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The Bonded-Particle Model as a Tool for Rock Mechanics Research and Application

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Virtual seminar for University of Twente (Enschede, Netherlands)
Multiscale Mechanics Research Group
May 6, 2021

Preamble

- We provide an overview of Bonded-Particle Modeling, and suggest avenues for further research by

  summarizing & expanding on the contents of:

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.

Potyondy, D.O, and P.A. Cundall (2004) "A Bonded-Particle Model for Rock," *Int. J. Rock Mech. & Min. Sci.*, ***41***(8), 1329–1364.

- You need not be a rock-mechanics practitioner to understand this talk. So, let's get started. . .

Overview

- Bonded-Particle Modeling
  - Basic idea & essential features

- Microstructural Physics of intact rock
  - Micromechanical processes that control brittle fracture
  - Nature of pore space: compact or porous
  - Two complimentary idealizations of rock (BPM & LEFM)

Overview

- Bonded-Particle Modeling Methodology
  - PFC model (distinct-element model of *synthetic material*: rigid grains that interact at contacts, vast microstructural space)
  - BPM (*bonded materials* & interface)
  - Microstructural models provided by BPM

Overview

- Bonded-Particle Modeling Methodology
  - PFC model (distinct-element model of *synthetic material*: rigid grains that interact at contacts, vast microstructural space)
  - BPM (*bonded materials* & interface)
  - Microstructural models provided by BPM

- Examples
  - Ceramic bead and undercut cemented backfill
  - Two intact BPMs that match both uniaxial & tensile strength of compact rock
  - Embed BPM in larger continuum model
  - Sandstone perforation damage
- Conclusions & Future Directions

Poem: “What’s In My Journal” by William Stafford

Clues that lead nowhere,

that never connected anyway.

Deliberate obfuscation, The action of making something obscure, unclear or unintelligible.

the kind that takes genius.

This talk: “What’s In My Lecture” by David Potyondy

Clues that spawn understanding,

arrived at by modeling.

Deliberate simplification,

the kind that gives clarity.

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.

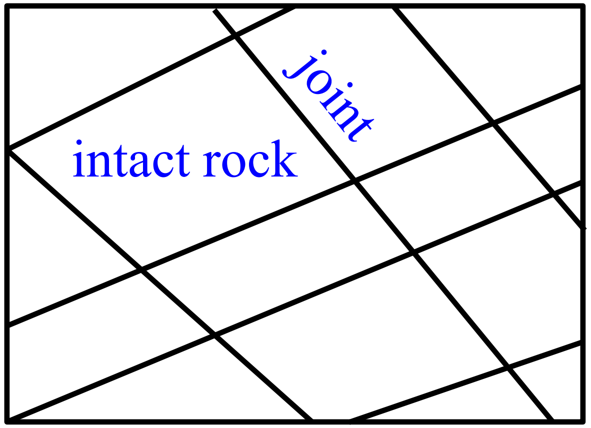
The art of modeling lies in determining what aspects of the geology are essential for the model.

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.

Basic Idea

Rock Mass

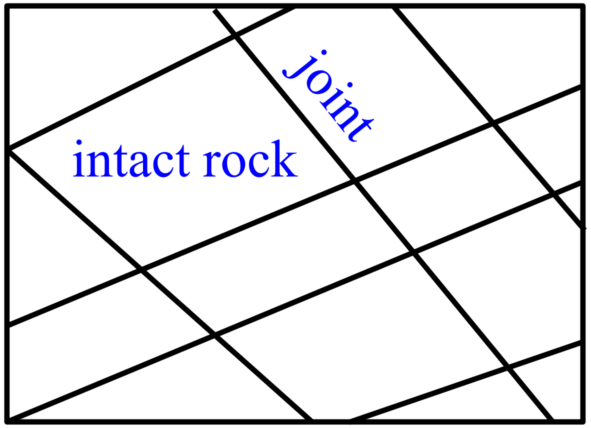


Mechanical behavior arises from interactions:

- microstructure (grain scale) of intact rock
- orientations & properties of joints

Basic Idea

Rock Mass



emergent phenomena

Mechanical behavior arises from interactions:

- microstructure (grain scale) of intact rock ➔ fracture & flow
- orientations & properties of joints ➔ rupture & sliding

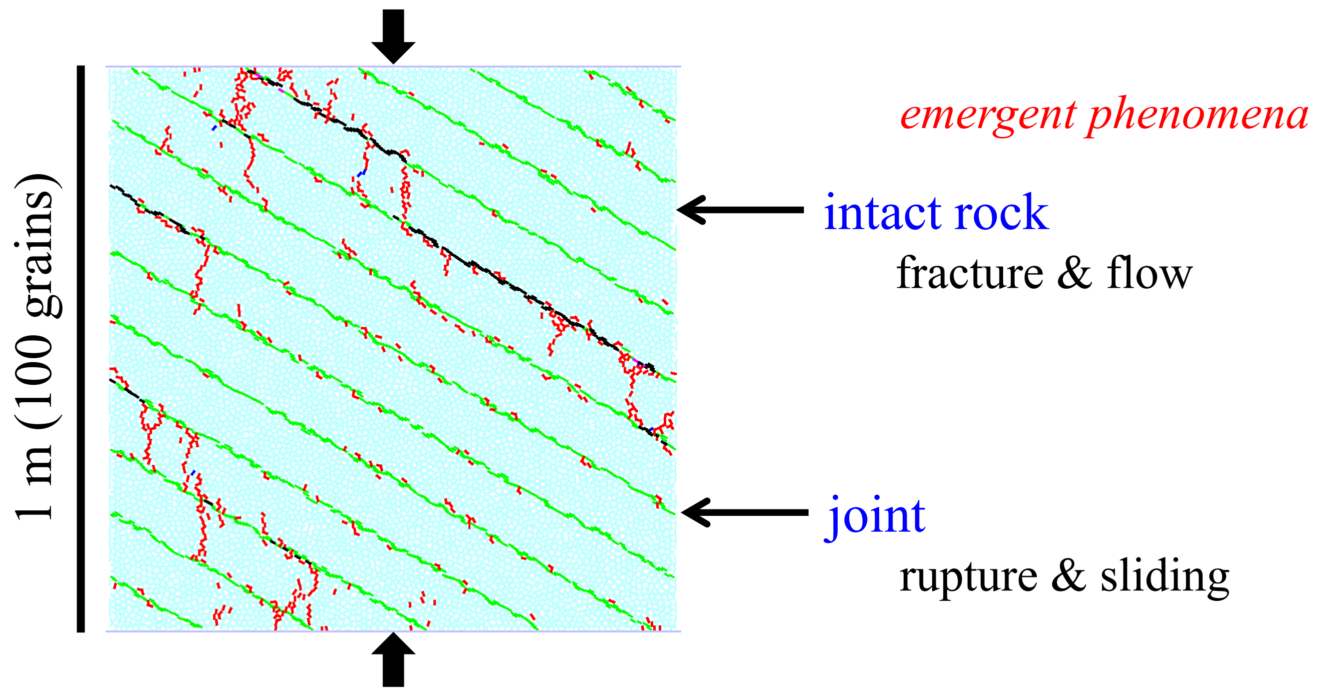
Bonded-Particle Models mimic intact rock & joints

Closer match to microstructural & structural features ➔
Closer match to macroscopic behavior

Essential Features of a BPM

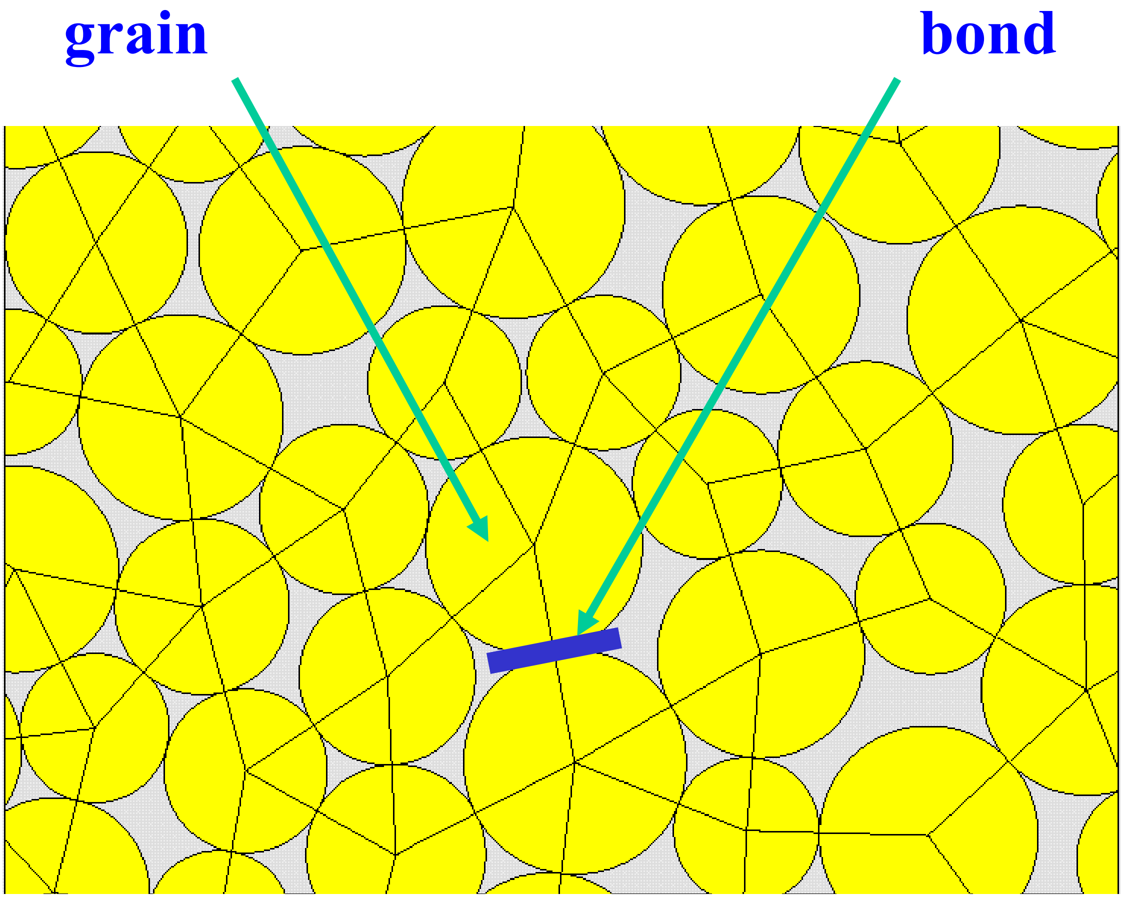
BPM consists of a base material (intact rock) to which larger-scale joints can be added.

- base material : bonded rigid grains
- joints : interfaces



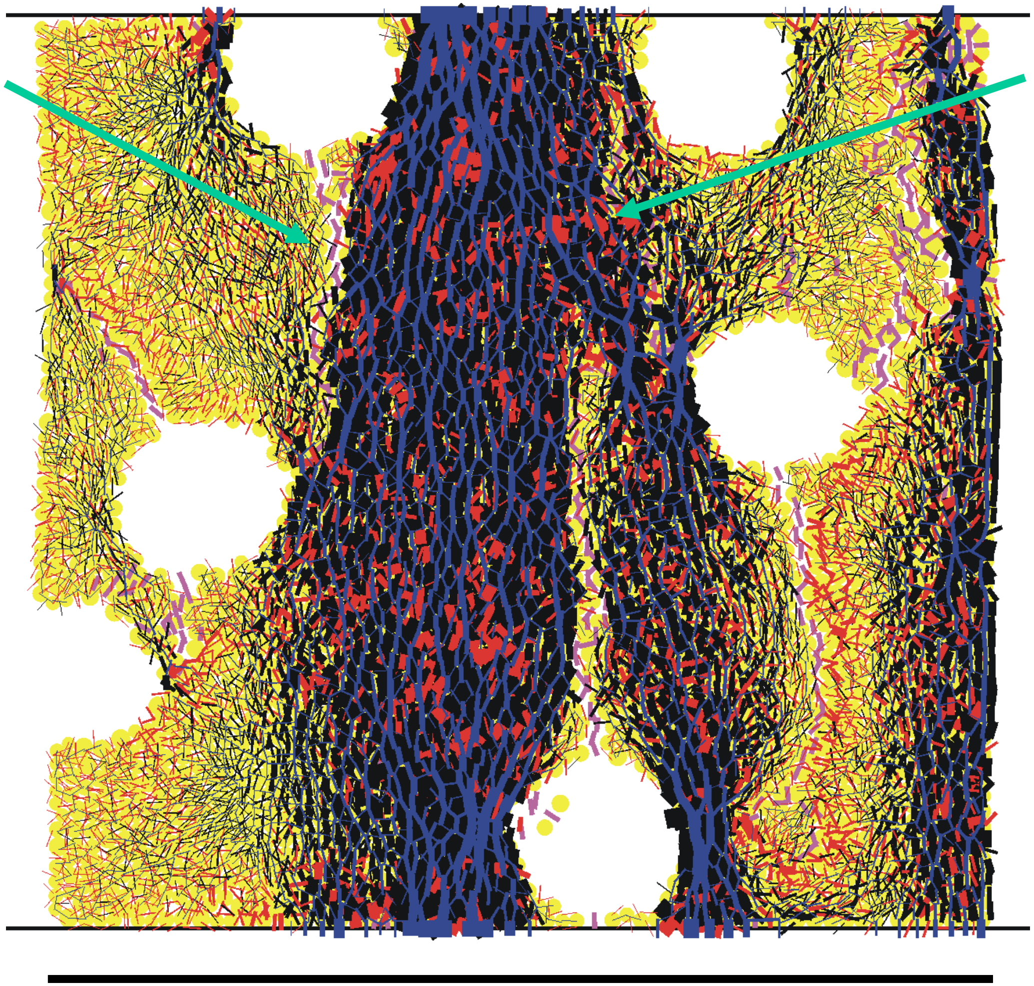
Damage consists of bond breakages.

Essential Features of a BPM



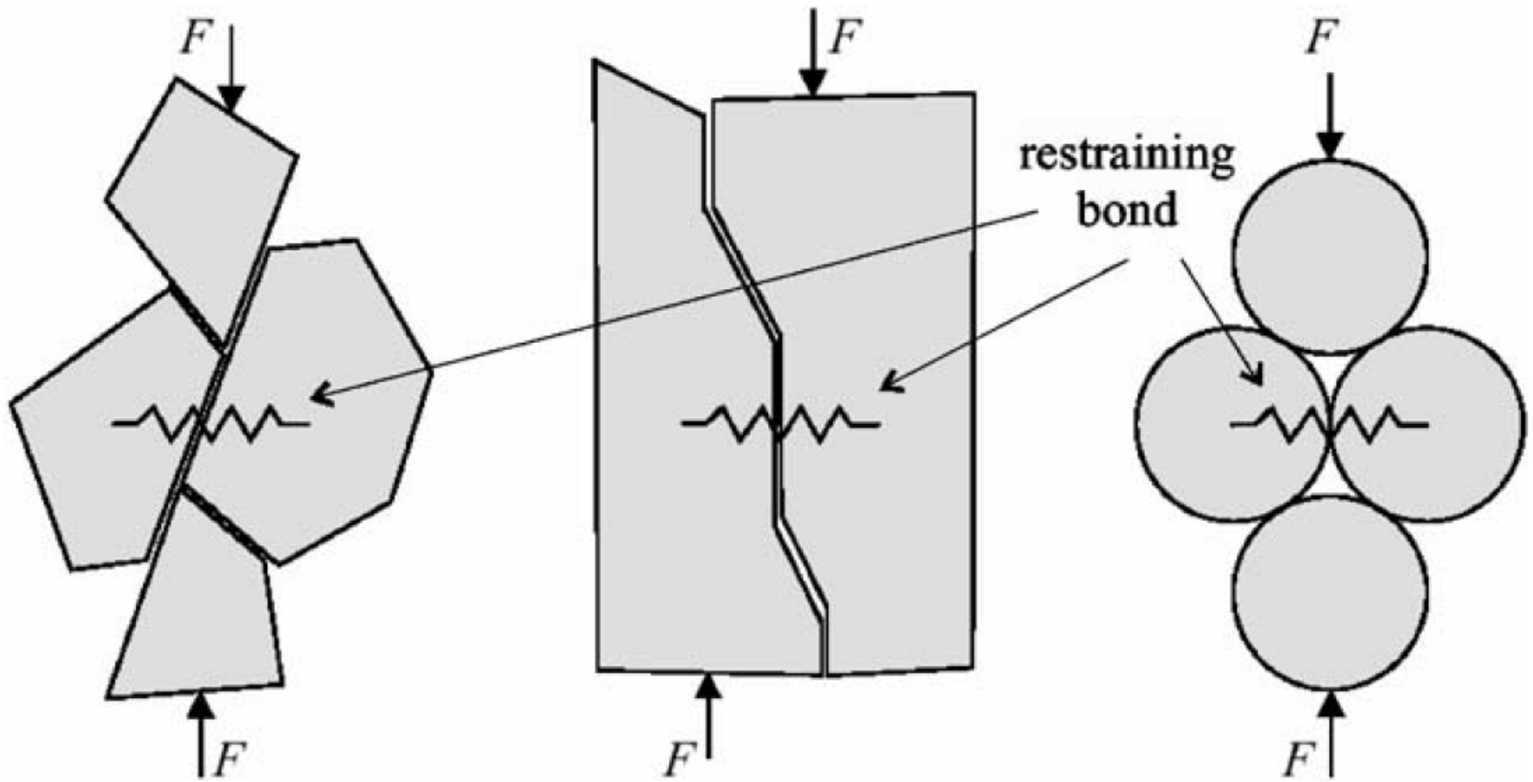
Damage consists of bond breakages.

Essential Features of a BPM



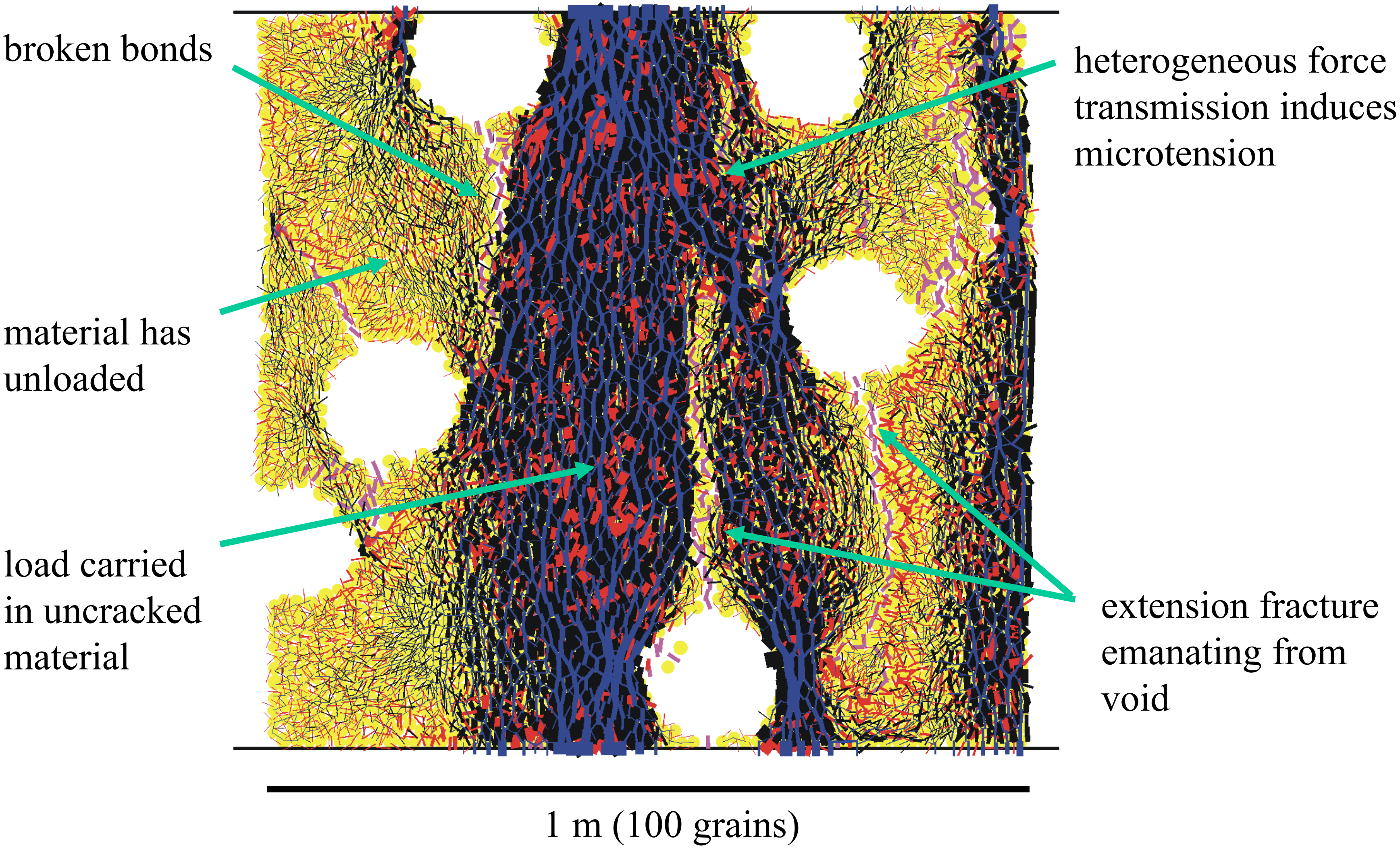
blue : compression between grains
black/red : compression/tension in cement

Essential Features of a BPM



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

Essential Features of a BPM



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.

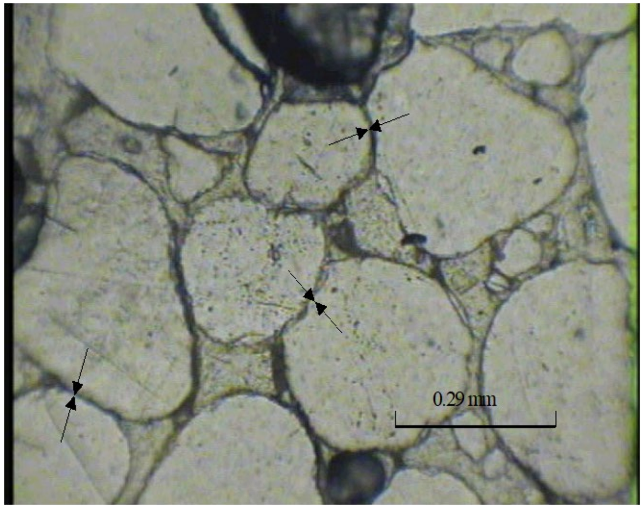
Much disorder in system:

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.

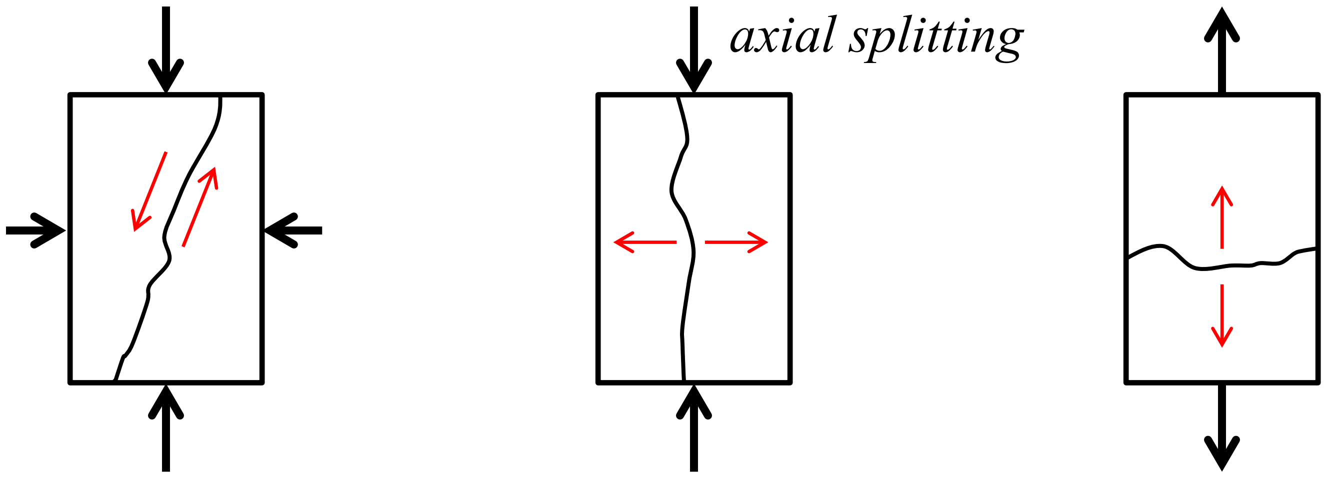
Microstructural Physics of Intact Rock

Brittle mechanical properties measured:

- uniaxial & triaxial compression tests
- tension tests

Two principal modes of brittle failure:

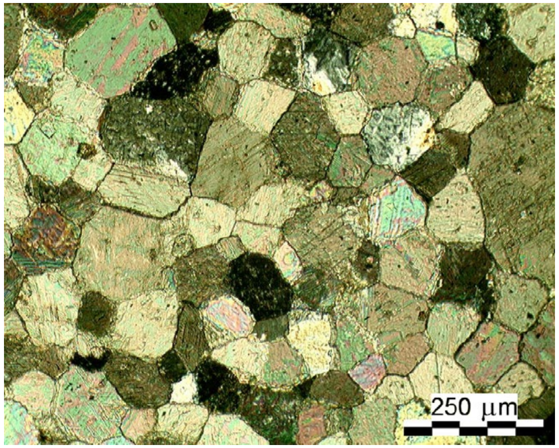
- shear fracture
- extension fracture



shear fracture — extension fracture

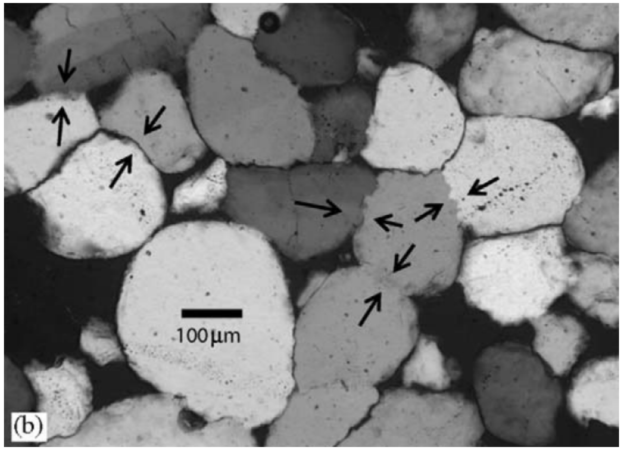
Microstructural Physics of Intact Rock

Brittle mechanical properties are controlled by nature of pore space ➔ classify intact rock as compact or porous



Bandini et al. (2012)

marble with interlocking grains



Haimson (2007)

sandstone with broad grain sutures

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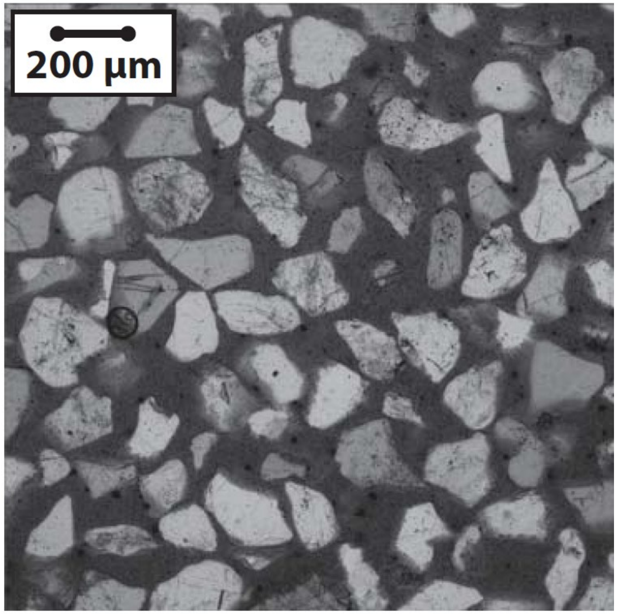
Bandini et al. (2012) "Effects of Intra-Crystalline Microcracks on the Mechanical Behavior of a Marble Under Indentation," *Int. J. Rock Mech. & Min. Sci.*, ***54***, 47-55.
Haimson, B. (2007) "Micromechanisms of Borehole Instability Leading to Breakouts in Rocks," *Int. J. Rock Mech. & Min. Sci.*, ***44***, 157–173.

