Consulting Group, Inc.

Simulating Perforation Damage with a Flat-Jointed Bonded-Particle Material

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Overview

Context

- Sandstone perforation failure
- Quantify this process via BPM
  - ➔ rock-strength degradation is emergent property
- BPM is flat-jointed material
  - ➔ sanction this model

Model Description

- Flat-jointed material
- CG material (represents Castlegate sandstone)

Overview

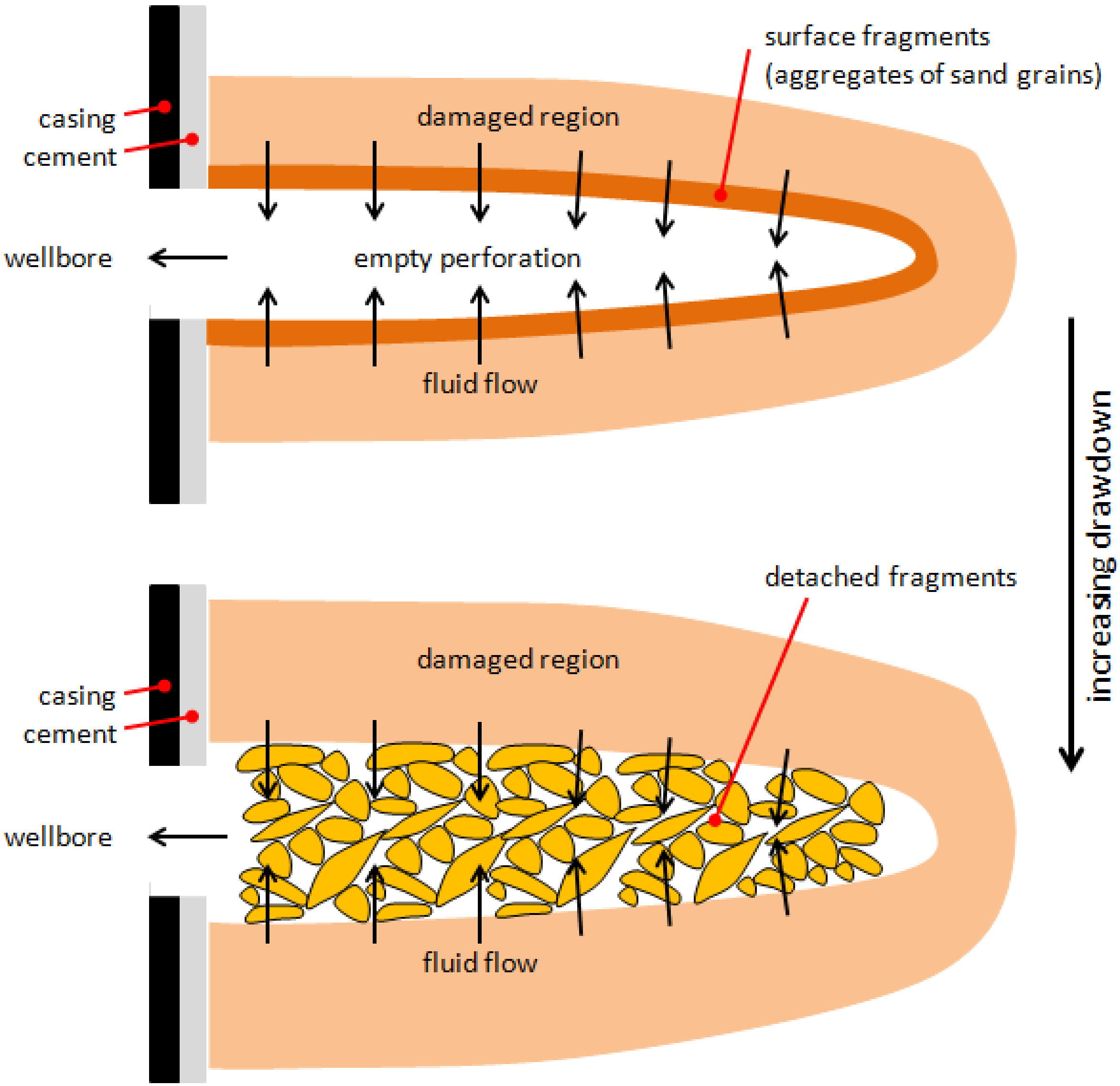
Material Behavior (CG material)

- Direct-tension & compression tests
- Thick-Walled Cylinder (TWC) tests

  ➔ primary mechanism: buckling-assisted fragmentation

Conclusions

Sand Production (conceptual model)



Typical perforation has 12.7-mm diameter, 1-m length

Two-stage process

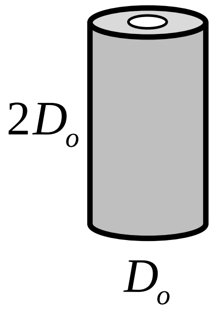
1. Perforation becomes filled with detached fragments.
2. Detached fragments become smaller.

Producible Aggregates

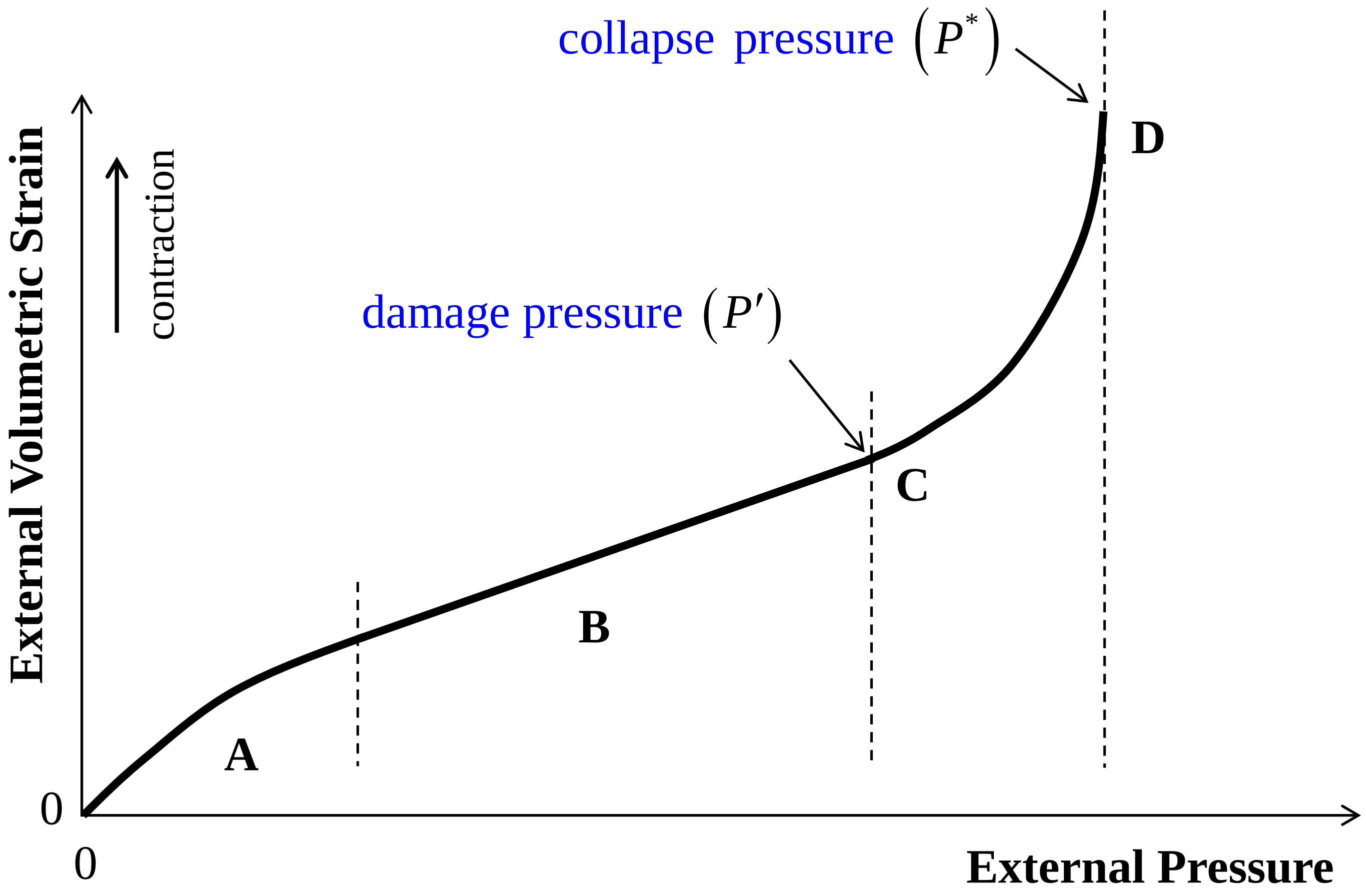
- Sand-prediction models (continuum) predict first stage.
- Second stage is difficult to characterize & assess quantitatively.

Quantify entire process via BPM (directly model grain-scale processes)

Sandstone Perforation Failure (TWC test)



Apply external pressure to outside of cylinder, measure external volumetric strain. Obtain damage and collapse pressures.



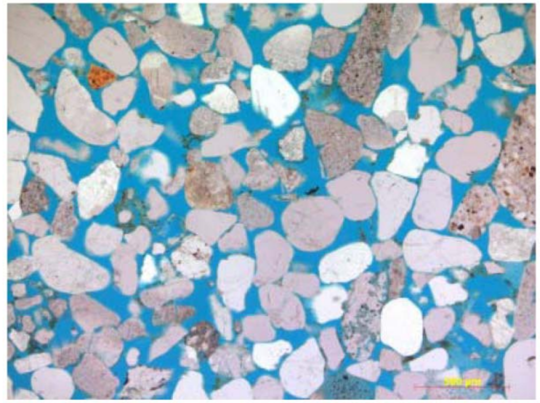
A : initial hardening (closure of pore space)

B : constant slope (elastic compression of cylinder)

C : inflection point (initiation of borehole failure)

D : vertical asymptote (borehole collapse)

Sandstone Perforation Failure



Loosely connected, rounded grains
➔ **slot-like failures**

Well-connected, angular grains
➔ **breakout failures**

The properties of the grain contacts and bonding (provided by grain-grain sutures and clay) have a large impact on the failure characteristics of sandstones, and perforations in relatively competent sandstones exhibit either slot-like or breakout failure types.

Sandstone Perforation Failure

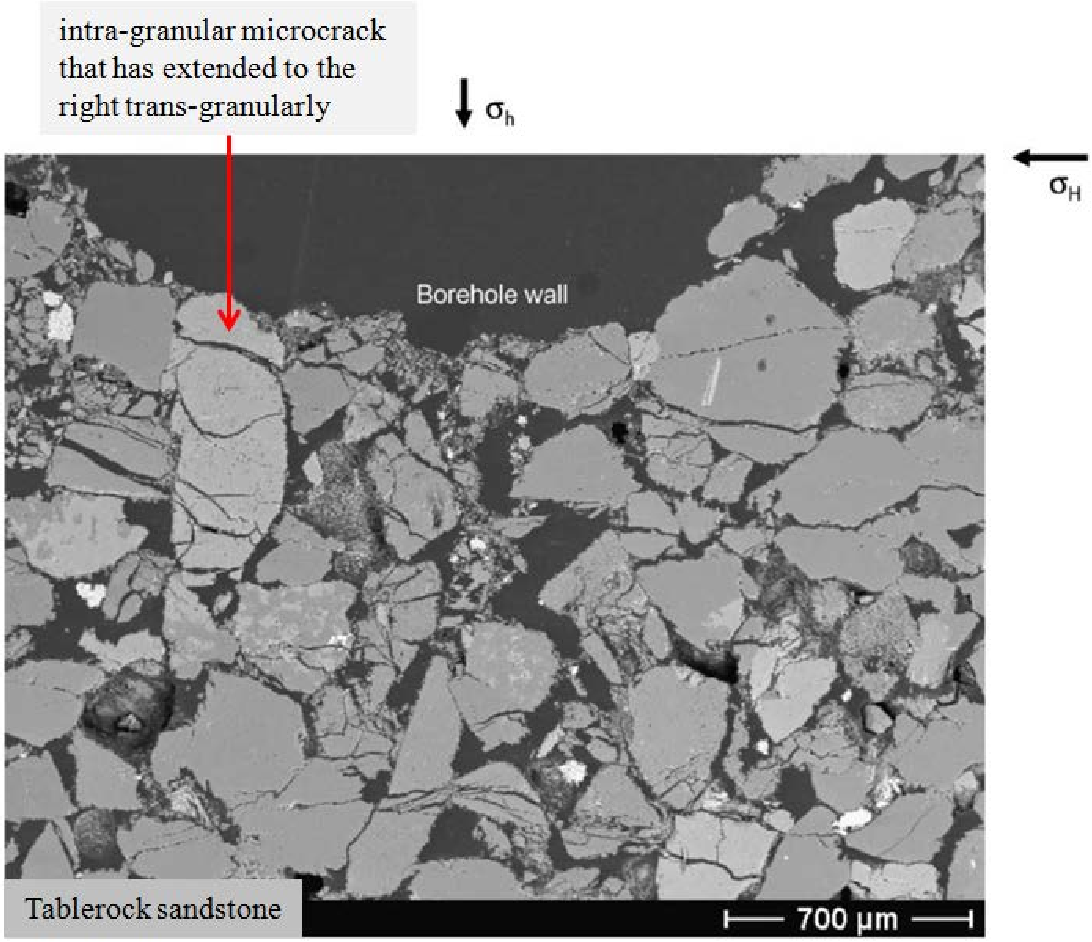
Haimson (2007) reviews drilling experiments in granites, limestones and sandstones that revealed similar breakout characteristics, and strikingly different micromechanisms.

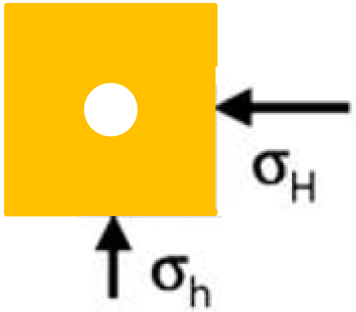
Drilled boreholes into prismatic rock blocks subjected to constant true triaxial stress intended to replicate field conditions. Drilling fluid helped remove fragments. Then injected epoxy into the borehole, and saw-cut the specimen into thin slices across the borehole axis.

The well-cemented sandstone specimens respond…

Haimson, B. (2007) "Micromechanisms of Borehole Instability Leading to Breakouts in Rocks," *Int. J. Rock Mech. & Min. Sci.*, ***44***, 157–173.

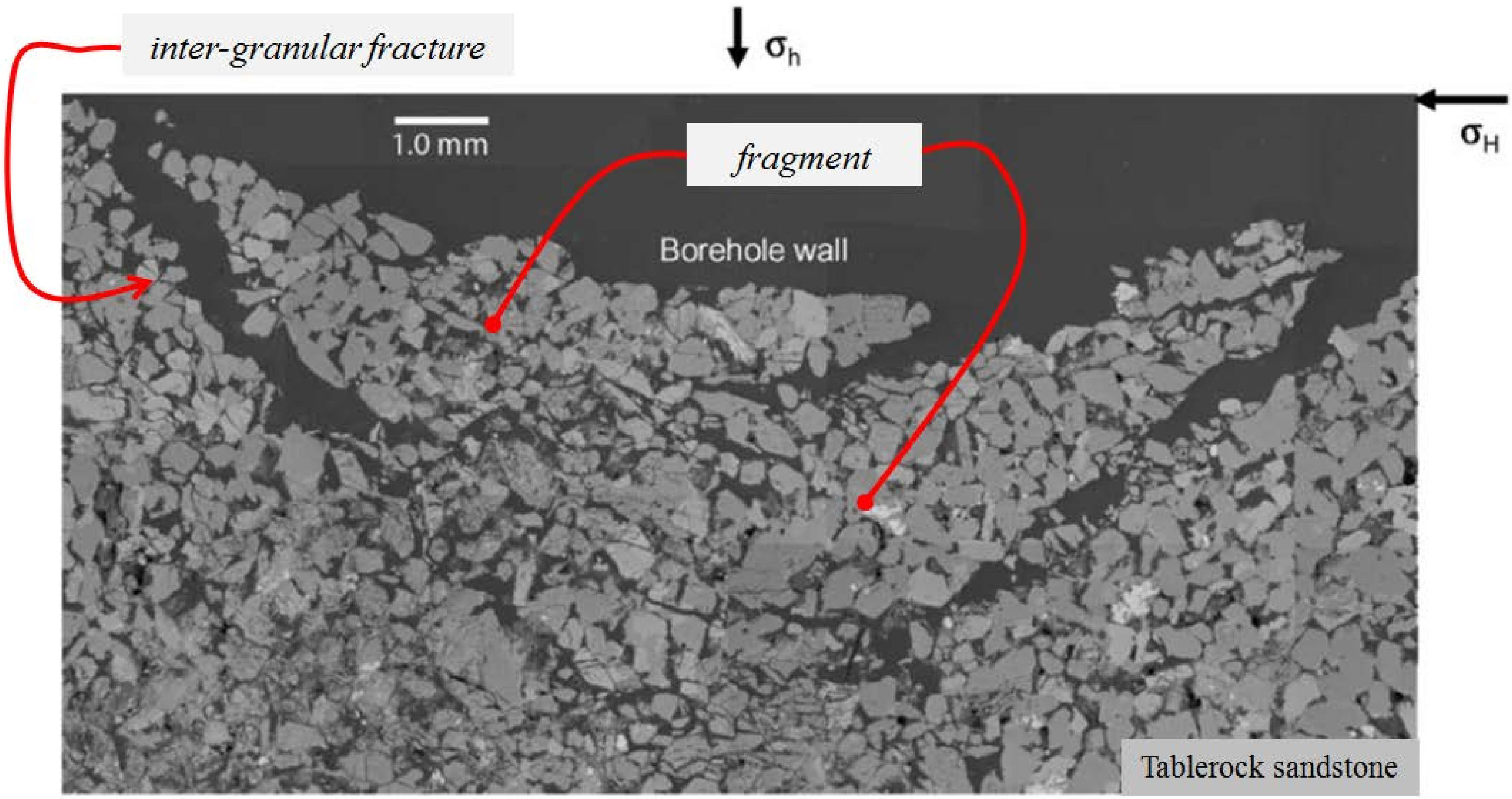
Sandstone Perforation Failure





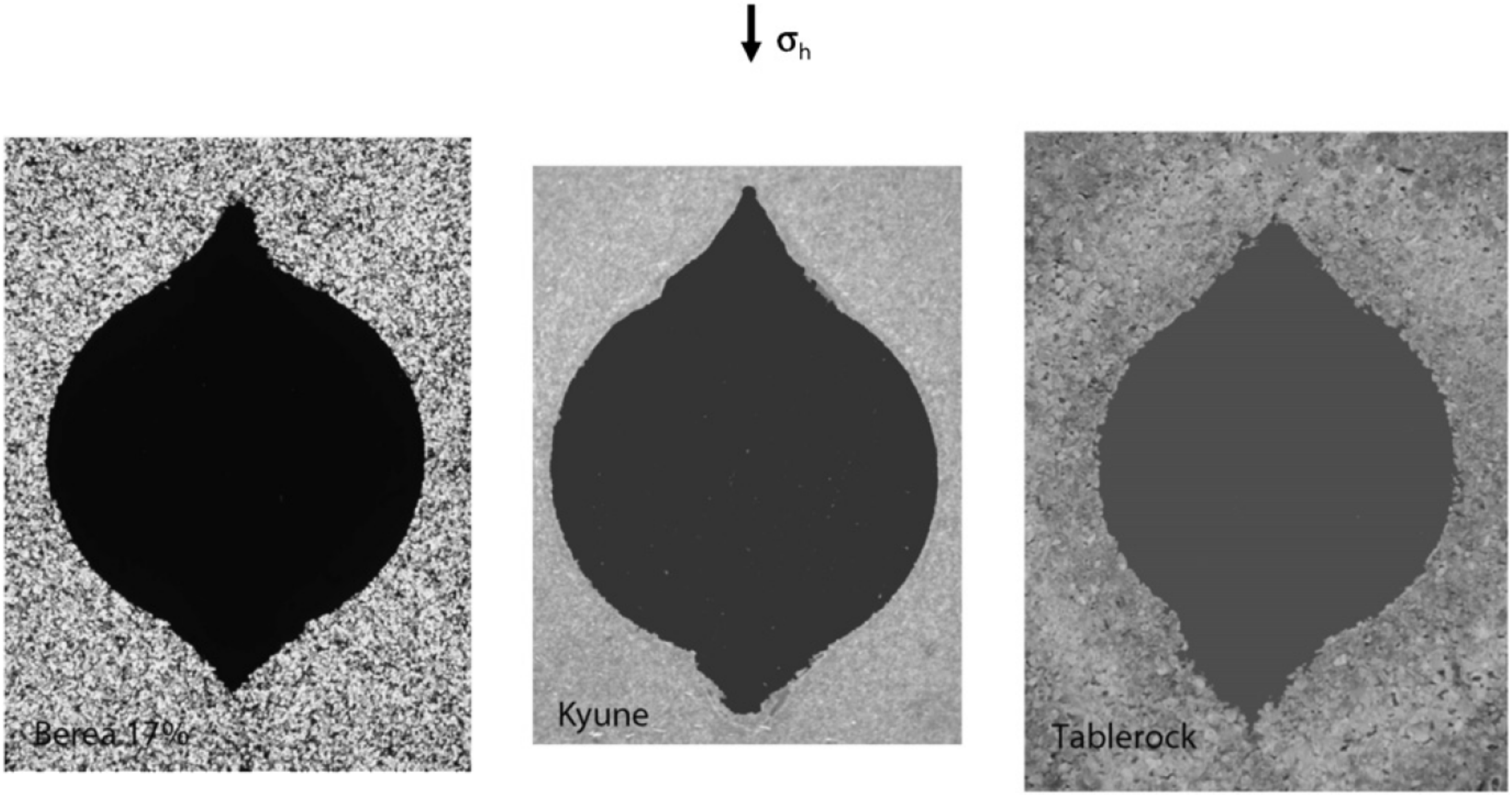
Damage begins as swarm of intra-granular microcracks, that first extend transgranularly, loosening grains and grain fragments…

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).

Sandstone Perforation Failure



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

Goal of Study

BPM replicates relevant grain-scale processes

?

Goal of Study

BPM replicates relevant grain-scale processes → Study perforation-failure process

Petrophysical Characteristics (mapped into appropriate flat-jointed material parameters) ⟷

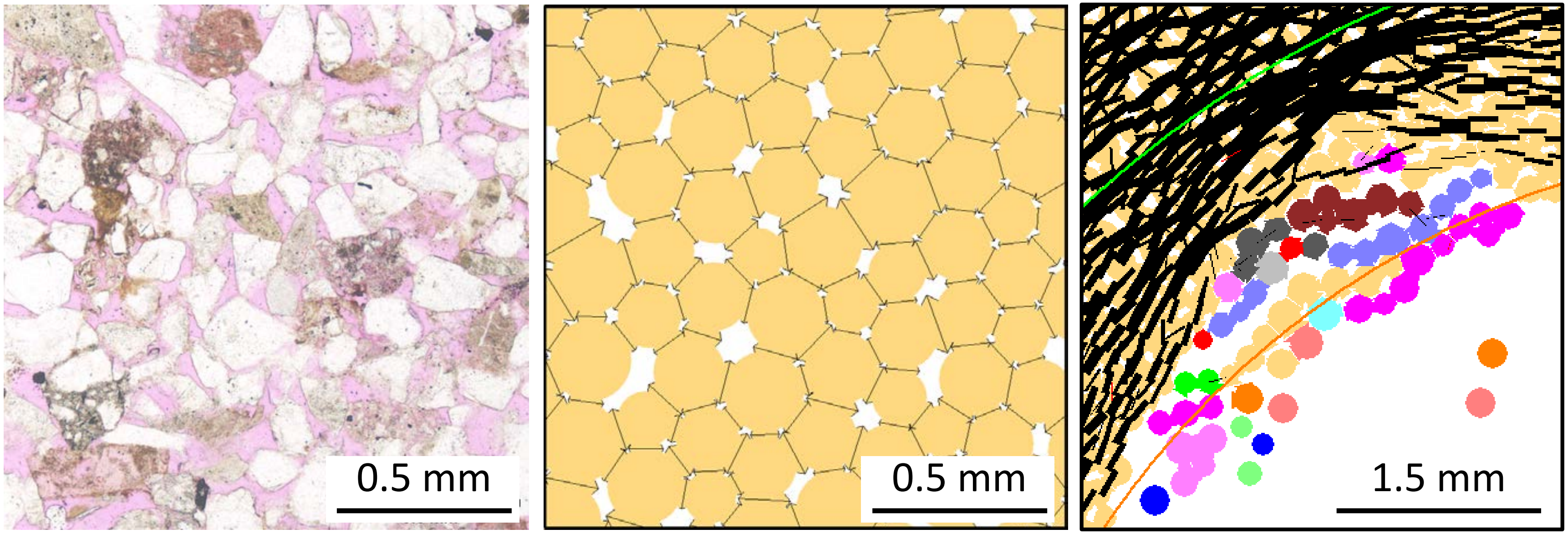
Failure morphologies
(slot-like or breakout)

TWC strength
(collapse pressure)

Can we construct a 2D BPM that produces surface fragments when subjected to boundary conditions similar to those around a wellbore perforation in dry sandstone?

