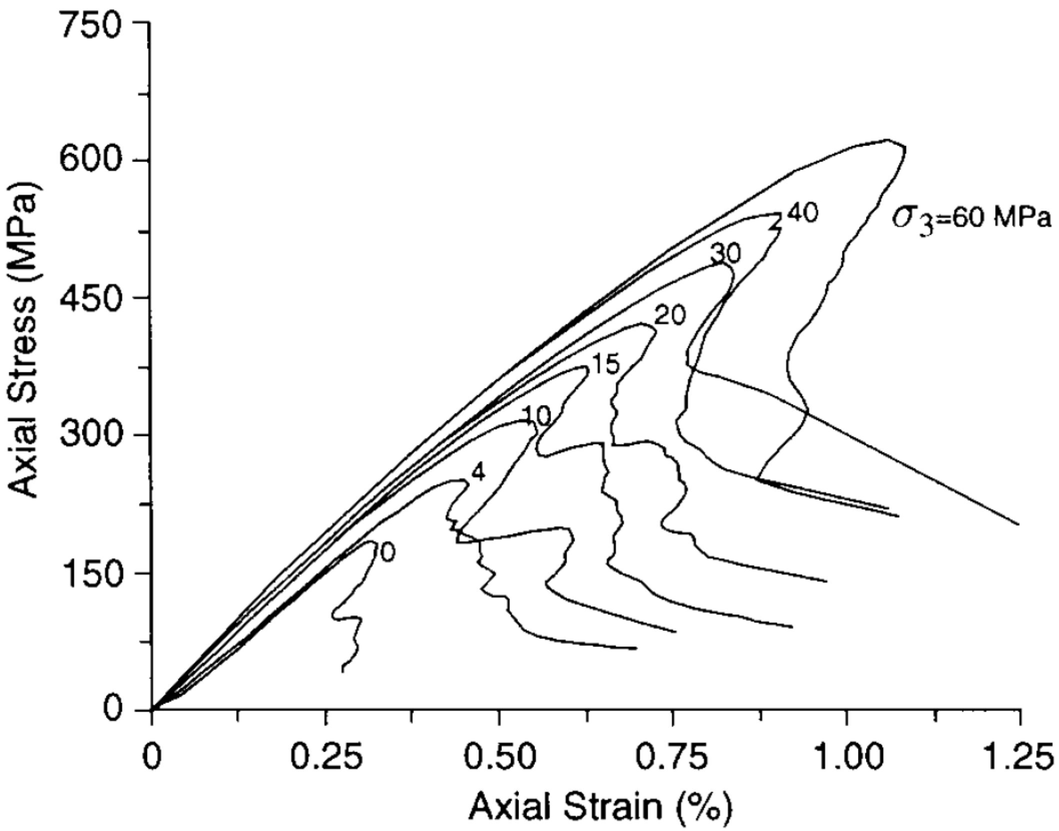


Failure at peak load coincides with a few micro-shear breakages.
➔ Can choose shear strength to match UCS.

3D FJ Model for Granite (matches compressive strength)