Microstructural Physics of Intact Rock

Compression-induced damage manifests itself as inelastic volume change (dilation or compaction) resulting from microstructural changes that are precursors to macroscopic failure.

granular aggregate

Deviatoric loading ➔
dilatancy, repacking of grains



Brzesowsky et al. (2014)

quartz sand

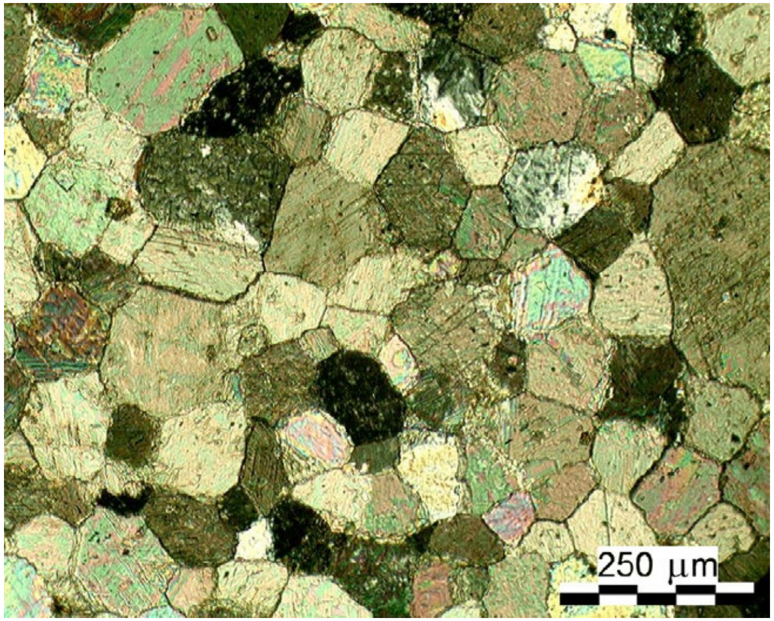
Brzesowsky et al. (2014) "Time-Independent Compaction Behavior of Sands," *J. Geophys. Res. Solid Earth*, ***119***, doi:10.1002/2013JB010444..

Microstructural Physics of Intact Rock

Compression-induced damage manifests itself as inelastic volume change (dilation or compaction) resulting from microstructural changes that are precursors to macroscopic failure.

compact rock

Deviatoric loading ➔ dilatancy, microcracking



marble

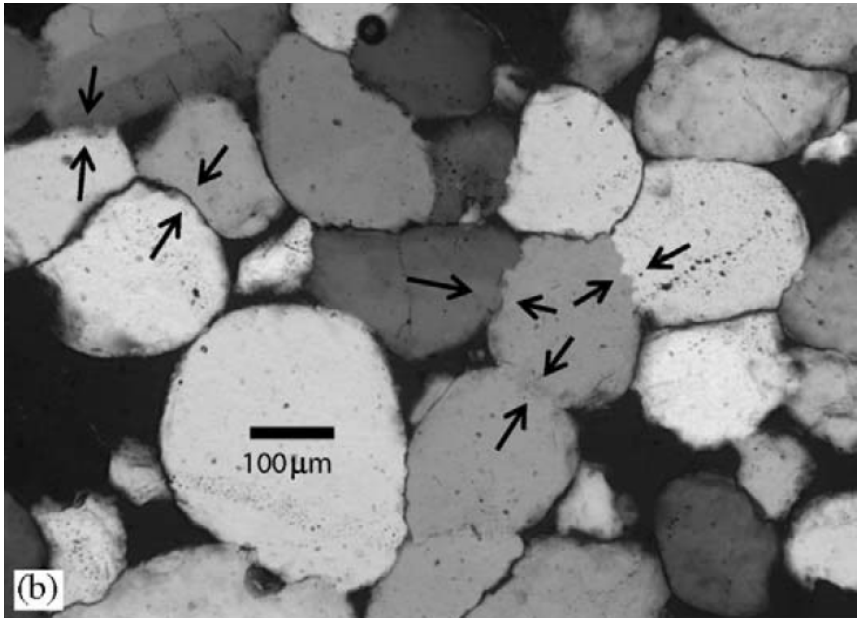
Microstructural Physics of Intact Rock

Compression-induced damage manifests itself as inelastic volume change (dilation or compaction) resulting from microstructural changes that are precursors to macroscopic failure.

porous rock

Hydrostatic loading ➔
compactancy, grain crushing

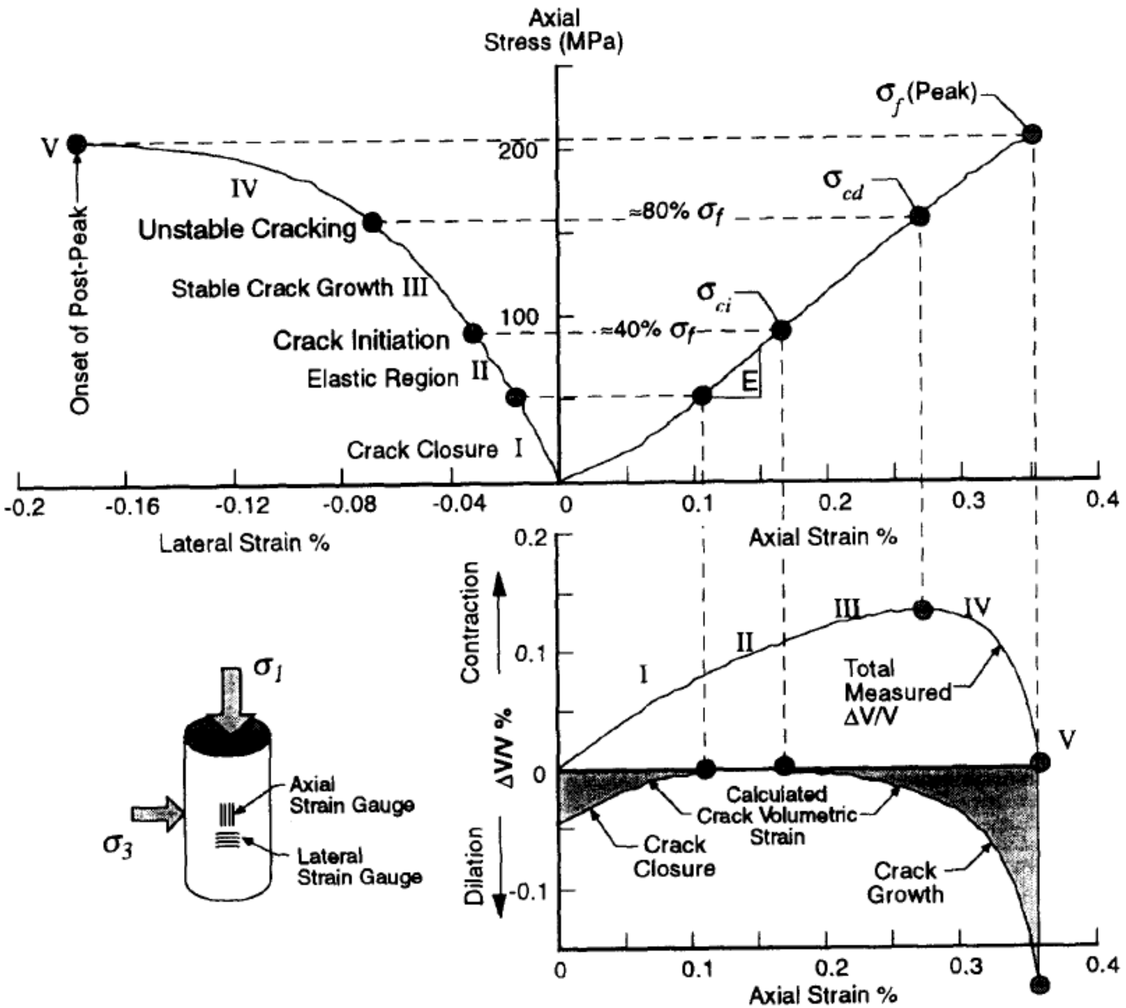
Deviatoric loading ➔
dilatancy, microcracking
OR
compactancy, brittle grain crushing or plastic collapse of pores (shear-enhanced compaction)



sandstone

Microstructural Physics of Intact Rock

Compressive behavior is described by stress-strain curves:



Martin & Chandler (1994)

Four stages:

1. crack closure
2. elastic region
3. stable crack growth
4. unstable crack growth

Martin, C.D., and N.A. Chandler (1994) “The Progressive Fracture of Lac du Bonnet Granite,” *Int. J. Rock Mech. & Min. Sci., **31**,* 643-659.

Microstructural Physics of Intact Rock

Compressive behavior is explained in terms of flaws & heterogeneities in the rock material on the microscopic scale in which brittle fracture is viewed as a localization in the proliferation of microcracking.

It is essential to have a realistic structural description of the rock as a basis for…theoretical developments, and to consider the evolution of the structure during the progression of the failure.

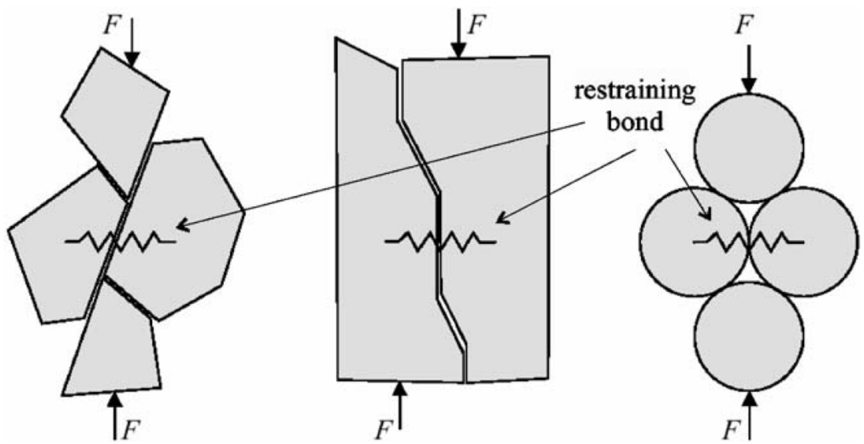
BPMs provide a micromechanical theory of brittle failure

- various physical models of the brittle-fracture process
- discern the effects of microstructure on macroscopic behavior

Two Complementary Idealizations of Rock

BPM material

(cemented granular material)

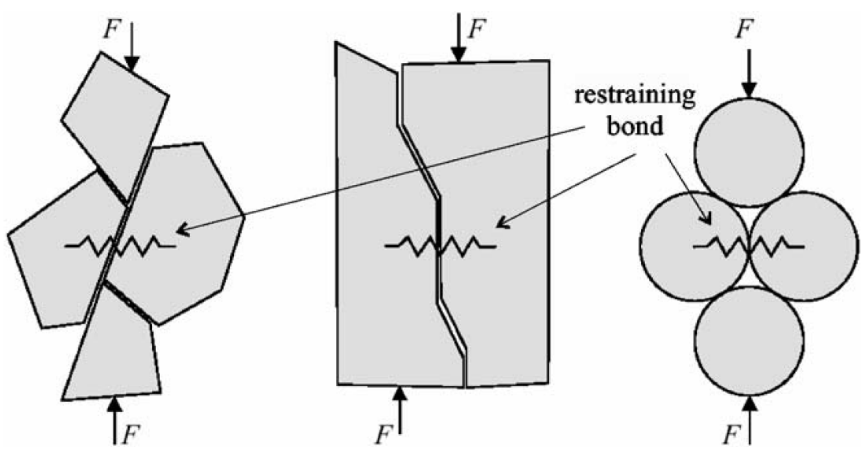


Microstructural mechanisms to induce microtension and bond breakage

Two Complementary Idealizations of Rock

BPM material

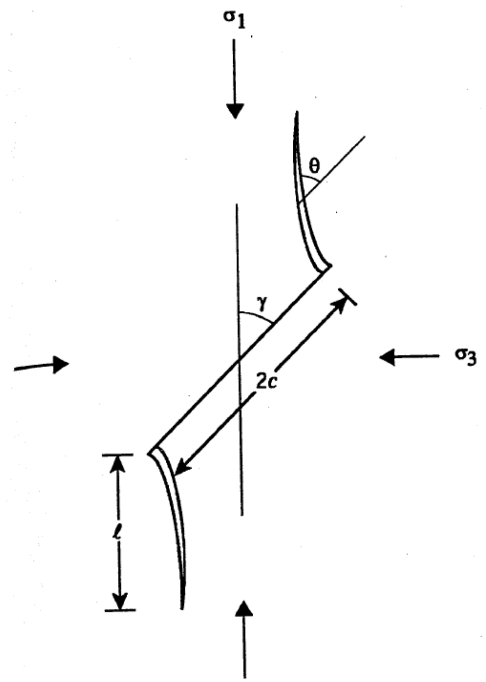
(cemented granular material)



Microstructural mechanisms to induce microtension and bond breakage

LEFM material

(linear-elastic body with initial population of cracks)



Microstructural mechanism to induce microtension and crack extension via sliding crack & wing cracks

Two Complementary Idealizations of Rock

Why does axial splitting occur?

It originates from local transverse tensile stresses at flaws or heterogeneities in the rock.

For both materials, the axial splits nucleate

- as wing cracks in LEFM material
- as broken bonds in BPM material

Two Complementary Idealizations of Rock

Why does axial splitting occur?

It originates from local transverse tensile stresses at flaws or heterogeneities in the rock.

For both materials, the axial splits nucleate

- as wing cracks in LEFM material
- as broken bonds in BPM material

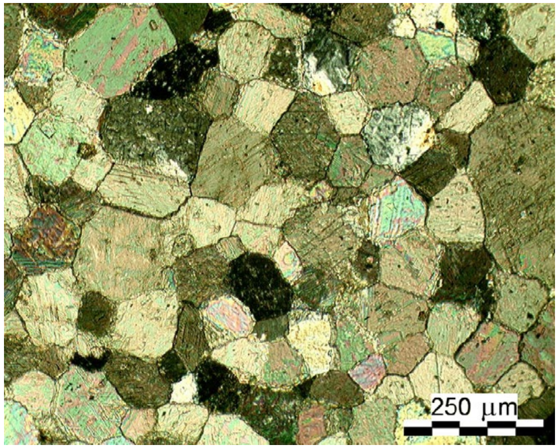
and then grow into an orientation parallel to direction of compression

- as lengthening cracks in LEFM material
- as additional broken bonds that coalesce into extension fractures in BPM material

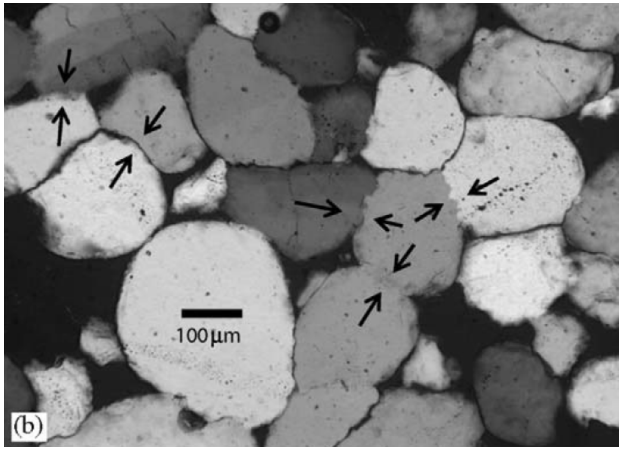
Two Complementary Idealizations of Rock

BPM material

- Supports microcrack nucleation as well as growth and eventual interaction
- Provides rich set of grain-scale discontinuities that can be related to microstructural features



marble with interlocking grains



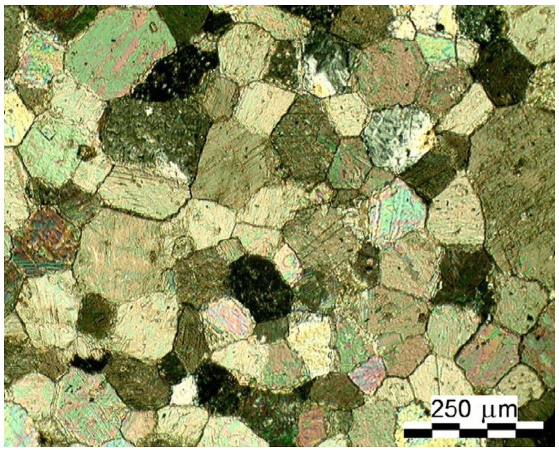
sandstone with broad grain sutures

- Grain-scale discontinuities need not be mapped into initial population of cracks

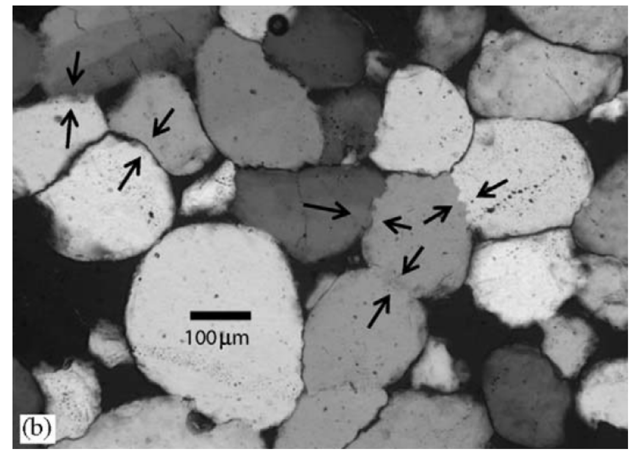
Two Complementary Idealizations of Rock

BPM material

- Provides rich set of grain-scale discontinuities that can be related to microstructural features



marble with interlocking grains



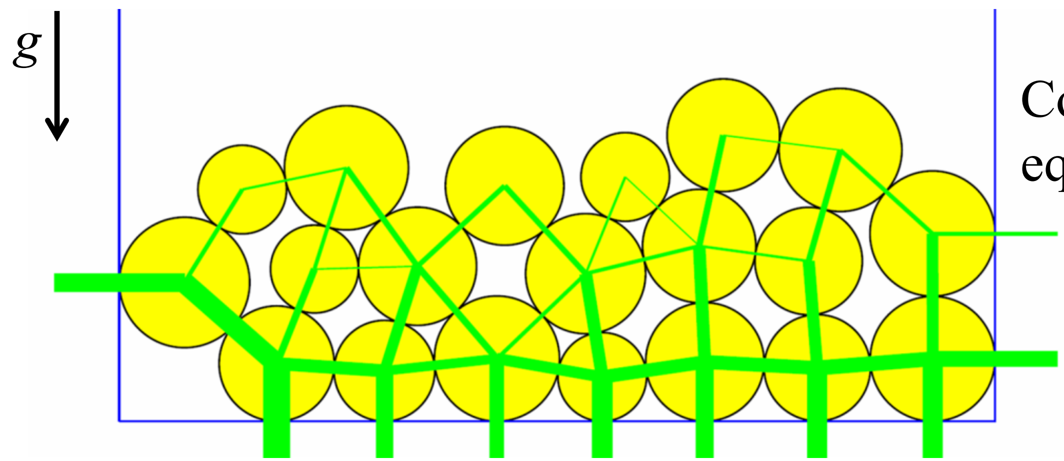
sandstone with broad grain sutures

Closer match to microstructural & structural features ➔
Closer match to macroscopic behavior

Bonded-Particle Modeling Methodology (PFC model)

PFC programs (PFC2D & PFC3D) provide a general-purpose, distinct-element modeling framework that includes a computational engine and a graphical user interface.

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

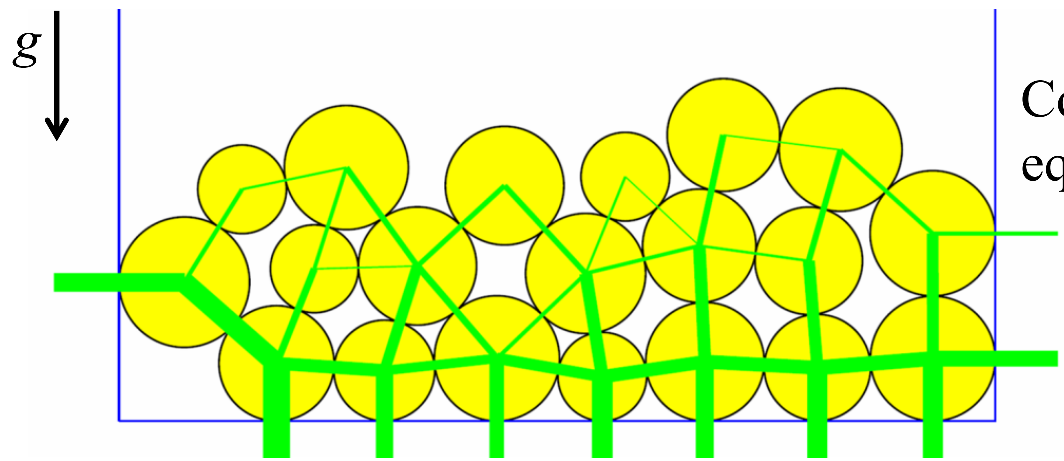


Contact forces are equal & opposite

Bonded-Particle Modeling Methodology (PFC model)

Particles are rigid bodies with finite mass that move independently of one another and can both translate and rotate. Particles interact at pair-wise contacts by means of internal force and moment.

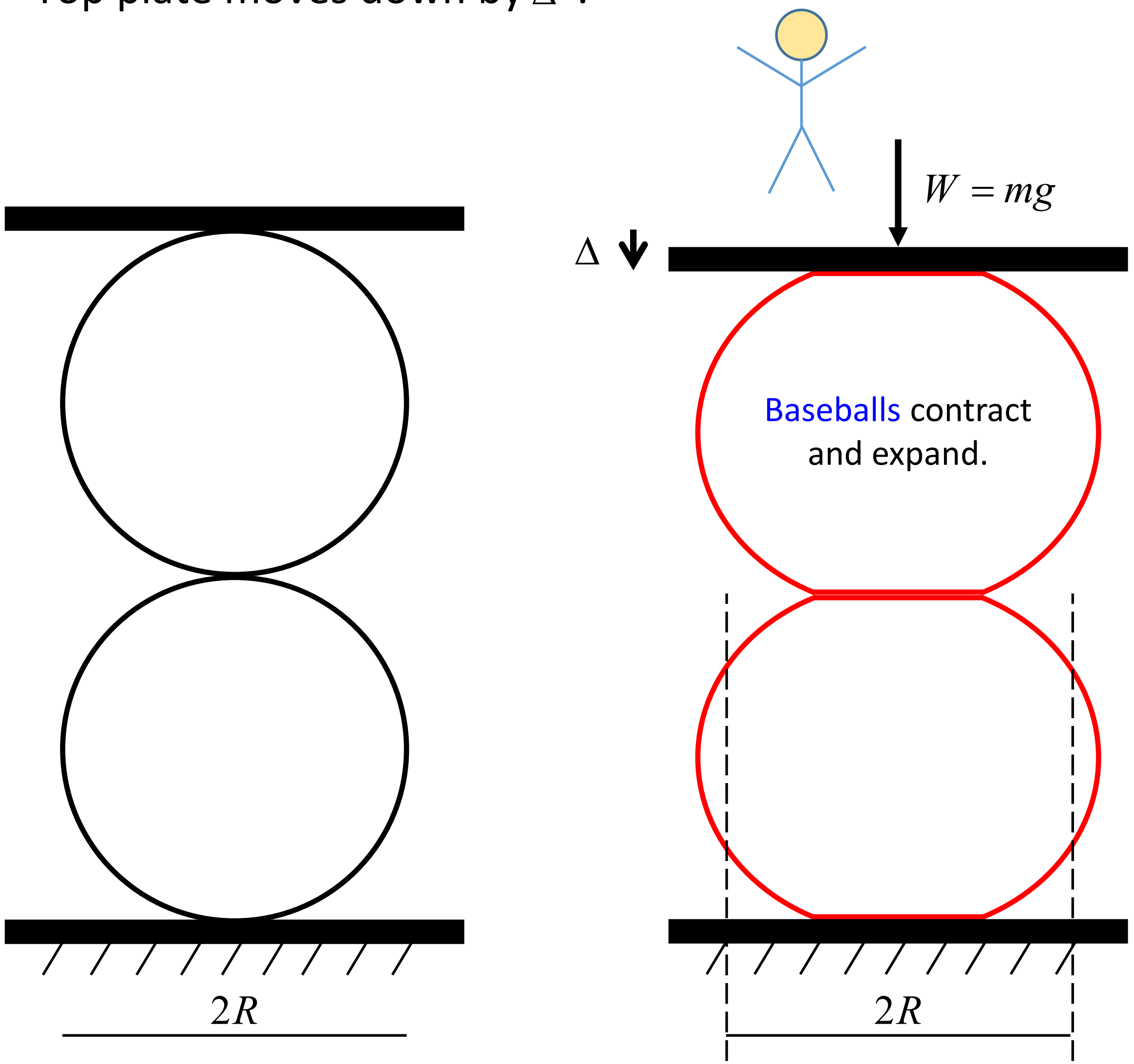
Contact mechanics is embodied in particle-interaction laws that employ a soft-contact approach for which all deformation occurs at the contacts between the rigid bodies. The particle-interaction law (contact model) updates the internal force and moment.