YES

2D flat-jointed material (to represent Castlegate sandstone)



Castlegate sandstone

CG material ($D_m = 0.20$ mm)

Breakout failure via buckling-assisted fragmentation

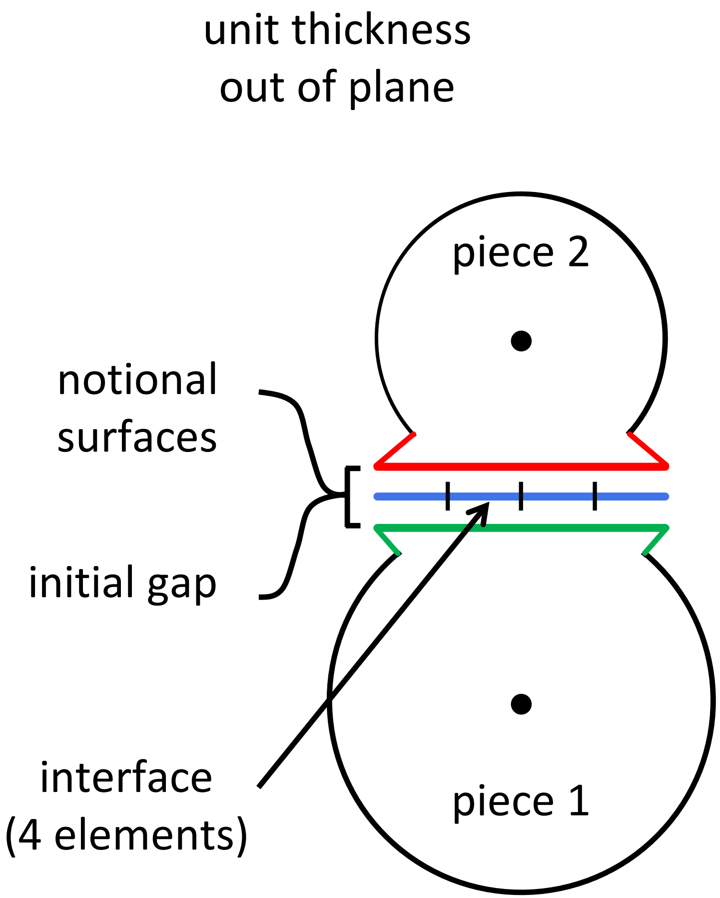
Remainder of Talk (summary)

We can construct a 2D flat-jointed material to represent Castlegate sandstone. Our synthetic material matches:

- Much of the macroscopic response and many of the mechanisms that occur during direct-tension and compression tests.

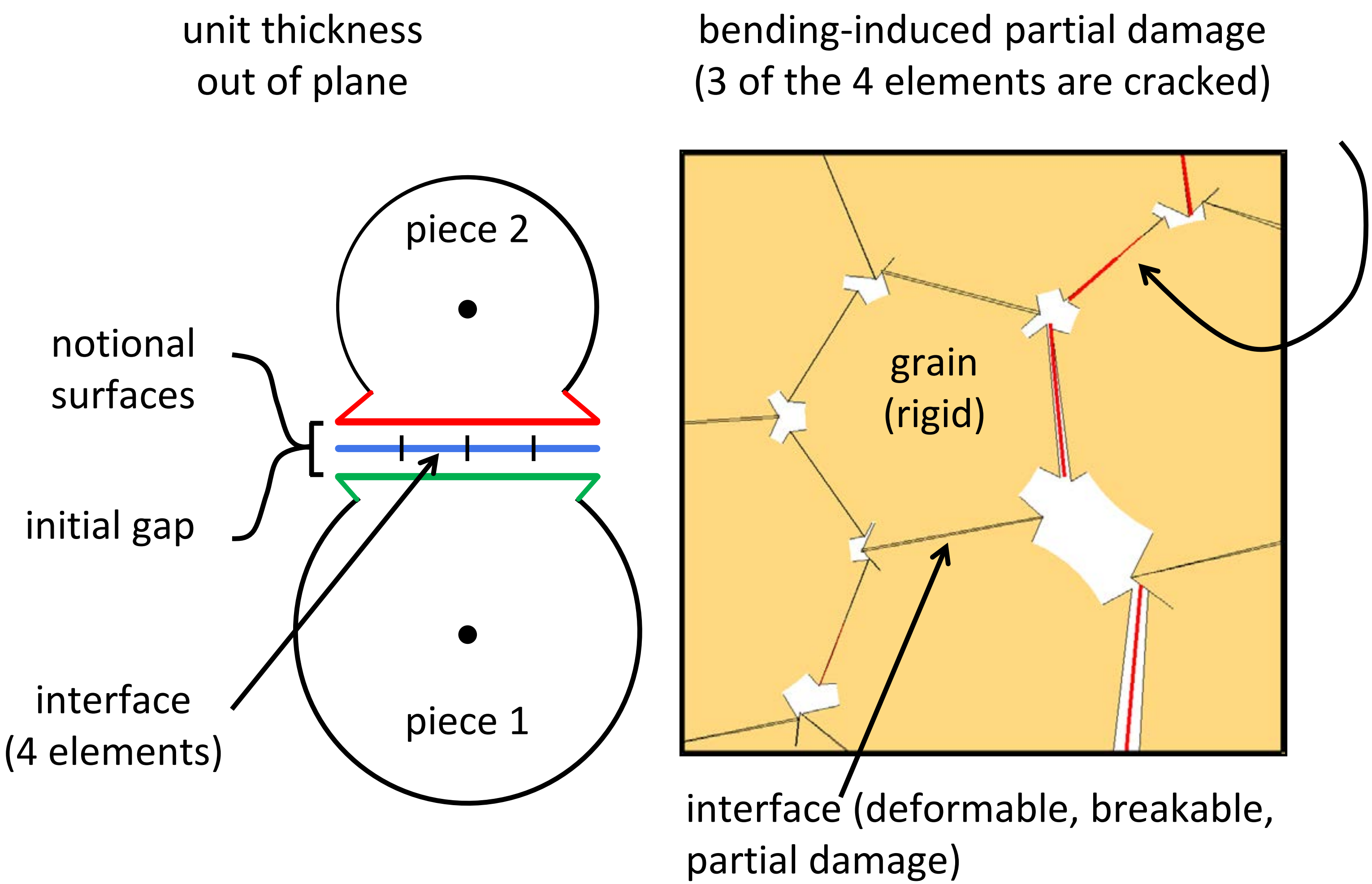
- The trends in the macroscopic response and the primary mechanism (*buckling-assisted fragmentation*) that occurs during TWC tests to produce a breakout failure type.

Model Description (flat-jointed material)



Flat-joint contact: provides macroscopic behavior of finite-size, linear elastic and either bonded or frictional interface that may sustain partial damage.

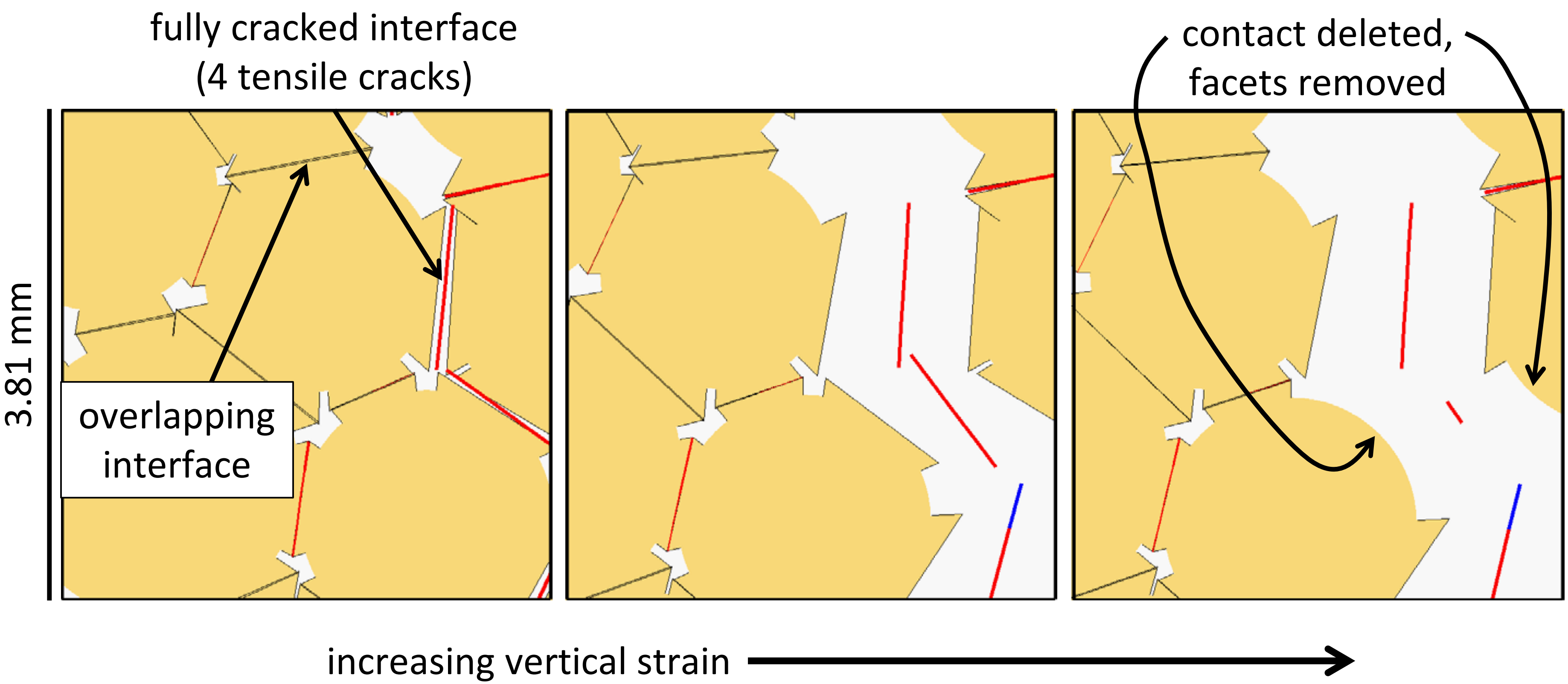
Model Description (flat-jointed material)



Flat-jointed material: rigid grains joined by flat-joint contacts. Grain surfaces are faceted.

Model Description (flat-jointed material)

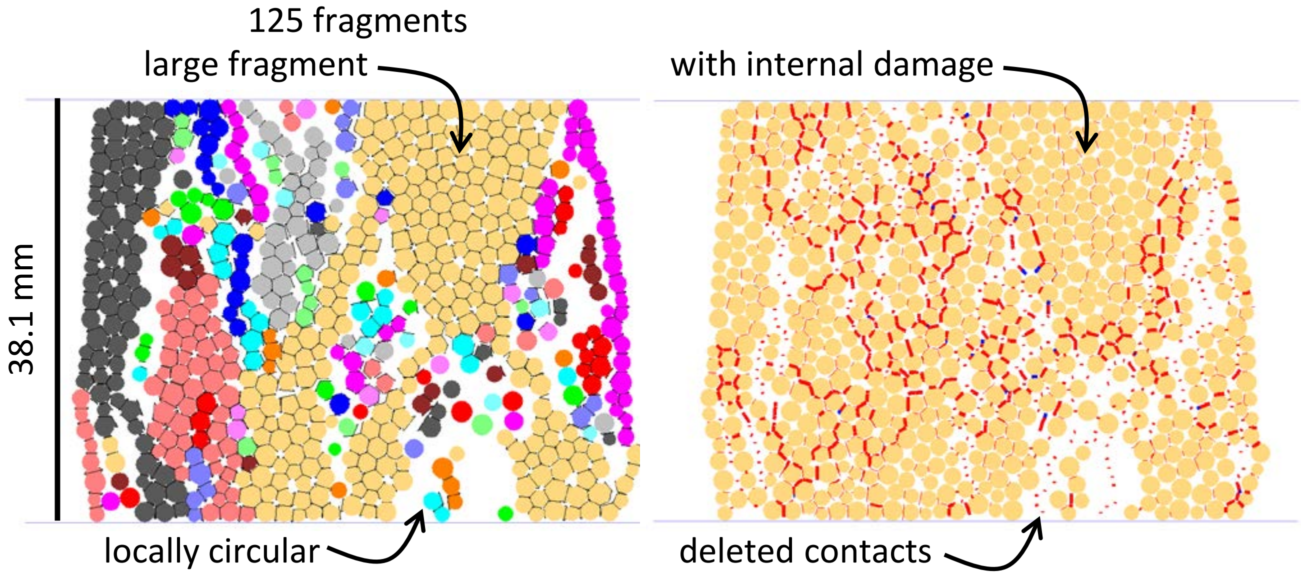
Damage in post-peak portion of UCS test as specimen exhibits axial splitting.



Damage consists of bond-breakage events, which we denote as cracks. Cracks are depicted as colored lines lying on the interface between the two grains with color depicting breakage mode (red/blue for tensile/shear failure) and line thickness proportional to interface gap.

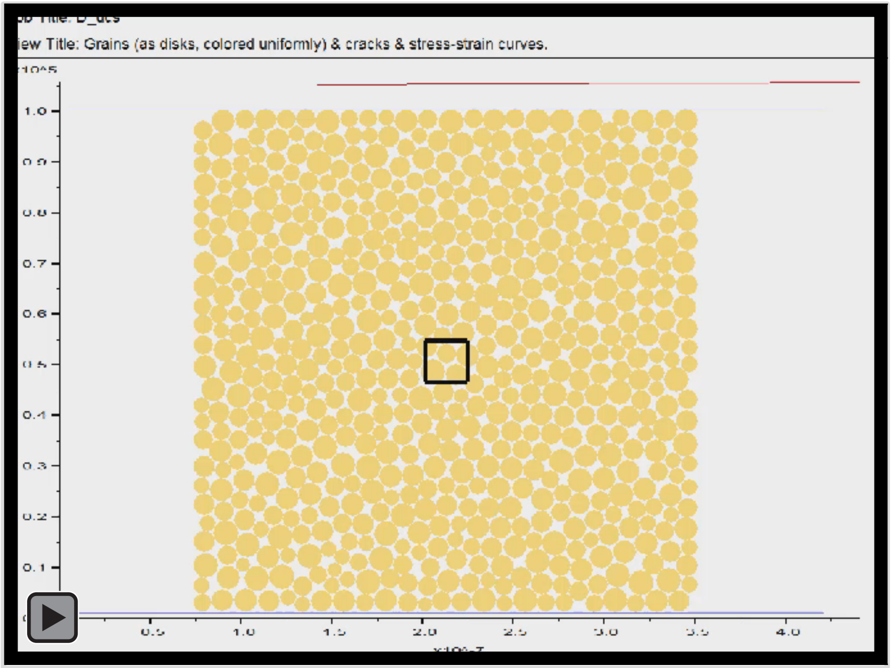
Model Description (flat-jointed material)

Fragmentation of 2D flat-jointed material in post-peak portion of UCS test when axial load has dropped to zero: grains drawn as faceted bodies and colored by fragment (left); grains drawn as disks and cracks colored red/blue for tensile/shear failure with thickness proportional to gap (right).

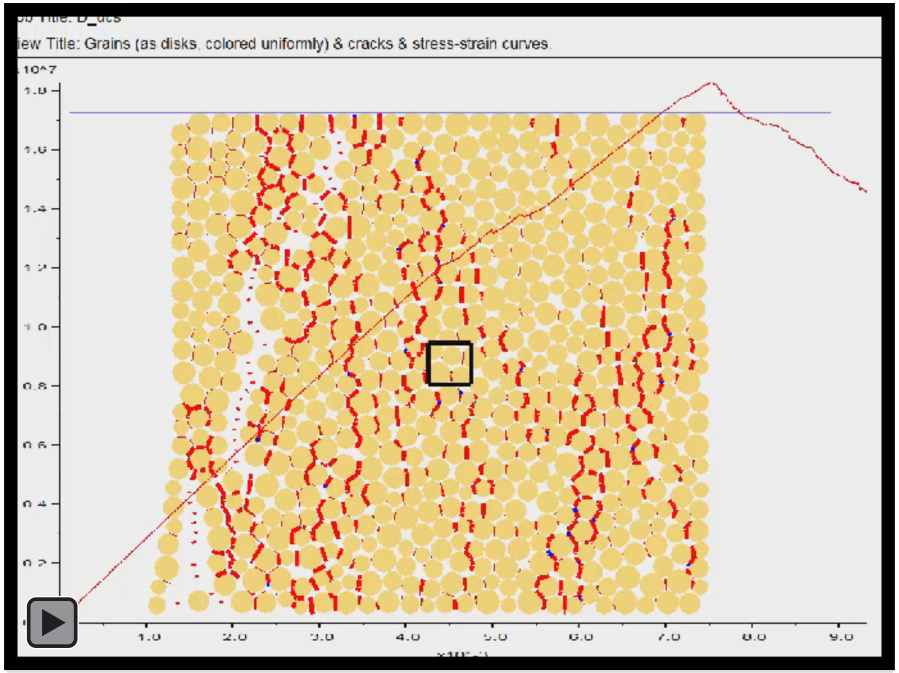


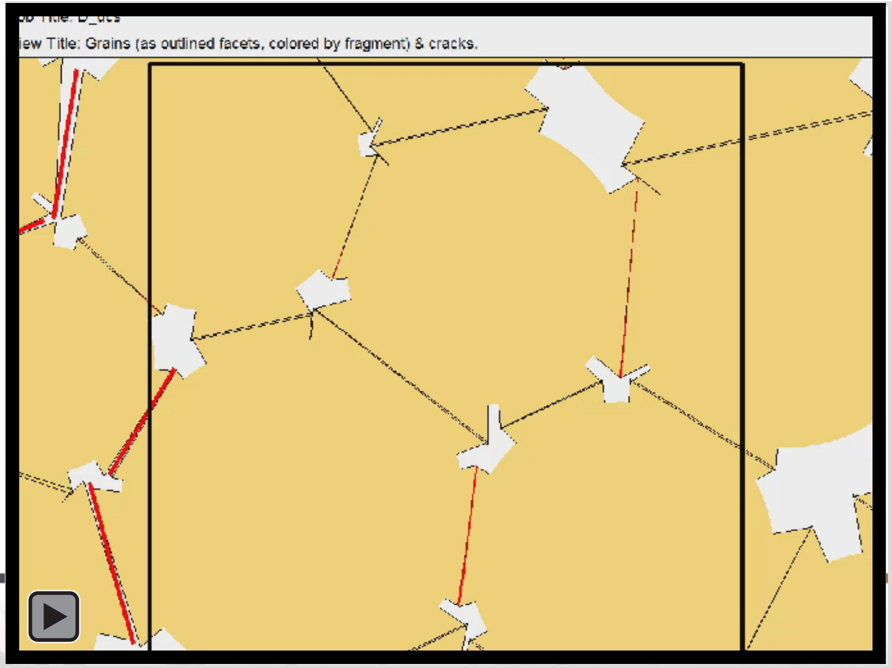
Cracks may link up to form fractures that break the material into fragments. Each fragment is defined as the set of grains joined by flat-joint contacts that have at least one of their elements bonded.

damage



damage (post peak)

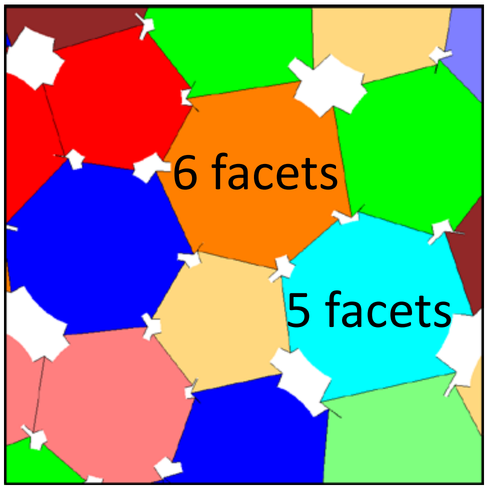




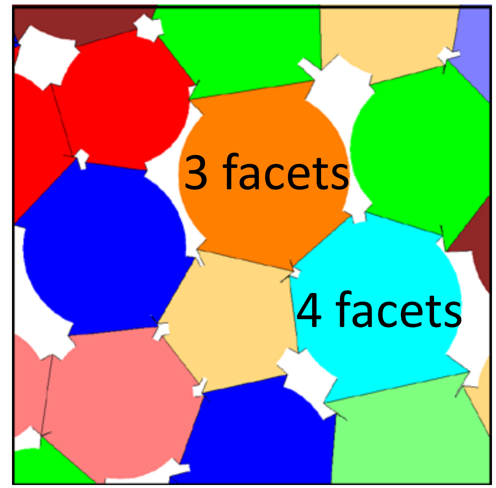
damage (post peak, zoom)

Model Description (CG material : Castlegate sandstone)

Microstructural features of CG material



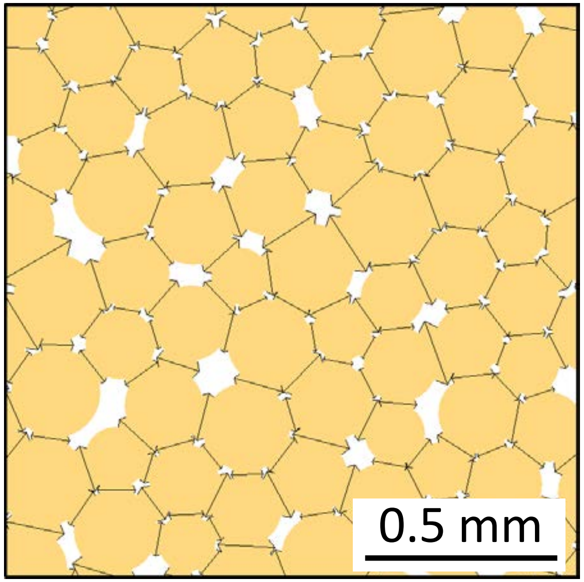
compact
maximal grain connectivity



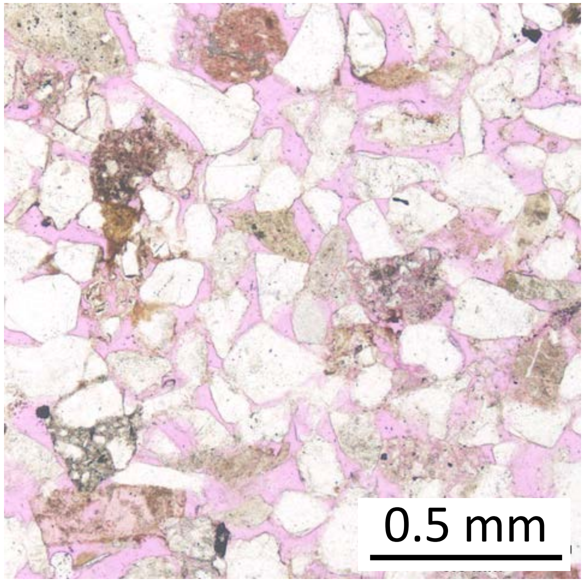
compact
reduced grain connectivity

Model Description (CG material : Castlegate sandstone)

Construct four CG materials that differ only in their grain size.



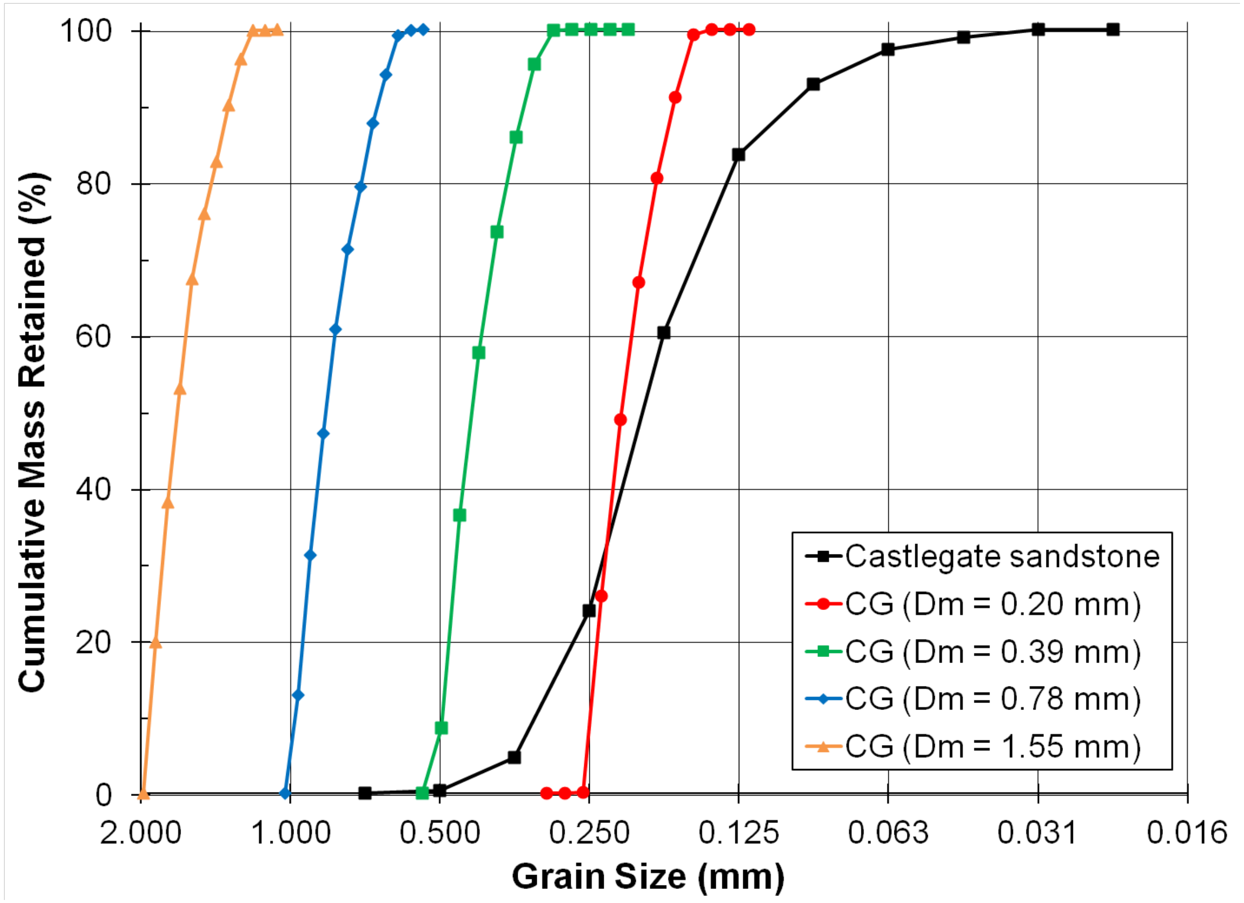
CG material ($D_m = 0.20\ \mathrm{mm}$)



Castlegate sandstone

Grain-size distributions differ. . .