3D FJ Model



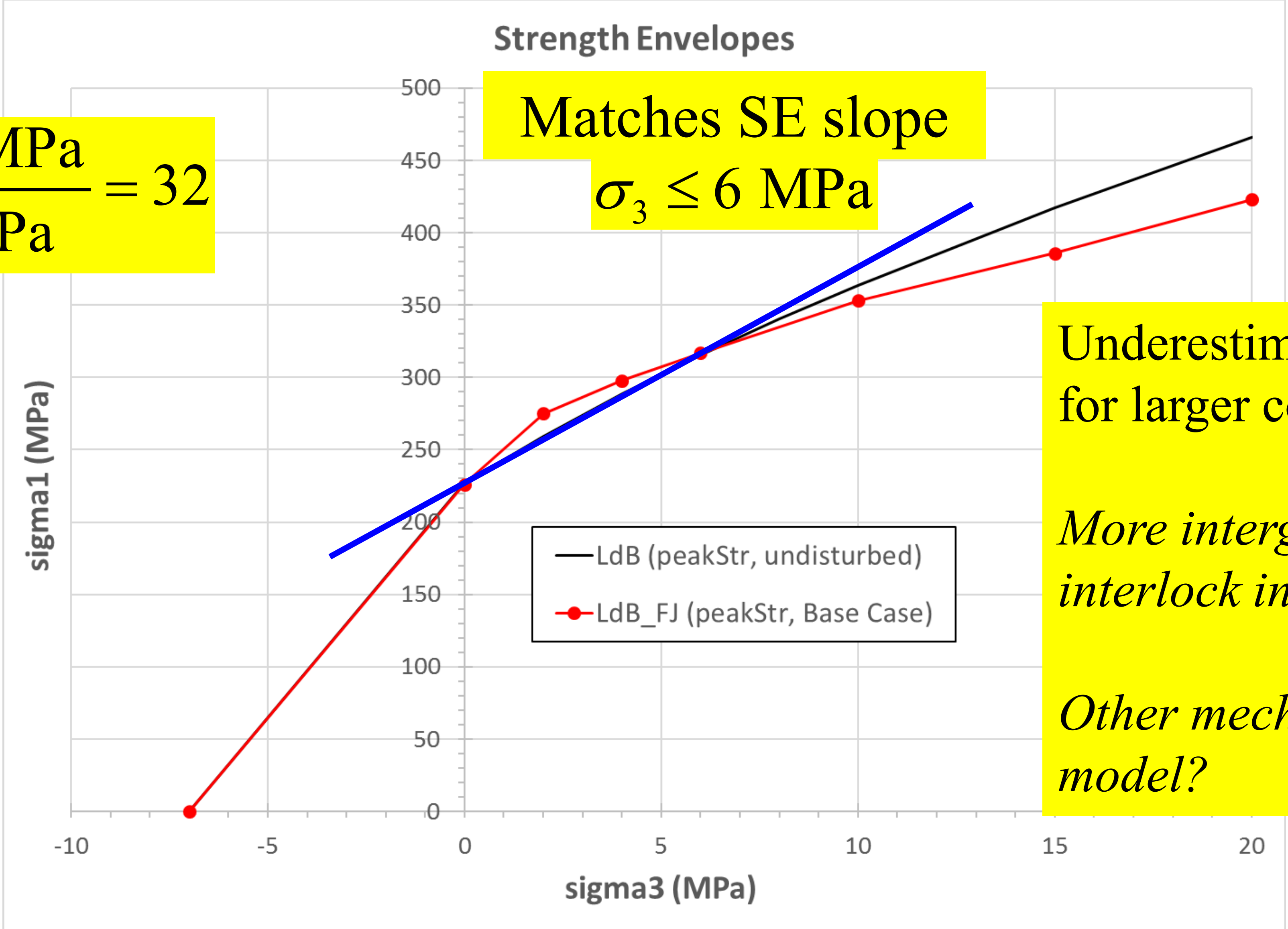
Lac du Bonnet granite

As confinement increases,
strength increases & brittleness decreases.

ITASCA

3D FJ Model for Granite (matches compressive strength)

$$\frac{q_u}{\sigma_t} = \frac{226\text{ MPa}}{7\text{ MPa}} = 32$$



Matches SE slope

$\sigma_3 \leq 6$ MPa

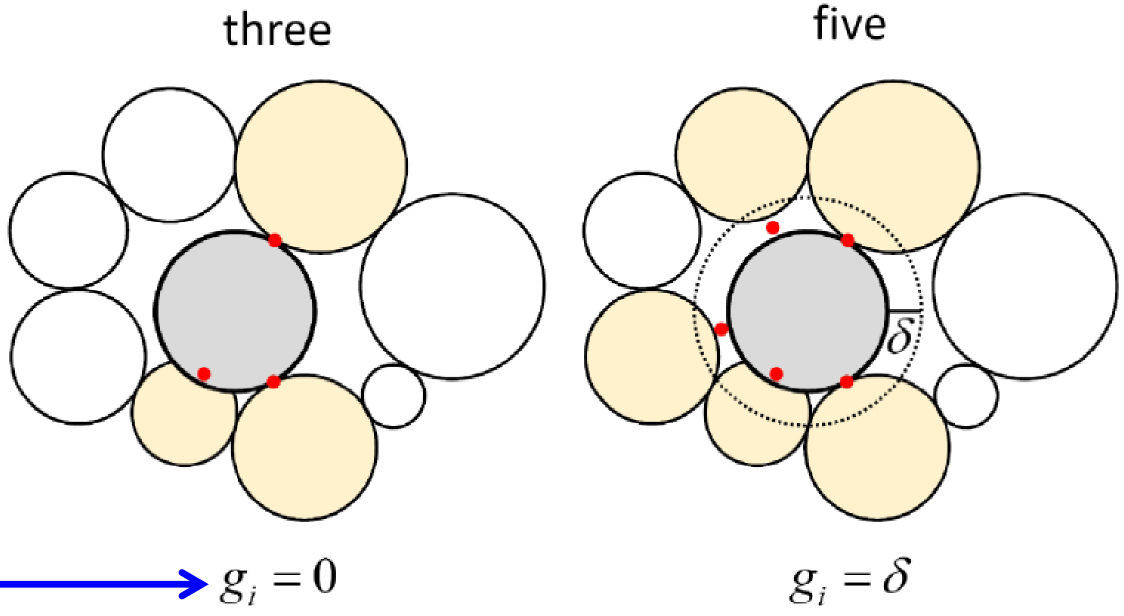
Underestimates strength for larger confinement.