Contact forces are equal & opposite

soft-contact approach

Consider the system of me standing on two baseballs, pressed between steel plates.
Top plate moves down by Δ .



initial system

loaded system

soft-contact approach

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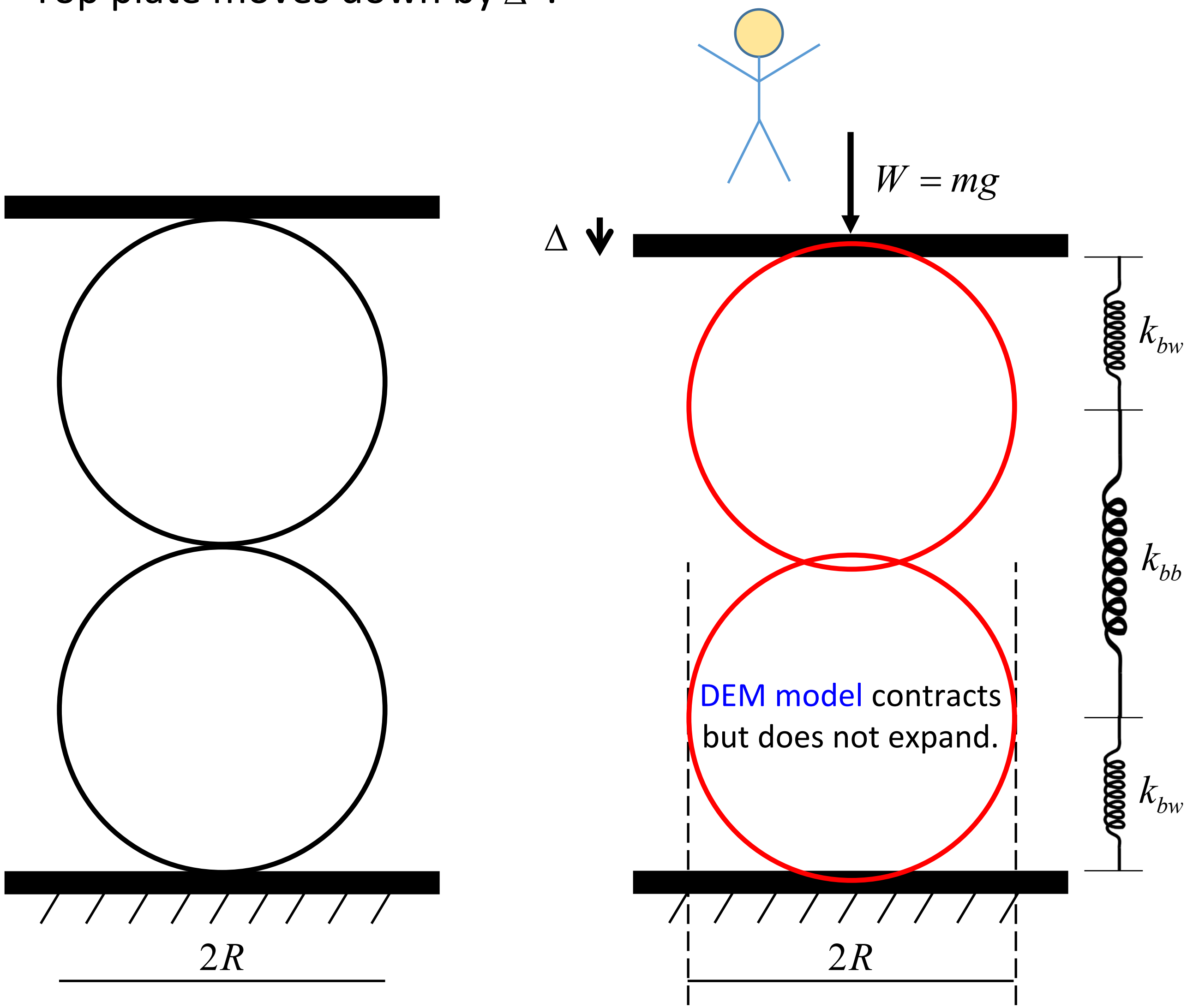
Top plate moves down by Δ .



initial system

loaded system

DEM model employs a "soft contact" approach:

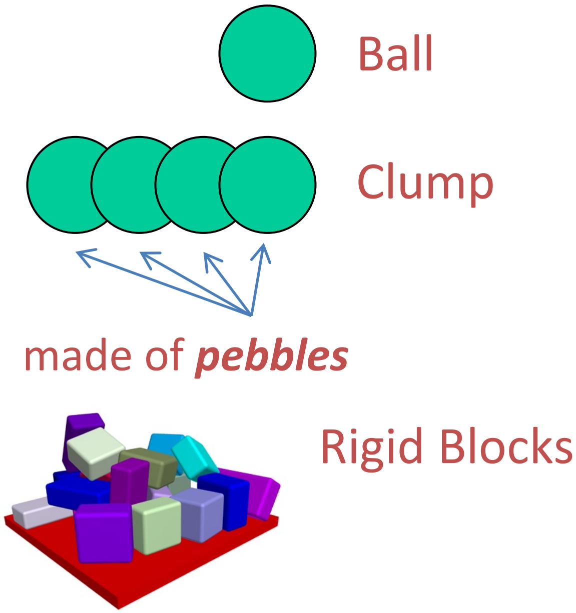
all deformation occurs at the contacts between the rigid bodies.

Bonded-Particle Modeling (PFC model)

PFC model provides four basic entities:

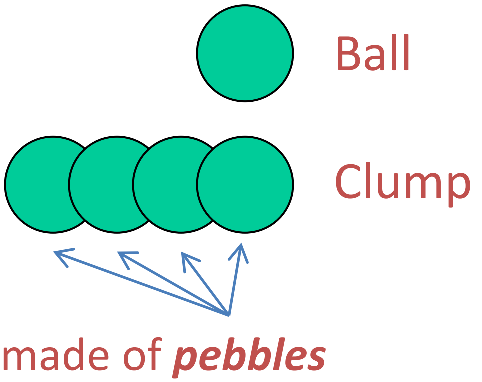
balls, clumps & rigid blocks

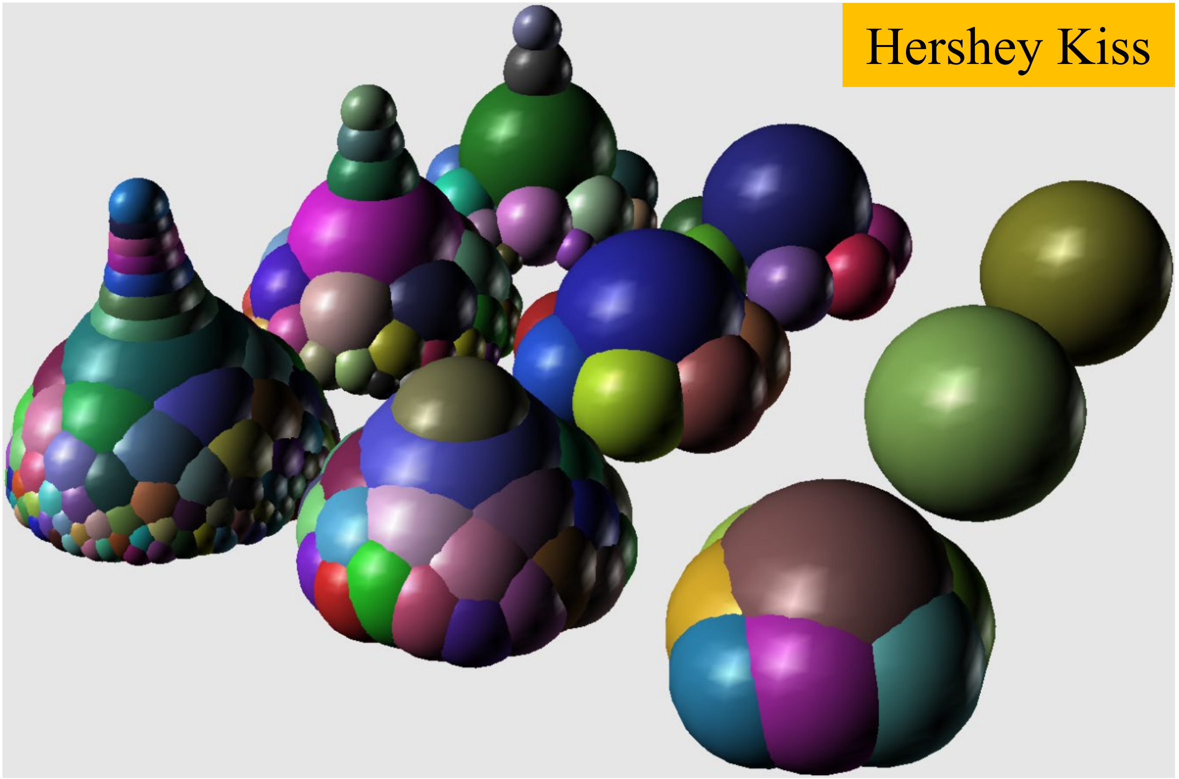
- obey laws of motion
- interact with one another and with walls



What is a clump?

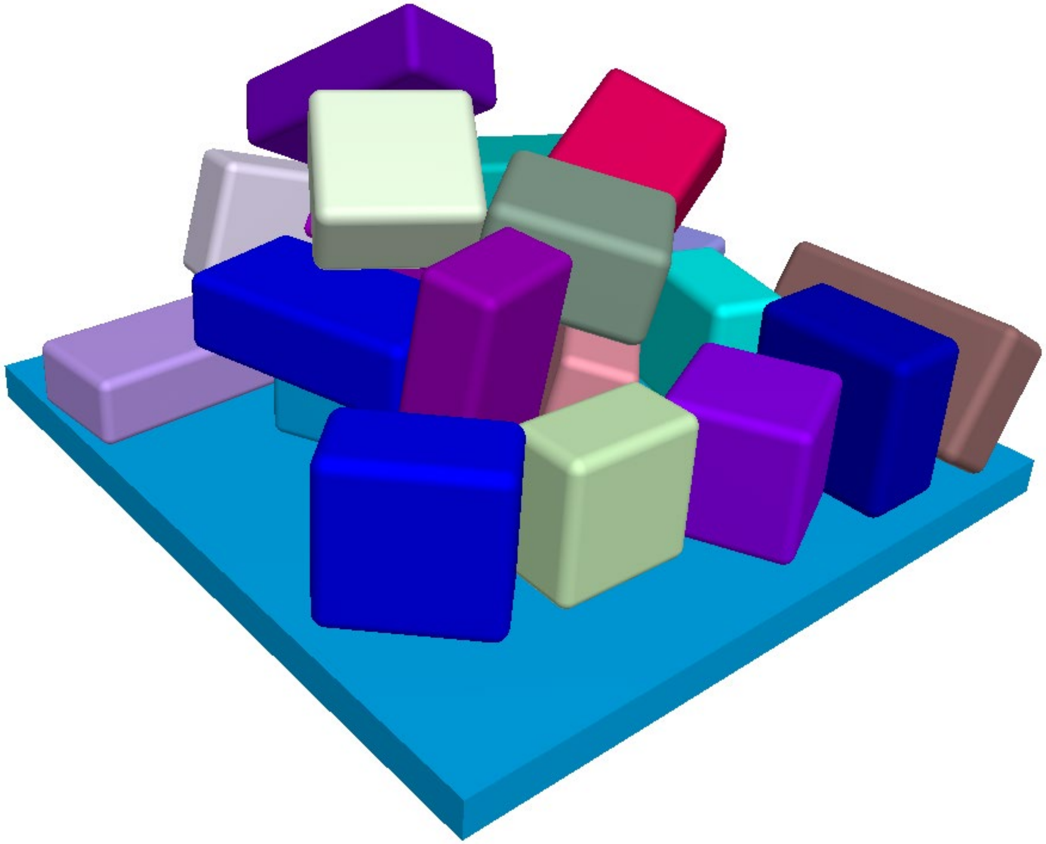
- Group of pebbles that behaves as rigid body with deformable boundary.
- Provides generalized particle shapes.

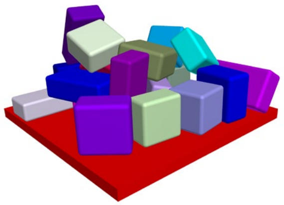




What is a rigid block?

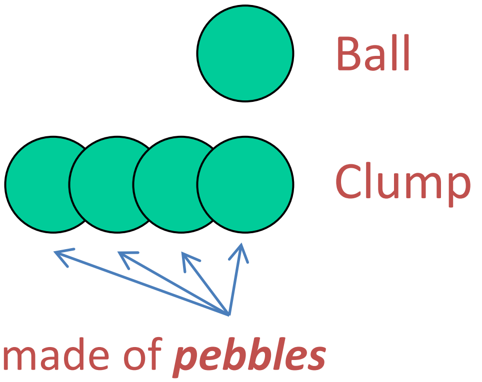
- Convex polyhedron with rounded edges.
- Granular: angular shapes, good interlock
- Solid: zero-porosity intact rock (BBM)





Rigid Blocks

Bonded-Particle Modeling (PFC model)



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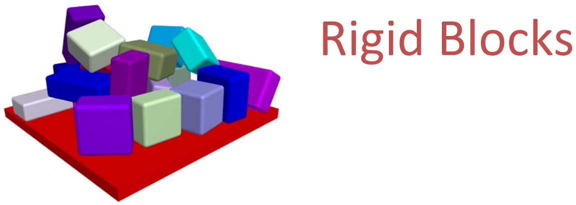
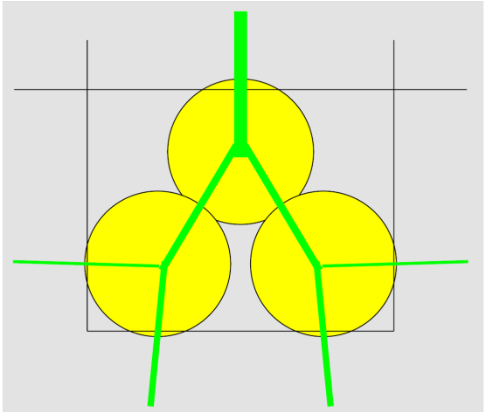


walls

- do not obey laws of motion
- used to apply velocity boundary conditions
- interact *only* with balls, clumps & rigid blocks
- made of facets



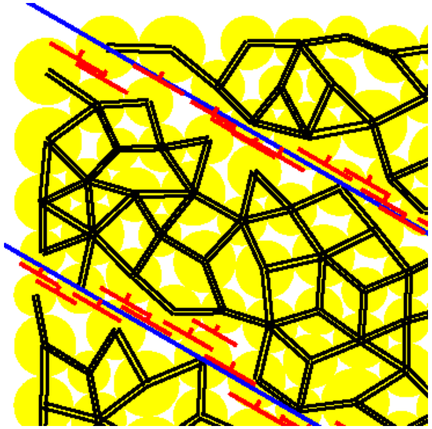
These entities interact at contacts.

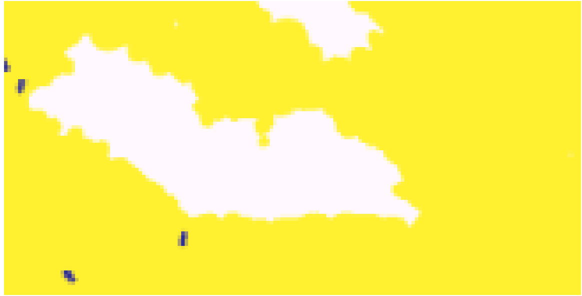
Each contact stores force & moment that act on the two contacting entities.

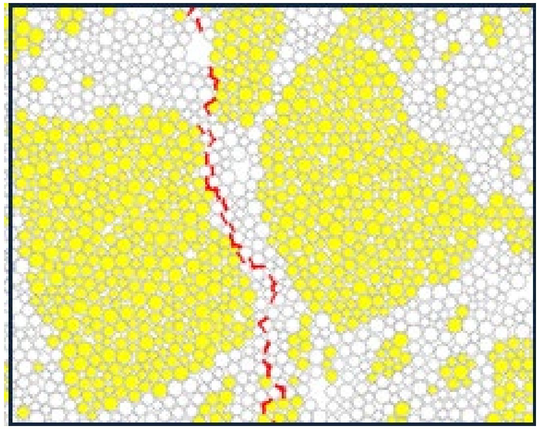
Microstructural Models Provided by BPM

Rich variety of models, described and classified

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







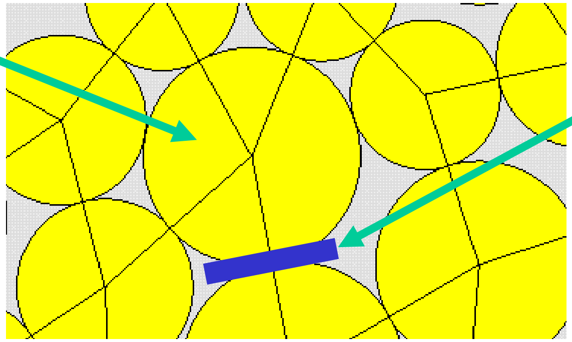
Provide wide range of rock behaviors that encompass

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

Microstructural Models Provided by BPM

Base material itself can serve as model of intact rock

- rigid **grains** joined by deformable & breakable **cement**



grains can be balls, clumps or rigid blocks

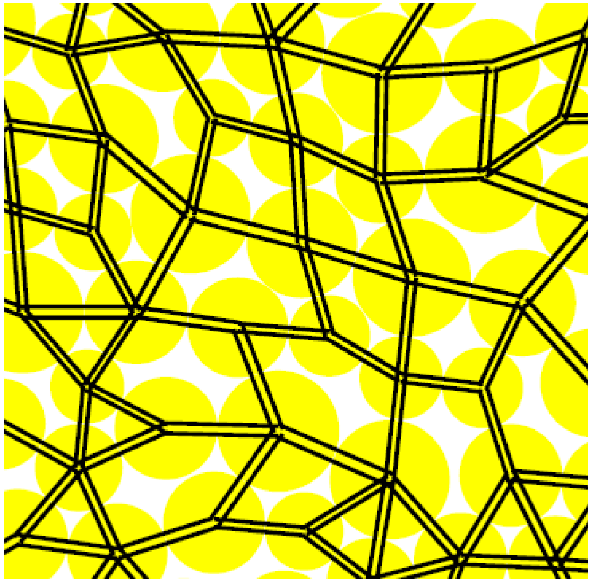
cement can be

- contact-bonded contact
- parallel-bonded contact
- flat-joint contact

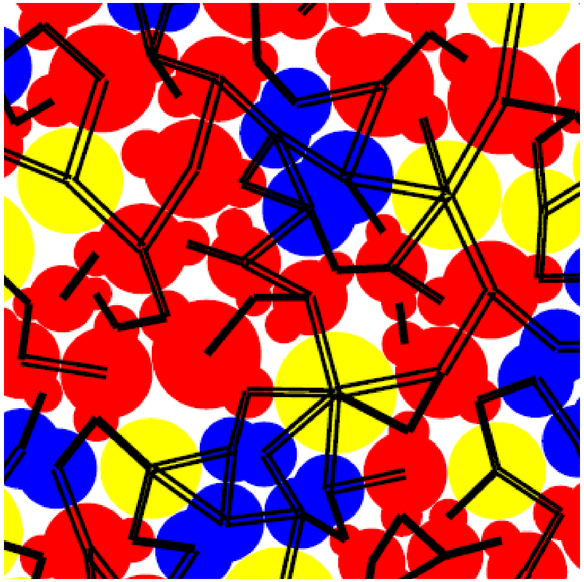
When bond breaks, behaves as linear contact.

Also soft-bonded contact

grains can be balls, clumps. . .



circular grains
(balls)

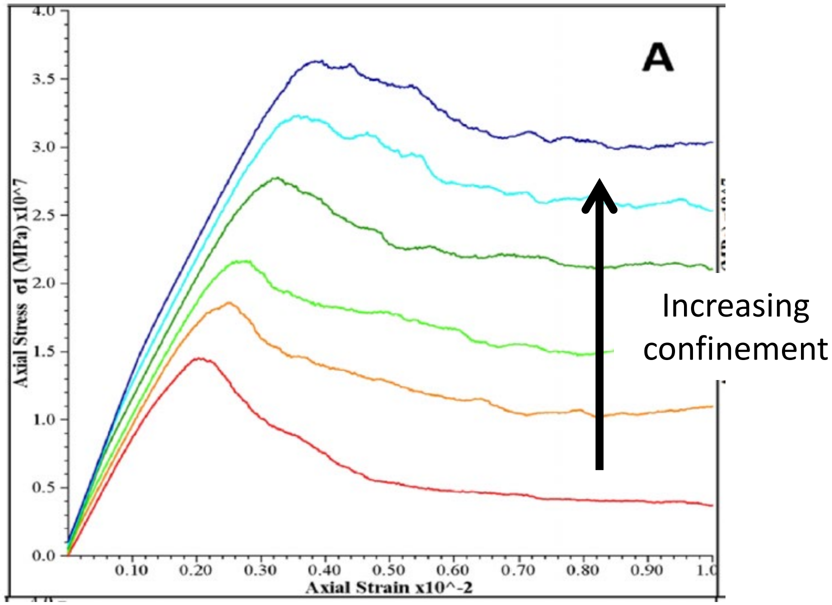


mixed-shape grains
(balls & clumps)

Bonded material consisting of grains (with balls in yellow and clumps in blue and red) and cement (drawn as pairs of black lines).

grains can be balls, clumps or **rigid blocks**

Bonded Tetrahedral Grains



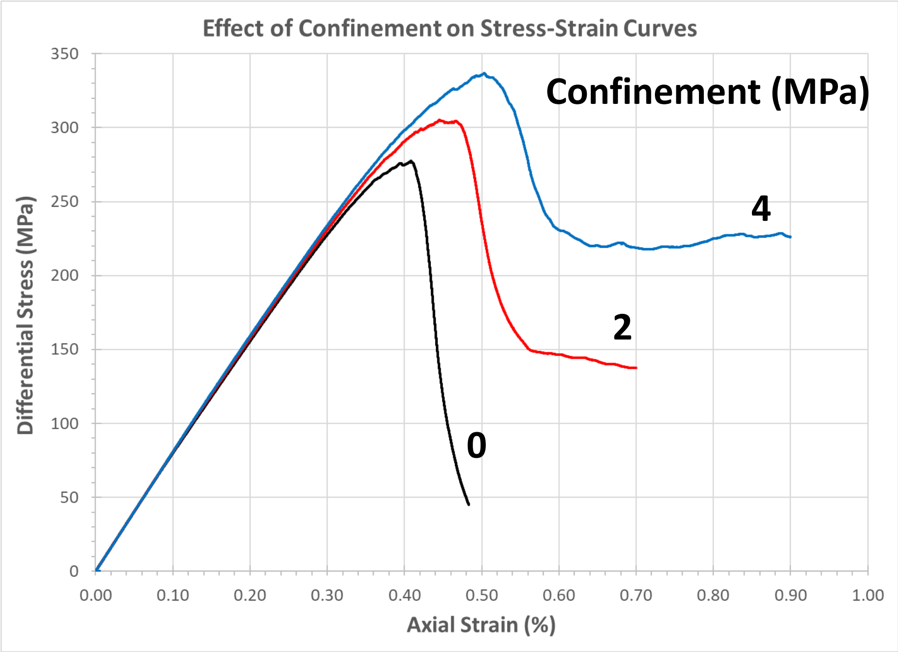
Bonded-block model consisting of grains (tetrahedrons) and cement between grain faces subjected to unconfined-compression test.

Lorig, L., D. Potyondy and Varun. (2020) "Quantifying Excavation-Induced Rock Mass Damage in Large Open Pits," in ***Proceedings, 2020 International Symposium on Slope Stability in Open Pit Mining and Civil Engineering (Virtual Conference, May 2020)***, 969–982. Perth: Australian Centre for Geomechanics.

grains can be balls, clumps or **rigid blocks**

Bonded Voronoi Grains

Triaxial Tests



Bonded-block model consisting of grains (Voronoi cells) and cement between grain faces subjected to unconfined-compression test.

Potyondy, D., J. Vatcher, and S. Emam (2020) "Modeling of Spalling with PFC3D: A Quantitative Assessment," Itasca Consulting Group, Inc., Report to Svensk Kärnbränslehantering AB (SKB), Stockholm, Sweden, 2-5732-02:20R50, October 22, 2020, Minneapolis, Minnesota.

cement can be

- contact-bonded contact
- parallel-bonded contact
- flat-joint contact

Also soft-bonded contact

When bond breaks, behaves as linear contact.

It is the type of contact model at the grain-grain contacts that defines the PFC material as being linear, contact-bonded, parallel-bonded, soft-bonded or flat-jointed.

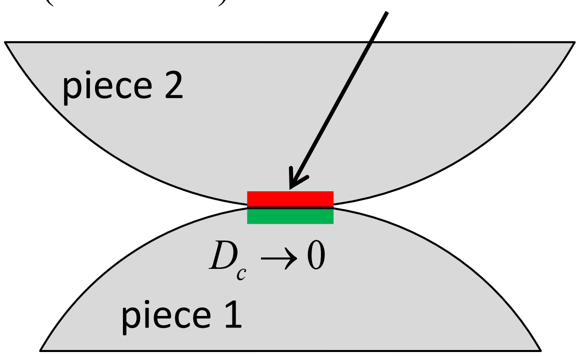
Let's examine each contact model:

Linear Model
Linear Contact Bond Model
Linear Parallel Bond Model
Soft-Bond Model
Flat-Joint Model

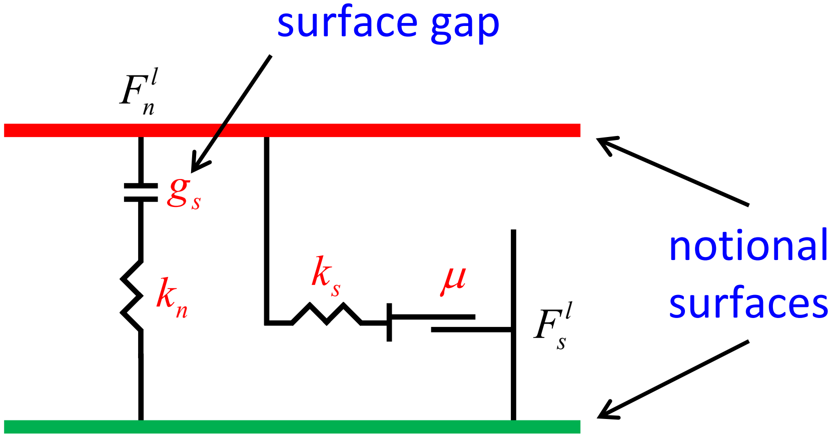
linear contact (behavior summary)

The linear model with a reference gap of zero corresponds with the model of Cundall & Strack (1979).

Linear force $\left(\mathbf{F}^{\mathrm{l}}\right)$, linear elastic (no tension) and frictional.



$$\mathbf{F_c} = \mathbf{F}^{\mathrm{l}}, \ \mathbf{M_c} \equiv \mathbf{0}$$

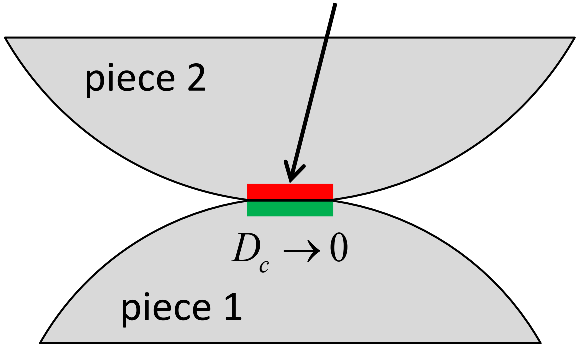


Cundall, P.A, and O.D.L. Strack. (1979) "A Discrete Numerical Model for Granular Assemblies," *Géotechnique*, **29**, 47–65.

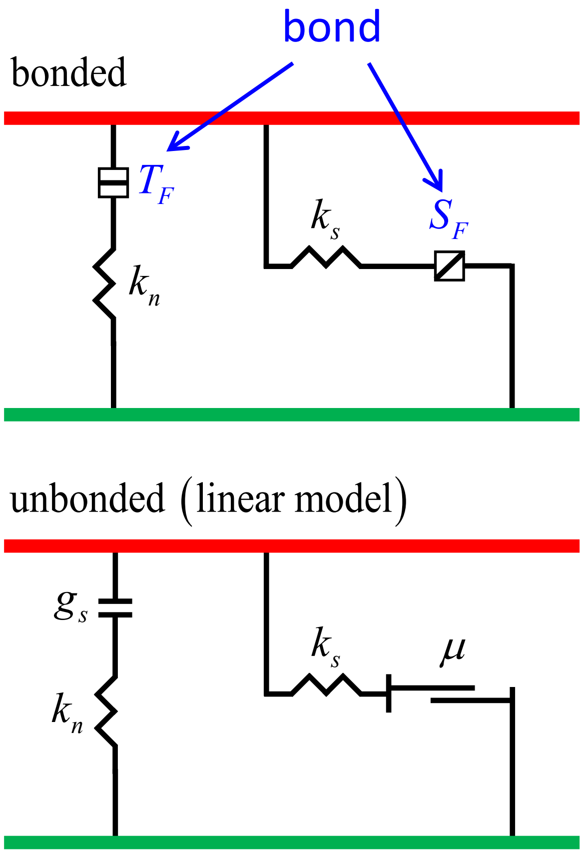
contact-bonded contact (behavior summary)

Add a spot of glue to the linear contact model, no slip while bond is intact.