Model Description (CG material : Castlegate sandstone)



Characterize grain-size distribution by median grain size (D_m)

Model Description (CG material : Castlegate sandstone)

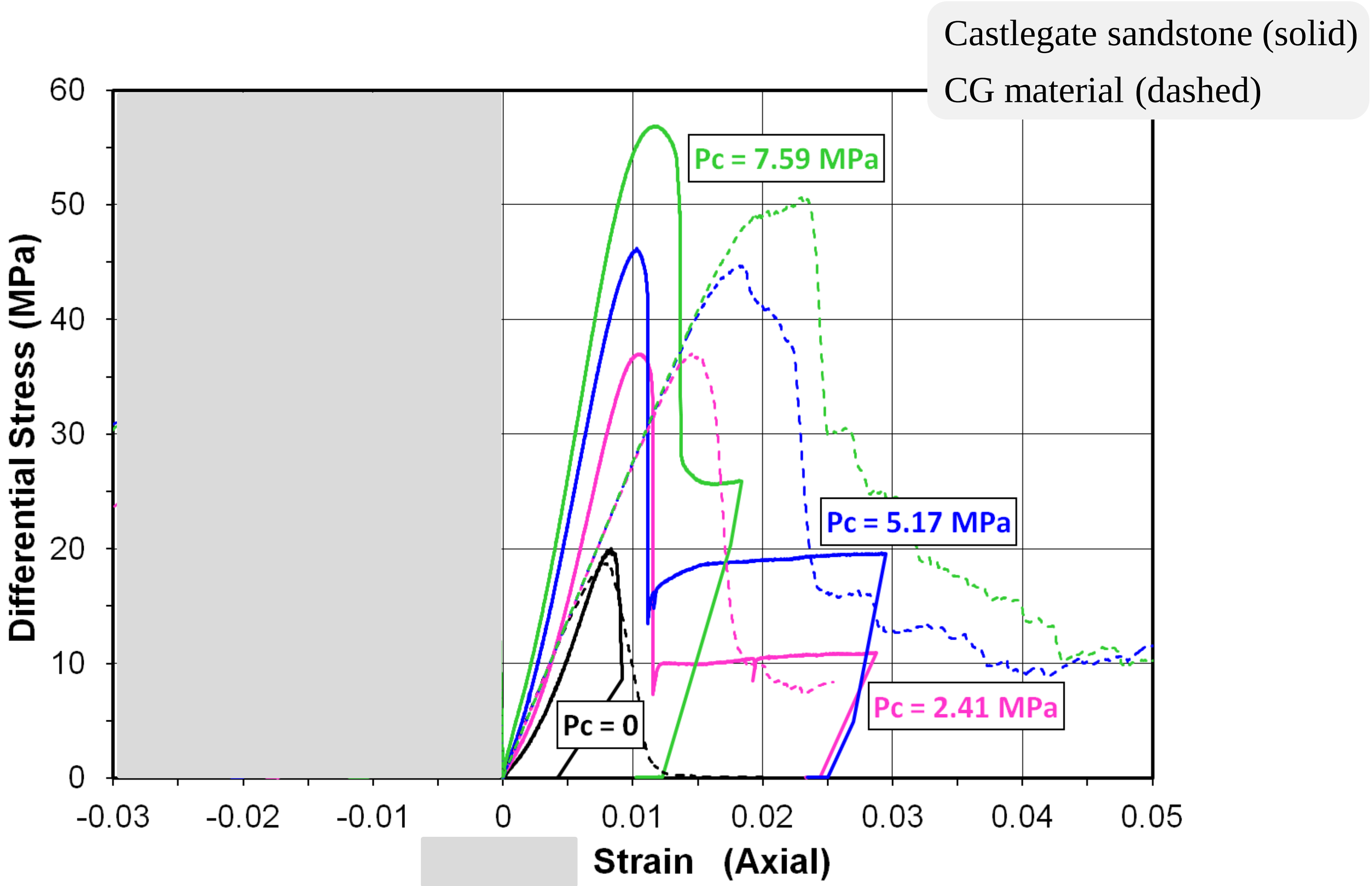
Microstructure of CG material is simplification of true microstructure; therefore, microproperties chosen via calibration process to match:

- Direct-tension strength
- Young's modulus and compressive strength from UCS test
- Compressive strength from 2.41-MPa confined compression test

next slide

These properties are matched for all grain sizes of the CG material.

Material Behavior (compression tests)



Stress-strain response during triaxial testing

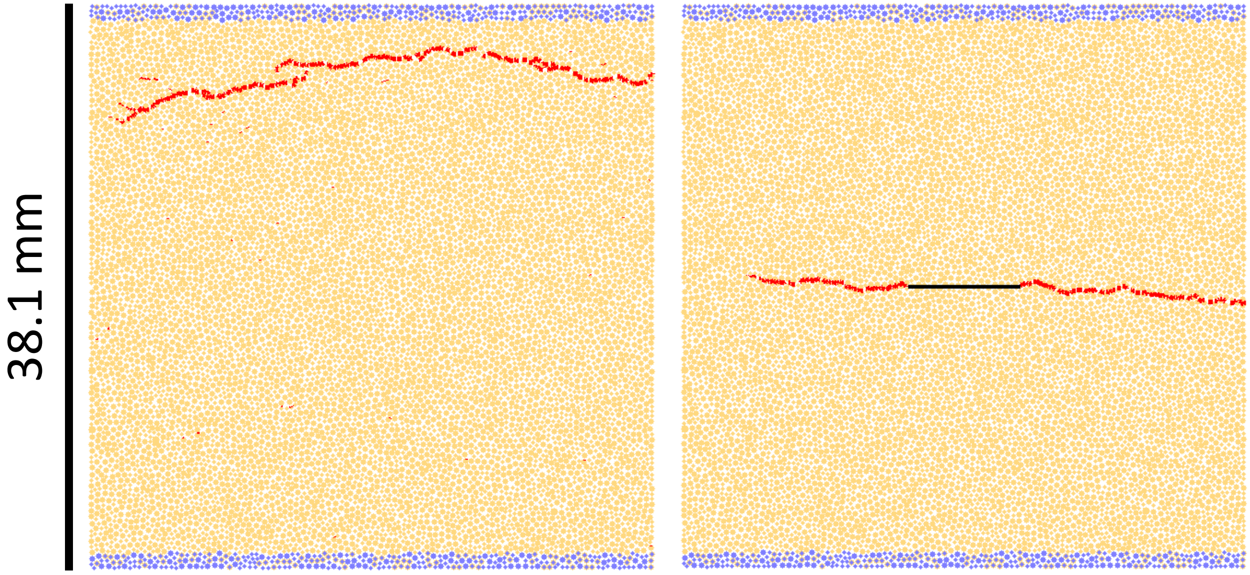
Material Behavior (tension & compression tests)

- The mechanisms that are exhibited during tension & compression tests are similar to 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 4 slides.

Direct-tension (& fracture-toughness) tests

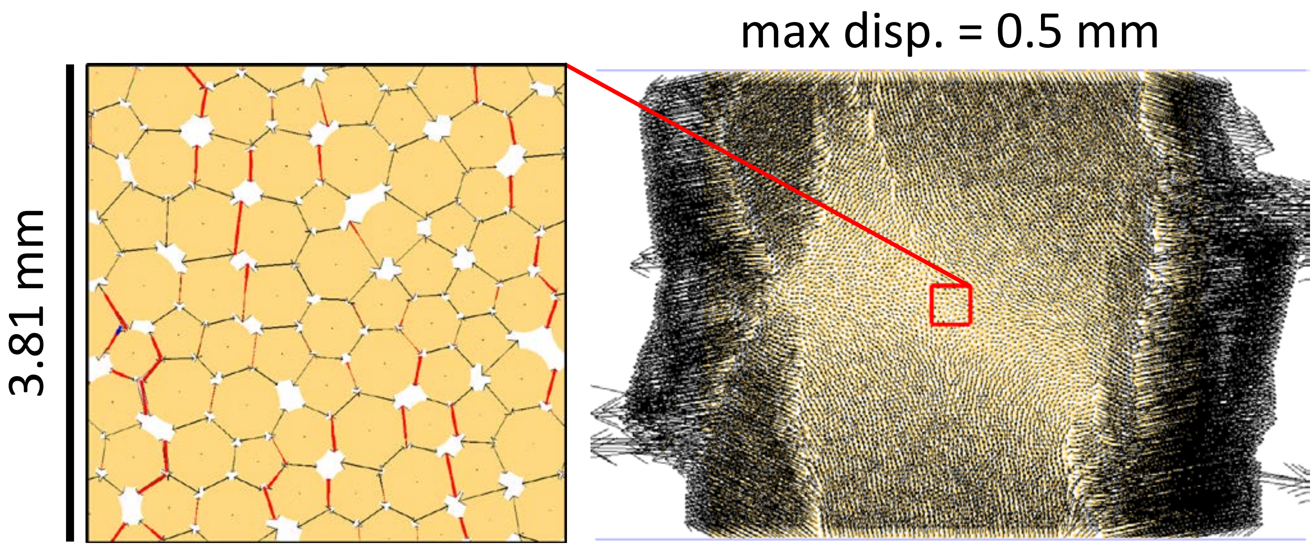
- Peak stress coincides with formation of a few tensile fractures aligned perpendicular to specimen axis.



Damaged microstructure at post-peak state of tension tests.

Compression test (unconfined)

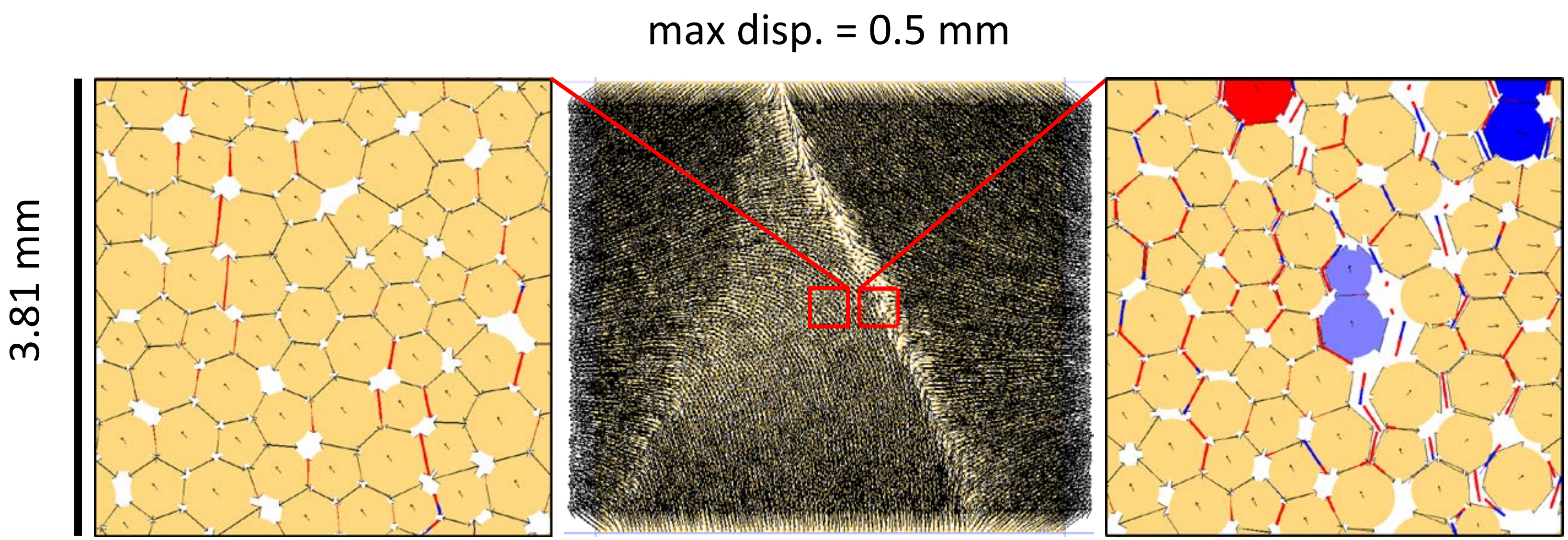
- Peak stress coincides with axial splitting in which the material breaks apart into multiple interlocking columns.



Damaged microstructure at post-peak state of UCS test.

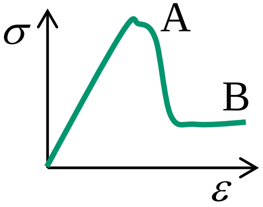
Compression test (confined)

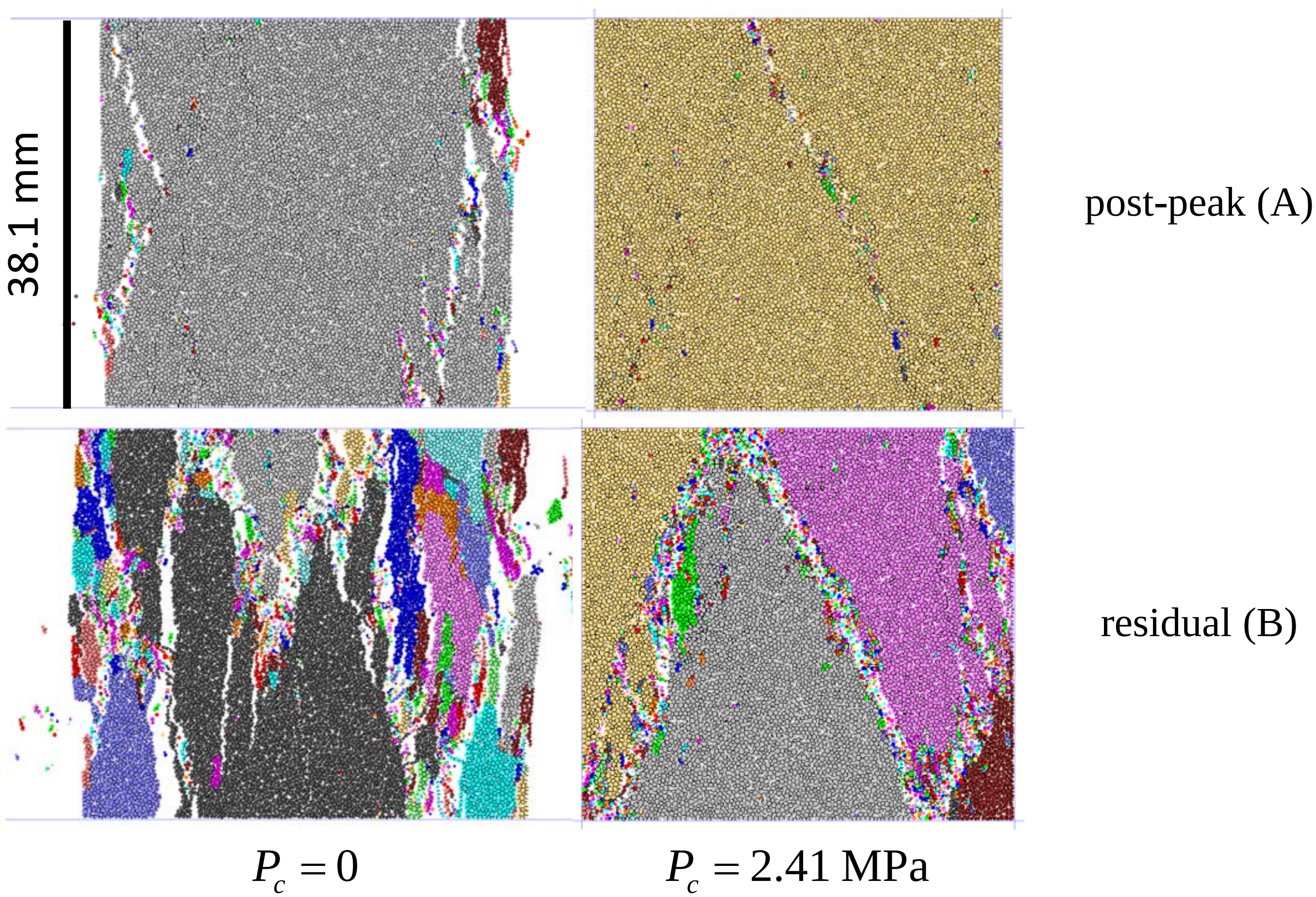
- Peak stress coincides with formation of a few diagonally aligned shear fractures.



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

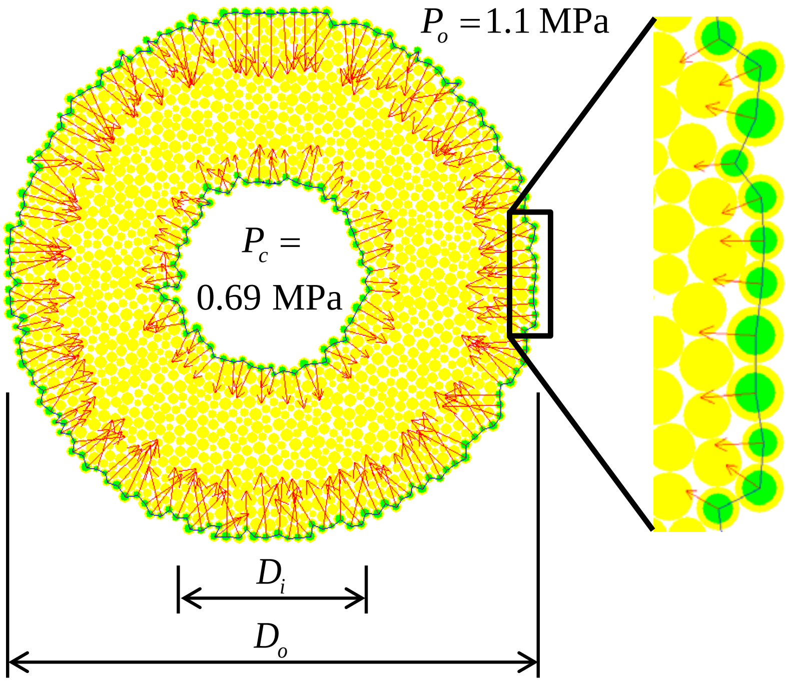
Compression tests (fragmentation)





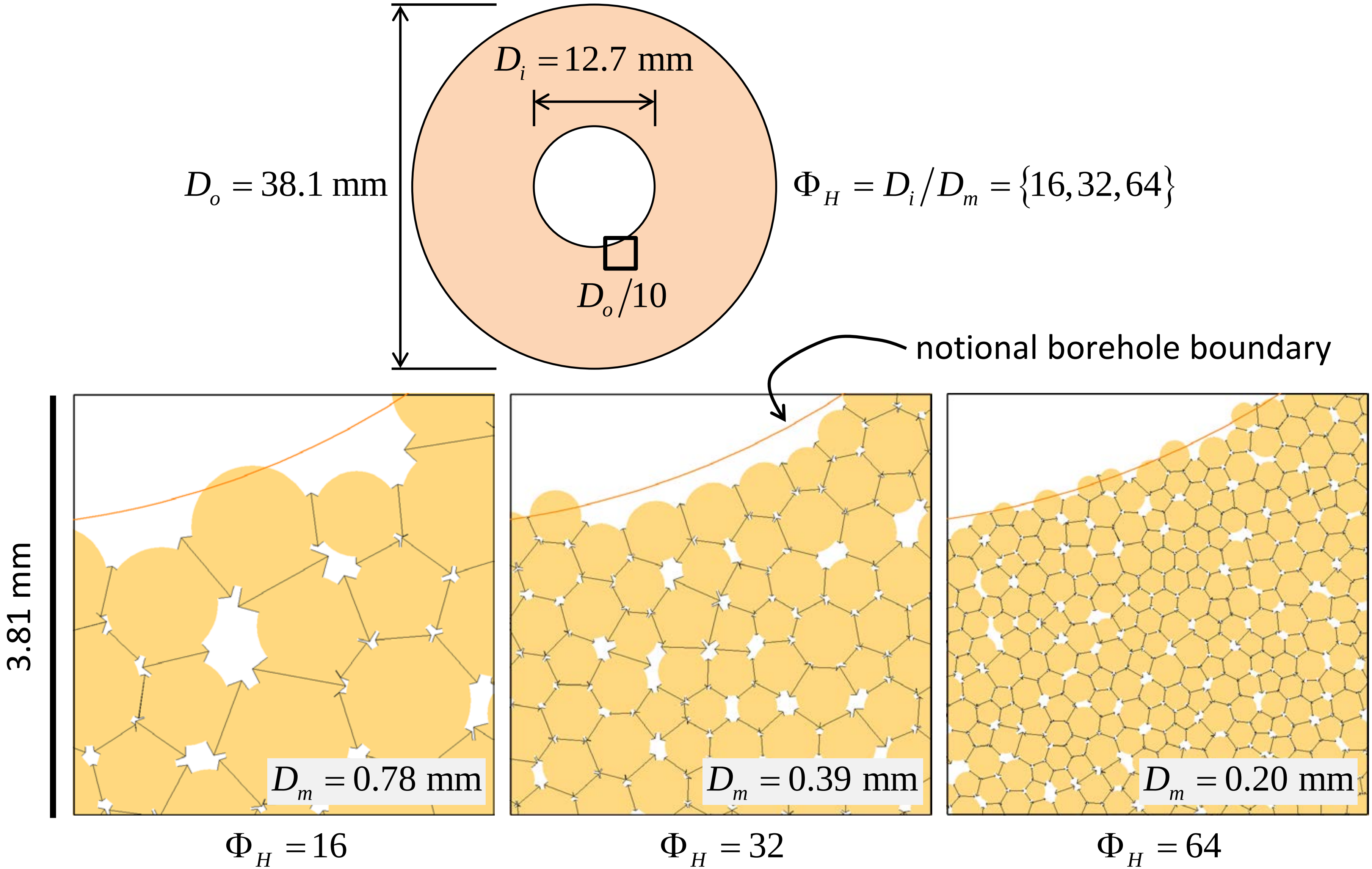
Fragmentation at post-peak (top) and residual (bottom) states of compression tests.

Model Description (TWC test)



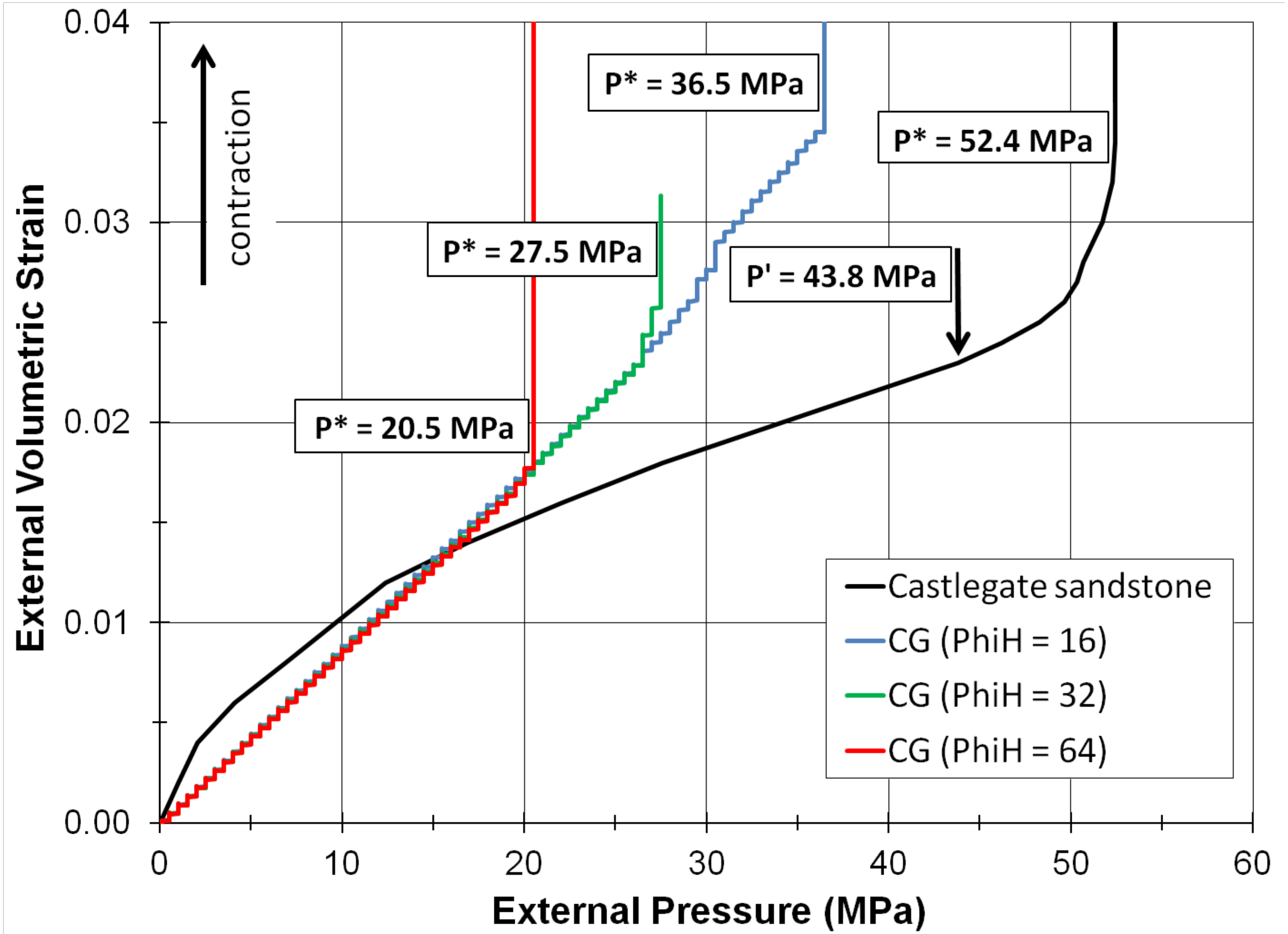
Model of a TWC test showing pressure-application procedure

Material Behavior (TWC test)



CG material (TWC specimen)

Material Behavior (TWC test)



TWC-test response (unconfined borehole)

Material Behavior **(TWC test)**

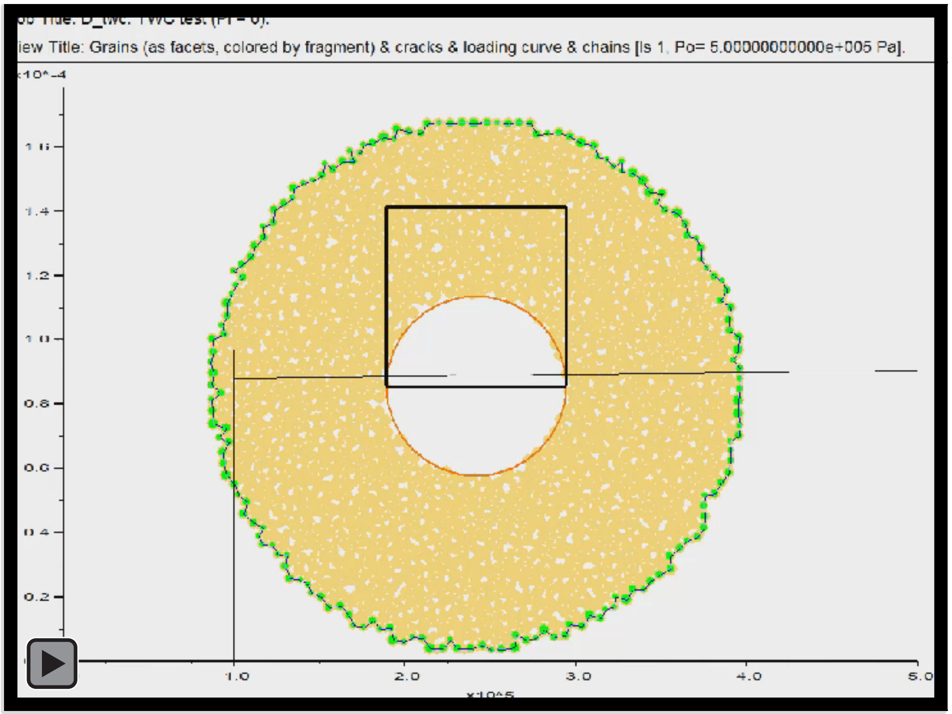
We will now describe and analyze the damage evolution in the CG material during the TWC tests.