More intergranular interlock in real granite?

Other mechanism not in model?

3D FJ Model for Granite (installation gap)

The installation gap controls the grain connectivity --- key parameter!

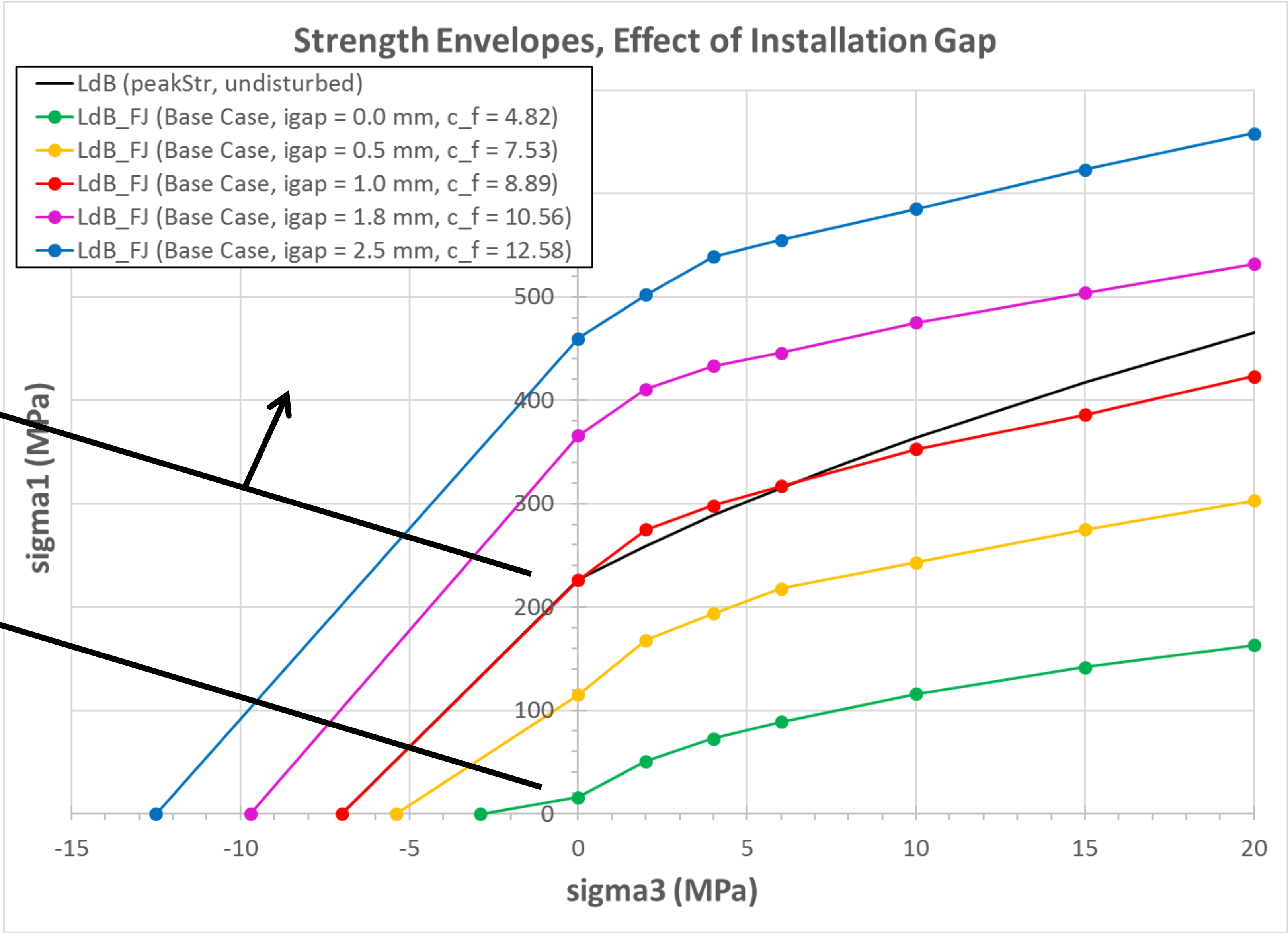


installation gap

Increasing the installation gap, increases the grain connectivity,

which increases the material modulus and strength.