Linear force $(\mathbf{F}^{l})$, linear elastic & either bonded or frictional.

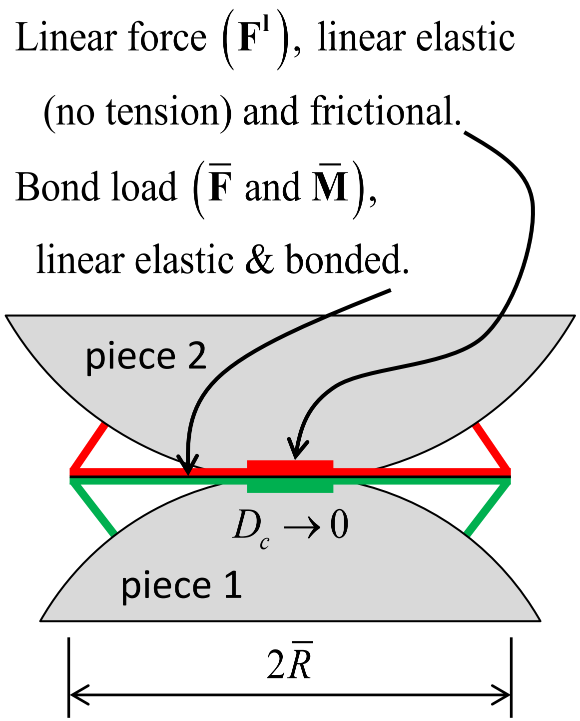


$$\mathbf{F_c} = \mathbf{F}^{l}, \ \mathbf{M_c} \equiv \mathbf{0}$$

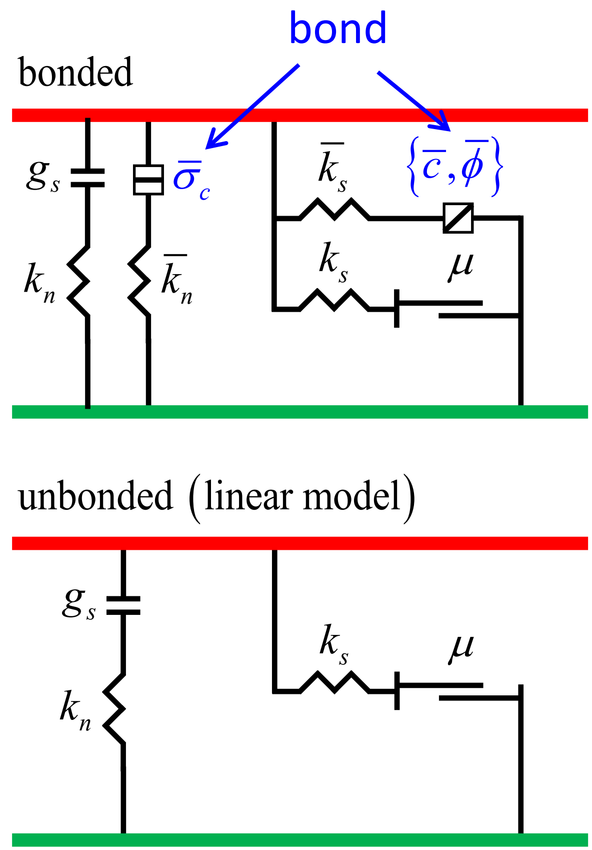


parallel-bonded contact (behavior summary)

Two interfaces.
First interface is same as linear model. Second interface is finite-sized.

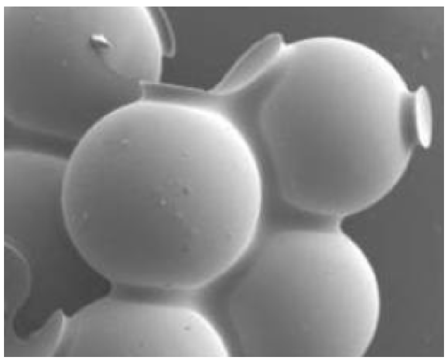


$$\mathbf{F_c} = \mathbf{F}^{l} + \bar{\mathbf{F}},\ \ \mathbf{M_c} = \bar{\mathbf{M}}$$

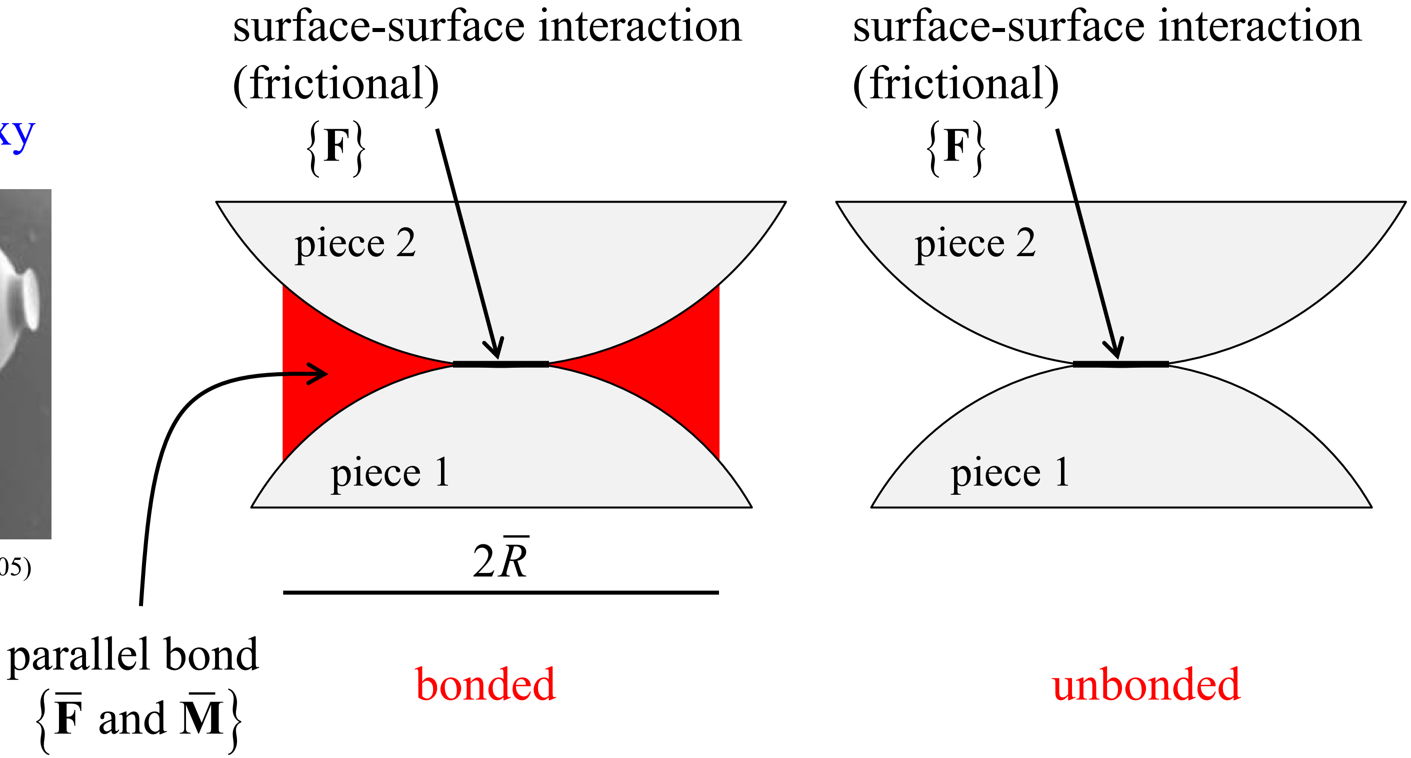


parallel-bonded contact (behavior summary 2)

Glass beads
cemented with epoxy



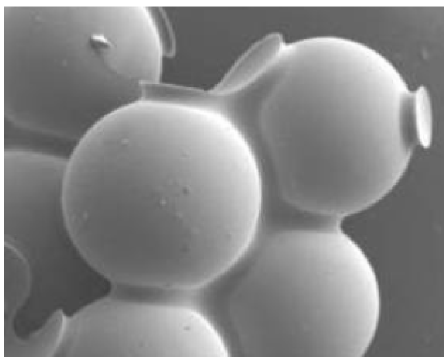
Holt et al. (2005)



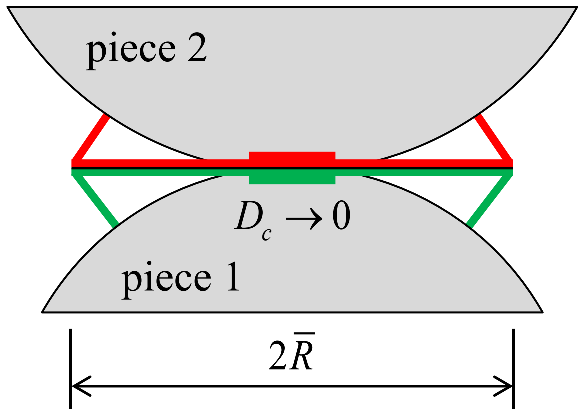
Holt et al. (2005) "Comparison Between Controlled Laboratory Experiments and Discrete Particle Simulations of the Mechanical Behavior of Rock," *Int. J. Rock Mech. & Min. Sci.*, ***42***, 985-995.

parallel-bonded contact (behavior summary 3)

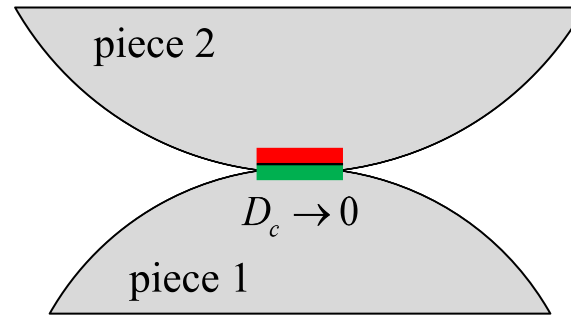
Glass beads cemented with epoxy



Holt et al. (2005)



bonded



unbonded

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

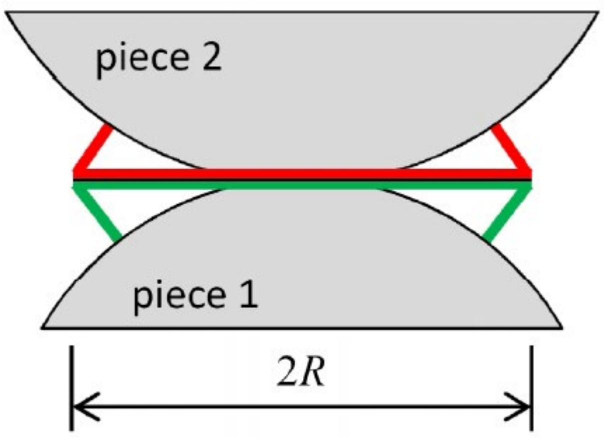
soft-bonded contact (behavior summary)

Like parallel bond with tensile softening.
When unbonded, has rolling resistance.

Dashpot force $(\mathbf{F}^d)$, not shown.

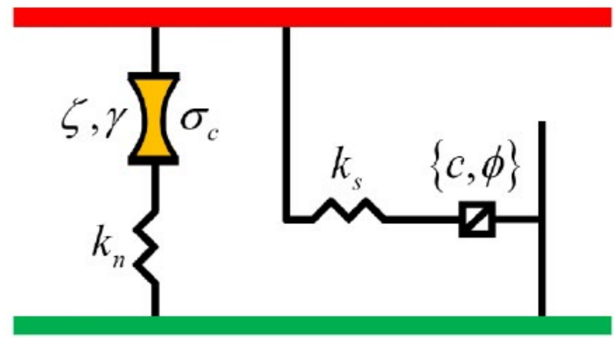
Unbonded: elastic (no tension), frictional with rolling resistance.

Bonded: elastic with tensile softening



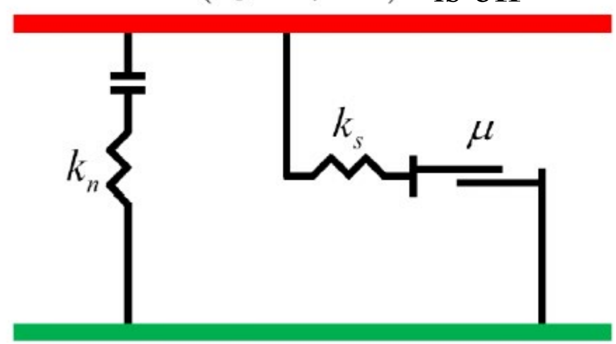
$$\mathbf{F}_c = \mathbf{F}^d + \mathbf{F}, \quad \mathbf{M}_c = \mathbf{M}$$

bonded

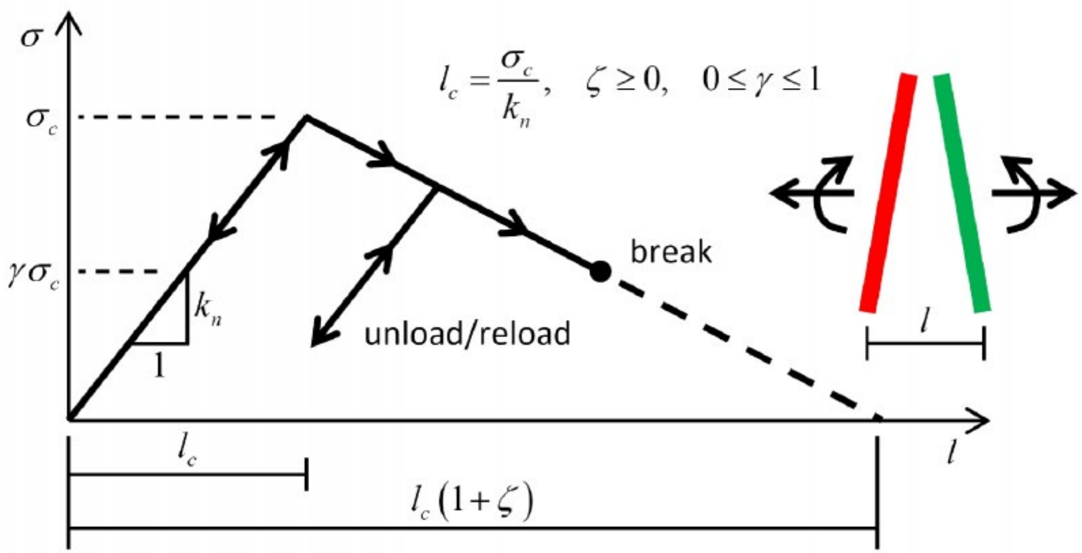


unbonded $(\lambda_b = \lambda_r = 0)$

rolling resistance is off



soft-bonded contact (behavior summary 2)



σ : maximum normal stress at bond periphery

l : elongation at bond periphery $(l \geq 0)$

l_c : critical bond elongation at peak strength

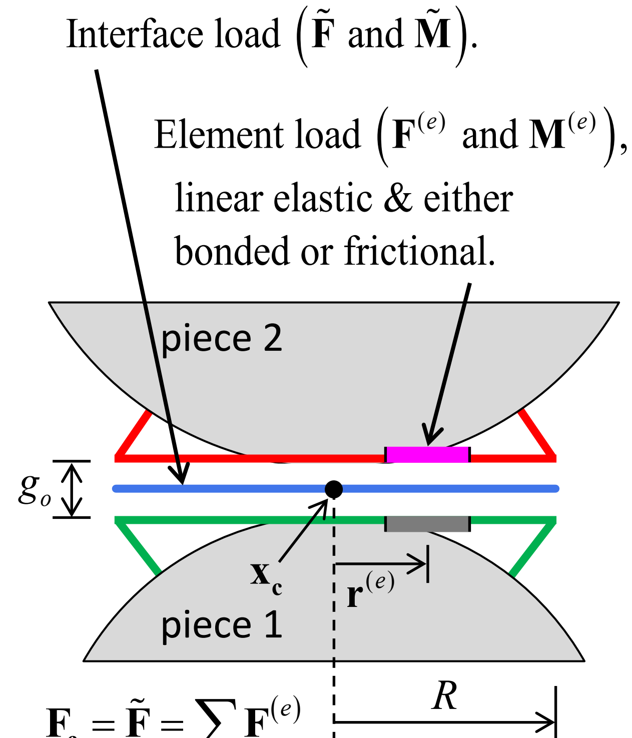
σ_c : tensile strength [stress]

k_n : normal stiffness [stress/displacement]

ζ : softening factor $(\zeta \geq 0, \ \zeta = 0$ is no softening$)$

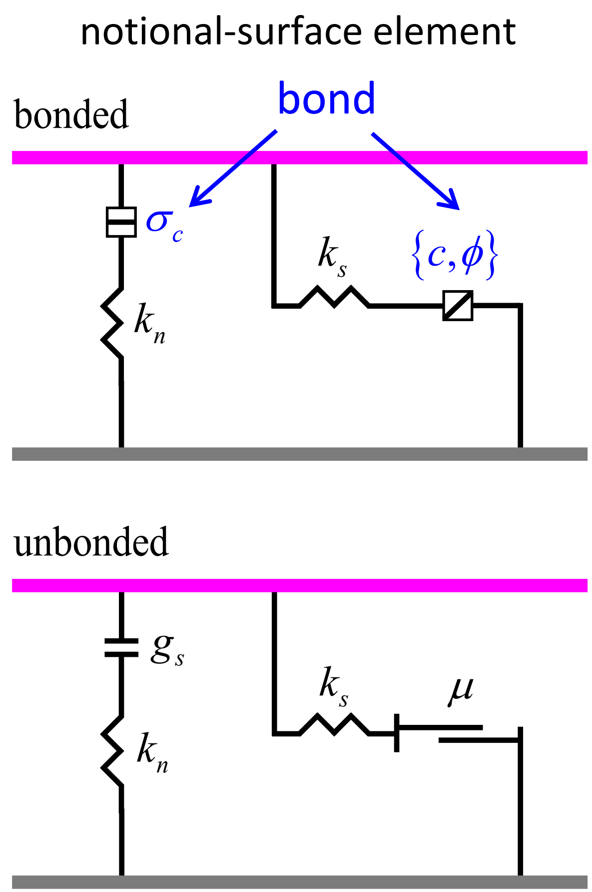
γ : strength-reduction factor $\begin{pmatrix} 0 \leq \gamma \leq 1 \\ \gamma = 0 \text{ is full softening} \\ \gamma = 1 \text{ is no softening} \end{pmatrix}$

flat-joint contact (behavior summary)



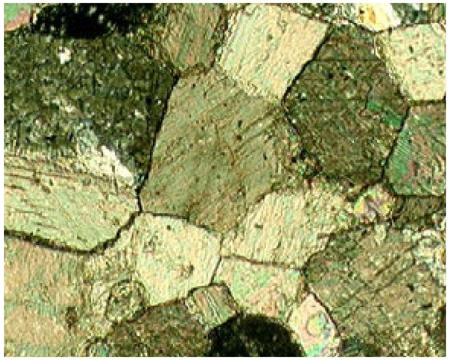
$$\mathbf{F}_c = \tilde{\mathbf{F}} = \sum_{\forall e} \mathbf{F}^{(e)}$$

$$\mathbf{M}_c = \tilde{\mathbf{M}} = \sum_{\forall e} \left\{ \left(\mathbf{r}^{(e)} \times \mathbf{F}^{(e)} \right) + \mathbf{M}^{(e)} \right\}$$

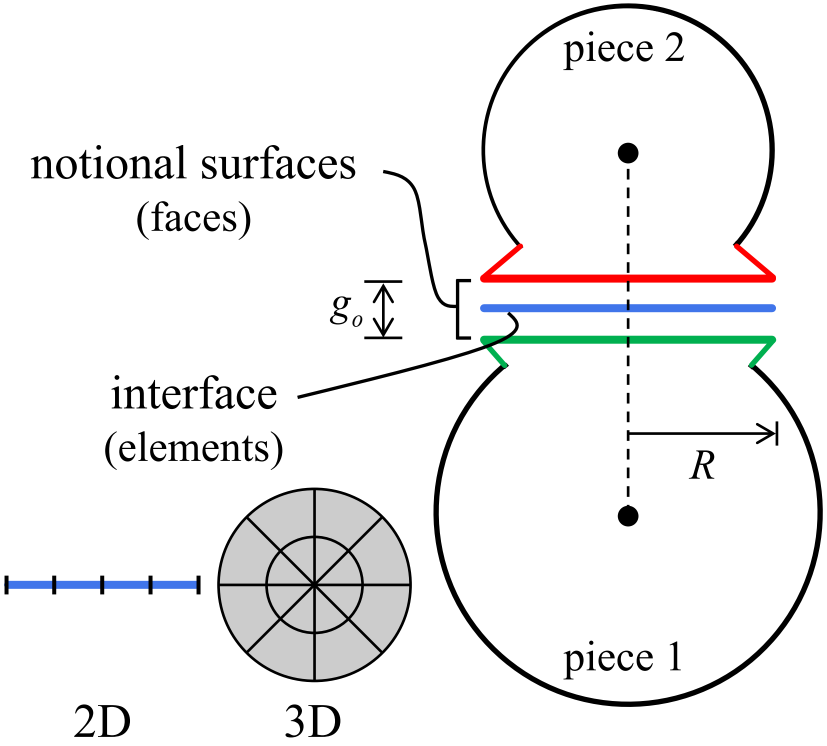


flat-joint contact (behavior summary 2)

Marble with angular, interlocked grains



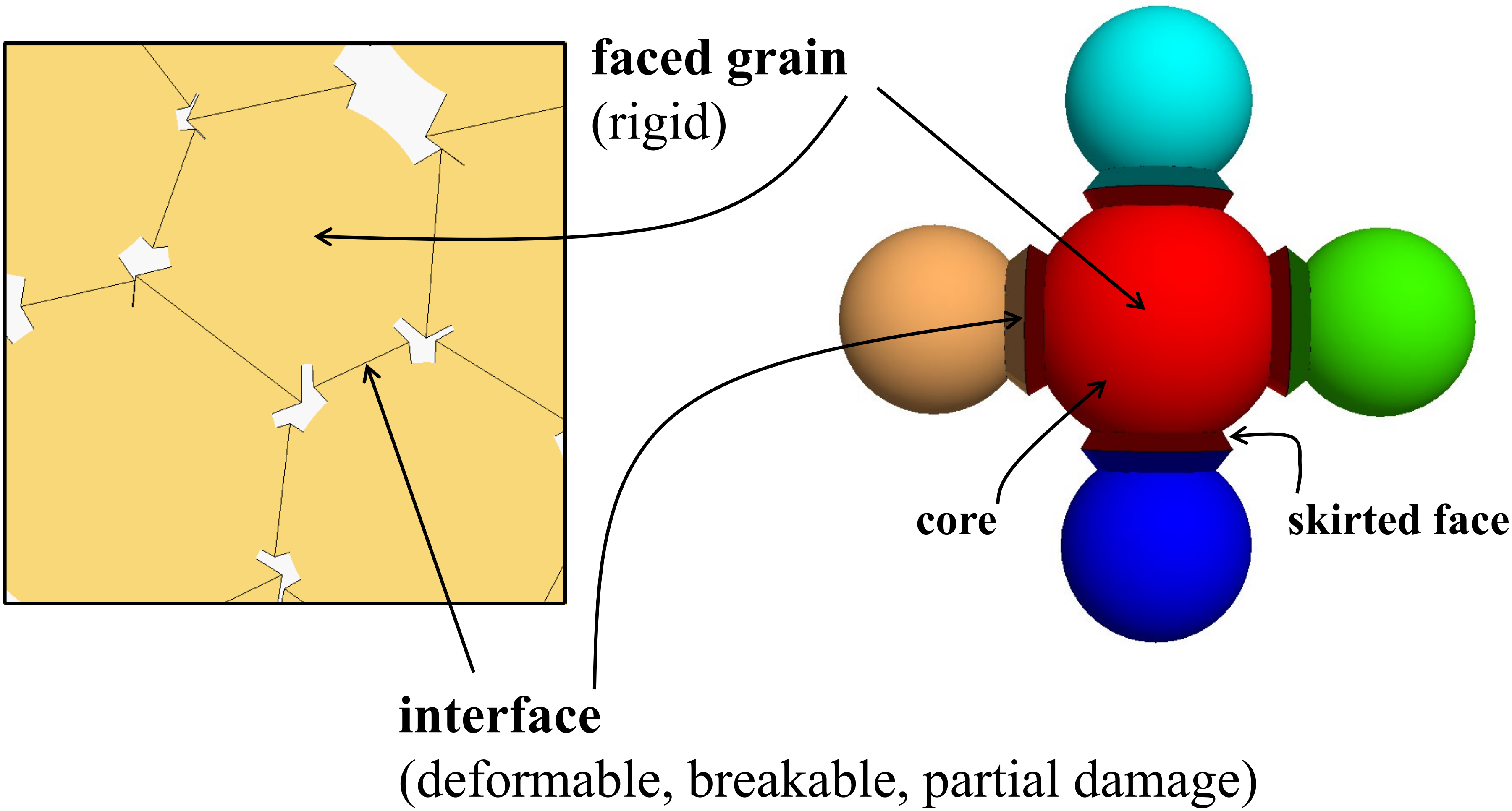
Bandini et al. (2012)



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

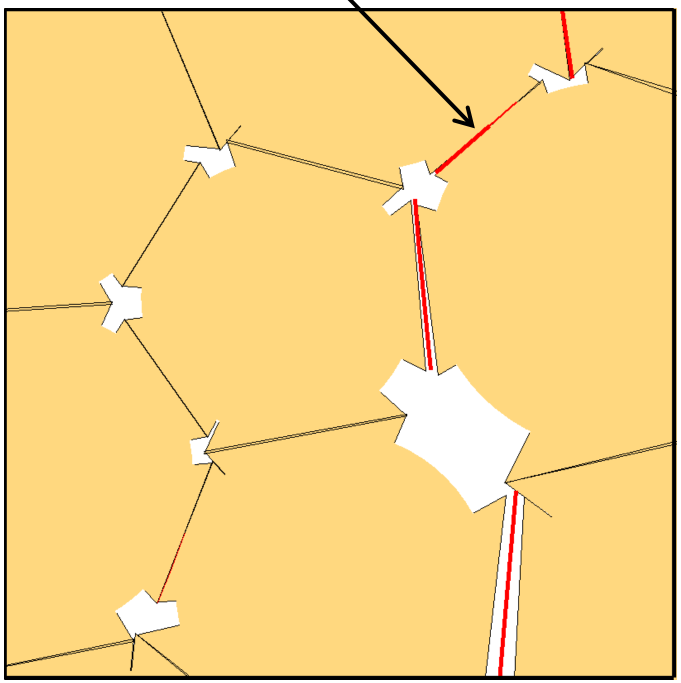
Bandini et al. (2012) "Effects of Intra-Crystalline Microcracks on the Mechanical Behavior of a Marble Under Indentation," *Int. J. Rock Mech. & Min. Sci.*, ***54***, 47-55.

flat-joint contact (behavior summary 3)

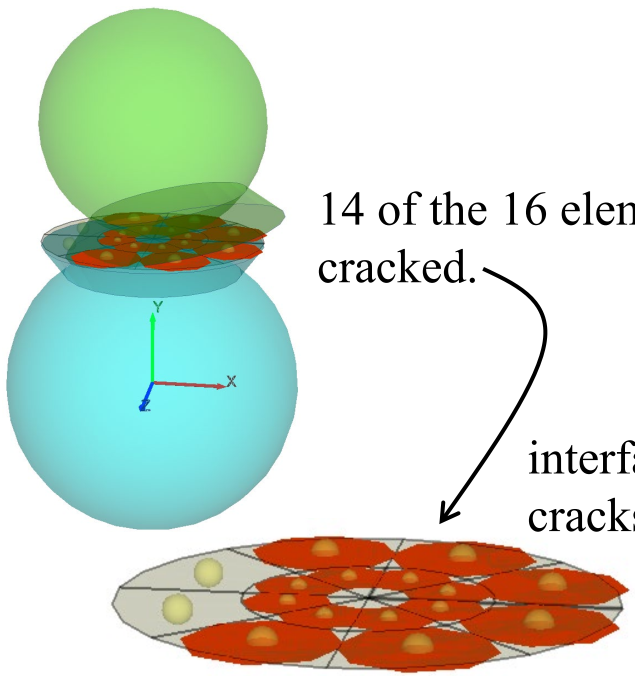


flat-joint contact (behavior summary 4)

Bending failure with. . .