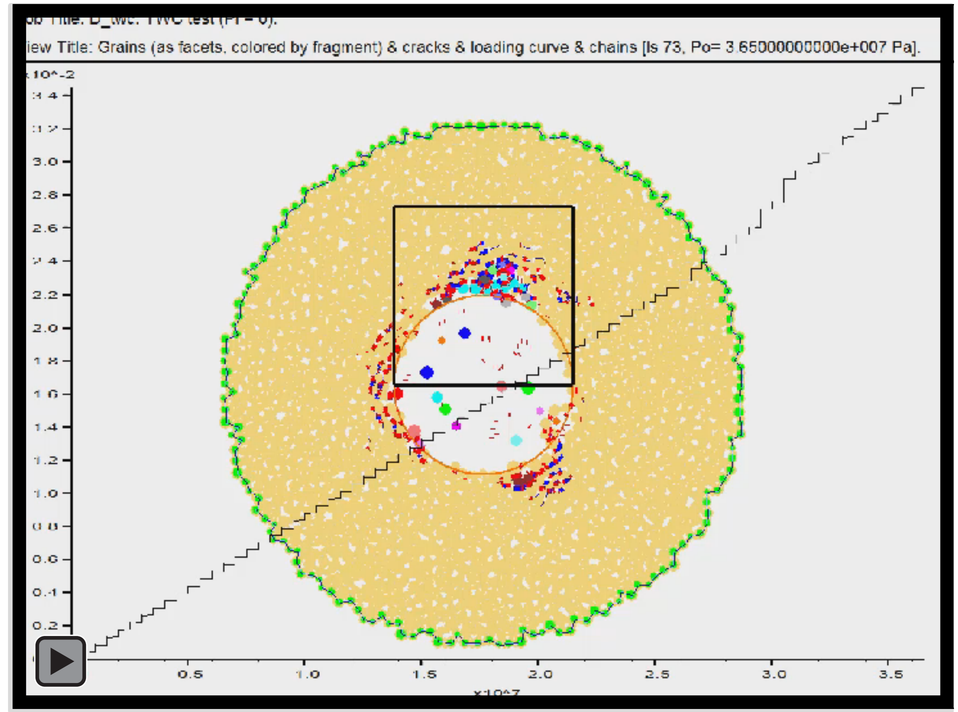
Response of CG material is similar for all grain sizes, with the exception that the damage & collapse pressures decrease with decreasing grain size.

We will focus on the CG material with the largest grain size.

$$\text{CG material } \left(\Phi_H = 16\right) : P' = 29.5 \text{ MPa}, \; P^* = 36.5 \text{ MPa}$$

Material Behavior (TWC test)





$P_o = 36.0 \text{ MPa (stable)}$

damage

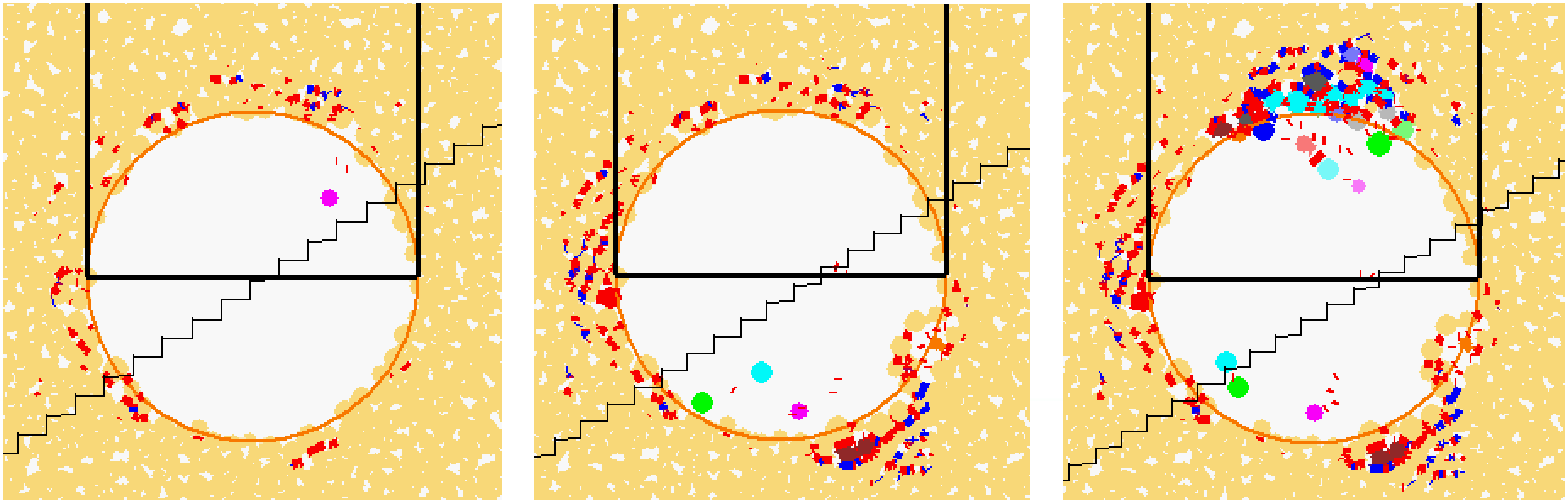
$P_o = 36.5 \text{ MPa} = P^*$

damage

Material Behavior (TWC test)

The damage process is summarized as follows.

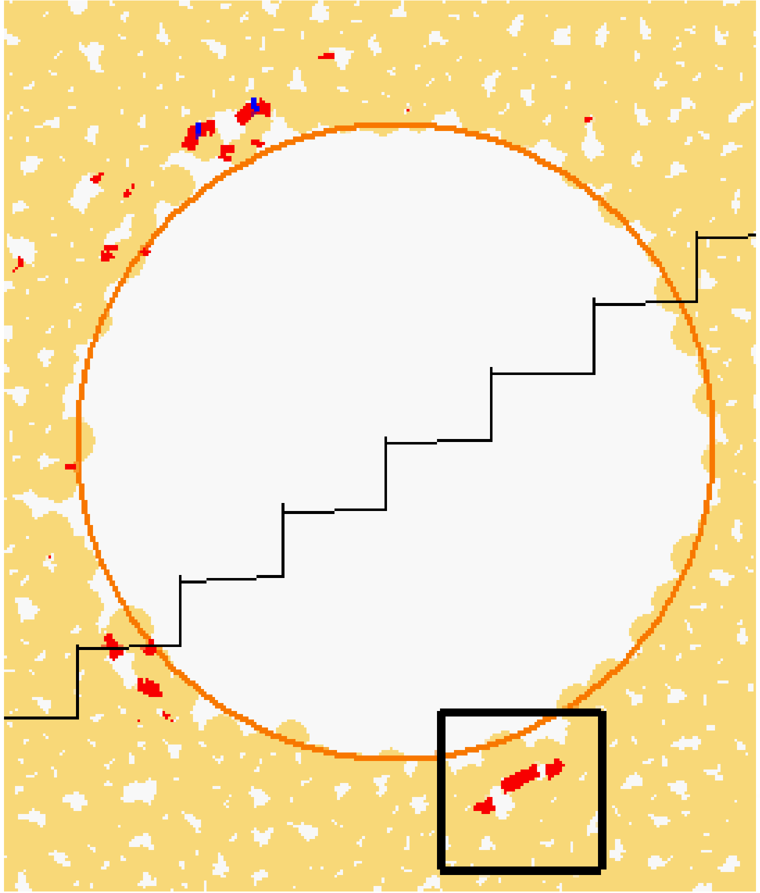
Damage forms near the borehole wall in response to the compressive circumferential stress, and as damage forms, the material softens and sheds load deeper into the rock. The increased load induces more damage so that the damage zone expands into the rock. The damage zone does not expand uniformly into the rock, but instead includes notch-shaped regions.



Material Behavior (TWC test)

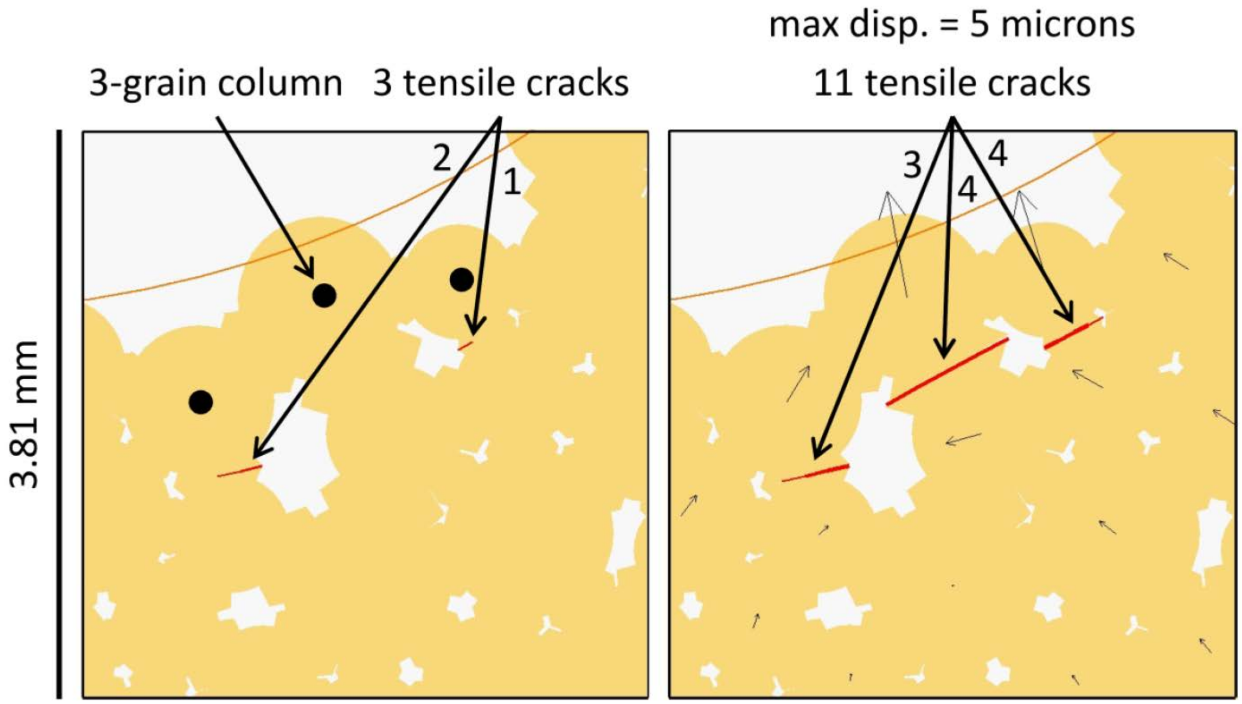
When $P_o = 20.0$ MPa $< P'$,

there is very little damage with nearly all cracks being tensile and lying within two grain layers of the borehole wall; the only macroscopic features are a few surface-parallel extension fractures, one of which is shown here.



Material Behavior (TWC test)

This fracture results from the inward bulging of a three-grain column, which remains attached to the surrounding rock. The fracture consists of 11 tensile cracks along three grain boundaries. Only three of the cracks are present at a pressure of 12.0 MPa; the fracture is produced by the addition of eight tensile cracks when the pressure is increased to 12.5 MPa.



$P_o = 12.0$ MPa (stable) $P_o = 12.5$ MPa (stable)

Material Behavior (TWC test)

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

Show next slide, while reading:

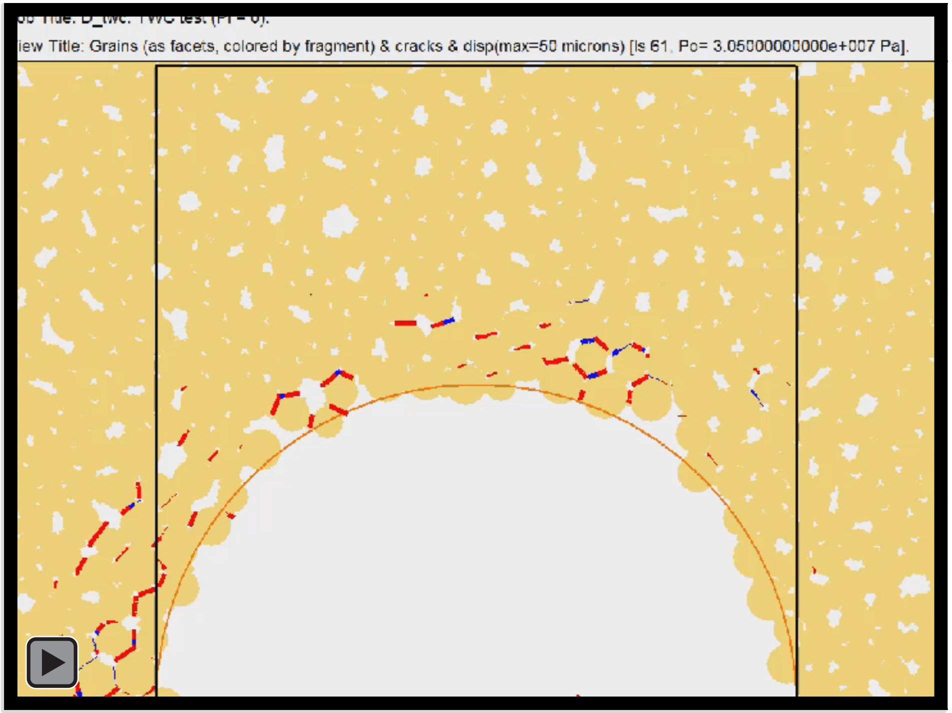
A series of surface-parallel fractures, followed by notch-flank parallel fractures, form as the material outside of the notch squeezes toward the notch sides, and then upward toward the notch tip, while the material within the notch dilates into the borehole.

Show second next slide, while reading:

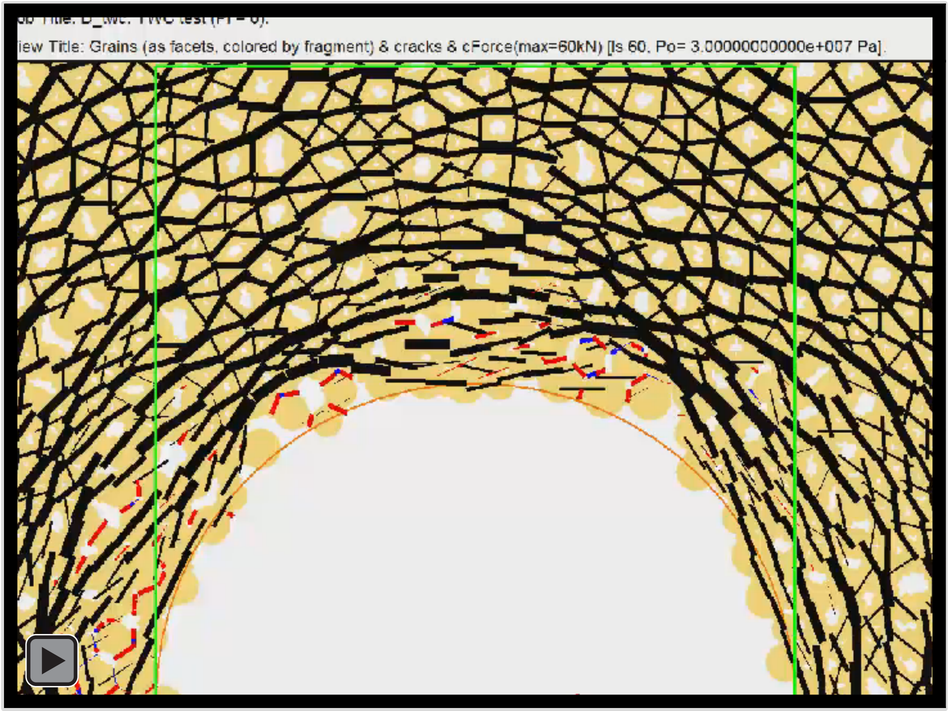
The material within the notch softens and diverts the load toward its tip at which a large compressive zone develops to stabilize the notch.

Show next slide, while reading:

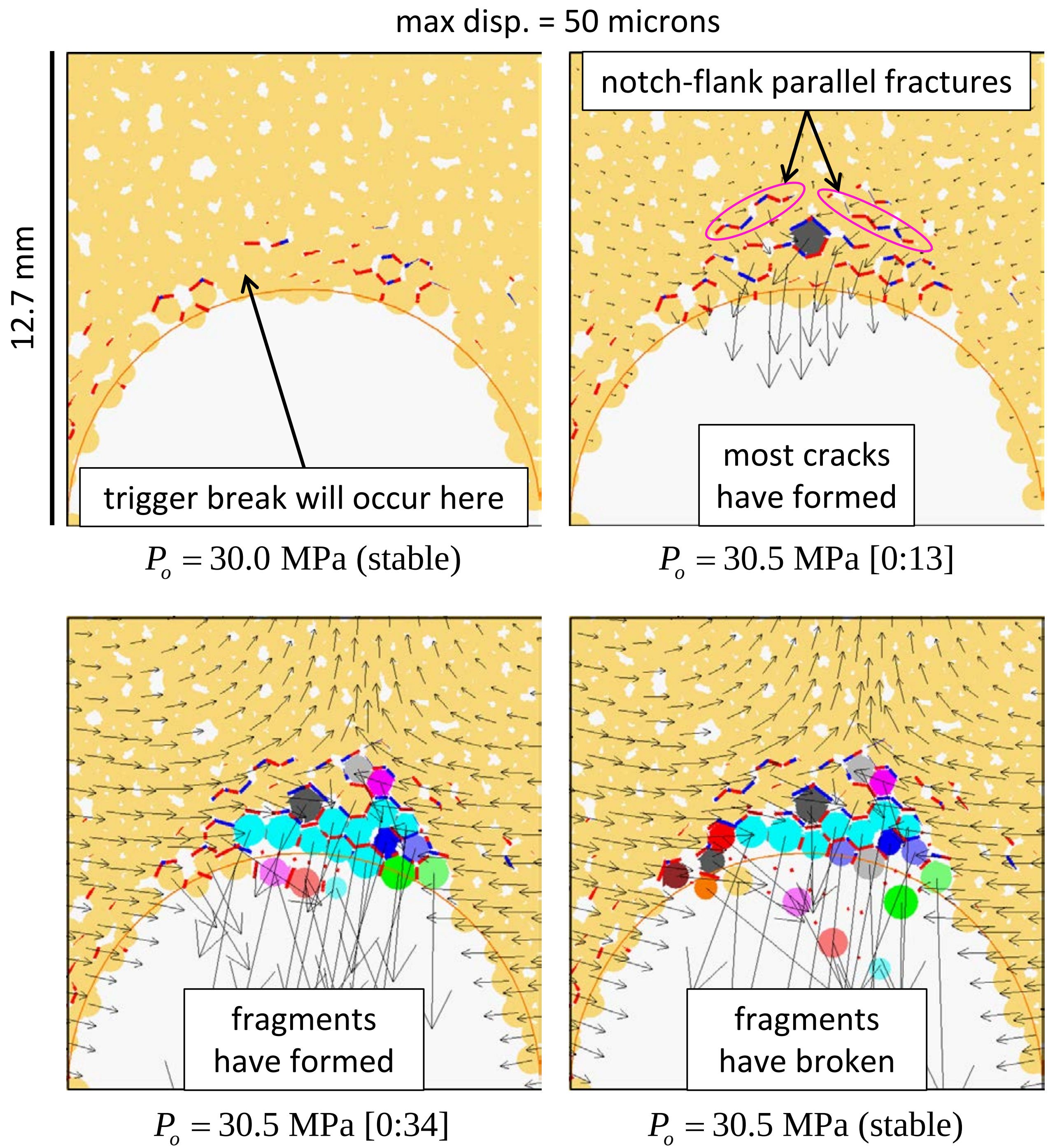
The notch-flank parallel fractures consist of a zigzag group of tensile and shear cracks and form a series of dilatant, interconnected, column-like structures of one- or two-grain thickness that are similar to interlocking thin slabs. The fractures are formed by a mix of extensile and shear motion. After 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.