3D FJ Model for Granite (installation gap)



$\frac{q_u}{\sigma_t} \cong 32$

$\frac{q_u}{\sigma_t} \cong 7$

Increasing installation gap

A large grain connectivity is necessary to match strength ratio of compact rock.

Conclusions

- BPM provides many microstructural models
  - Grain-based material is good model (2D only)
  - Flat-jointed material is good model (2D & 3D)

- FJ model can represent wide class of rocks with microstructures ranging from compact to porous, by varying
  - Area of each interface
  - Initial slits & gaps at each interface
  - Grain connectivity (via material pressure & installation gap)

- Can now create refined BPMs to mimic different rock types
  - Not just generic rock that matches tensile & compressive strengths

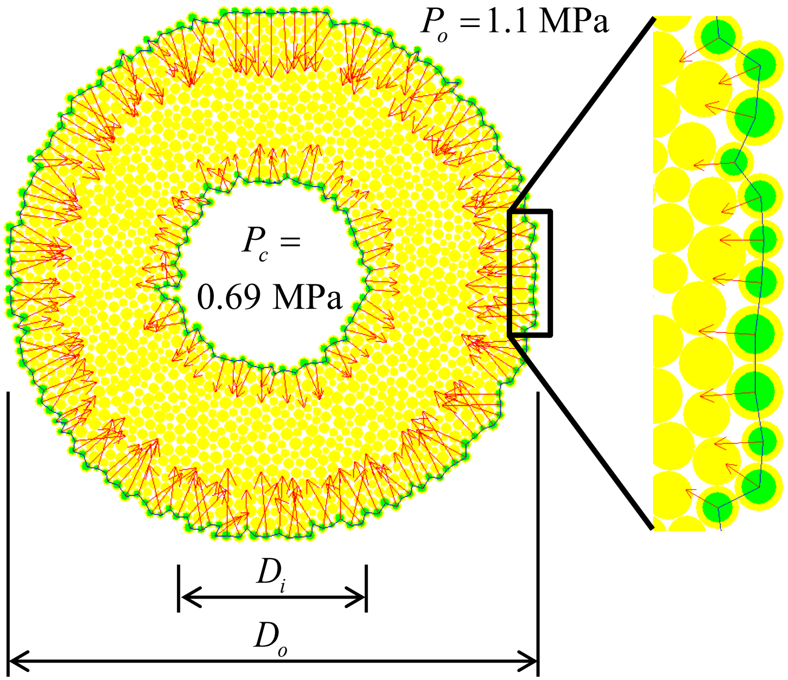
Done!

Questions?
Now and at Itasca booth.

Overview (organizational notes, do not show)

- Rock & Bonded-Particle Model (grains & cement)
- Behavior controlled by microstructure (grain shape, packing, cement, . . .)
- BPMs provide wide variety of microstructural models
- Limitation (low ratio) is overcome by providing “interlock”
- FJ model does this (both 2D and 3D)
- Demonstrate by matching response of LdB granite (Pc <= 6 MPa)

Flat-jointed material (Good behavior)



Model of a TWC test showing pressure-application procedure

Flat-jointed material (Good behavior)

We now describe the formation of a stable notch above the borehole when the external pressure reaches 30.5 MPa.

- damage
- damage & forces

Show next slide, while reading:

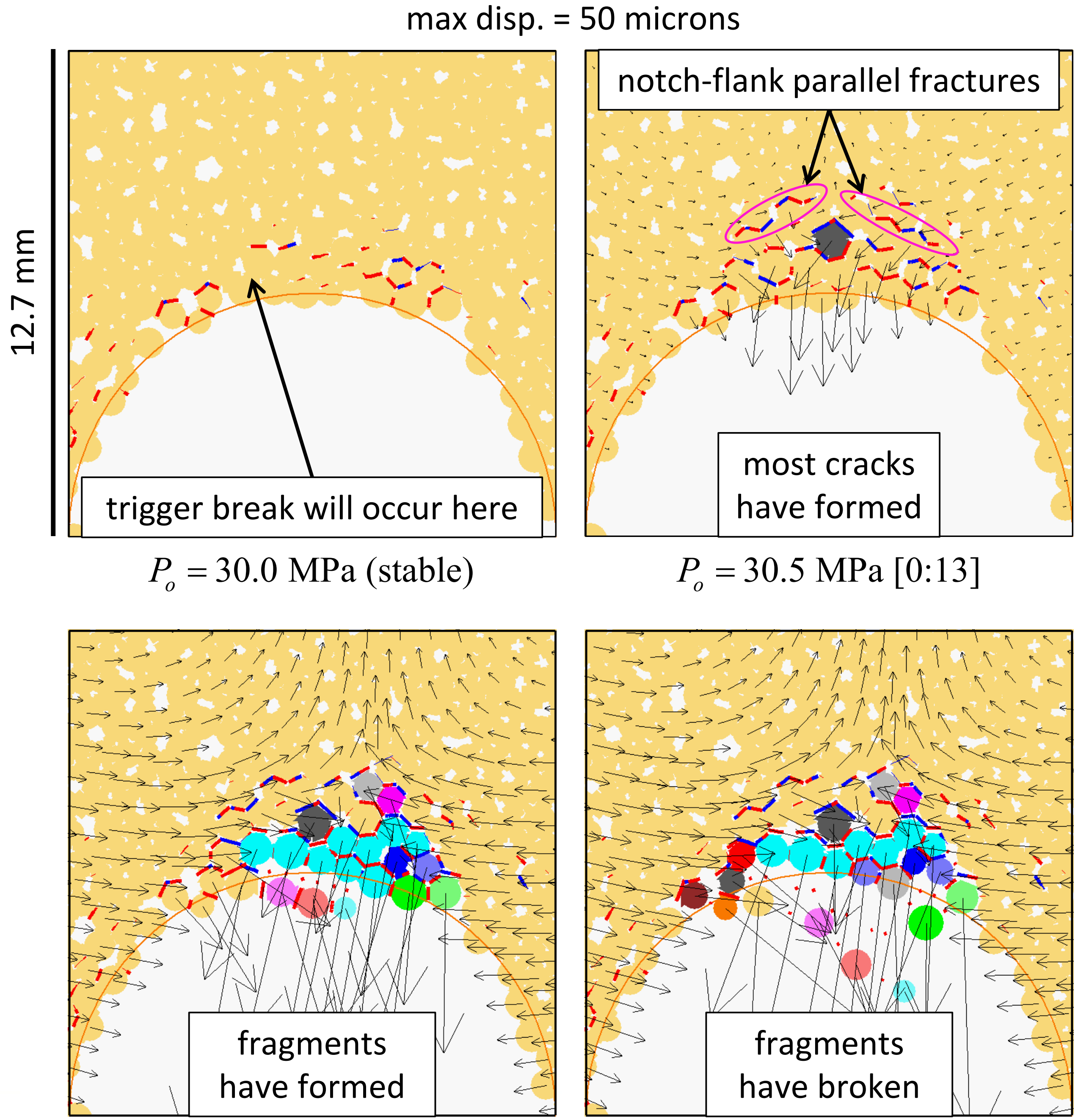
A series of surface-parallel fractures, followed by notch-flank parallel fractures, form as the material outside of the notch squeezes toward the notch sides, and then upward toward the notch tip, while the material within the notch dilates into the borehole.

Show second next slide, while reading:

The material within the notch softens and diverts the load toward its tip at which a large compressive zone develops to stabilize the notch.

Show next slide, while reading:

The notch-flank parallel fractures consist of a zigzag group of tensile and shear cracks and form a series of dilatant, interconnected, column-like structures of one- or two-grain thickness that are similar to interlocking thin slabs. The fractures are formed by a mix of extensile and shear motion. After they form, continued squeezing of the notch by the surrounding material induces relative extension, shear and bending motions, which cause the slabs to detach from the surrounding rock and form fragments.