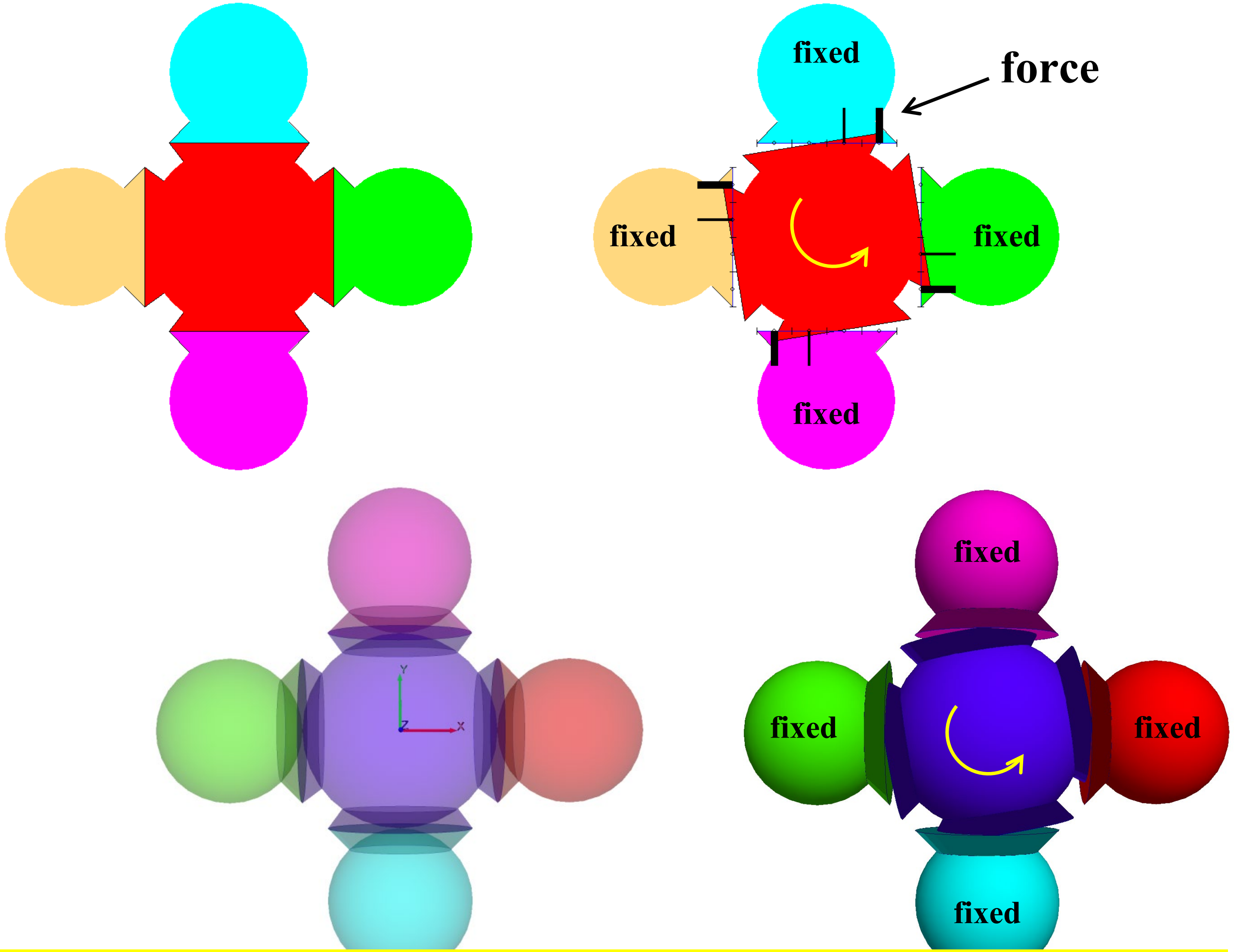


Crack thickness is proportional to gap.



The interface can sustain partial damage.

flat-joint contact (behavior summary 5)



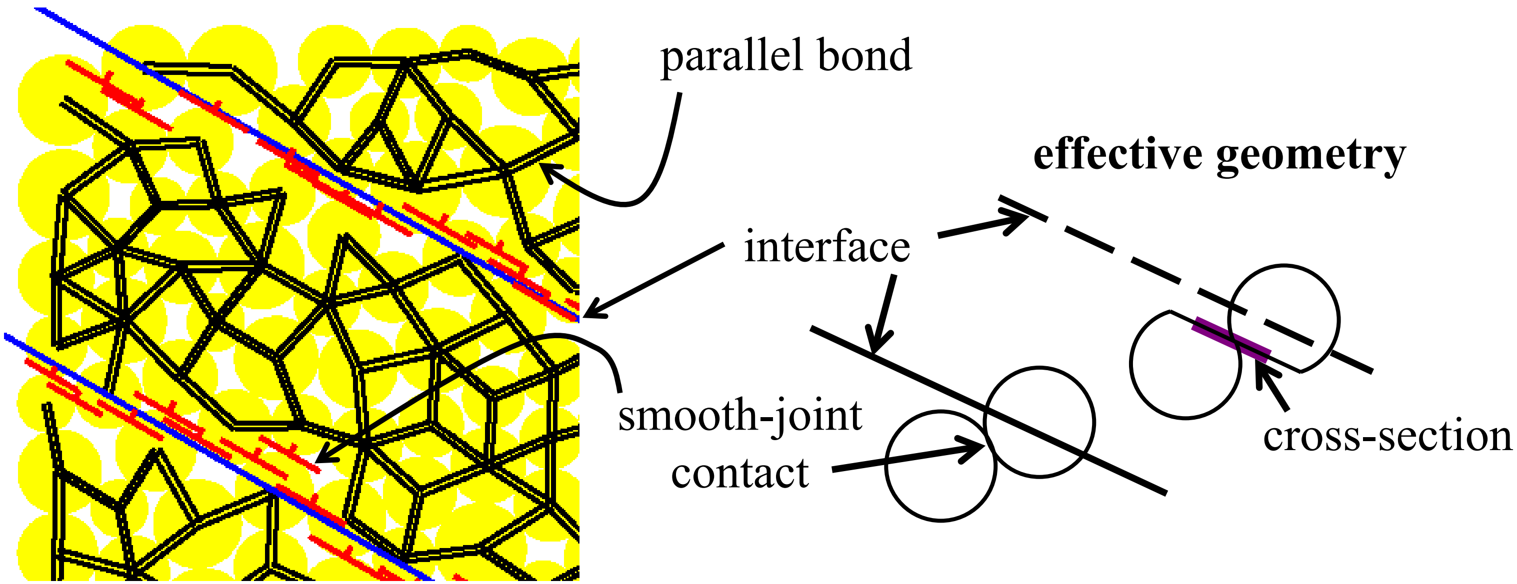
Even a fully broken interface continues to resist relative rotation.

Microstructural Models Provided by BPM

Joints can be overlaid on base material

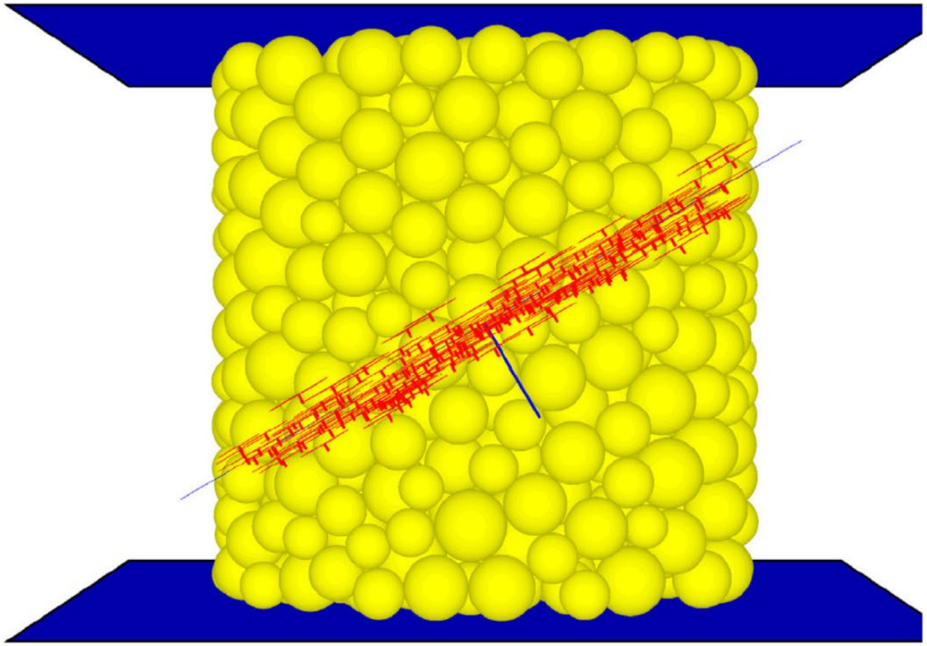
- joint behaves as **interface**

interface is collection of smooth-joint contacts

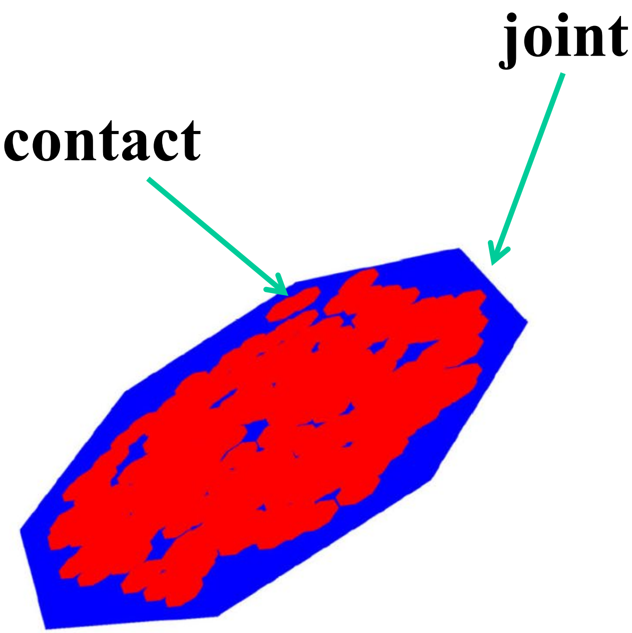


Smooth-joint contacts may be initially bonded. When bond breaks, they behave as linear contact.

smooth-joint contact (behavior summary)



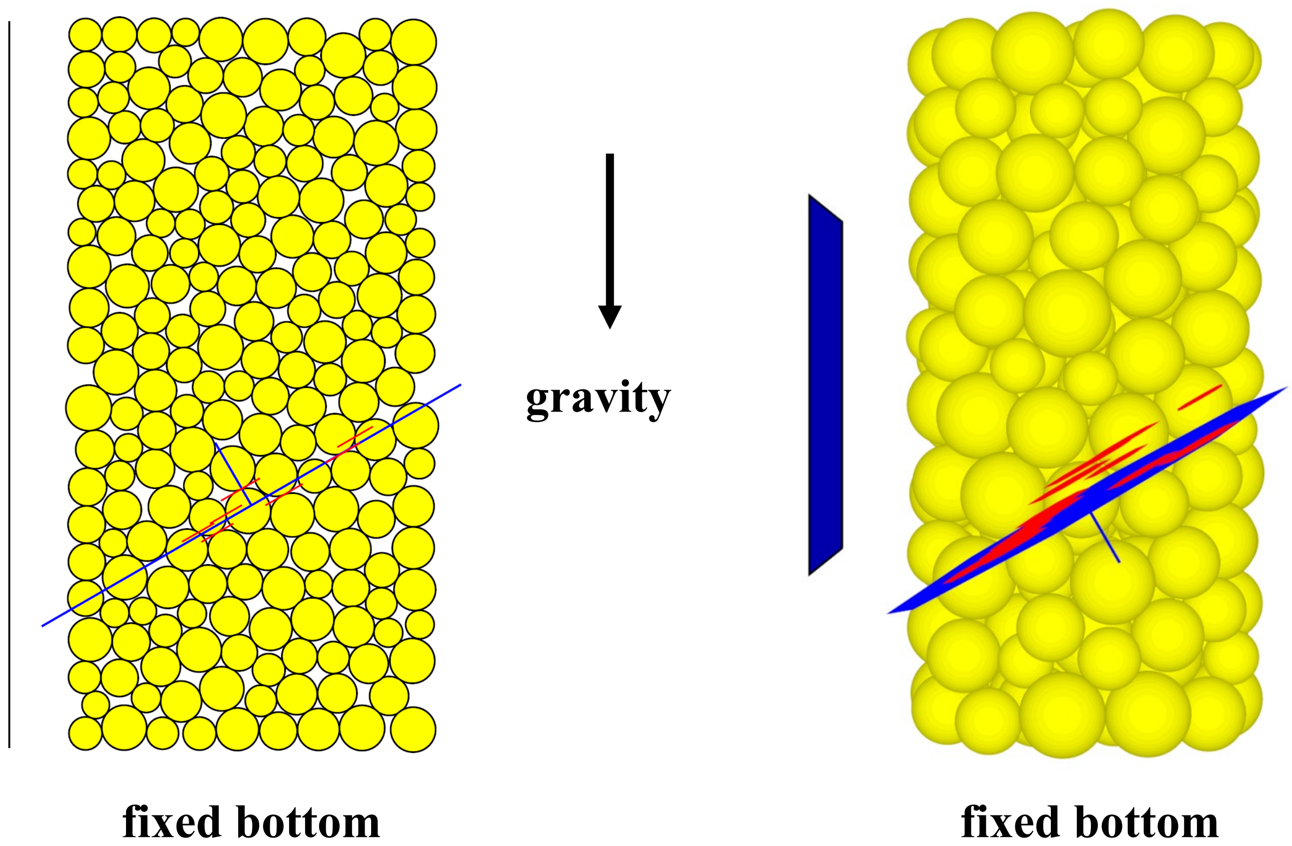
BPM with joint



Joint & smooth-joint contacts

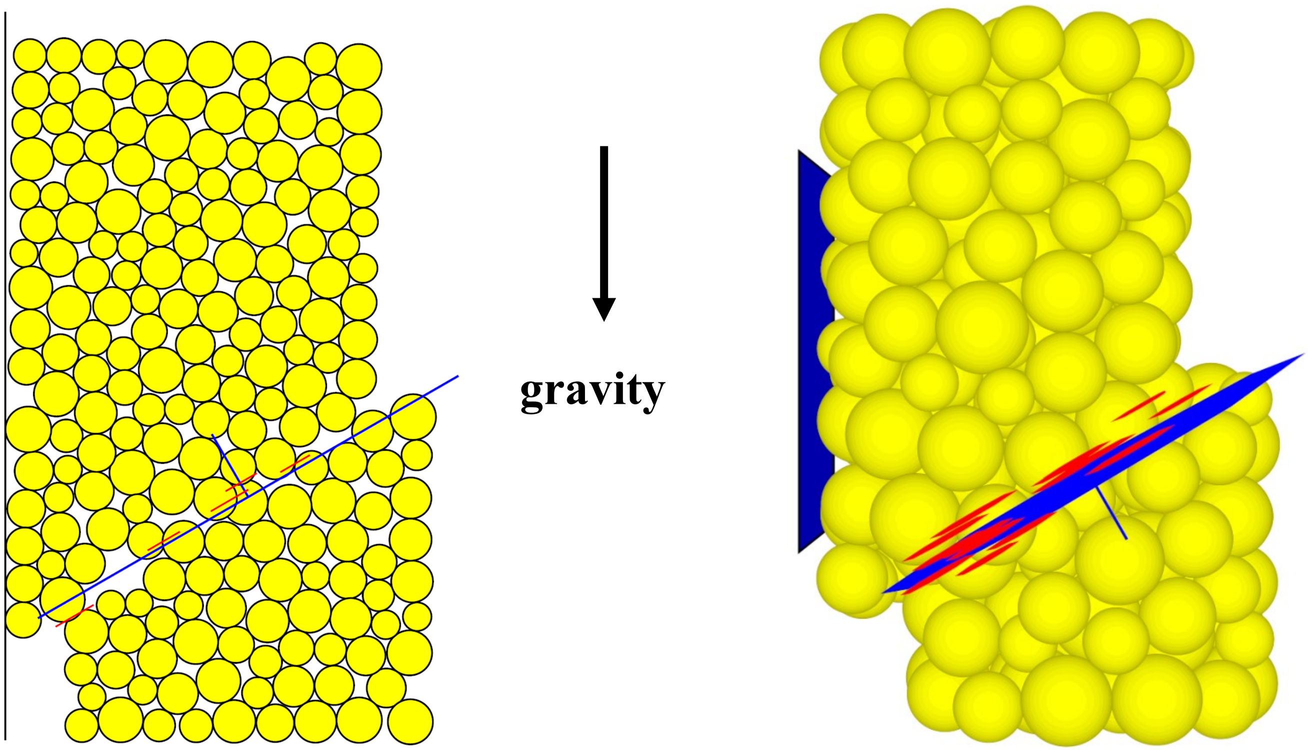
smooth-joint contact (behavior summary)

Joint friction coefficient equals one. . .



smooth-joint contact (behavior summary)

Joint friction coefficient equals zero. . .

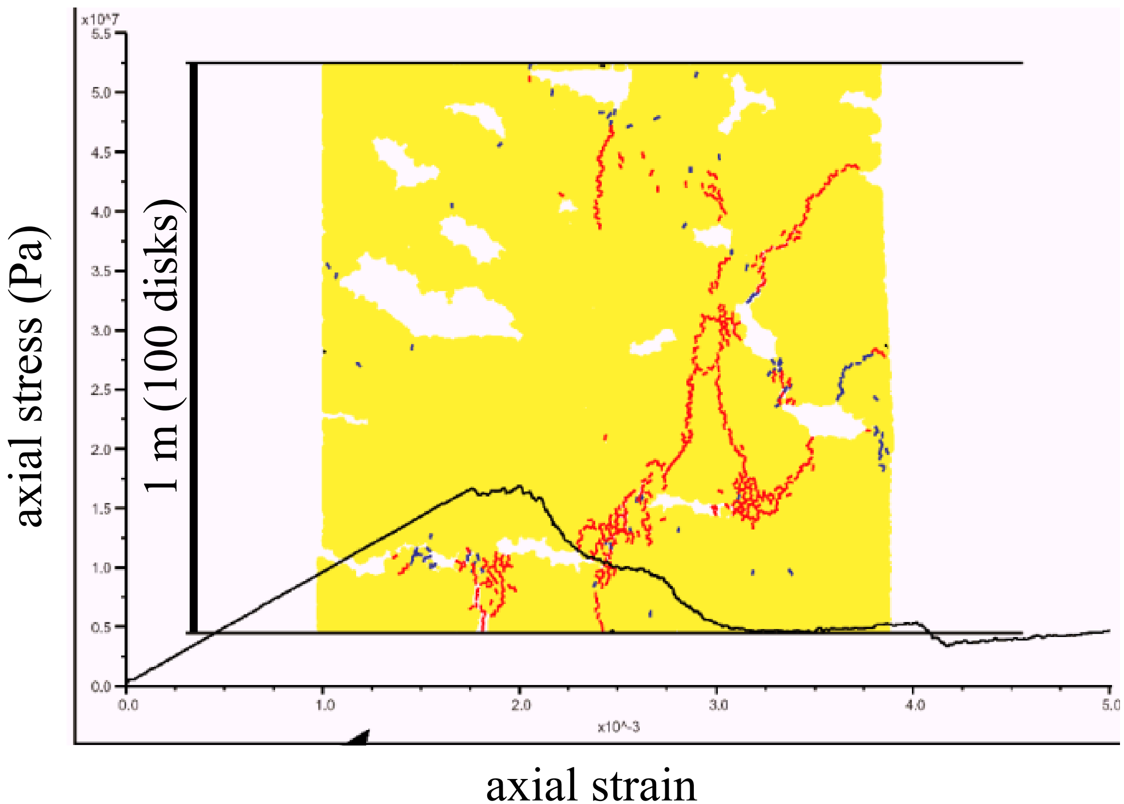


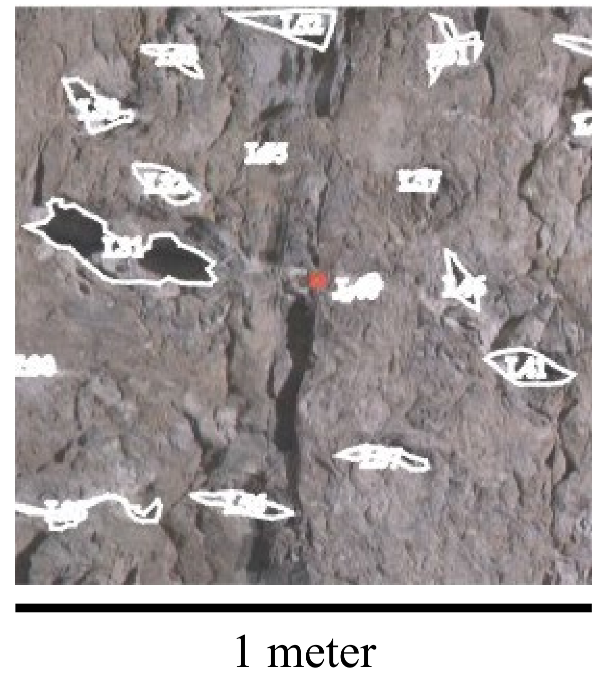
fixed bottom **fixed bottom**

Microstructural Models Provided by BPM

Void regions are identified…

- grains within these regions are removed





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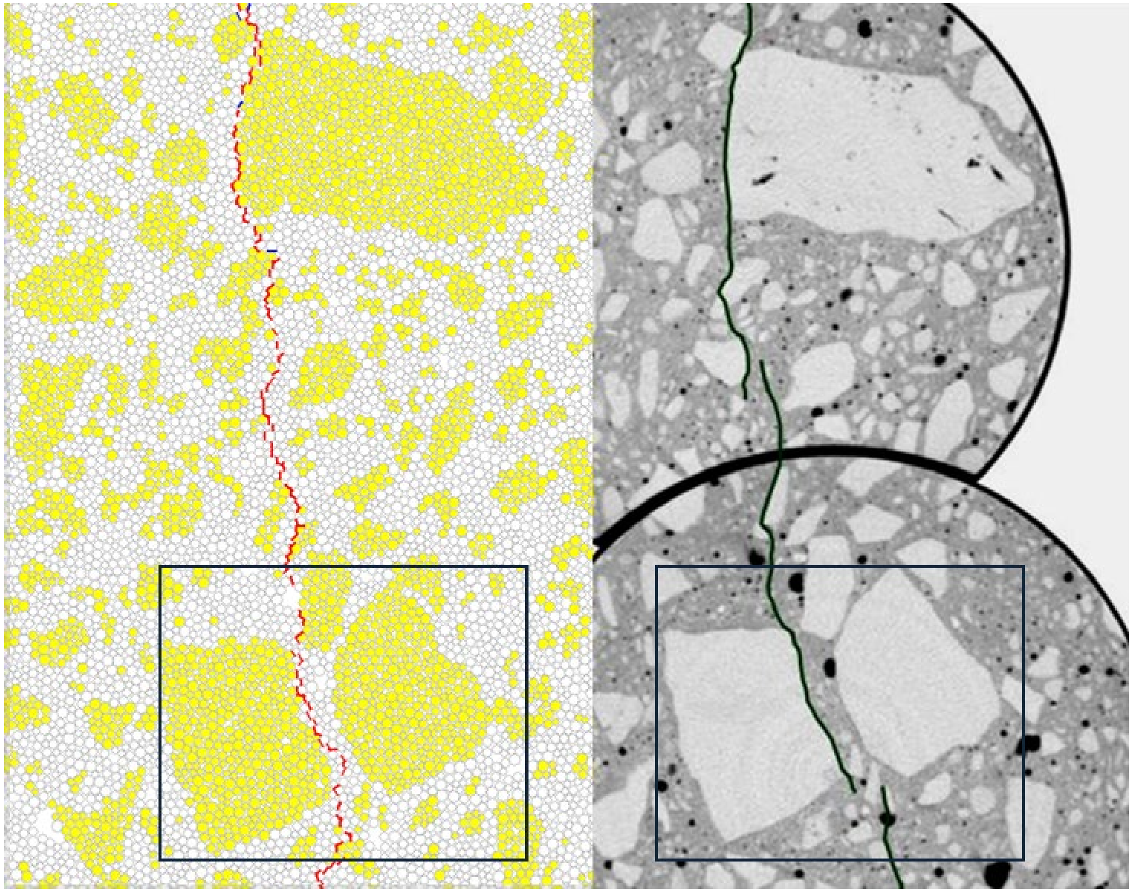
Potyondy (2007) "The Effect of Voids on the Mechanical Properties of Rock," in Proc. 4th Int. Conf. on Discrete Element Methods, Brisbane, Australia, Cleary, Ed., MEI Conferences, CD.

Microstructural Models Provided by BPM

Material regions are identified…

- grains & contacts within these regions are assigned properties



Katsaga (2010)

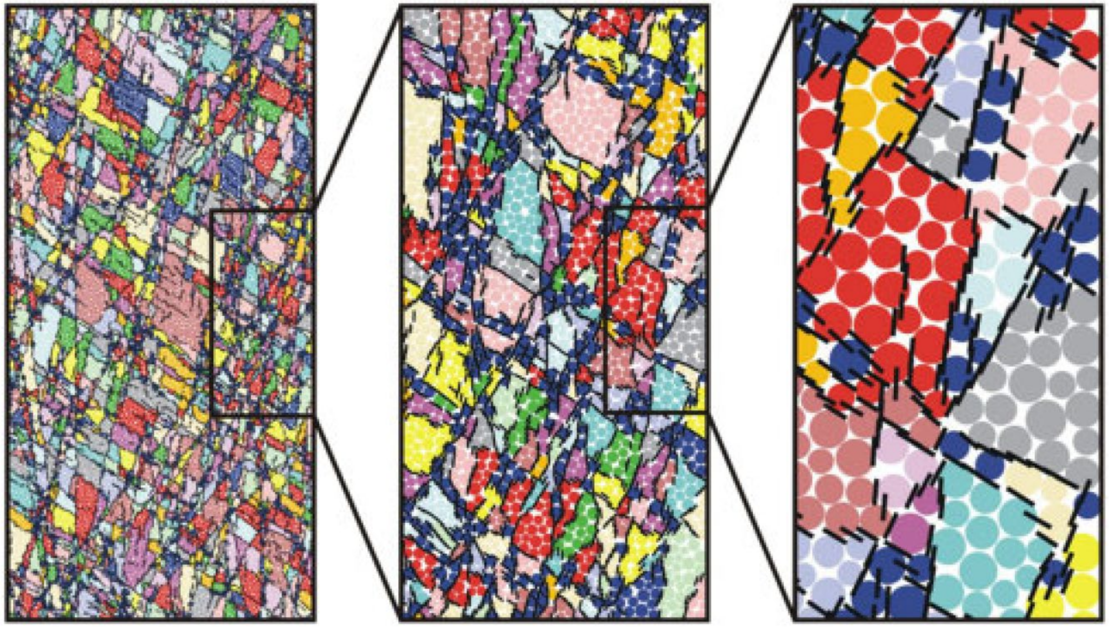
Katsaga, T. (2010) "Geophysical Imaging and Numerical Modelling of Fractures in Concrete," Ph.D. Thesis, University of Toronto.