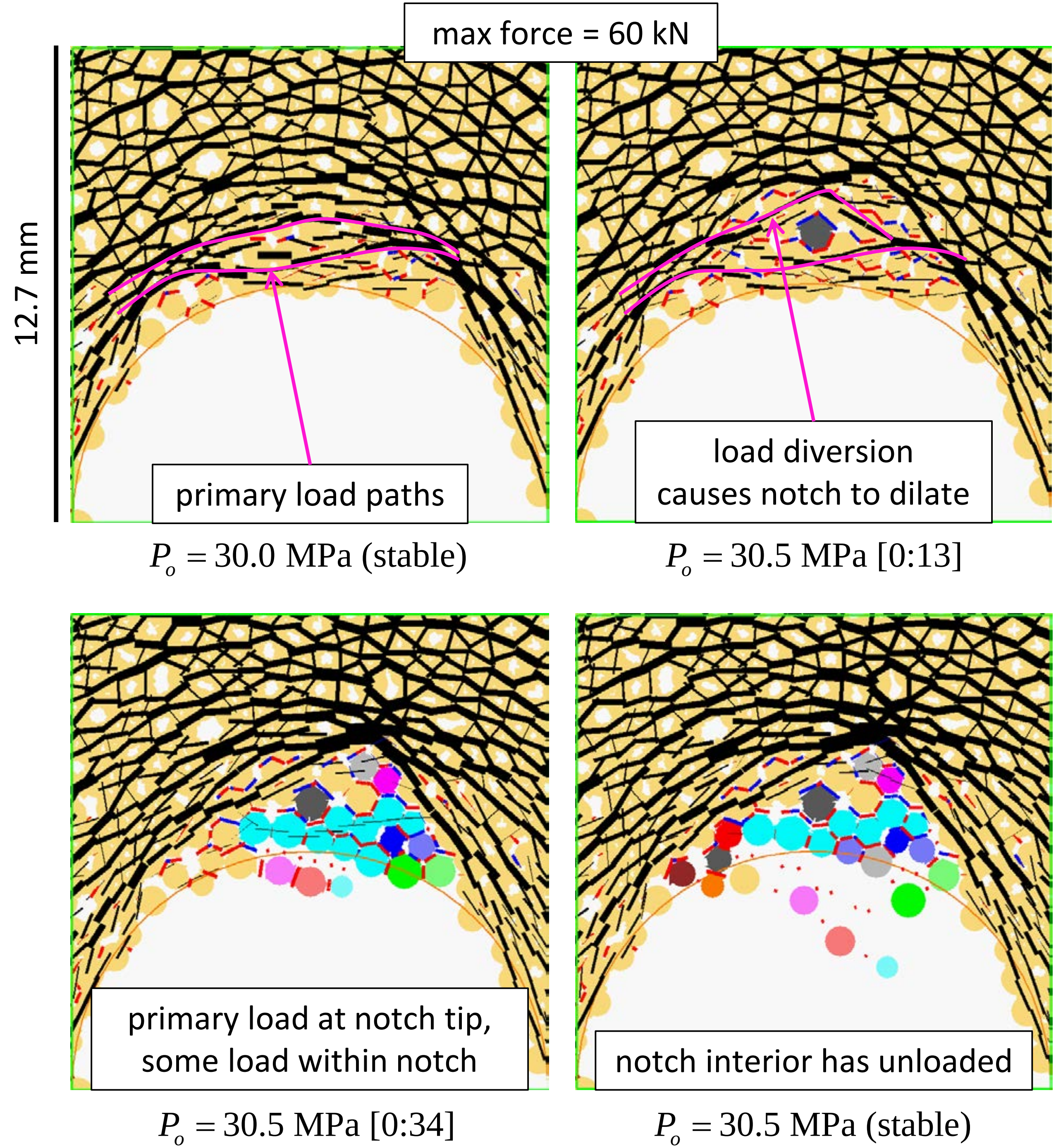


damage



damage & forces


max disp. = 50 microns
12.7 mm
trigger break will occur here
notch-flank parallel fractures
most cracks have formed
fragments have formed
fragments have broken
$P_o = 30.0$ MPa (stable)
$P_o = 30.5$ MPa [0:13]
$P_o = 30.5$ MPa [0:34]
$P_o = 30.5$ MPa (stable)

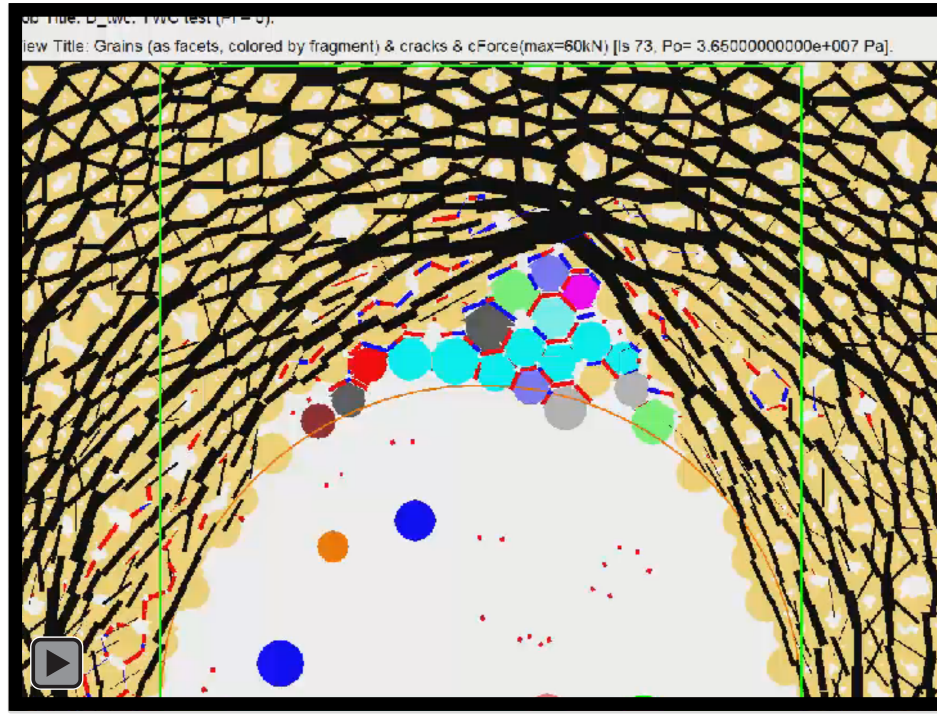

max force = 60 kN
12.7 mm
primary load paths
load diversion causes notch to dilate
$P_o = 30.0$ MPa (stable)
$P_o = 30.5$ MPa [0:13]
primary load at notch tip, some load within notch
notch interior has unloaded
$P_o = 30.5$ MPa [0:34]
$P_o = 30.5$ MPa (stable)

Material Behavior (TWC test)

We now describe the failure of the notch above the borehole when the external pressure reaches 36.5 MPa.

The newly formed fragments are relatively long, but break into shorter fragments as they bend inward. The breakage is also aided by relative shearing motion as fragments closer to the borehole are squeezed more than those farther from the borehole.

We define the primary damage mechanism as buckling-assisted fragmentation, whereby a buckling and spalling process produces thin fragments of rock similar to onion skins.

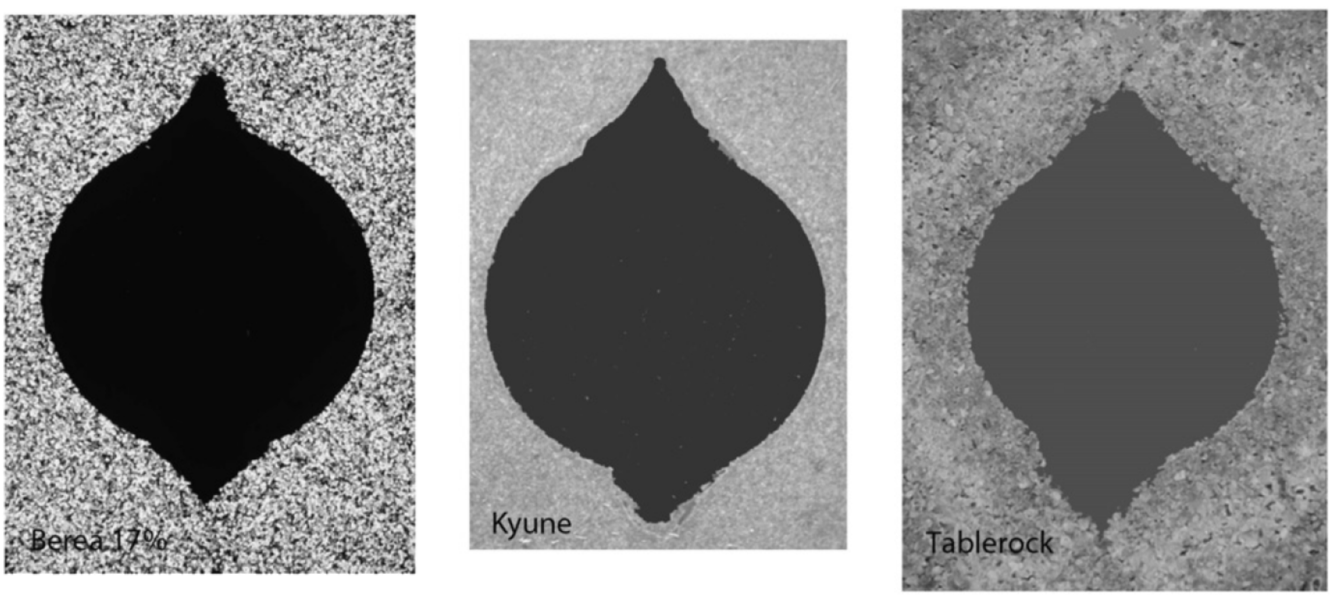


damage & forces

Material Behavior **(TWC test)**

The micromechanics of failure are strikingly similar to the following summary of behavior observed during drilling experiments in a variety of rock types.

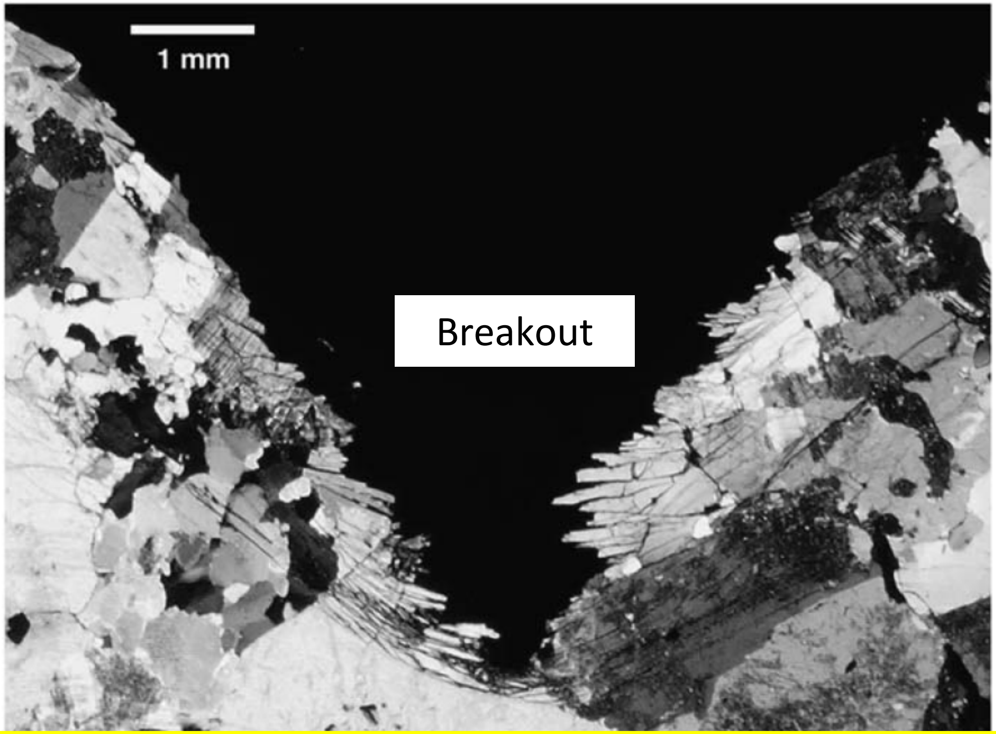
> All rocks tested. . .develop dog-eared breakouts. . .even though the grain-scale mechanisms leading to the final appearance may differ considerably. The common denominator is the incipient failure in the form of dilatant microcracking in the zones of the highest stress concentration around the borehole. (Haimson, 2007)



Haimson, B. (2007) "Micromechanisms of Borehole Instability Leading to Breakouts in Rocks," *Int. J. Rock Mech. & Min. Sci.*, ***44***, 157–173.

Material Behavior (TWC test)

Buckling-assisted fragmentation may be similar to the process that produces the cantilevered remnants of buckled and sheared off thin rock flakes near the breakout tip observed during drilling experiments in granite. Haimson (2007) suggests that these fragments were produced by buckling, and then sheared off and removed by the circulating drilling fluid in a buckling and spalling process similar to peeling off very thin layers of rock, like onion skins. The process is dilatant and similar to the extensile cracking in rock specimens subjected to high uniaxial compressive stress.



Cantilevered remnants of buckled and sheared-off thin rock flakes formed during drilling experiments in Lac du Bonnet granite. [From Fig. 8 of Haimson (2007).]

Conclusions

Qualitative connection has been established between model & field behavior during perforation-failure process.

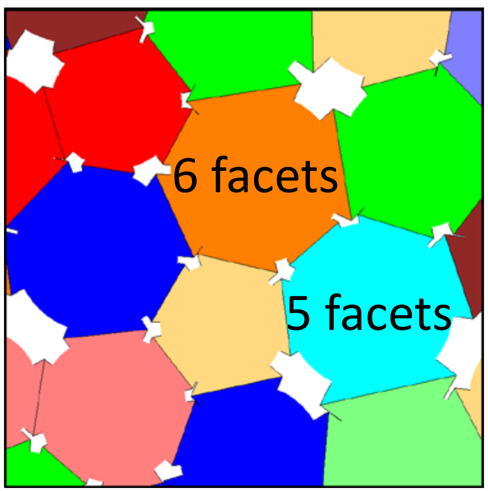
Underestimation of TWC strength for CG material with average grain size nearly equal to the median grain size of Castlegate sandstone should be resolved before making quantitative perforation-failure predictions.

$$\text{CG material } \left(D_m = 0.20 \text{ mm}\right) : P^* \cong 21 \text{ MPa}$$

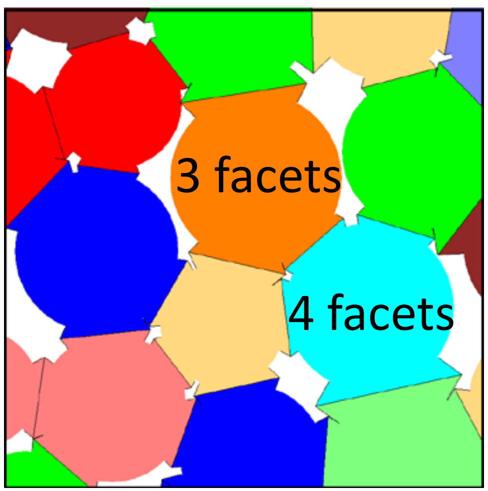
$$\text{Castlegate sandstone } \left(D_{50} = 0.19 \text{ mm}\right) : P^* \cong \{37, 52\} \text{ MPa}$$

Conclusions

- Further development of the 2D flat-jointed material to better match sandstone behavior includes:
  - producing a more porous microstructure by reducing the grain connectivity of the current compact microstructure



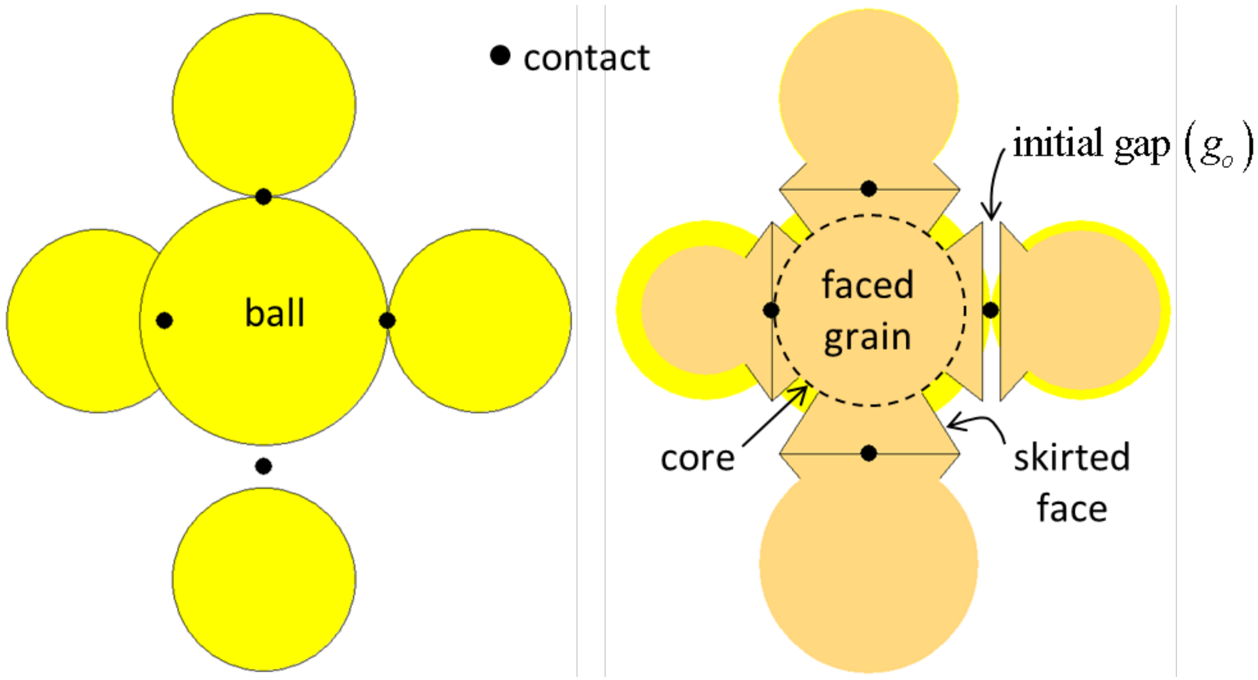
compact
maximal grain connectivity



compact
reduced grain connectivity

Conclusions

- Further development of the 2D flat-jointed material to better match sandstone behavior includes:
  - adding initial slits and gaps



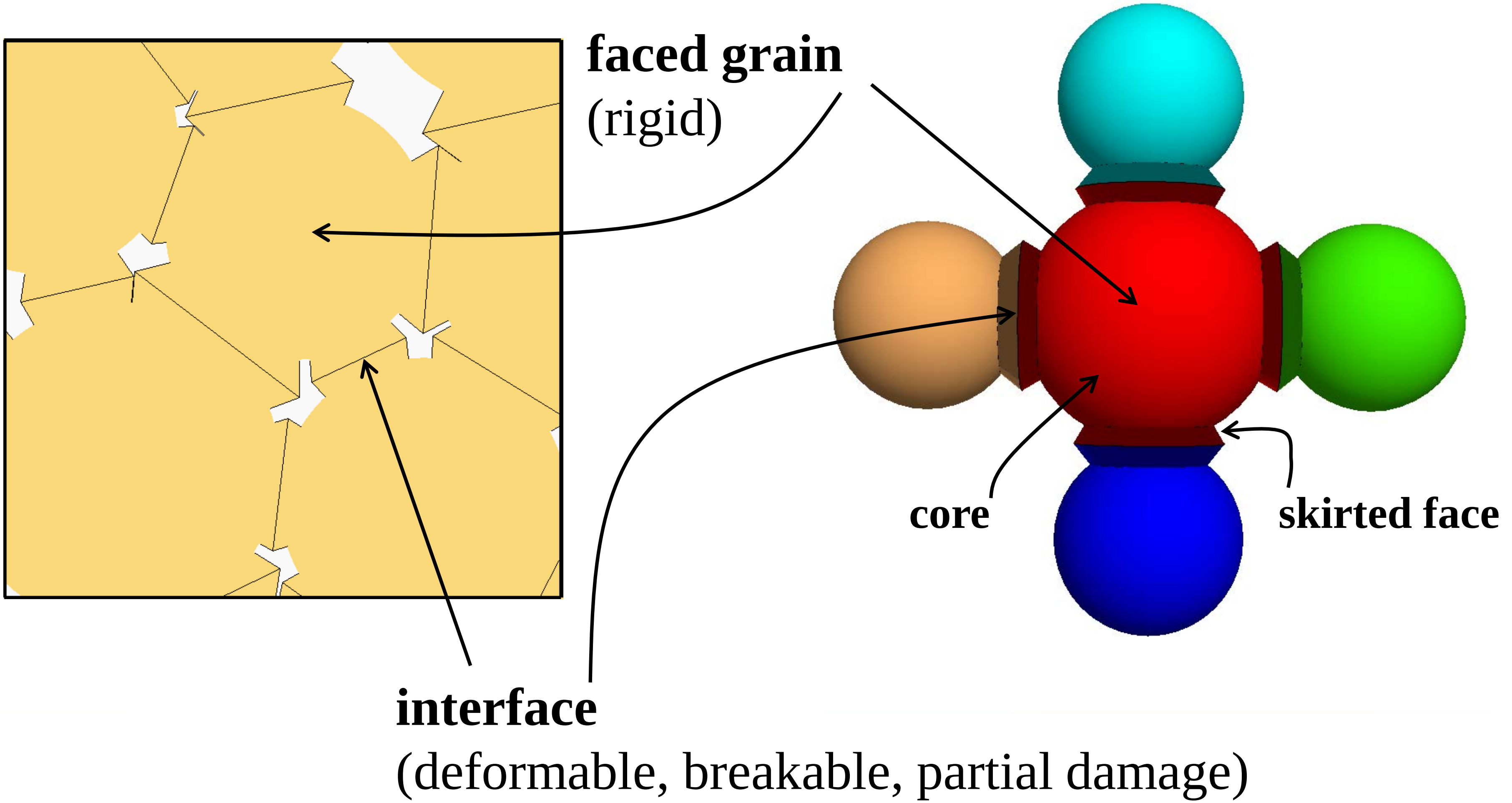
Conclusions

- Slot-like failures may be related to formation of compaction bands (narrow zones in which there has been grain debonding and repacking with grain damage varying from none to thorough cracking and crushing).
  - CG material is compact.
  - Microstructural modifications could be made to accommodate compaction-band formation:

    ➔ Create material with sparsely connected microstructure, and/or allow grains to break at some critical stress.

Conclusions

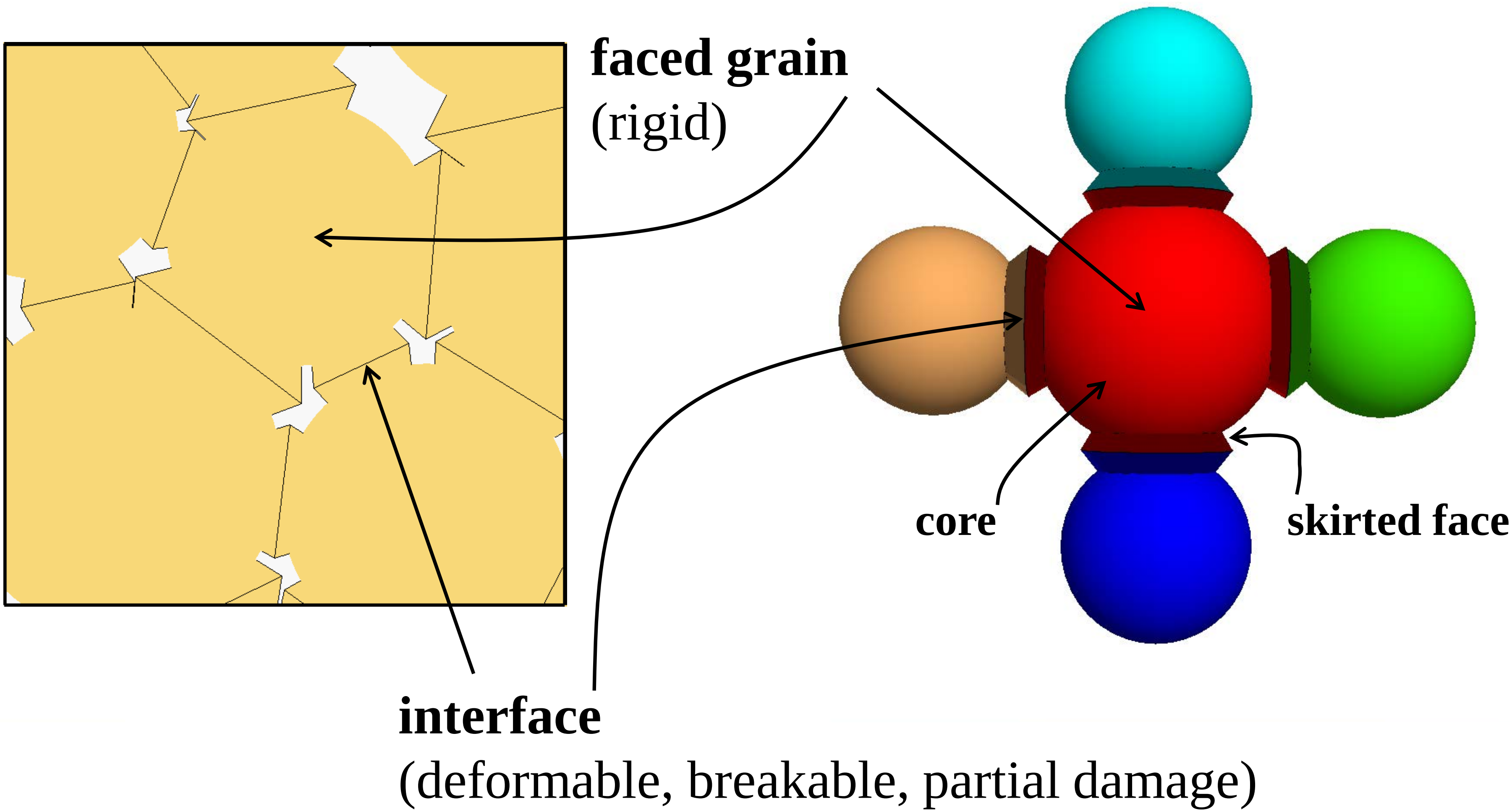
- 3D flat-jointed material exists, and we expect that it will provide similar behavior to that of the 2D flat-jointed material described here.



Conclusions

Provided in material-modeling support package for PFC 5.0, ready for research use!

- 3D flat-jointed material exists, and we expect that it will provide similar behavior to that of the 2D flat-jointed material described here.