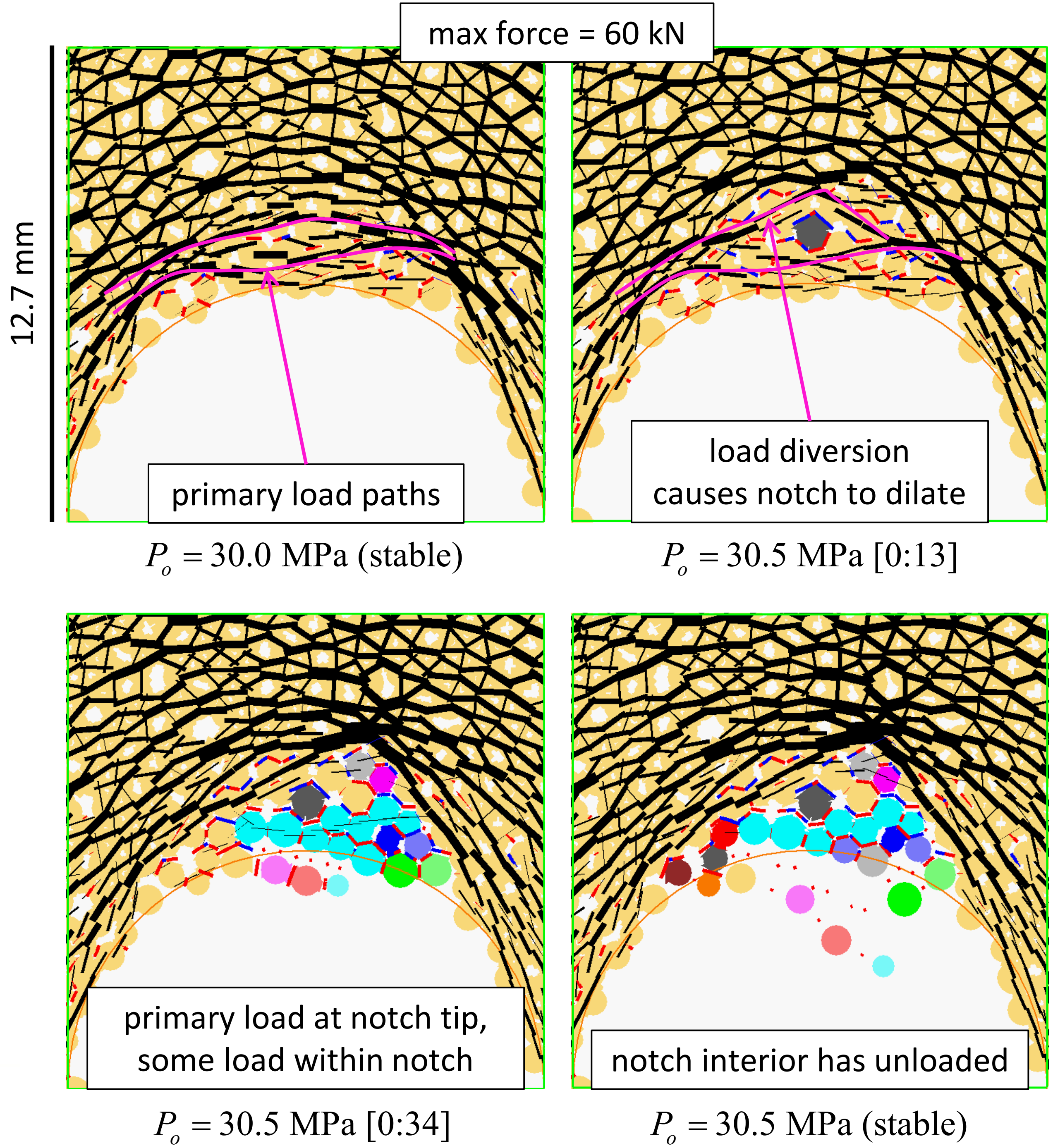


$P_o = 30.0$ MPa (stable)

$P_o = 30.5$ MPa [0:13]

$P_o = 30.5$ MPa [0:34]

$P_o = 30.5$ MPa (stable)


max force = 60 kN
12.7 mm
primary load paths
$P_o = 30.0$ MPa (stable)
load diversion
causes notch to dilate
$P_o = 30.5$ MPa [0:13]
primary load at notch tip,
some load within notch
$P_o = 30.5$ MPa [0:34]
notch interior has unloaded
$P_o = 30.5$ MPa (stable)

There is a need for simplification in rock-mechanics modeling.

We build models because the real world is too complex for our understanding; it does not help if we build models that are also too complex.

The art of modeling lies in determining what aspects of the geology are essential for the model.

Starfield & Cundall (1988)

Starfield, A.M., and P.A. Cundall (1988) "Towards a Methodology for Rock Mechanics Modeling," *Int. J. Rock Mech. & Min. Sci.*, **25**, 99–106.