Microstructural Models Provided by BPM

Joints are identified…

- contacts that lie along these joints are assigned properties

Synthetic Rock Mass (SRM)



SRMs are used to represent a rock mass. The BPMs are remarkably complex, and used to study impact of joint fabric on rock mass strength, brittleness and fragmentation.

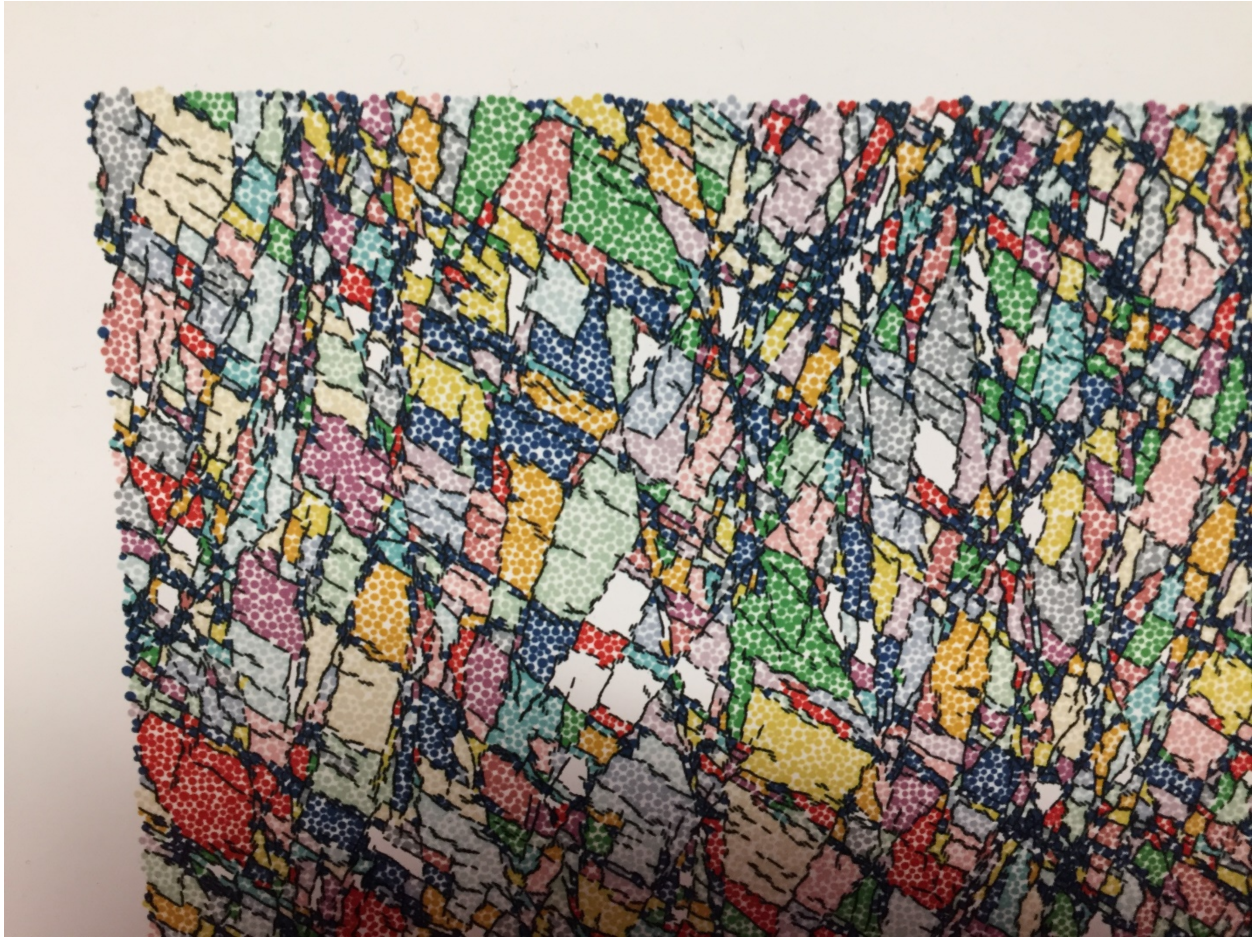
Mas Ivars et al. (2011) "The Synthetic Rock Mass Approach for Jointed Rock Mass Modelling," *Int. J. Rock Mech. & Min. Sci.*, ***48***, 219–244.

Microstructural Models Provided by BPM

Synthetic Rock Mass (SRM)

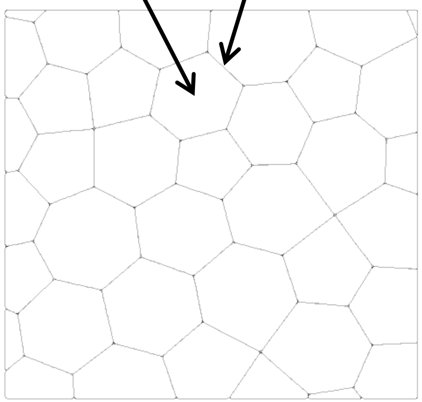
Microstructural Models Provided by BPM

Synthetic Rock Mass (SRM)



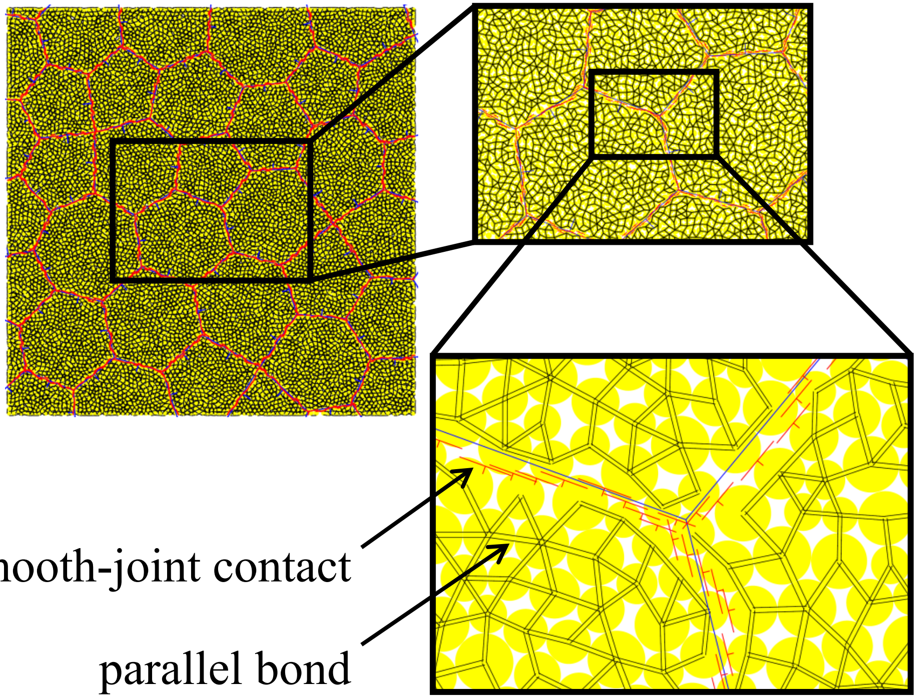
Microstructural Models Provided by BPM

Material regions & joints are identified…



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.

Examples

Ceramic bead & Undercut cemented backfill

Matching uniaxial & tensile strengths of compact rock

- two alternative intact BPMs

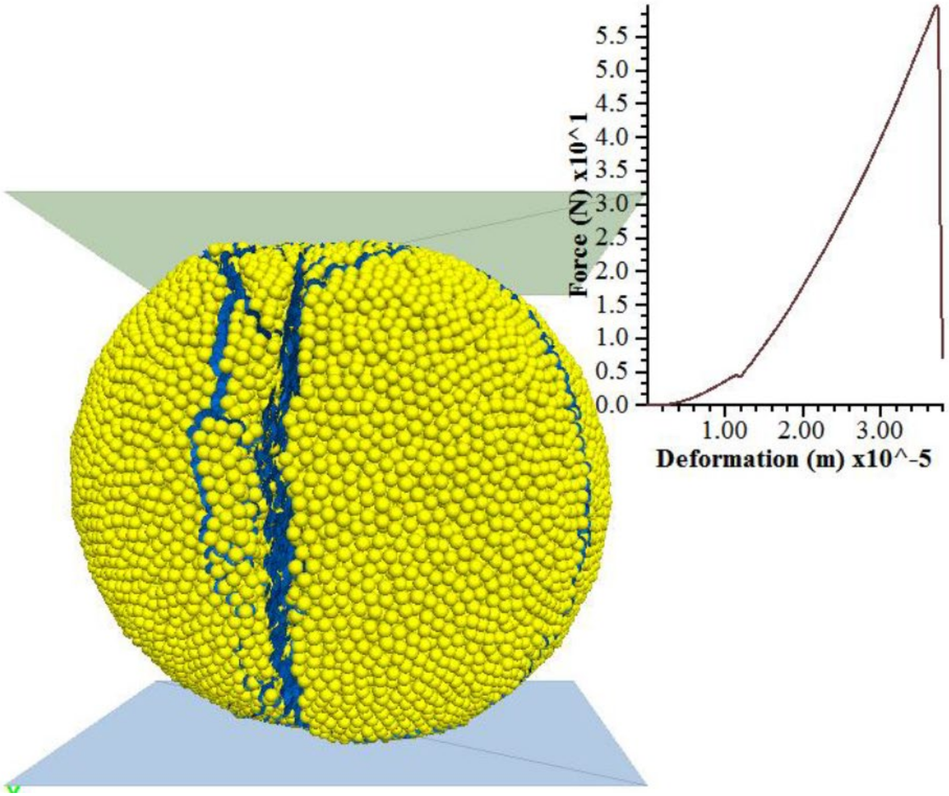
Embed BPM within larger continuum model

- study fracturing around advancing stope in quartzite

Sandstone Perforation Failure

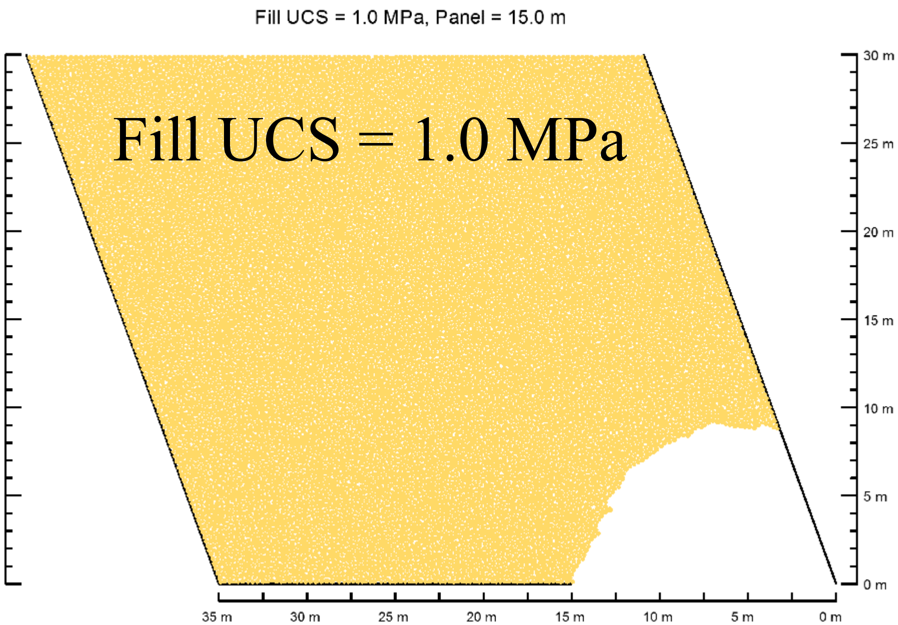
Examples (ceramic bead PFC3D, parallel-bonded material)

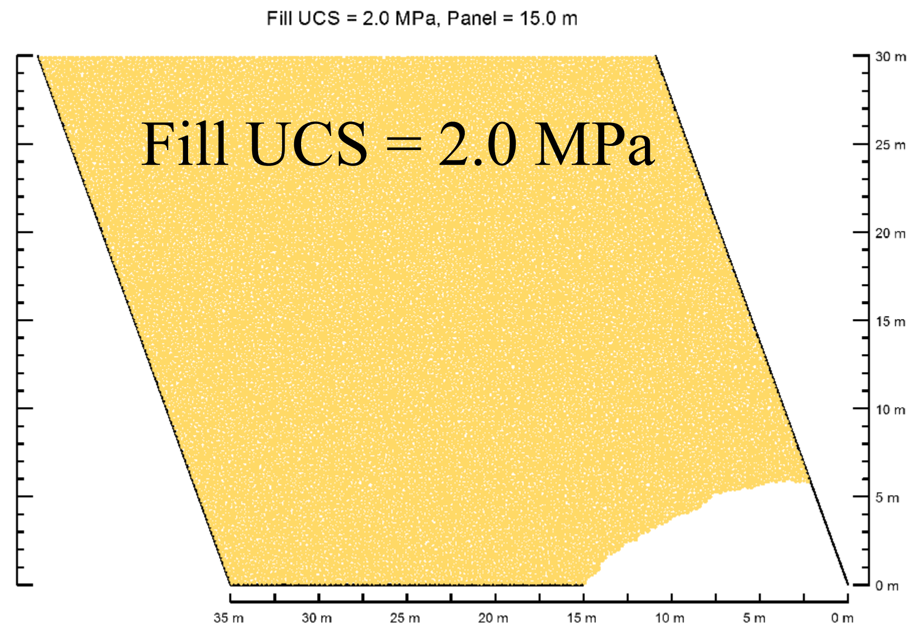
These models:
* Matched Hertzian response
* Computed breakage stress (solid & hollow beads)

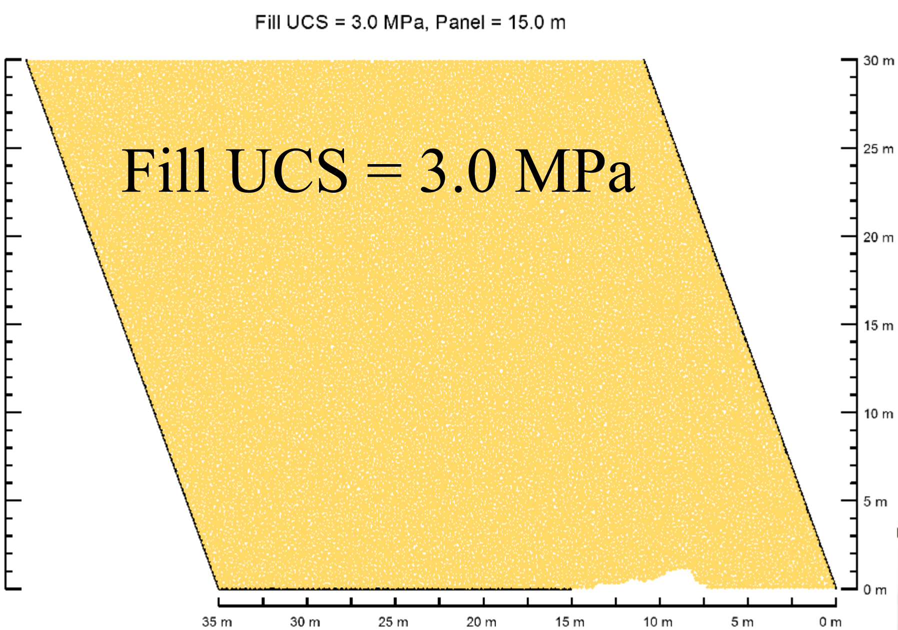


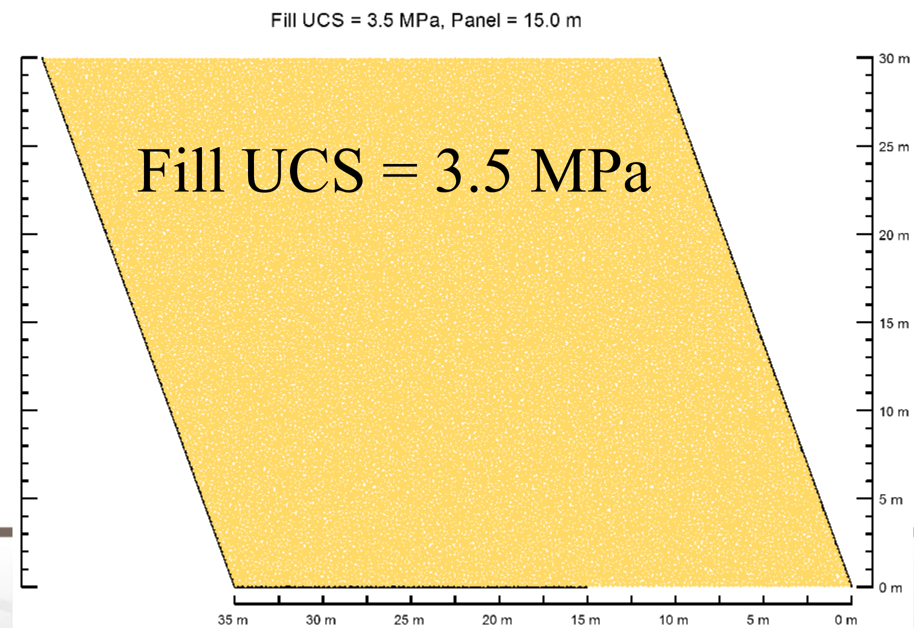
Varun, and D.O. Potyondy (2015) "Mechanical Modeling of Ceramic Beads," Itasca Consulting Group, Inc., Report to JPL: Thermal Energy Conversion Technologies Group, Pasadena, CA, 15-2929-40, May 18, 2015.

Examples (undercut cemented backfill PFC2D, flat-jointed material)

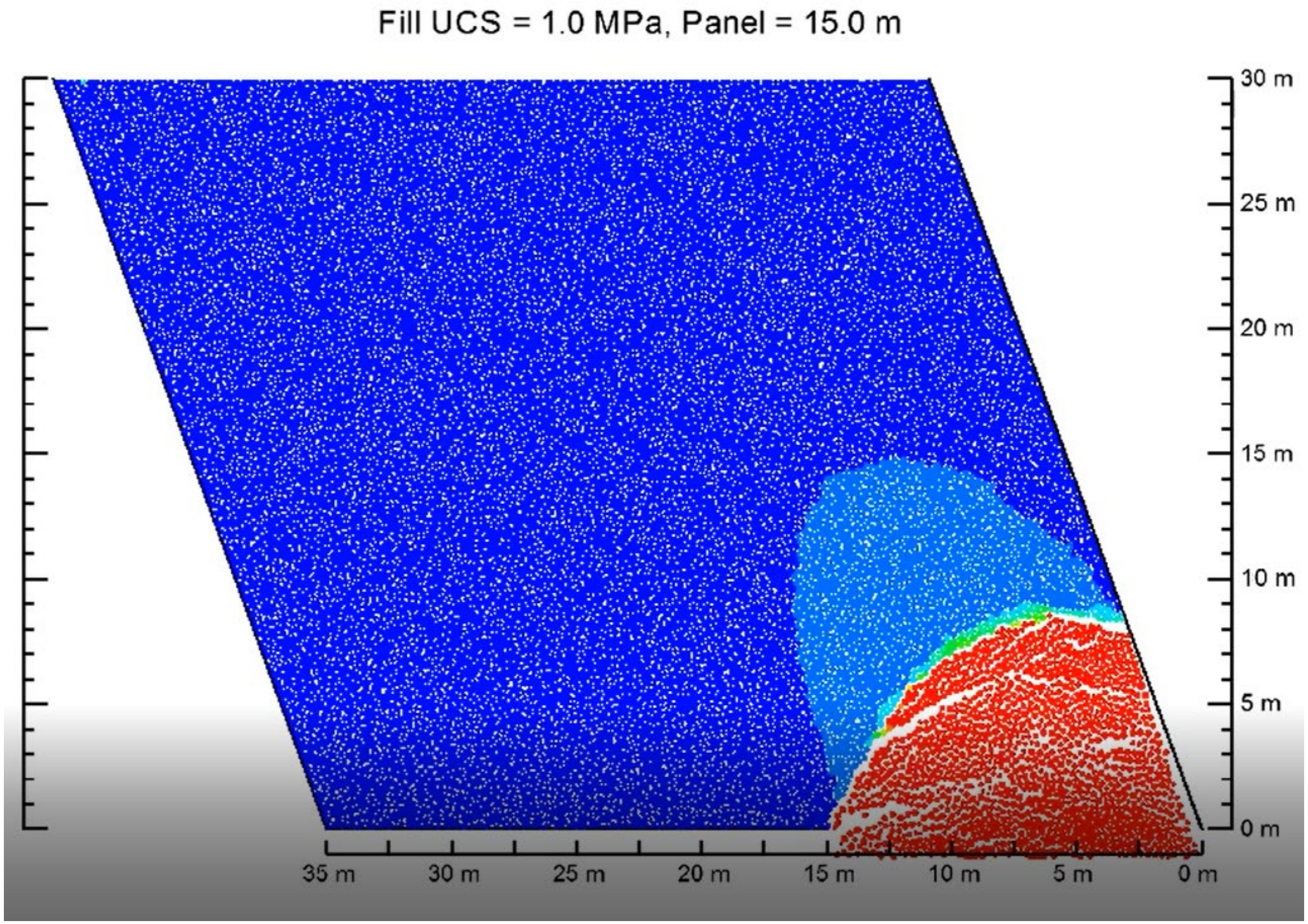








Examples (undercut cemented backfill PFC2D, flat-jointed material)



Examples

Ceramic bead & Undercut cemented backfill

Matching uniaxial & tensile strengths of compact rock

- two alternative intact BPMs

Embed BPM within larger continuum model

- study fracturing around advancing stope in quartzite

Sandstone Perforation Failure

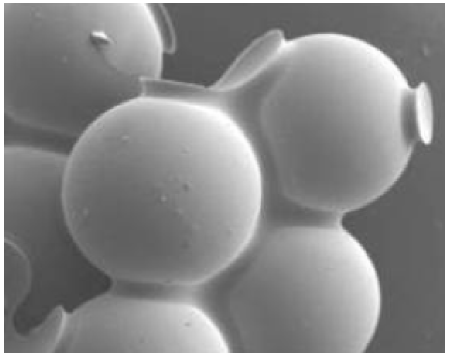
Examples (match uniaxial & tensile strengths)

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

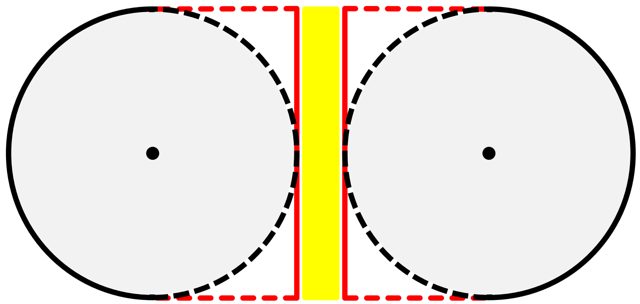
This limitation is overcome by introducing intergranular interlock in the form of a well-connected grain structure with interfaces that are deformable, breakable and can sustain partial damage.