Final Words

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

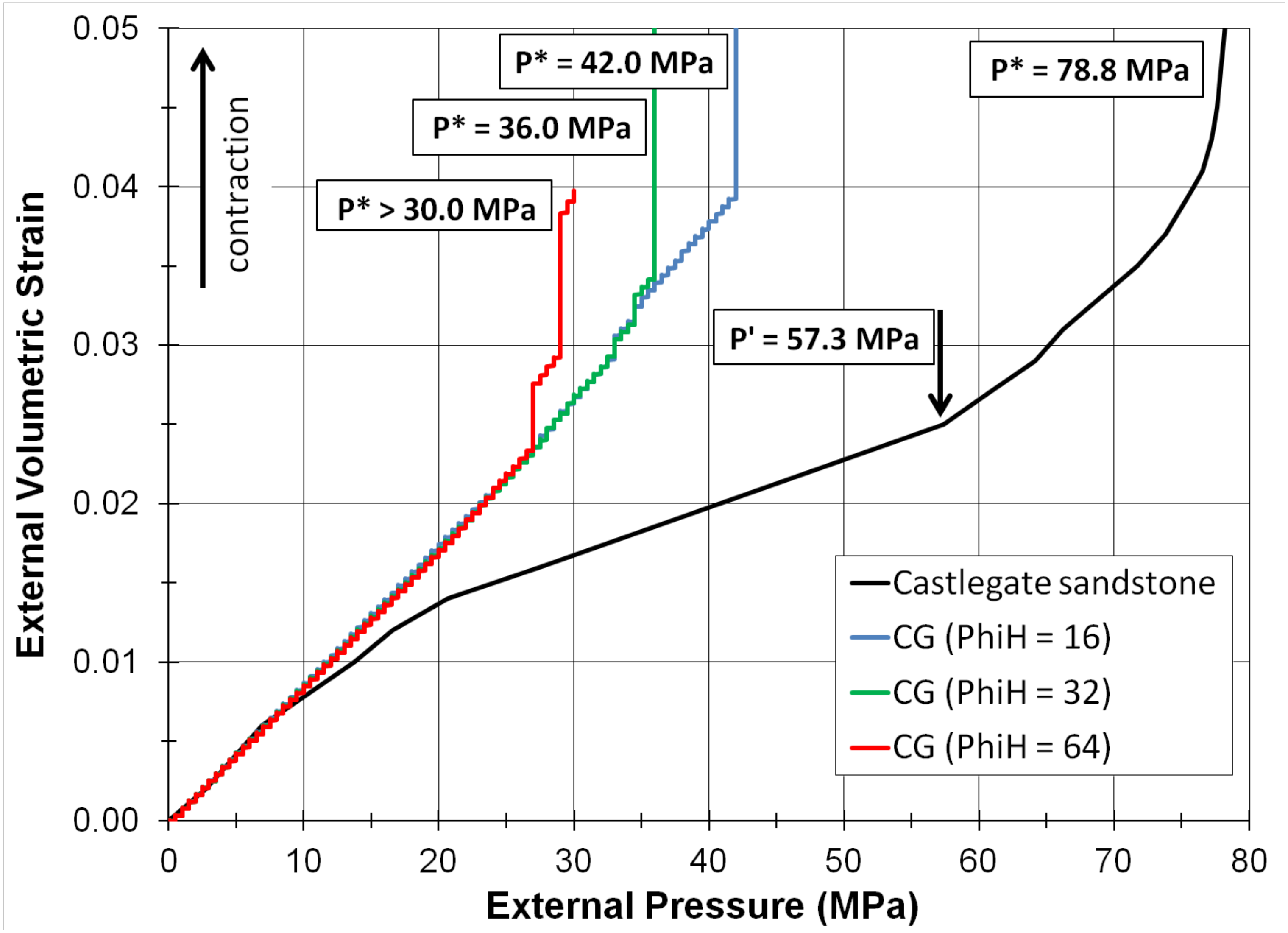
Challenge is to keep models as simple as possible

- include features to allow relevant micromechanisms to occur

END OF TALK

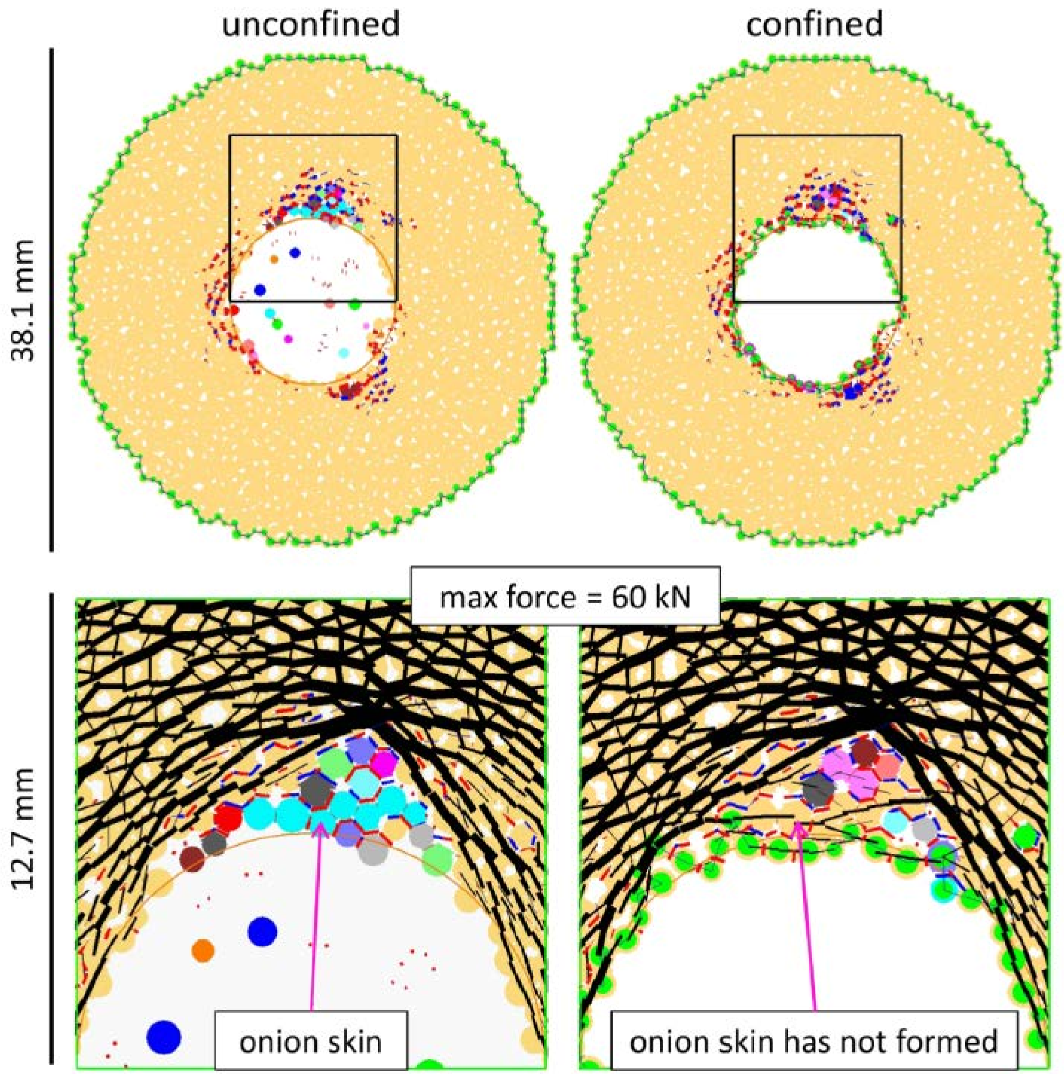
EXTRA MATERIAL

Material Behavior (TWC test)



TWC-test response (0.69-MPa confined borehole)

Material Behavior (TWC test)



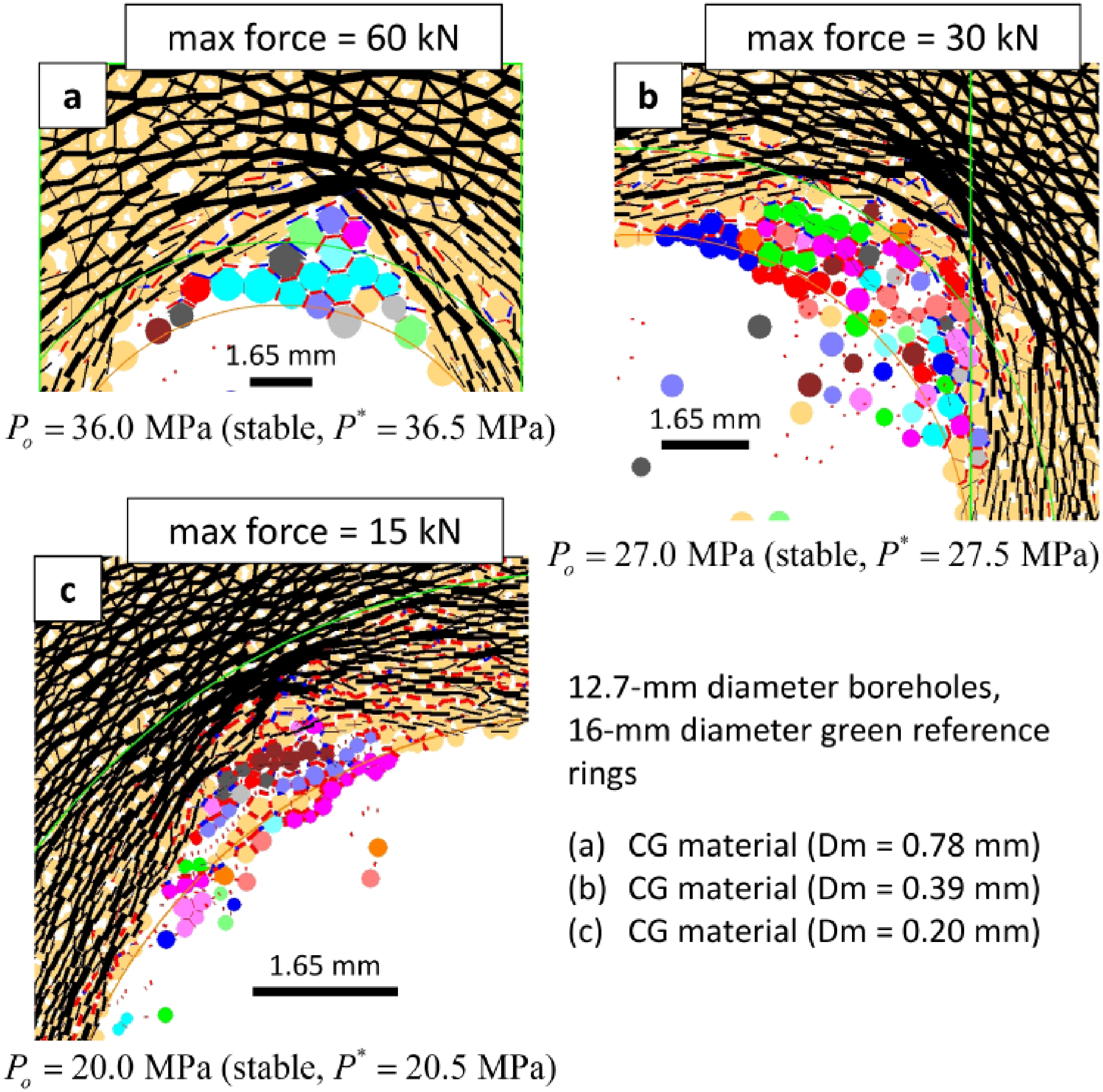
$P_o = 36.0$ MPa (stable, near col.) $P_o = 41.5$ MPa (stable, near col.)

Figure 57 Effect of confinement in suppressing damage in the CG material ($\Phi_H = 16$) during TWC tests.

Remainder of Talk (summary)

We can construct a 2D flat-jointed material to represent Castlegate sandstone.

- The perforation-collapse behavior of this material is related to the hole resolution (number of grains across the borehole diameter), with TWC strength decreasing as hole resolution increases. This observation suggests that perforation strength in a given material will decrease with increasing perforation size.



12.7-mm diameter boreholes, 16-mm diameter green reference rings

(a) CG material (Dm = 0.78 mm)
(b) CG material (Dm = 0.39 mm)
(c) CG material (Dm = 0.20 mm)

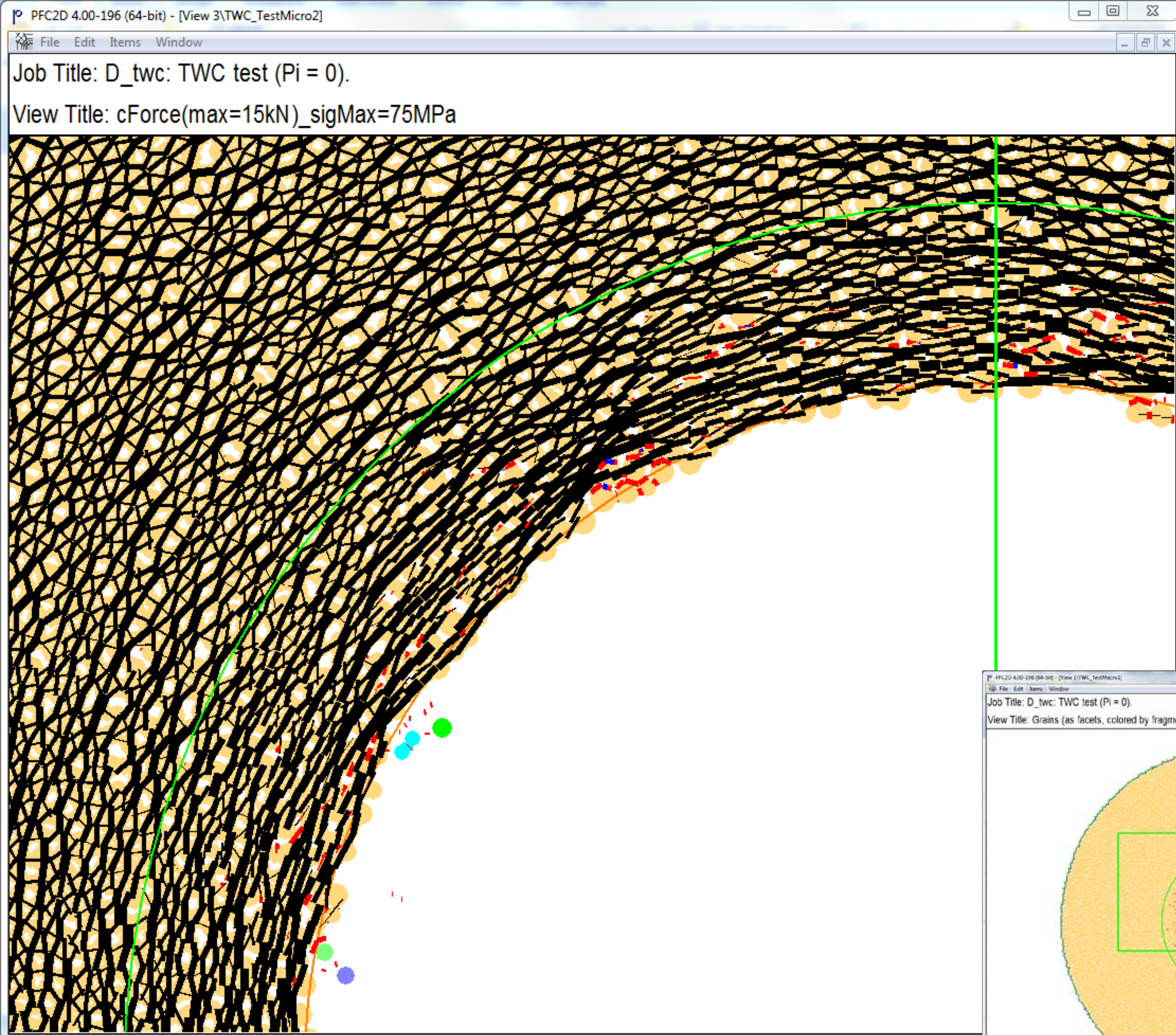
ITASCA

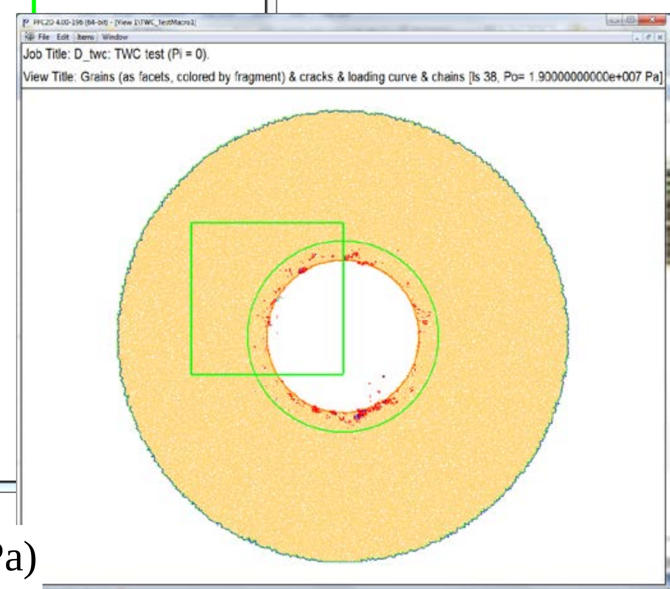
Fig. 23. Damage and force-chain fabric delineating the effective boundary just prior to borehole collapse in the CG materials with different grain sizes (hole resolutions of 16, 32 and 64) during unconfined TWC tests.

TWC test behavior of material with smallest grain size (equal to that of Castlegate sandstone).

$$\text{CG material } \left(\Phi_H = 64\right): P' = P^* = 20.5 \text{ MPa}$$

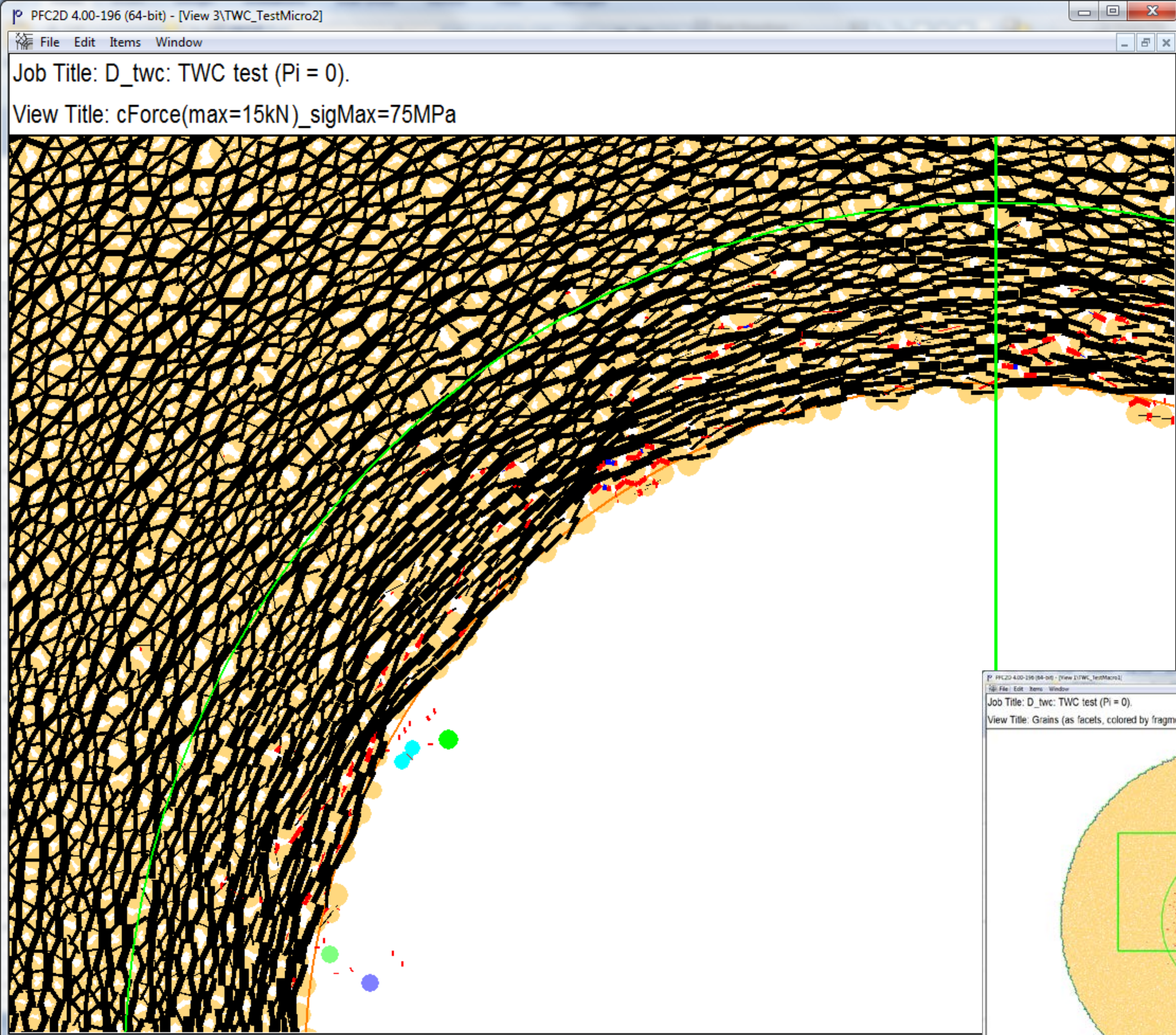
Next 15 slides. . .

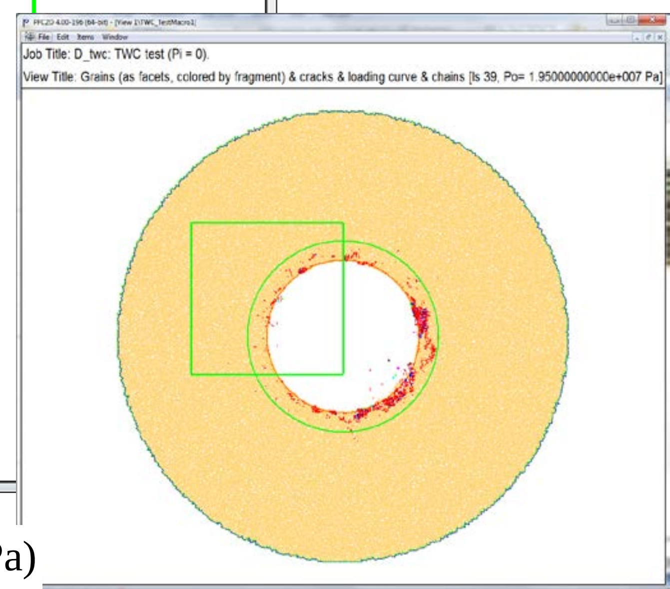




CG_a1

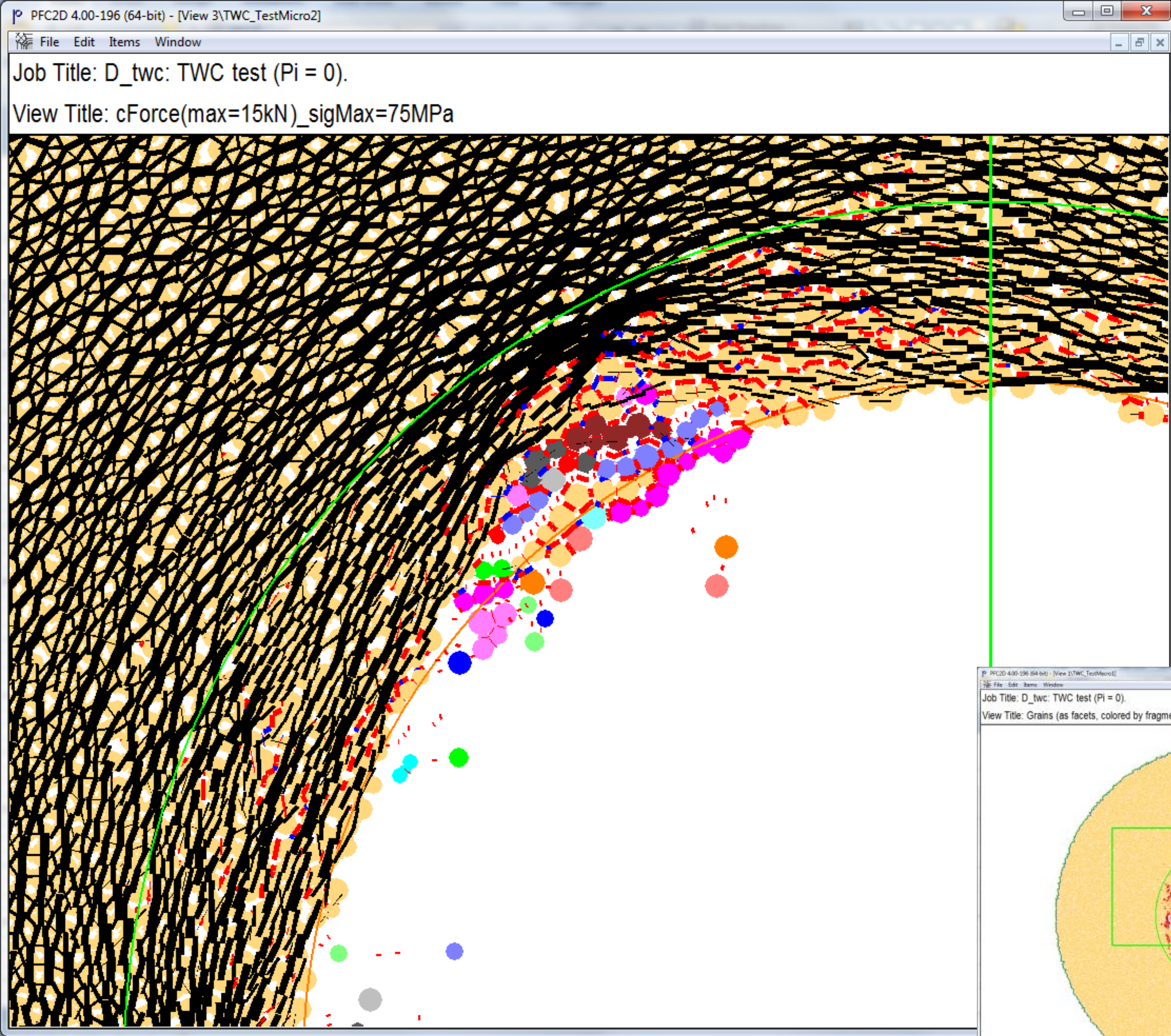
$P_o = 19.0$ MPa (stable, $P^* = 20.5$ MPa)

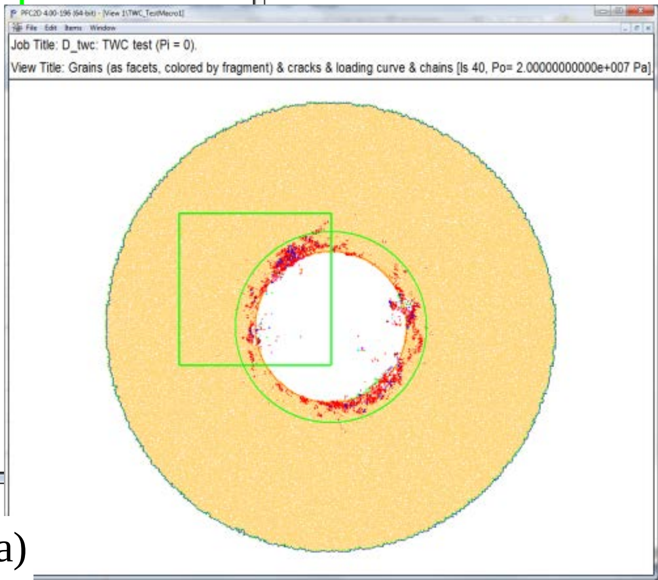




CG_a1

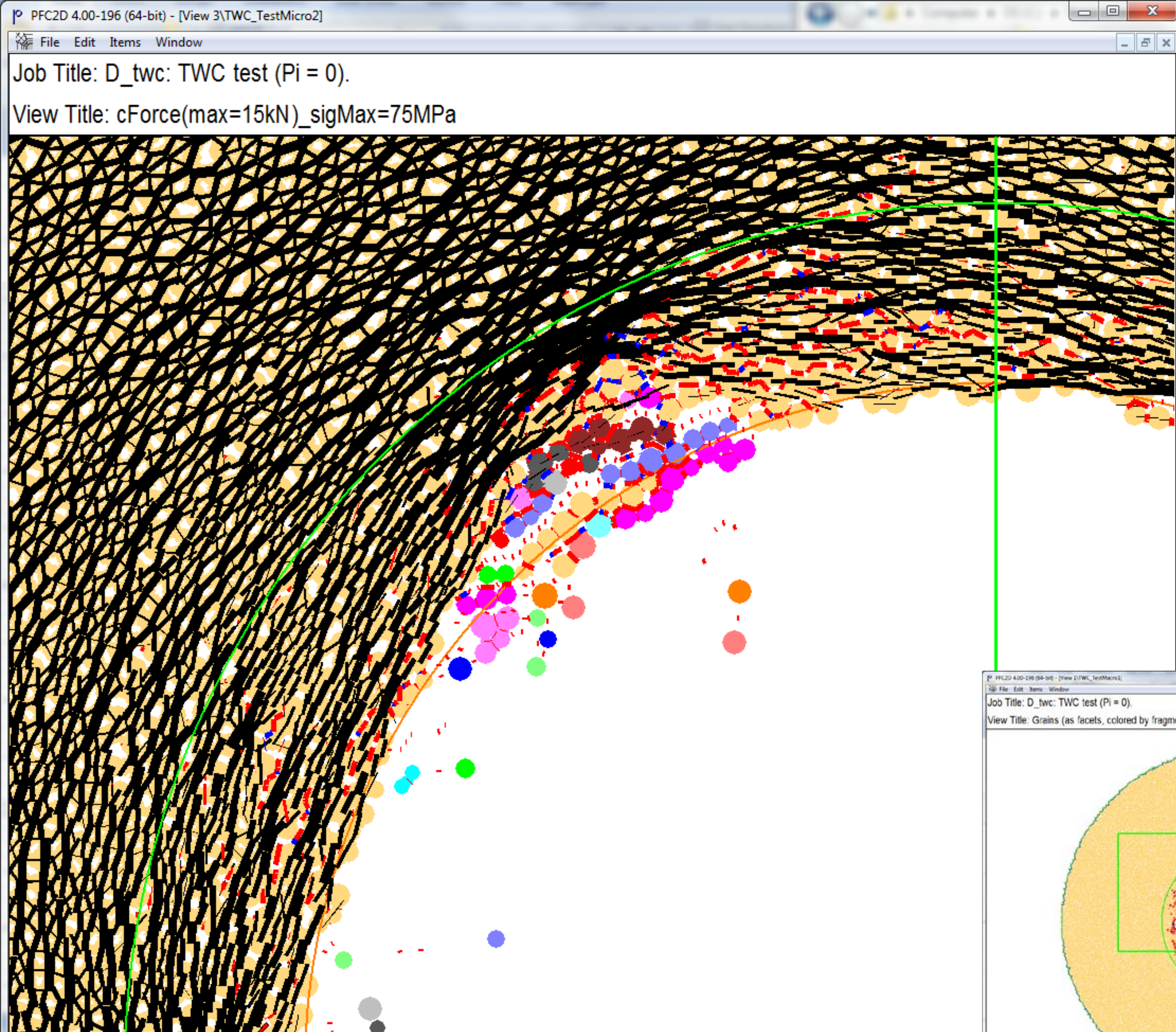
$P_o = 19.5$ MPa (stable, $P^* = 20.5$ MPa)

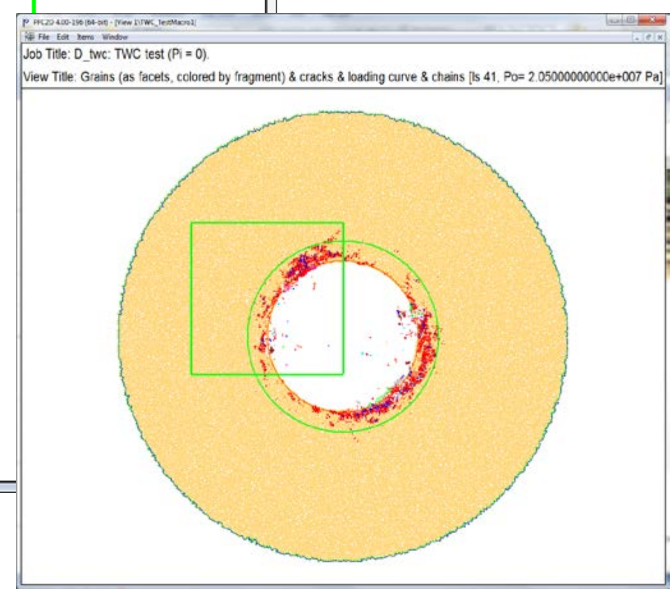




CG_a1

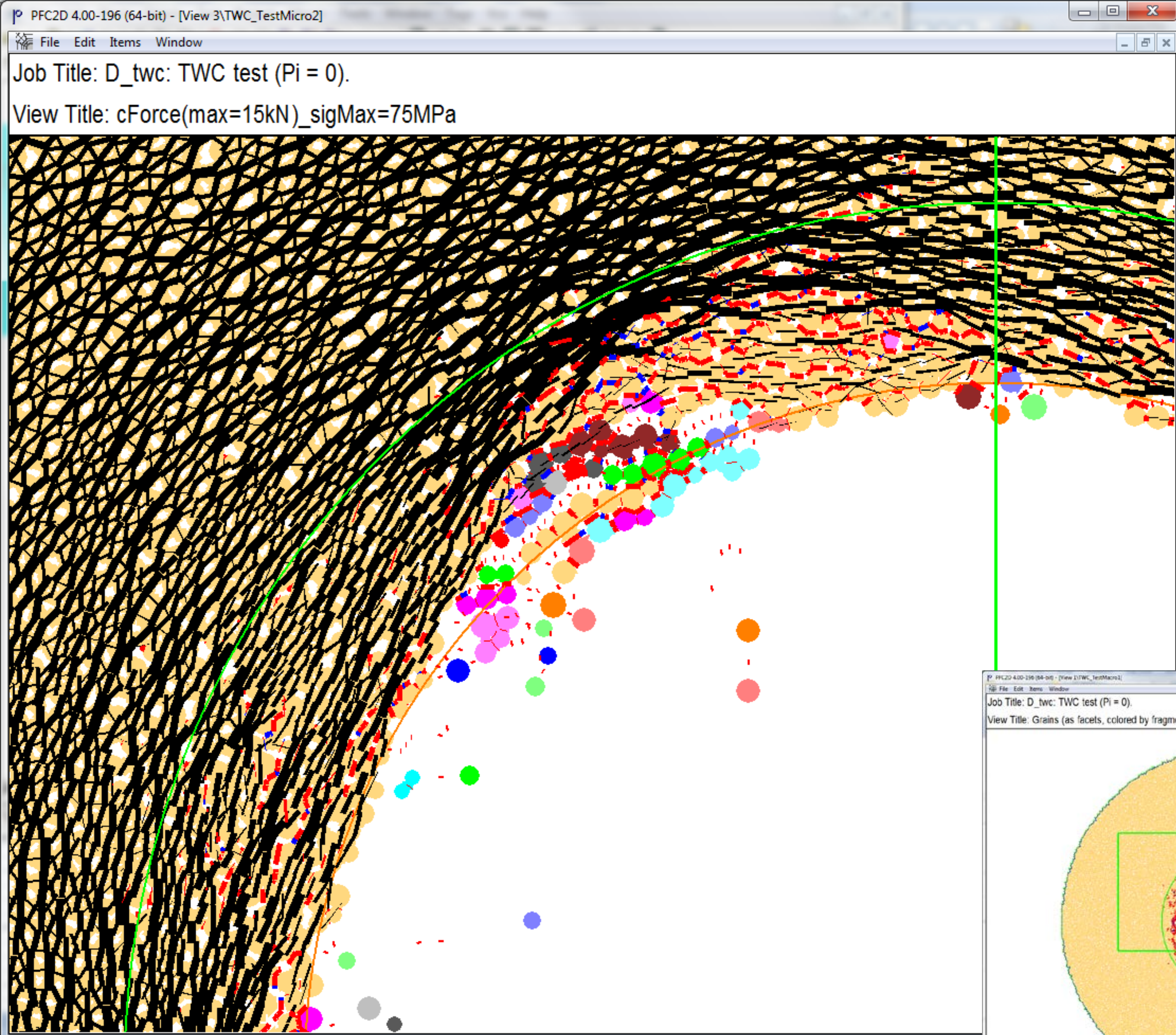
$$P_o = 20.0 \text{ MPa (stable, } P^* = 20.5 \text{ MPa)}$$

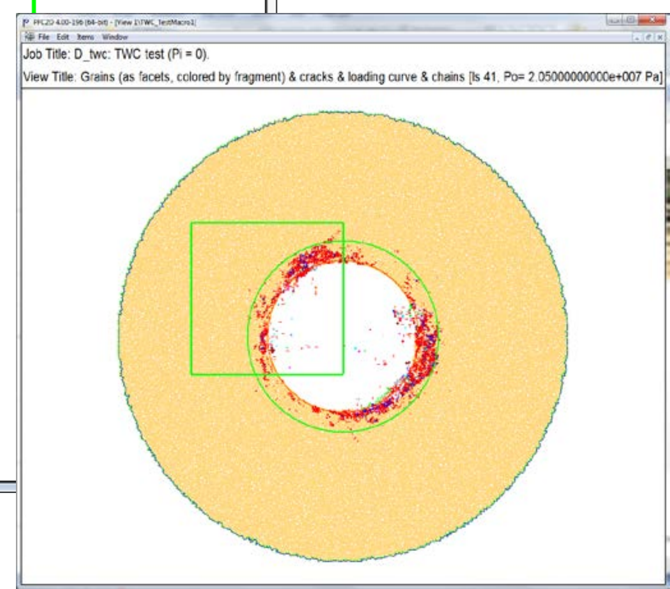




CG_a1

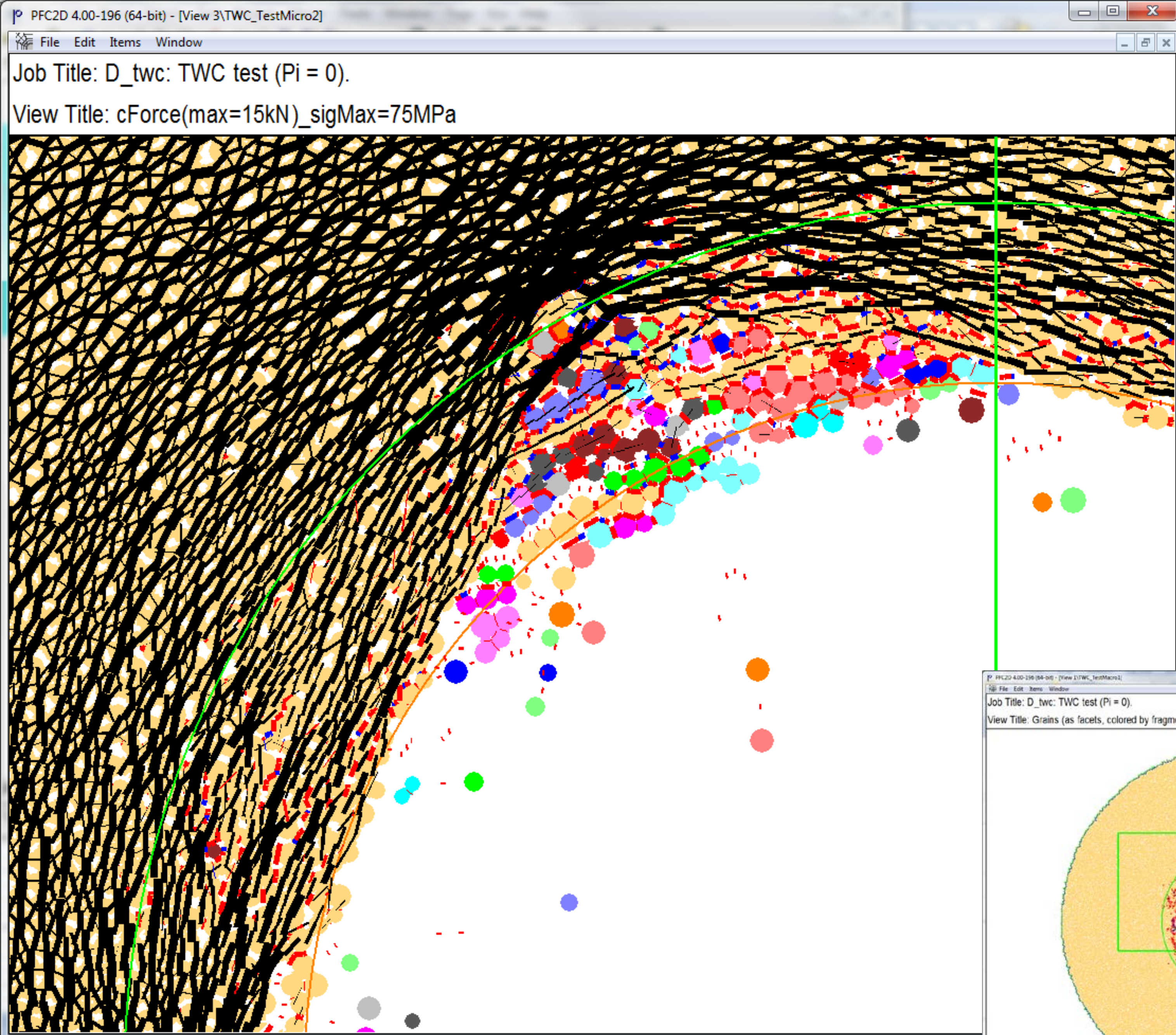
$P_o = 20.5\ \text{MPa}\ \left(\text{plus5k-twc41f}\right)$

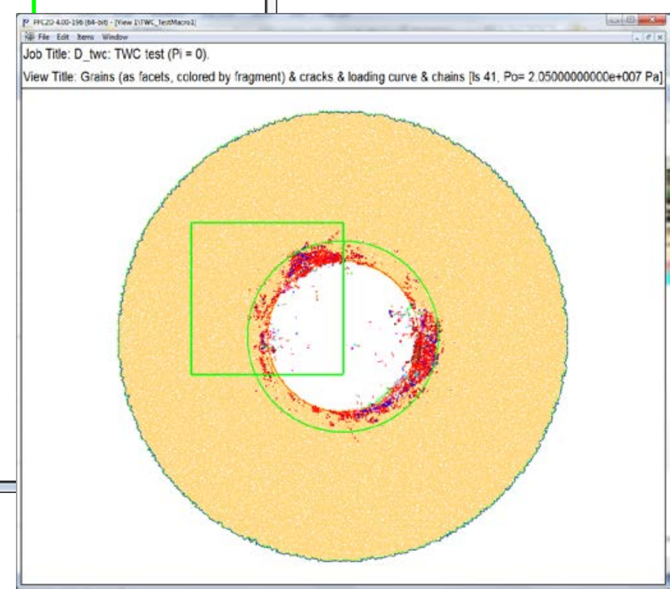




CG_a1

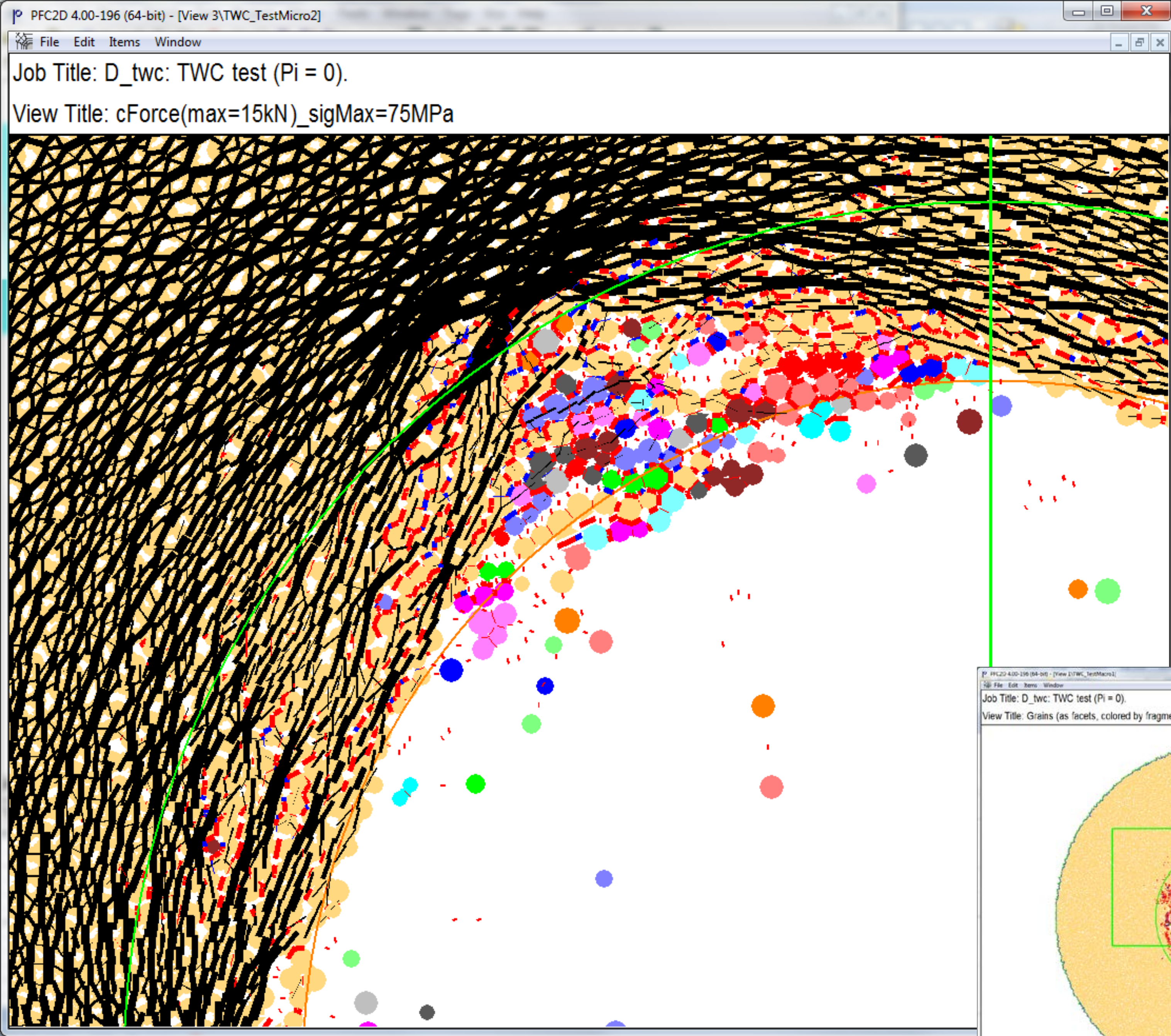
$P_o = 20.5$ MPa (plus10k-twc41f)

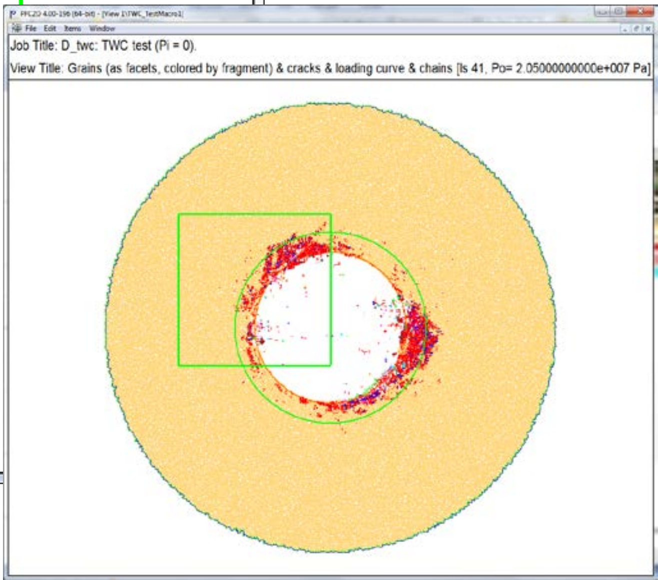




CG_a1

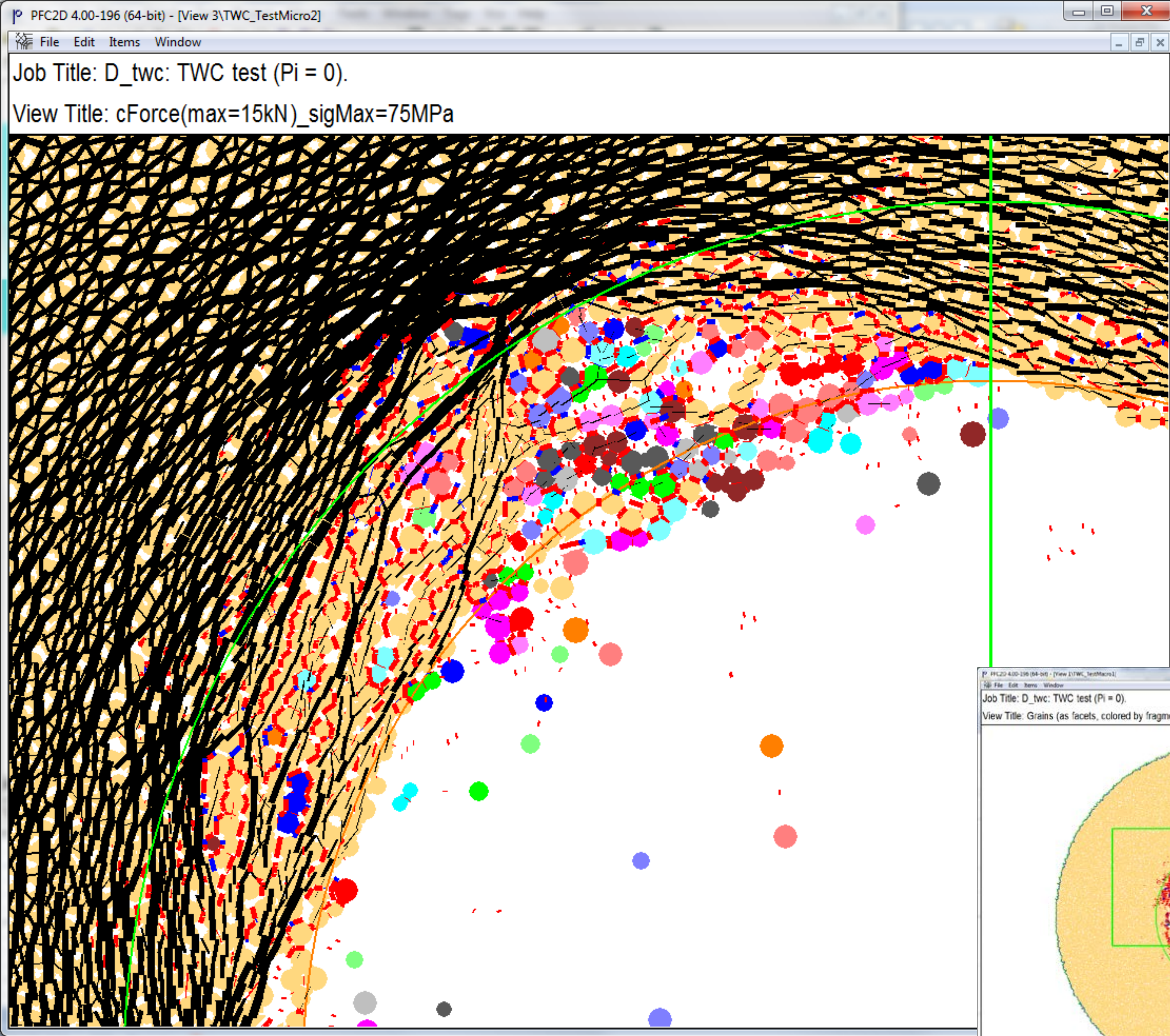
$P_o = 20.5$ MPa $\left(\text{plus15k-twc41f}\right)$