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

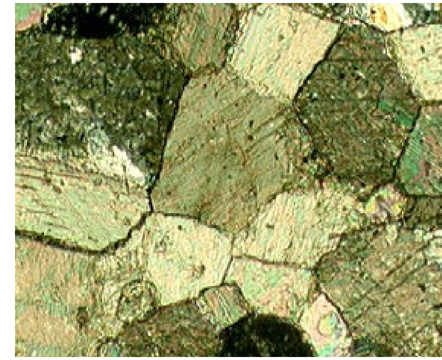
Flat-jointed material (Differs from parallel bond)



intact parallel bond

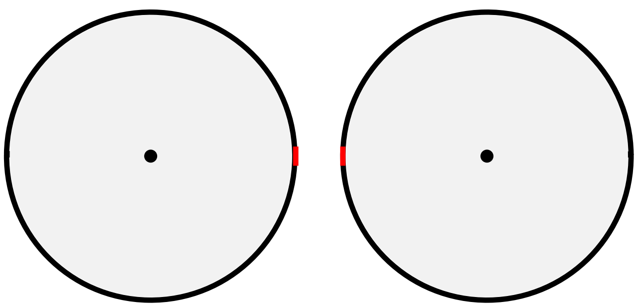


bonded finite-length interface

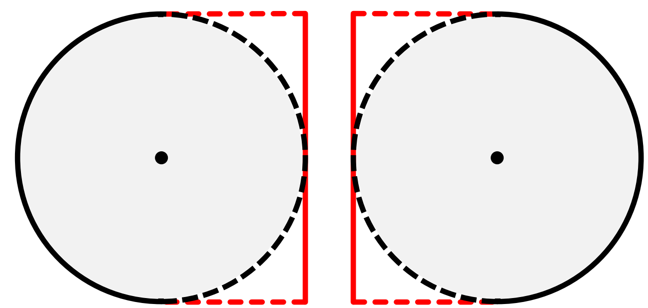


broken parallel bond

fully broken flat joint



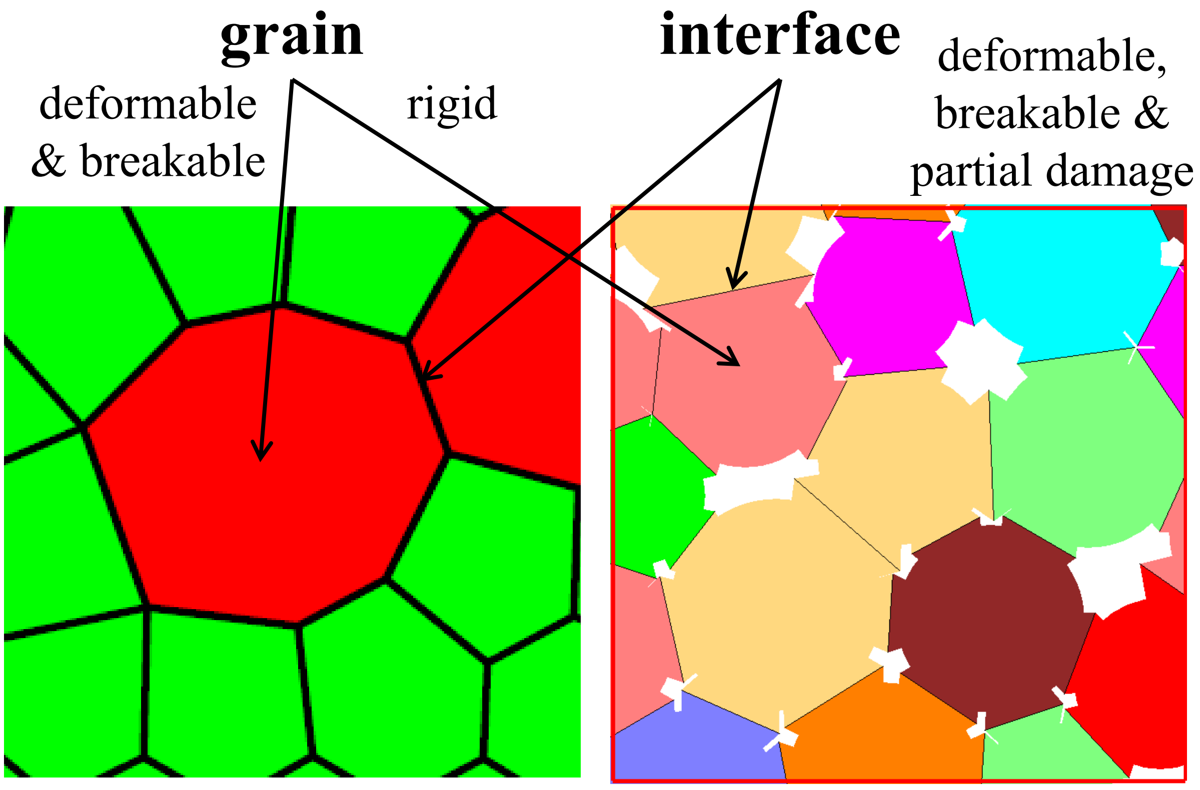
frictional zero-length interface



frictional finite-length interface

Examples (match uniaxial & tensile strengths)

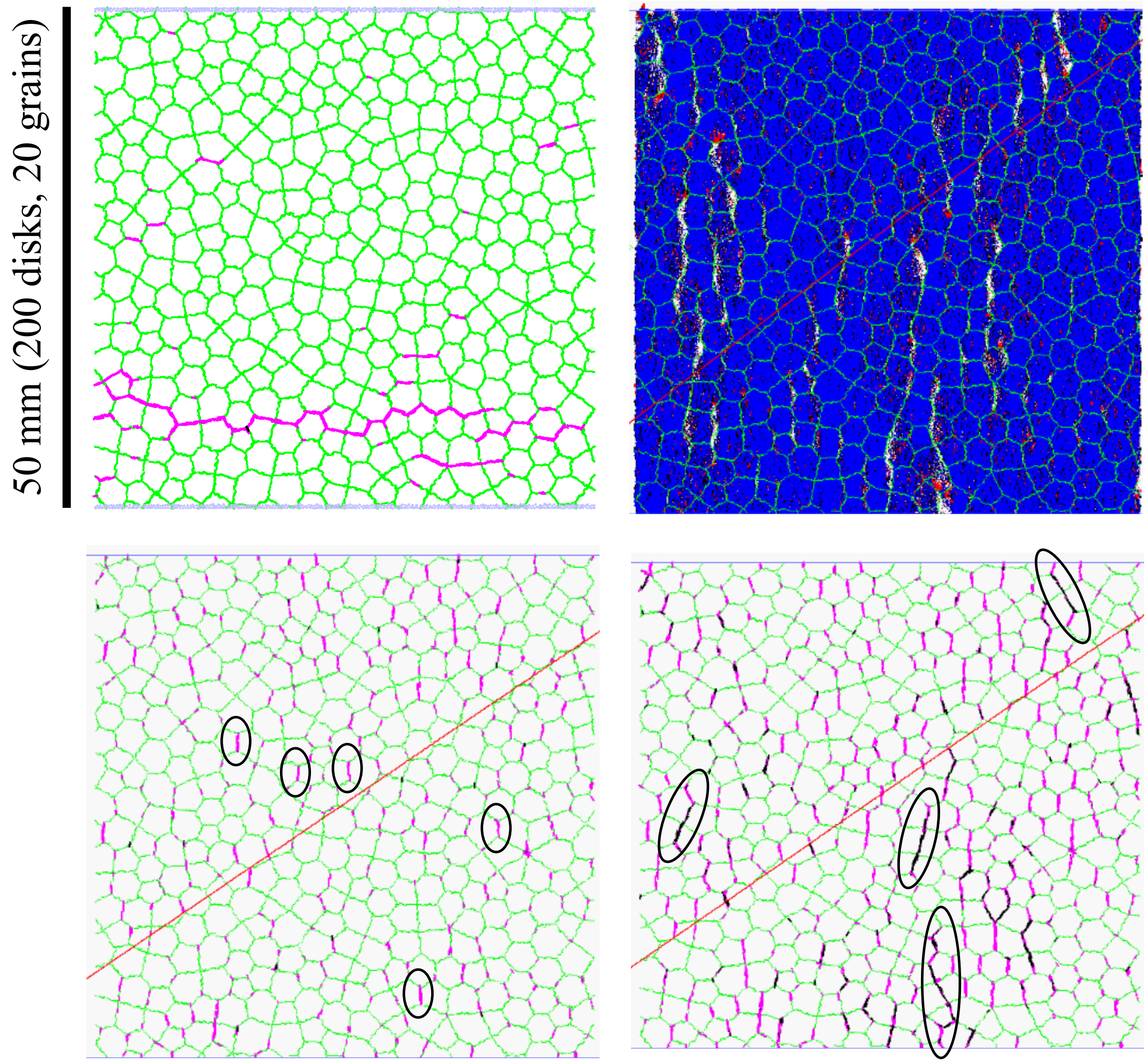
Two alternative intact BPMs:



grain-based material flat-jointed material

Examples (grain-based material)

axial splitting



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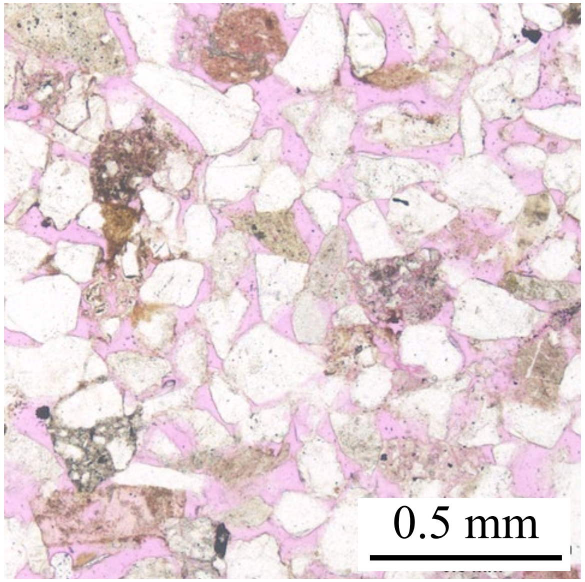
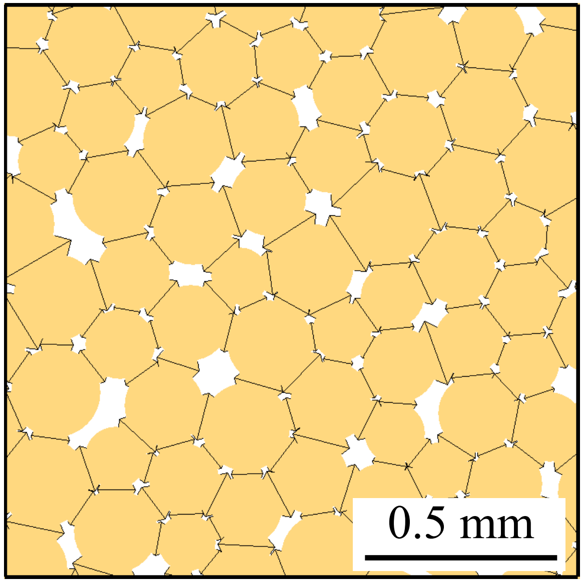
Potyondy (2010) "A Grain-Based Model for Rock: Approaching the True Microstructure," in *Rock Mechanics in the Nordic Countries 2010*, pp. 225–234, C.C. Li, et al., Eds., ISBN: 978-82-8208-017-0, Kongsberg: Norwegian Group for Rock Mechanics.

Examples (flat-jointed material)



Castlegate sandstone

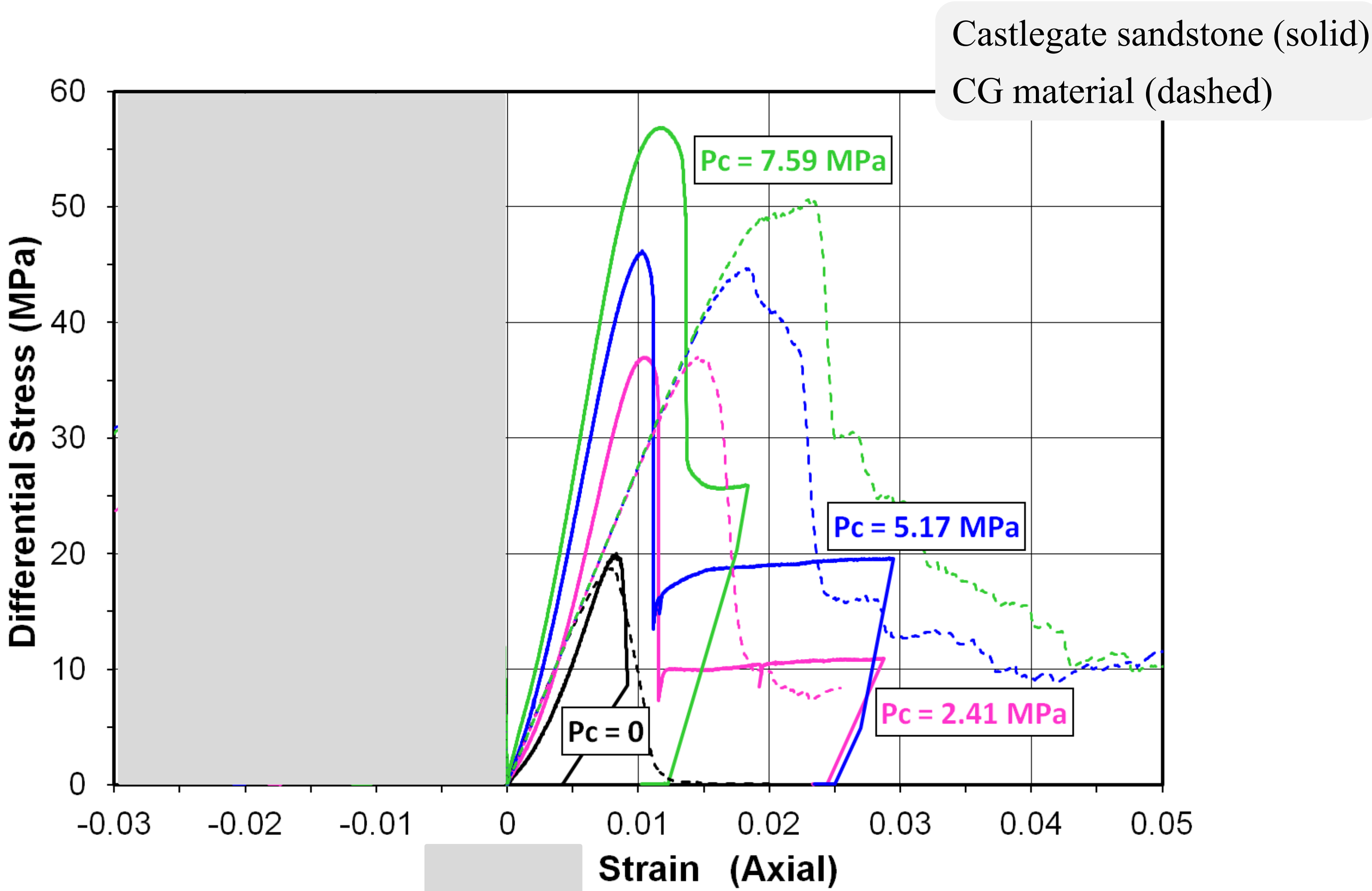


CG material

Potyondy, D.O. (2017) "Simulating Perforation Damage with a Flat-Jointed Bonded-Particle Material," paper ARMA 17-223 in Proceedings of 51st U.S. Rock Mechanics/Geomechanics Symposium, San Francisco, USA, 25–28 June 2017. [2D flat-jointed sandstone material --- described here.]

Potyondy, D.O. (2018) "A Flat-Jointed Bonded-Particle Model for Rock," paper ARMA 18-1208 in Proceedings of 52nd U.S. Rock Mechanics/Geomechanics Symposium, Seattle, USA, 17–20 June 2018. [3D flat-jointed granite material]

Material Behavior (compression tests)



Stress-strain response during triaxial testing

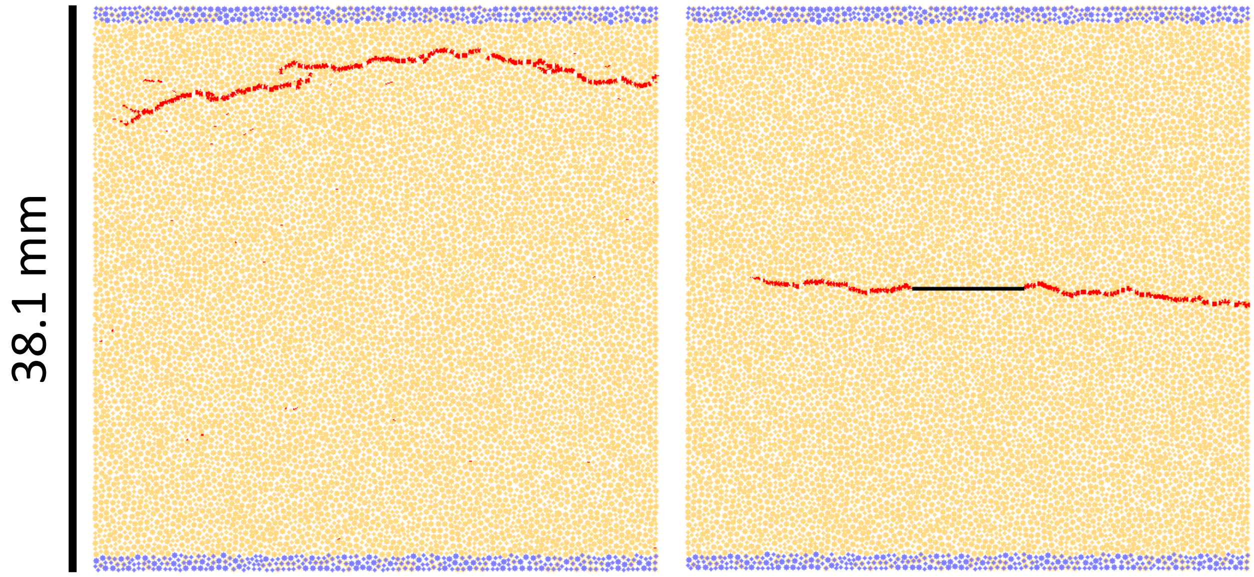
Material Behavior (tension & compression tests)

- The mechanisms that are exhibited during tension & compression tests are like the brittle failure behavior of compact rock, with the exception that transgranular cracking occurring within and across grains during compression tests is absent.

  - The following mechanisms are exhibited during these tests and shown on the next 5 slides.

Direct-tension (& fracture-toughness) tests

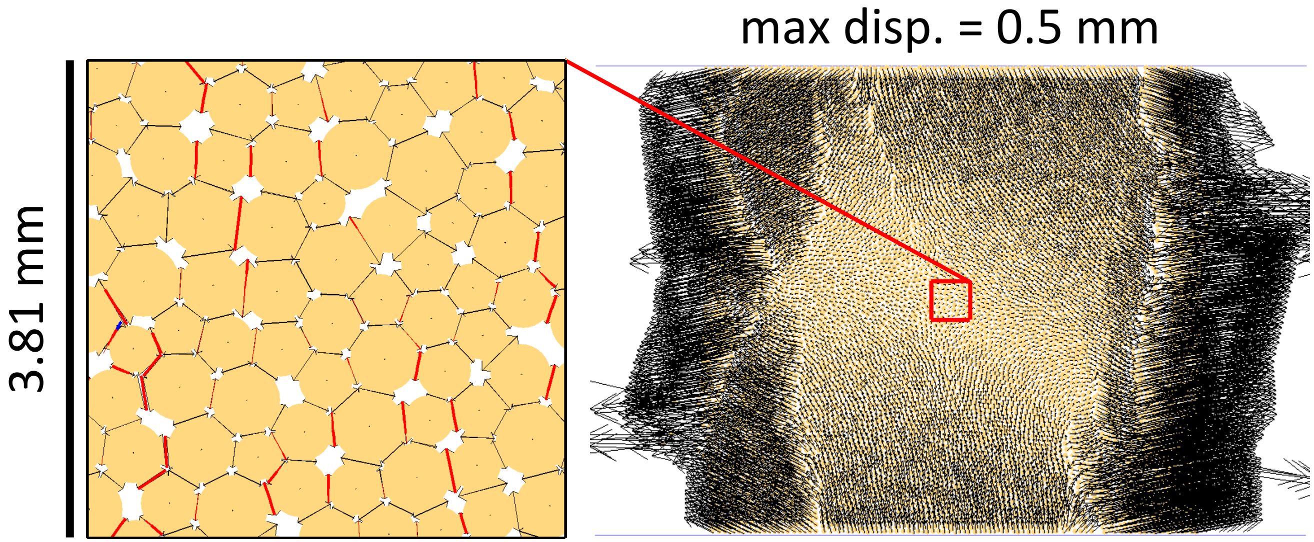
- Peak stress coincides with formation of a few tensile fractures aligned perpendicular to specimen axis.



Damaged microstructure at post-peak state of tension tests.

Compression test (unconfined)

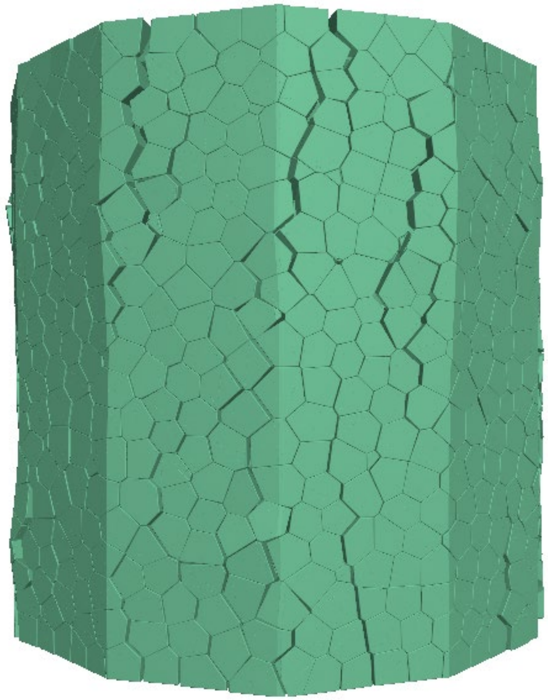
- Peak stress coincides with axial splitting in which the material breaks apart into multiple interlocking columns.



Damaged microstructure at post-peak state of UCS test.

Compression test (unconfined)

- Peak stress coincides with axial splitting in which the material breaks apart into multiple interlocking columns.

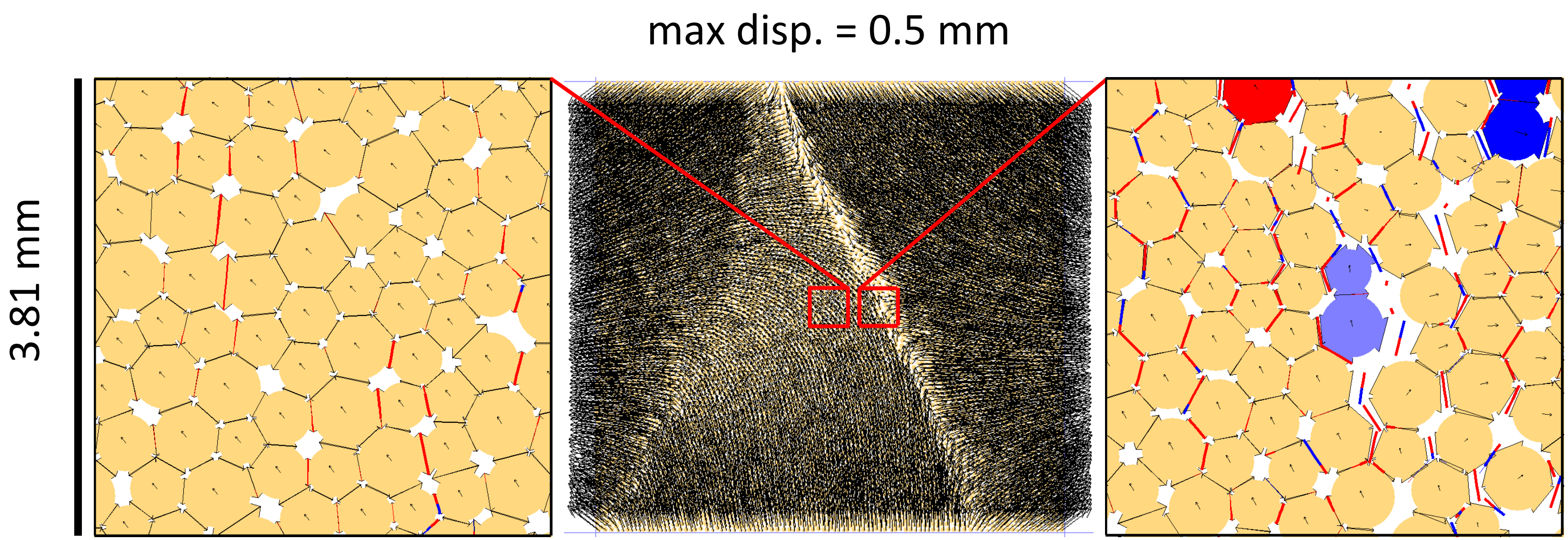


bonded Voronoi grains

Damaged microstructure at post-peak state of UCS test.

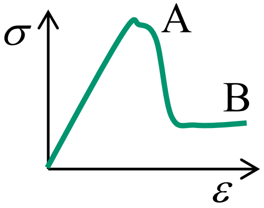
Compression test (confined)

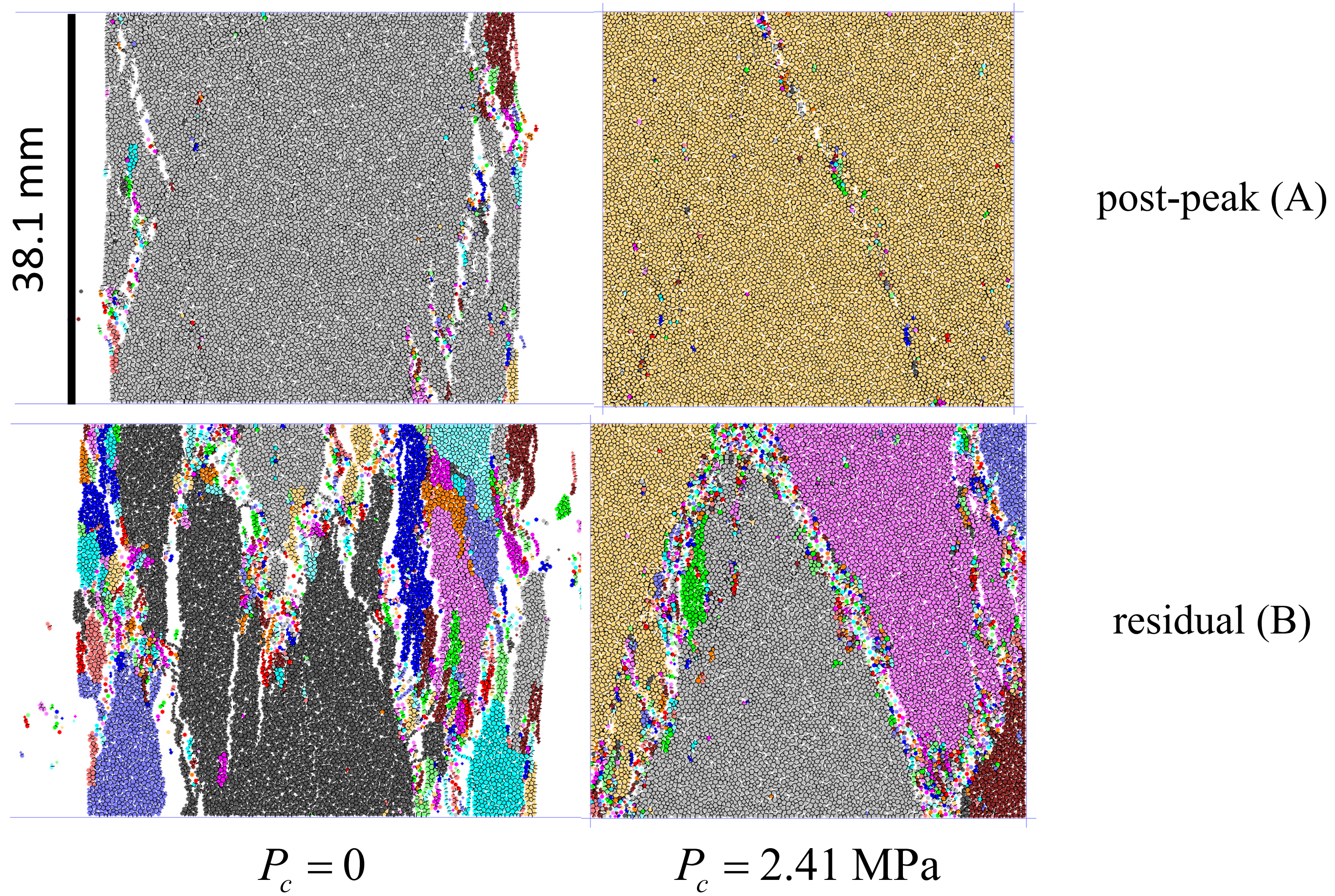
- Peak stress coincides with formation of a few diagonally aligned shear fractures.



Damaged microstructure at post-peak state of confined-compression test.

Compression tests (fragmentation)





Fragmentation at post-peak (top) and residual (bottom) states of compression tests.

Examples

Ceramic bead & Undercut cemented backfill

Matching uniaxial & tensile strengths of compact rock

- two alternative intact BPMs

Embed BPM within larger continuum model

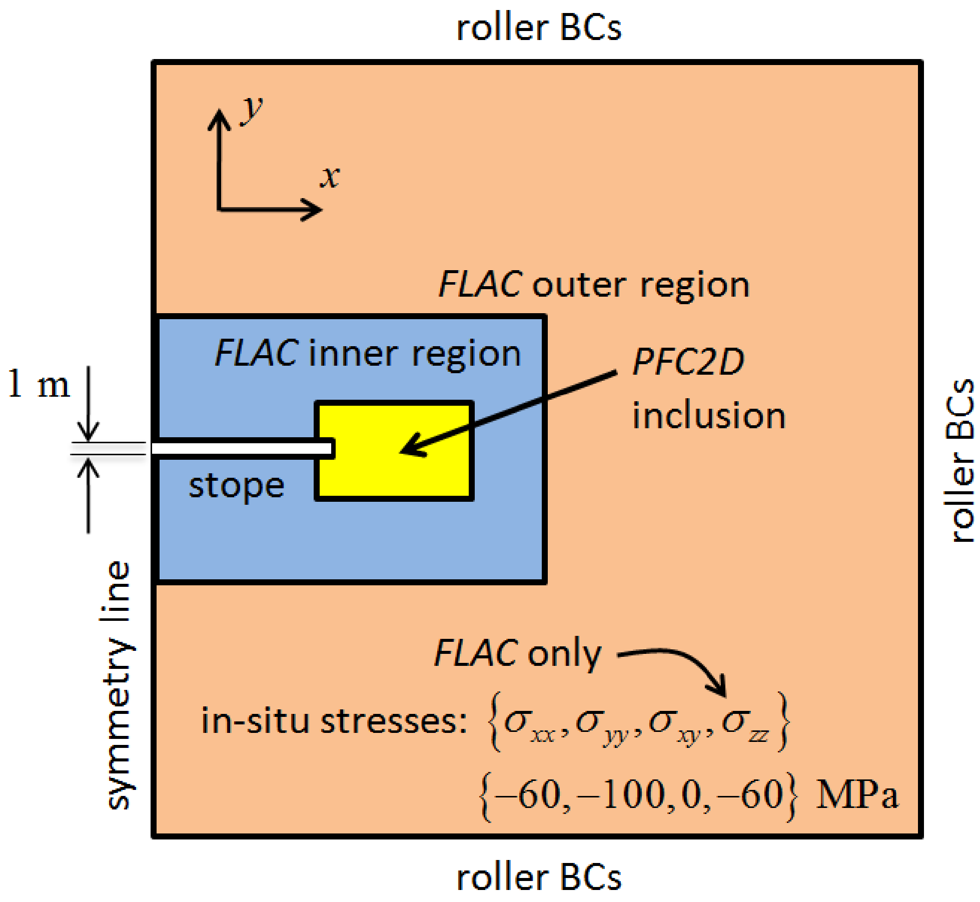
- study fracturing around advancing stope in quartzite

Sandstone Perforation Failure

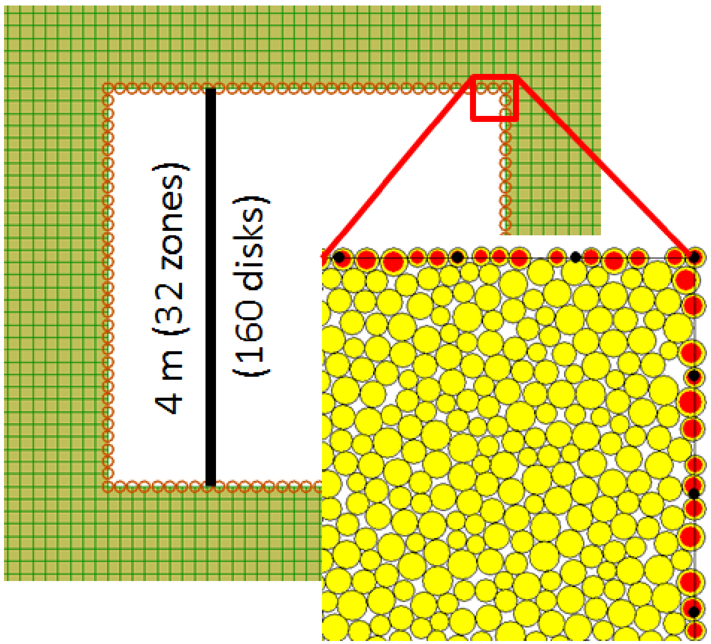
Examples (embed BPM in continuum model)

quartzite modeled (continuum) as strain-hardening/softening material

ad hoc strength reduction (intact ➔ in-situ)



Coupled model

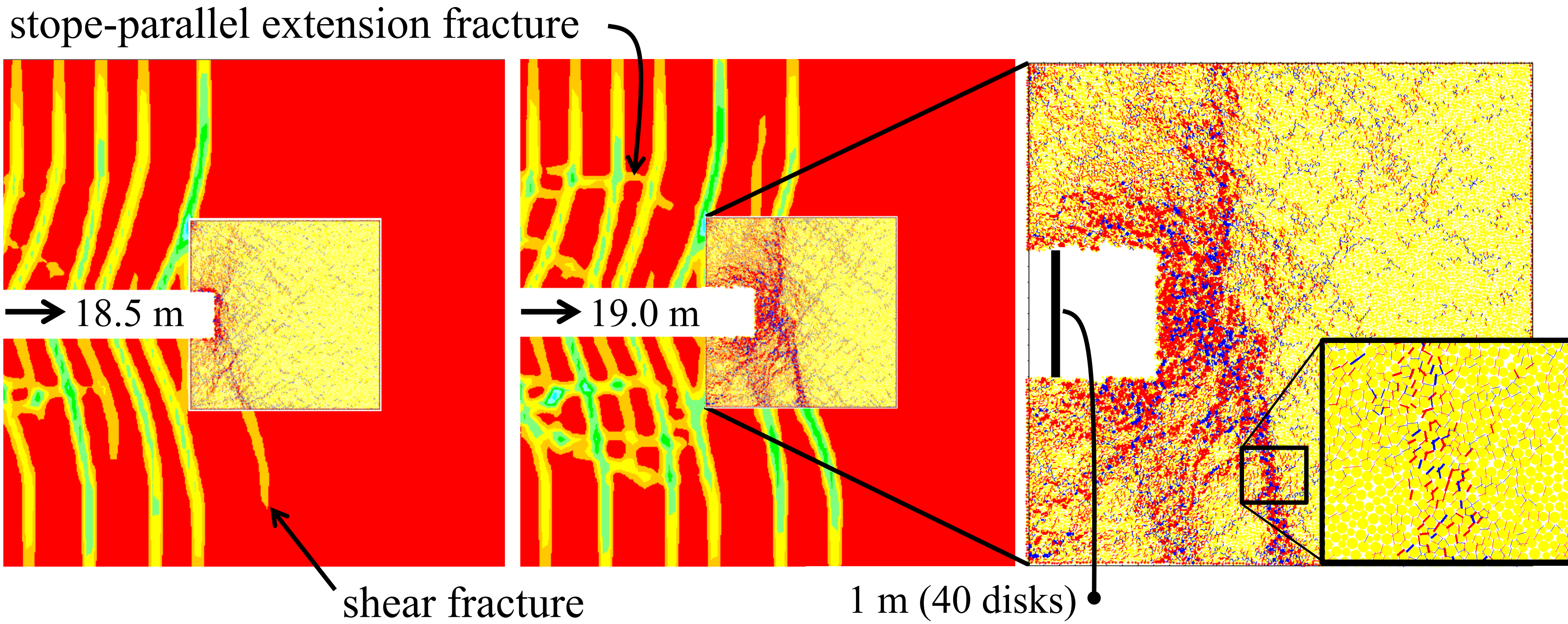


***PFC2D* inclusion**

Katsaga, T., and D. O. Potyondy (2012) "A Generic Stope Model for Investigation of Fracturing Mechanisms in Deep Gold Mines," paper ARMA 12-541 in Proceedings of 46th U.S. Rock Mechanics/Geomechanics Symposium, Chicago, USA, 24–27 June 2012.

Examples (embed BPM in continuum model)

Fracture pattern compares well with expected pattern.



Could benefit by comparing responses of these two different material idealizations (e.g., damage processes in shear fractures).

Examples

Ceramic bead & Undercut cemented backfill

Matching uniaxial & tensile strengths of compact rock

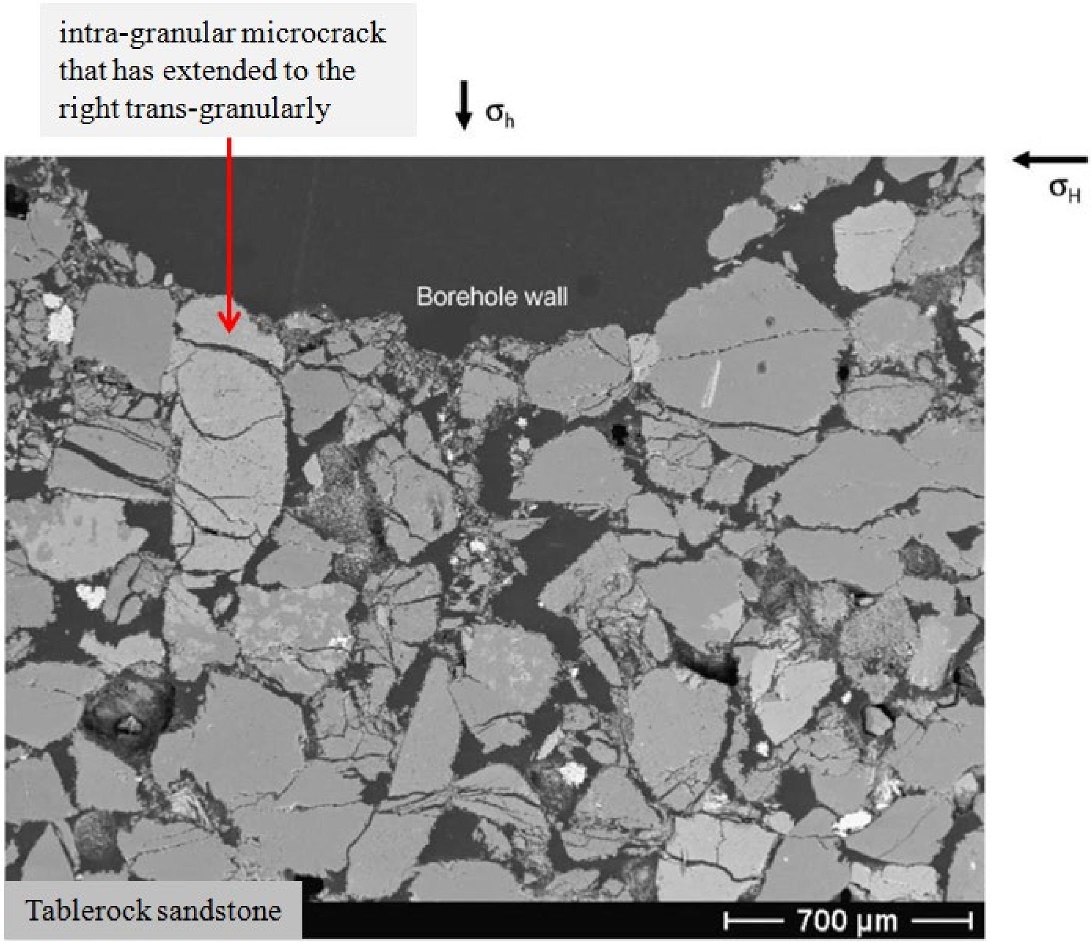
- two alternative intact BPMs

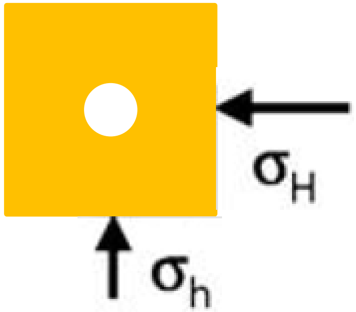
Embed BPM within larger continuum model

- study fracturing around advancing stope in quartzite

Sandstone Perforation Failure

Examples (sandstone perforation failure)

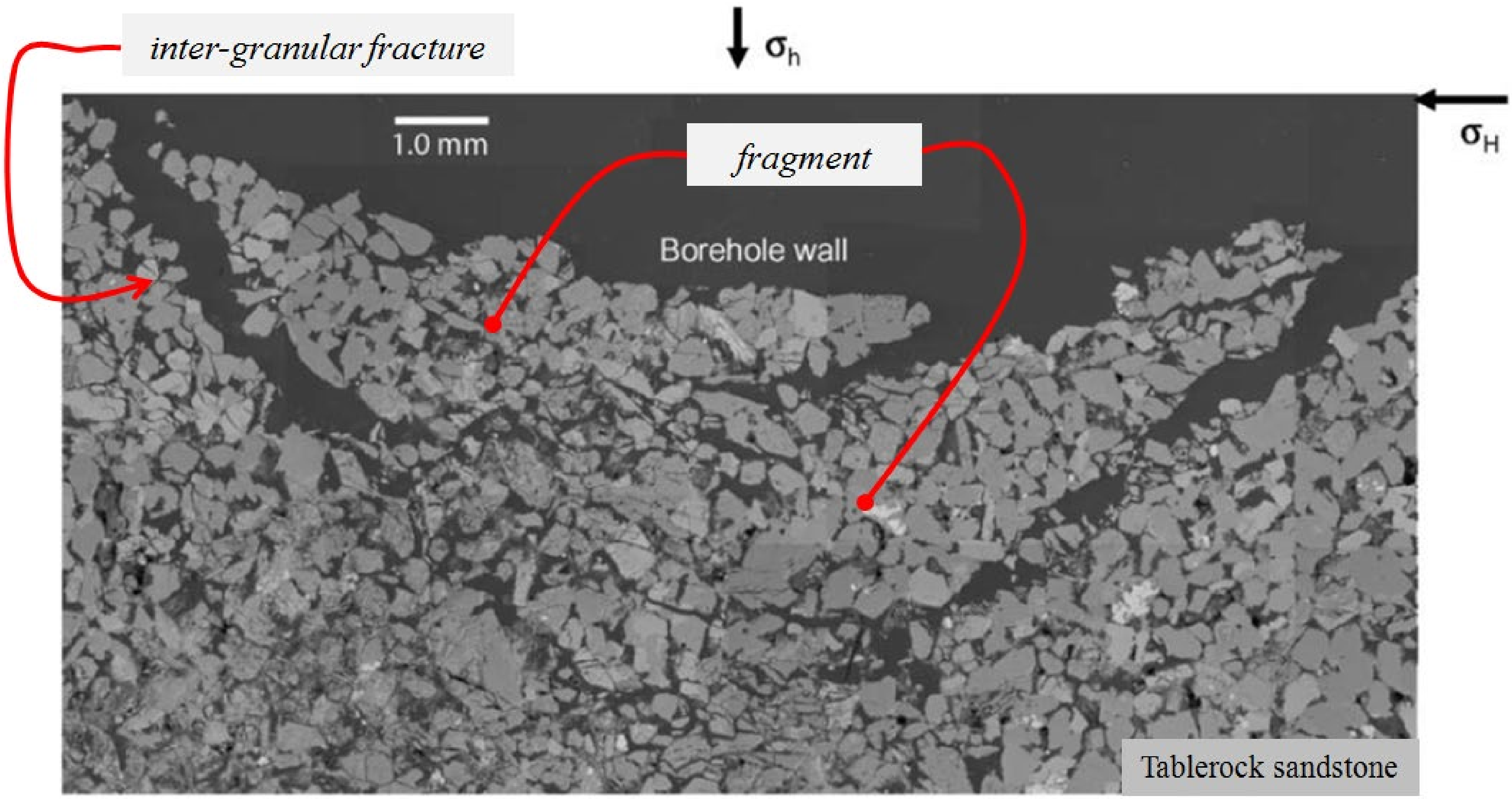




Damage begins as swarm of intra-granular microcracks, that first extend transgranularly, loosening grains and grain fragments…

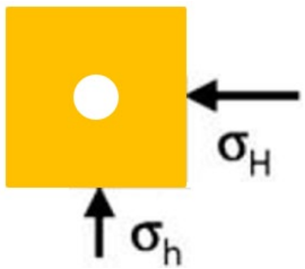
Potyondy, D.O. (2017) "Simulating Perforation Damage with a Flat-Jointed Bonded-Particle Material," paper ARMA 17-223 in Proceedings of 51st U.S. Rock Mechanics/Geomechanics Symposium, San Francisco, USA, 25–28 June 2017.

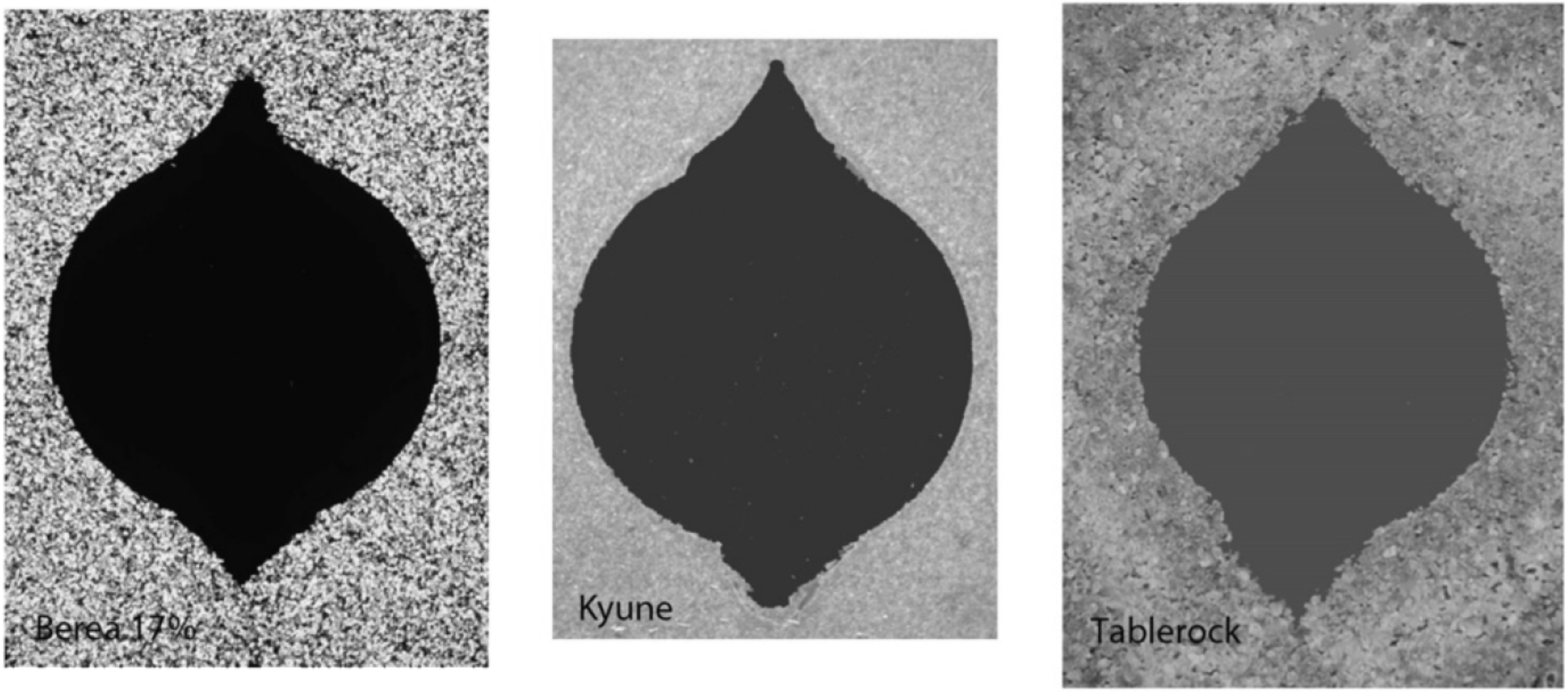
Examples (sandstone perforation failure)



…and then extend inter-granularly toward borehole wall, where a thin layer of grains & fragments begins to separate (ready to spall or be removed by drilling fluid).

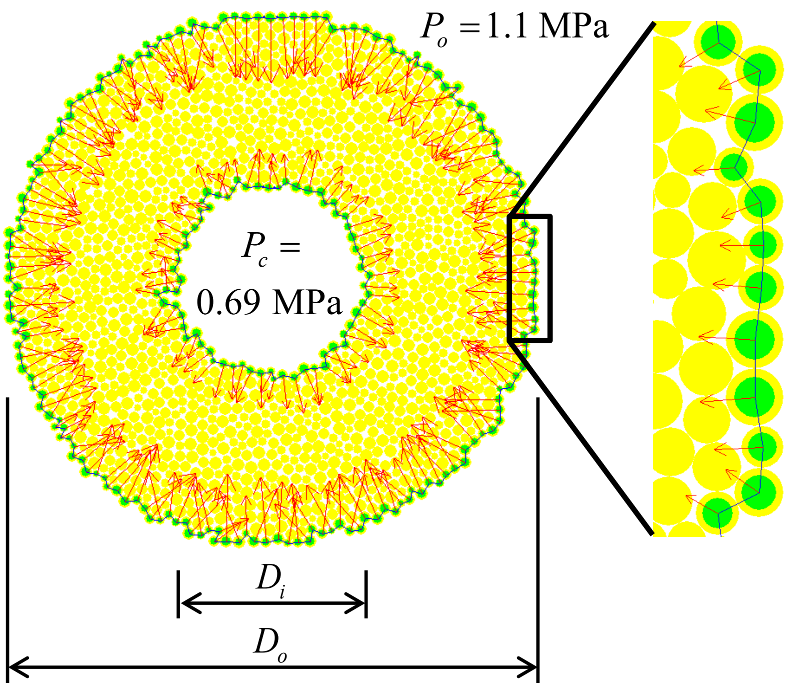
Examples (sandstone perforation failure)





This episodic process produces wide-angle, dog-eared breakouts.

Examples (sandstone perforation failure)

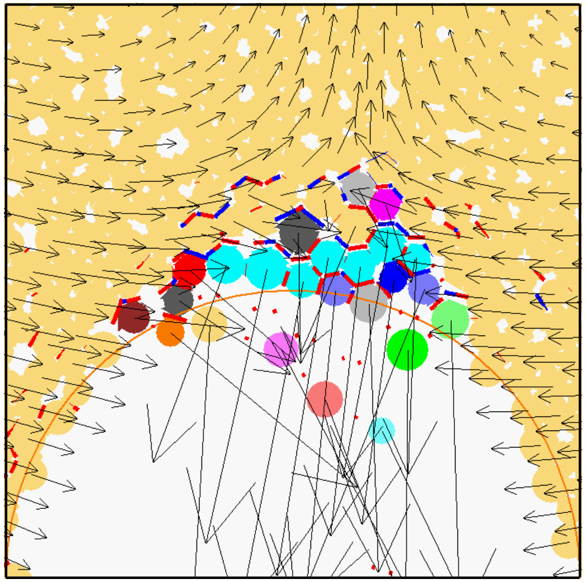


Model of a Thick-Walled Cylinder test
showing pressure-application procedure

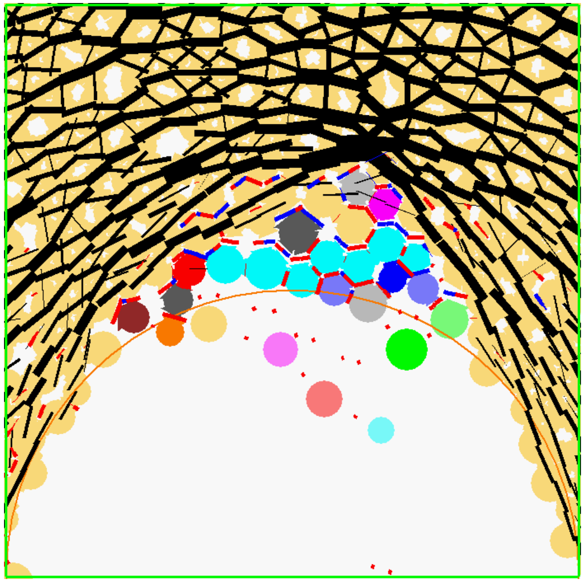
Examples (sandstone perforation failure)

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

- damage
- damage & forces



$P_o = 30.5$ MPa (stable)

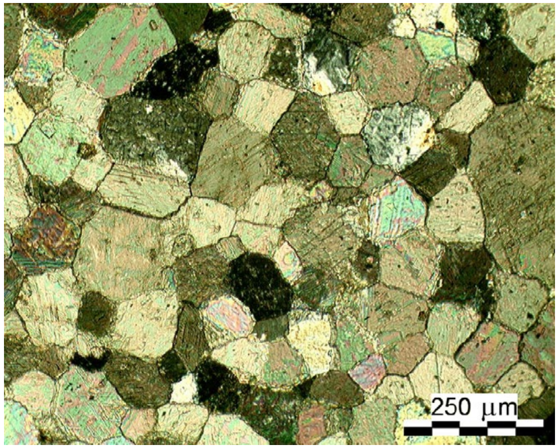


$P_o = 30.5$ MPa (stable)

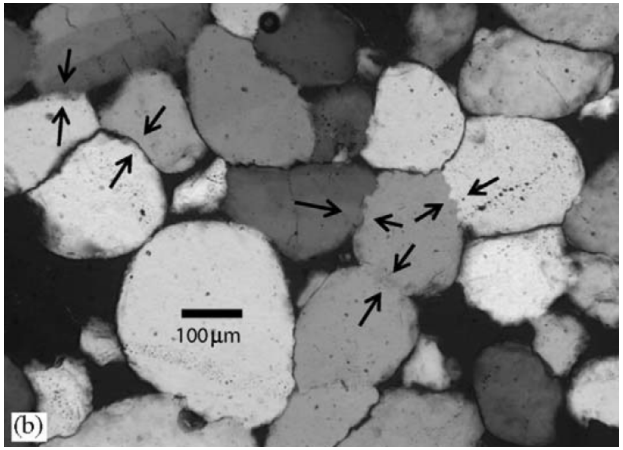
Conclusions & Future Directions

Bonded-particle modeling is in early phase of development

- have generic models for 2D & 3D intact compact rock
- Next step: generic model of intact porous rock



marble with interlocking grains



Haimson (2007)

sandstone with broad grain sutures

Conclusions & Future Directions

All BPM modeling benefits from increased computational speed via

- multi-threading capability in *PFC2D* and *PFC3D* 5.0 & above!
- support for MPI under development

Conclusions & Future Directions

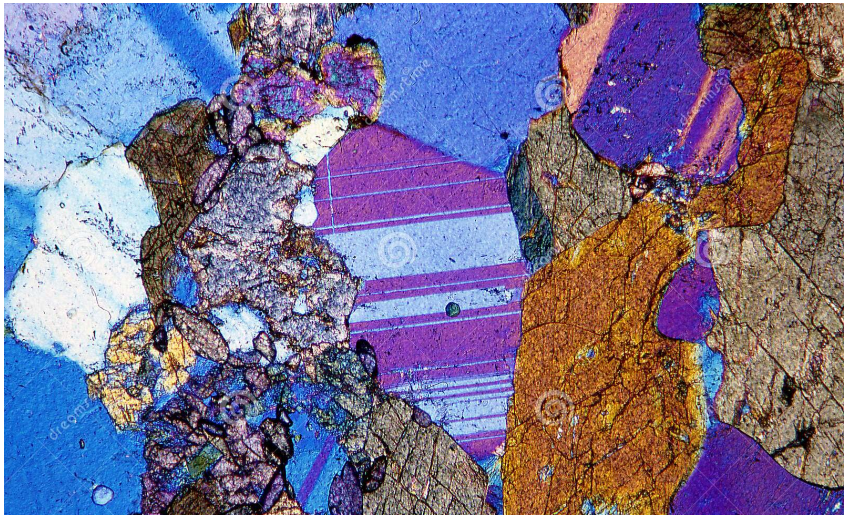
With continuing increases in computational speed, BPM modeling will be increasingly applied to boundary-value problems

- How to incorporate scale effects that make in-situ strength less than intact strength?

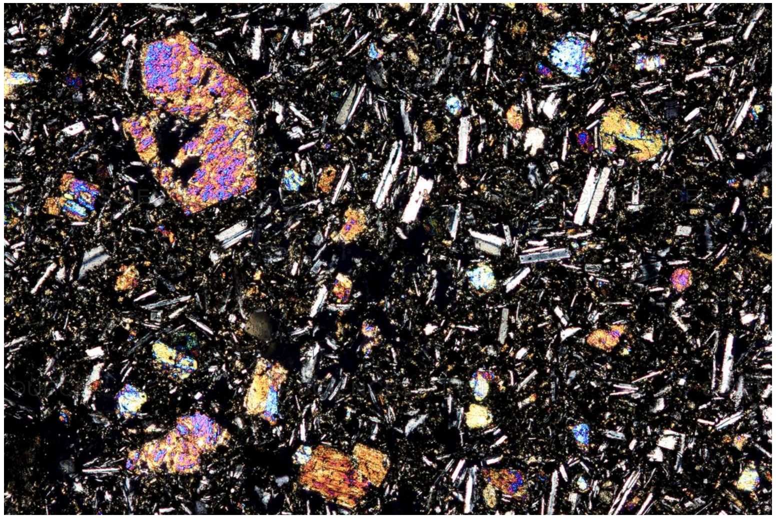
Conclusions & Future Directions

Future BPMs should be constructed to match particular types of rock

- granite, sandstone, limestone,…



Granite
(minerals)



Basalt
(minerals & matrix)

Images from Enes Zengin

Conclusions & Future Directions

Challenge is to keep models as simple as possible

- include features to allow relevant micromechanisms to occur

Closer match to microstructural & structural features →
Closer match to macroscopic behavior