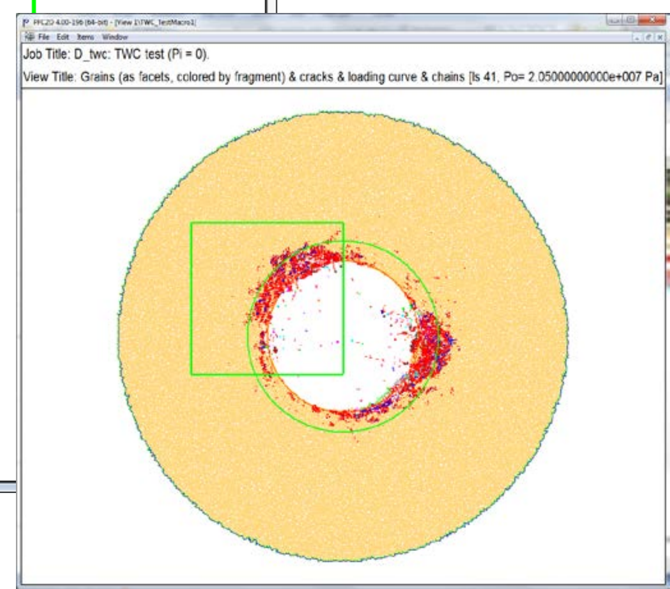




CG_a1

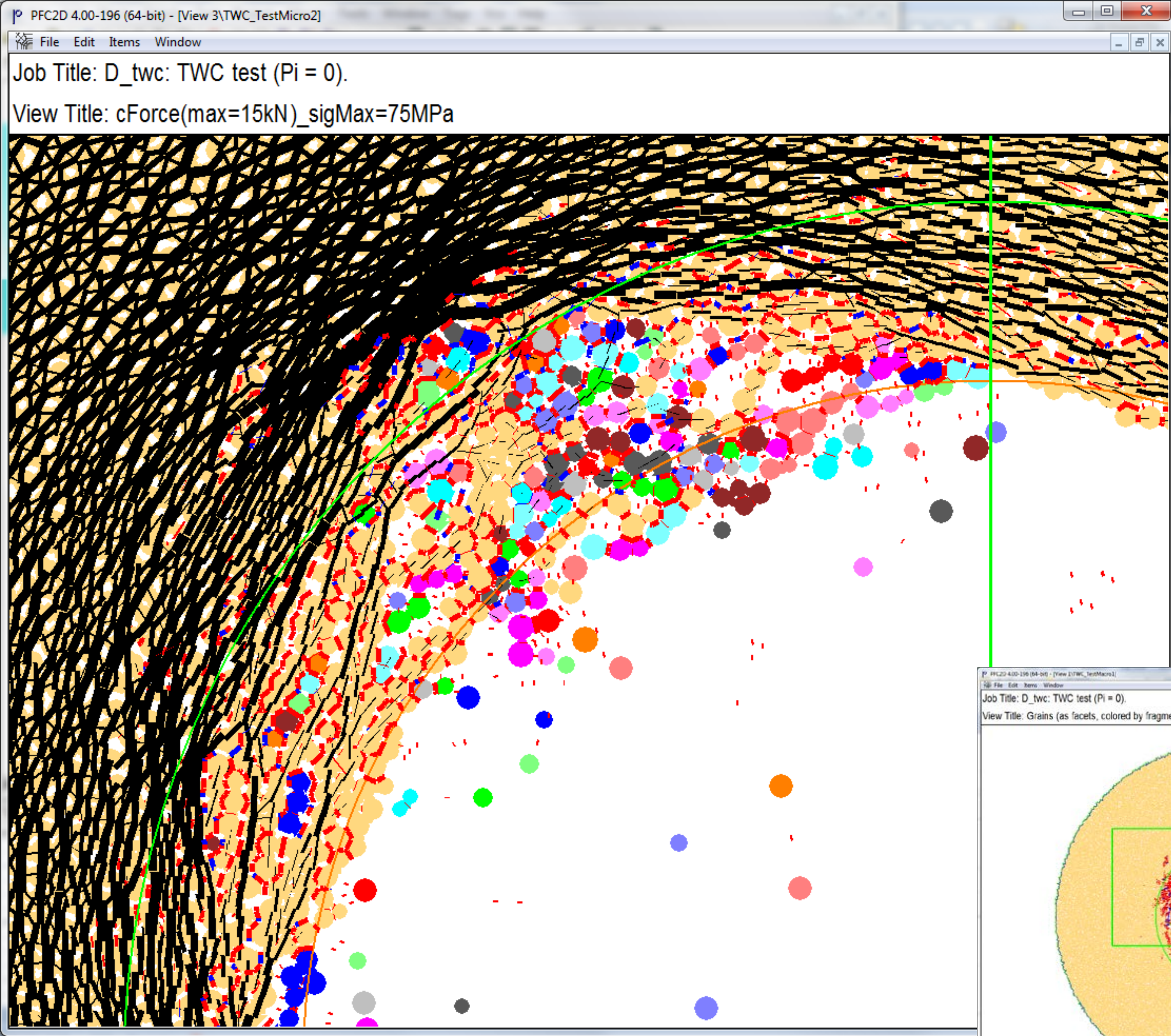
$P_o = 20.5\ \text{MPa}\ \left(\text{plus20k-twc41f}\right)$

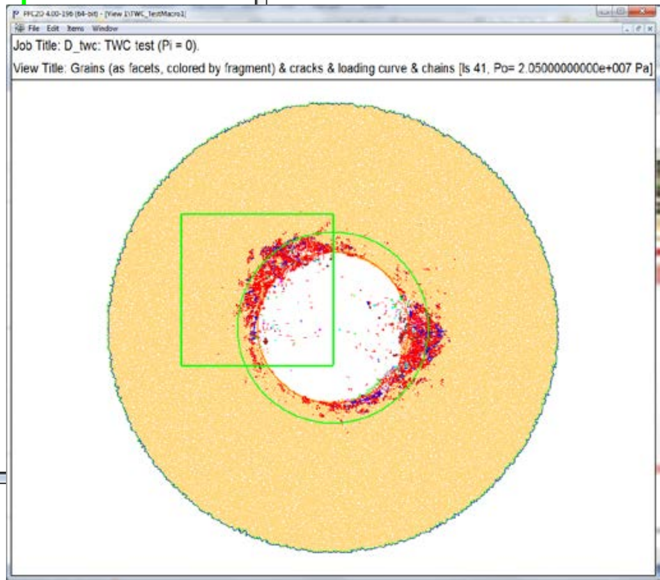




CG_a1

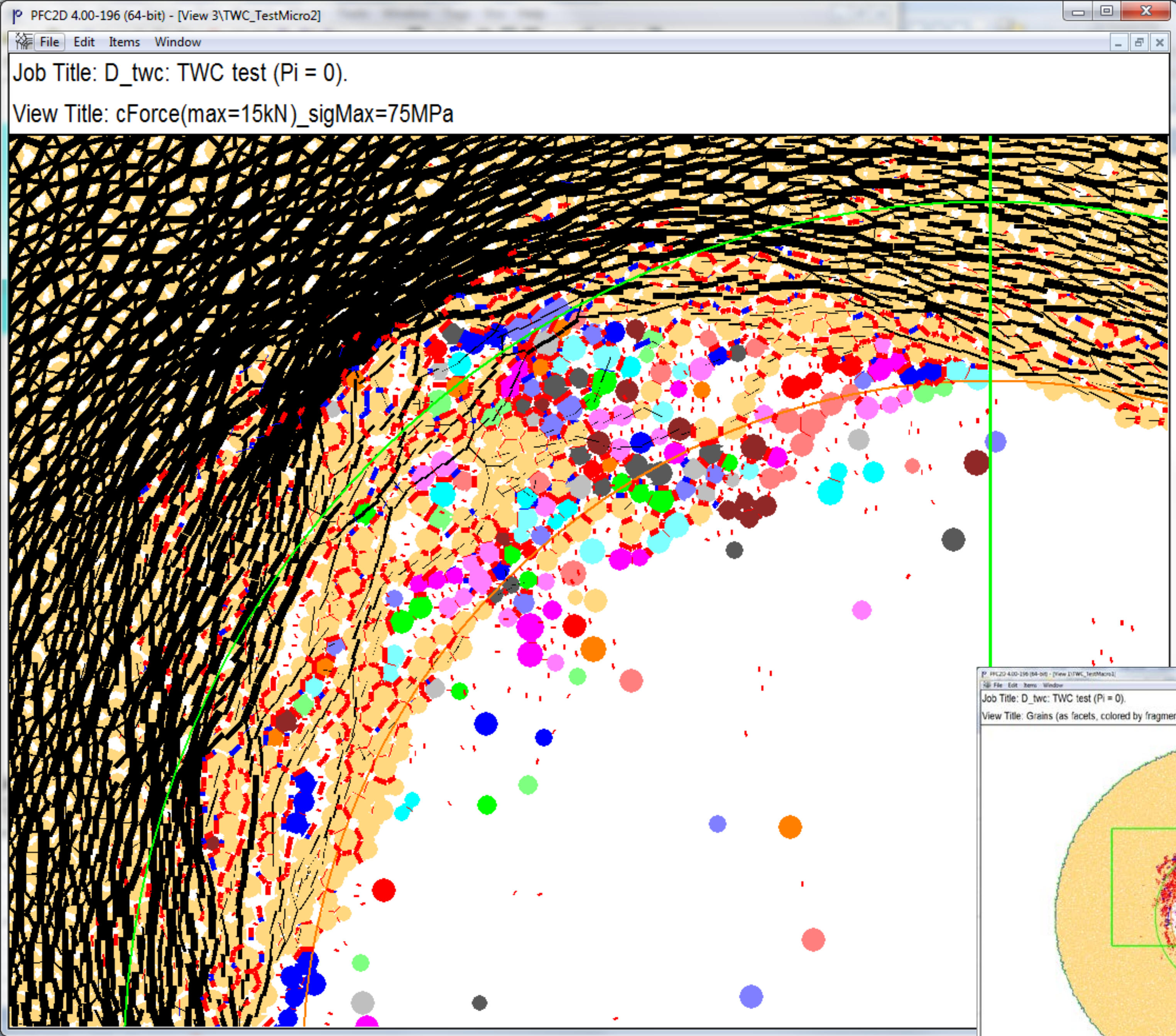
$P_o = 20.5$ MPa (plus25k-twc41f)

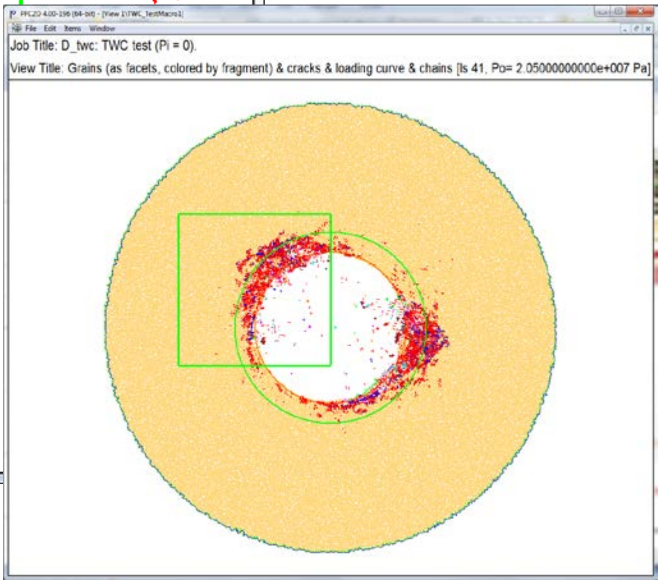




CG_a1

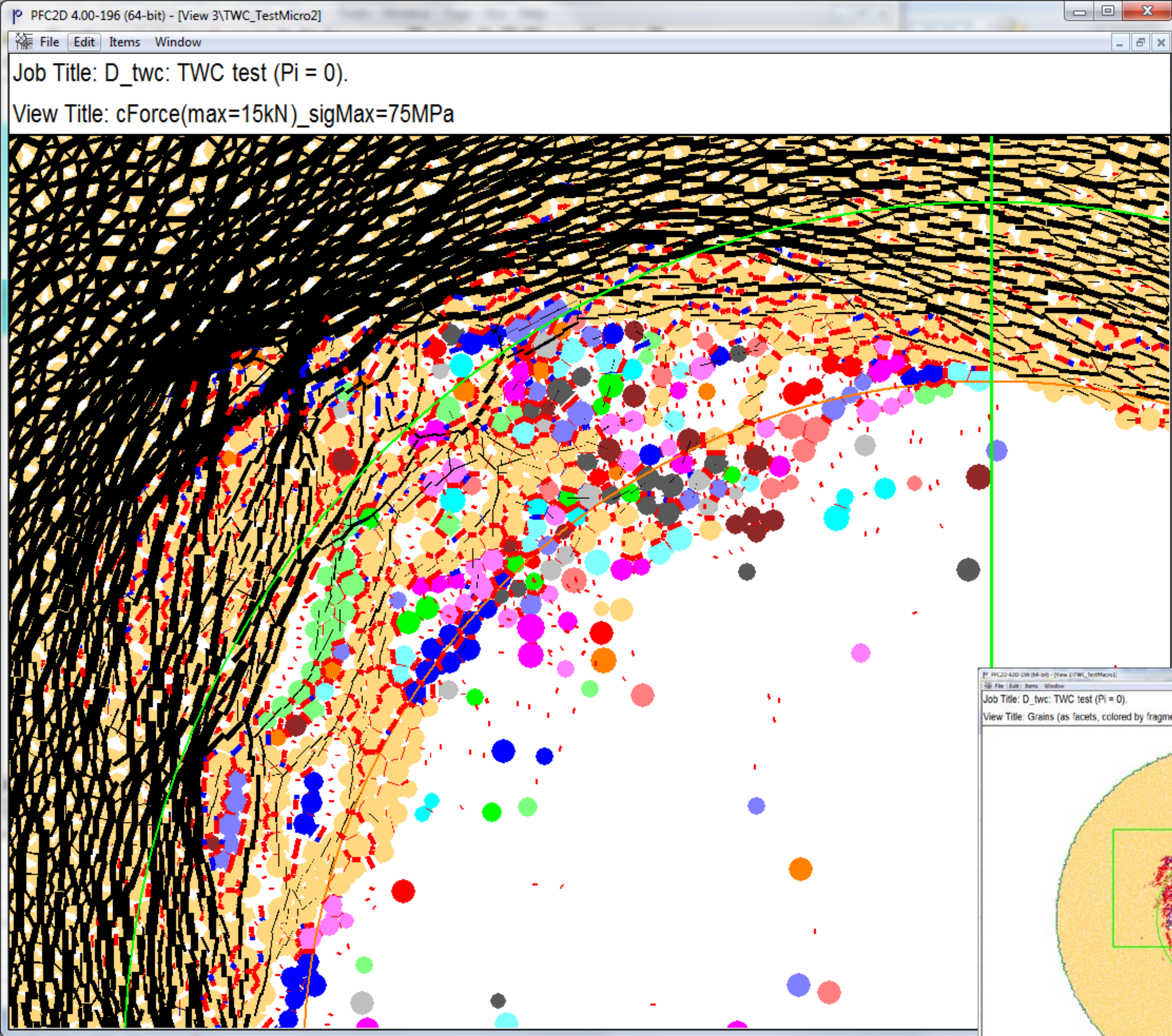
$P_o = 20.5\ \mathrm{MPa}\ (\text{plus30k-twc41f})$

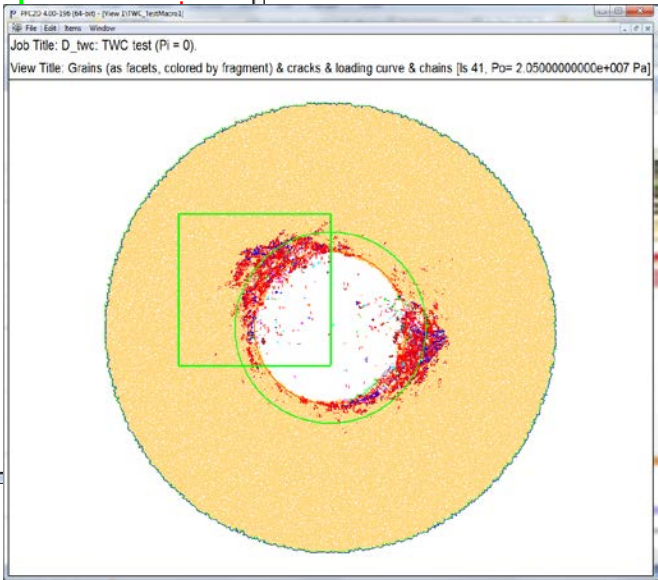




CG_a1

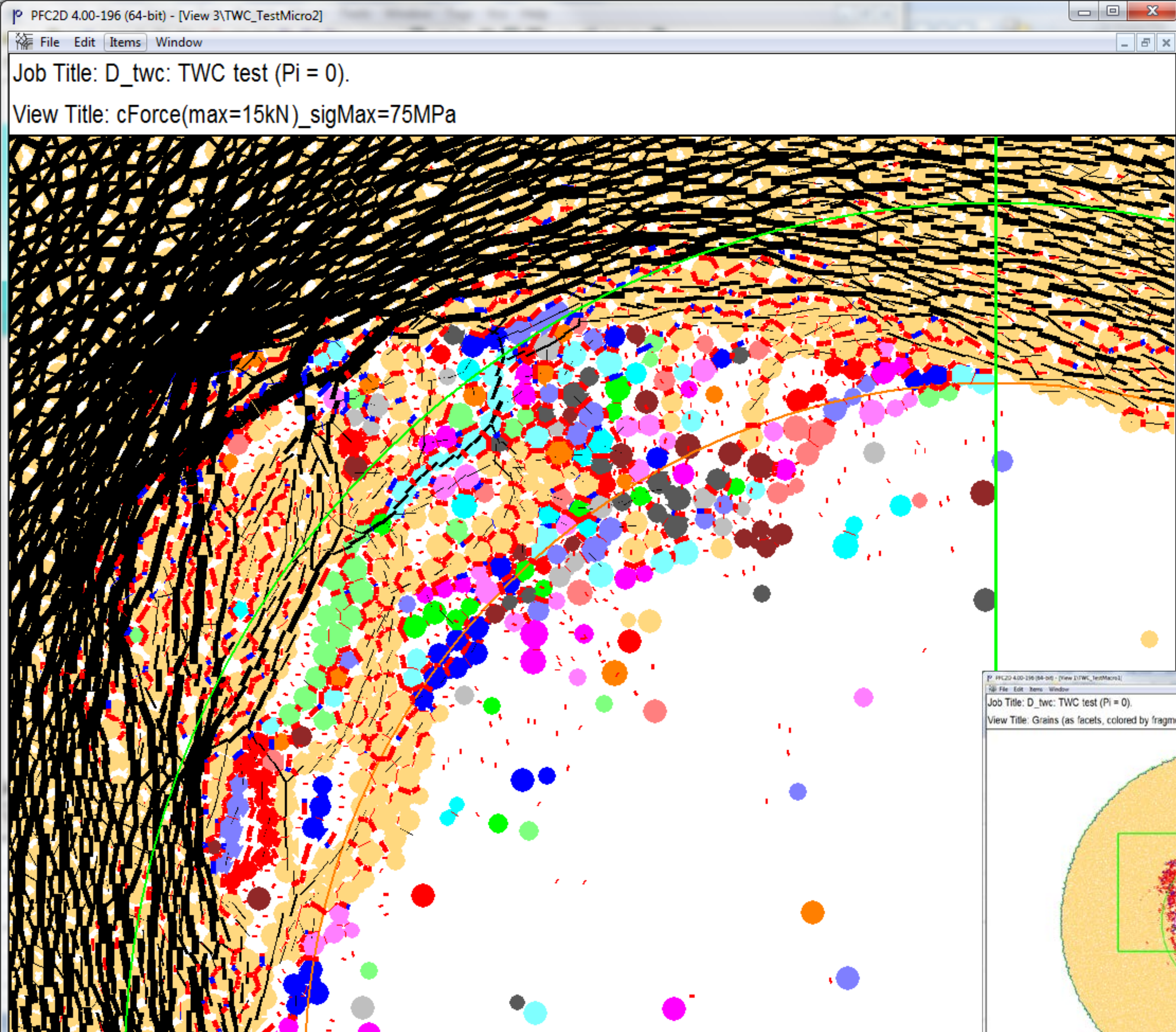
$P_o = 20.5$ MPa (plus35k-twc41f)

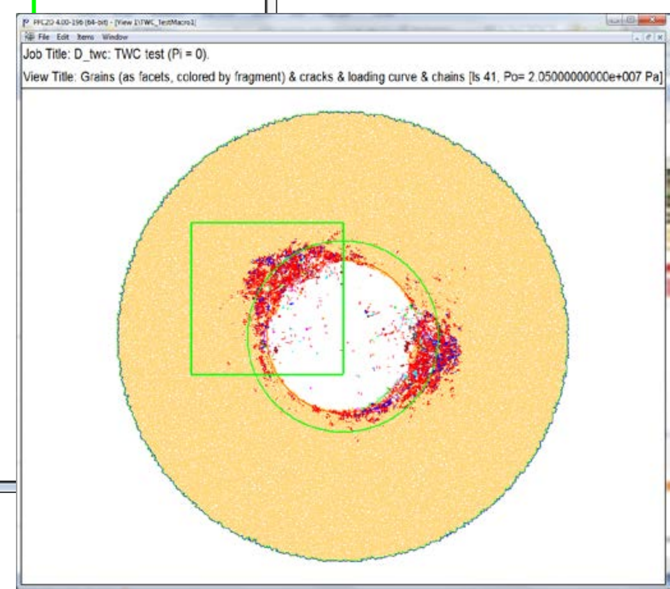




CG_a1

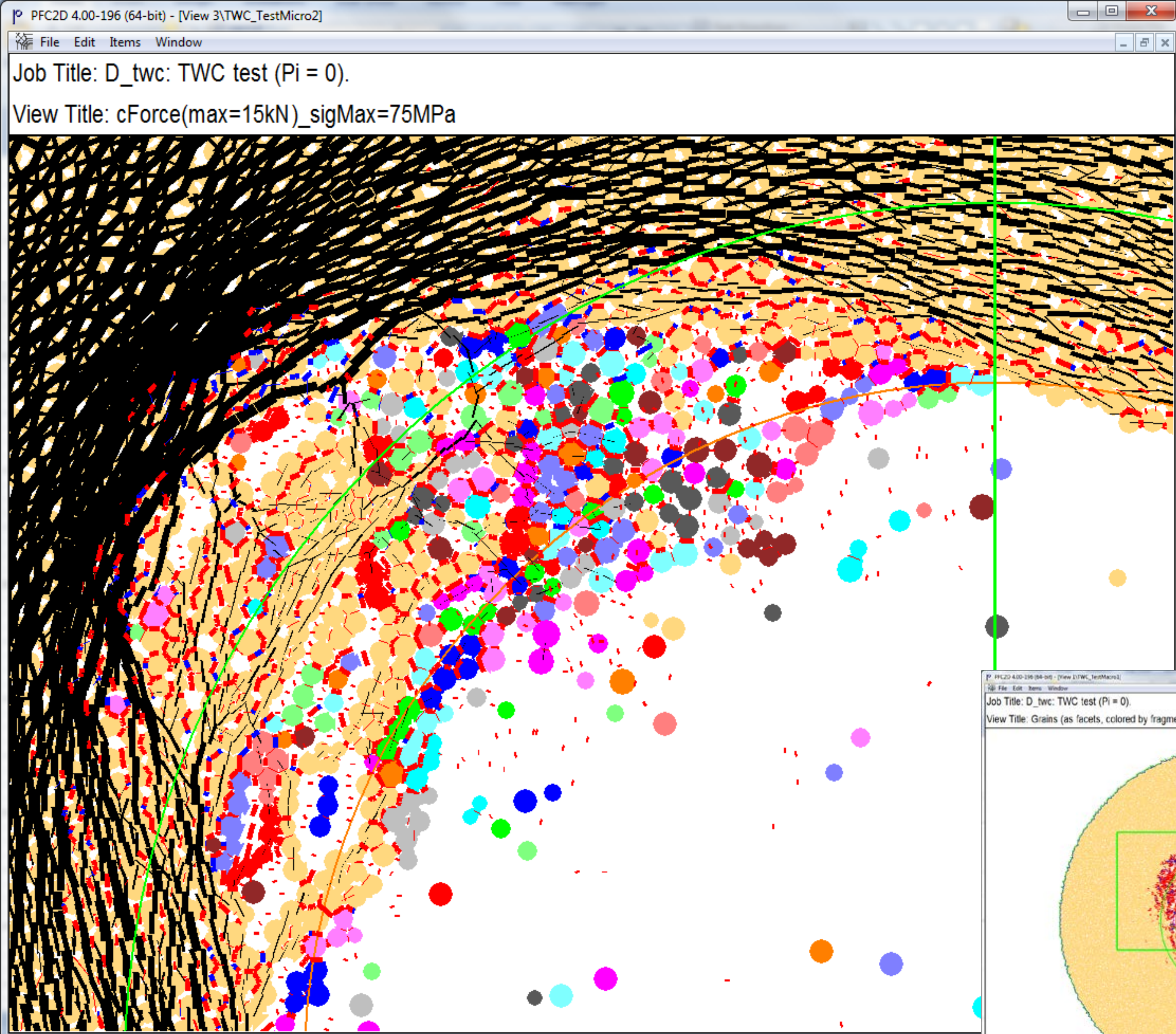
$P_o = 20.5\ \text{MPa}\ \left(\text{plus40k-twc41f}\right)$

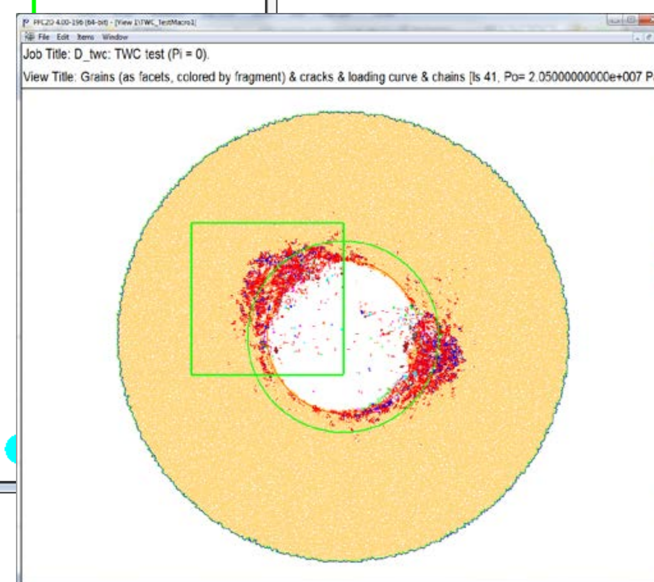




CG_a1

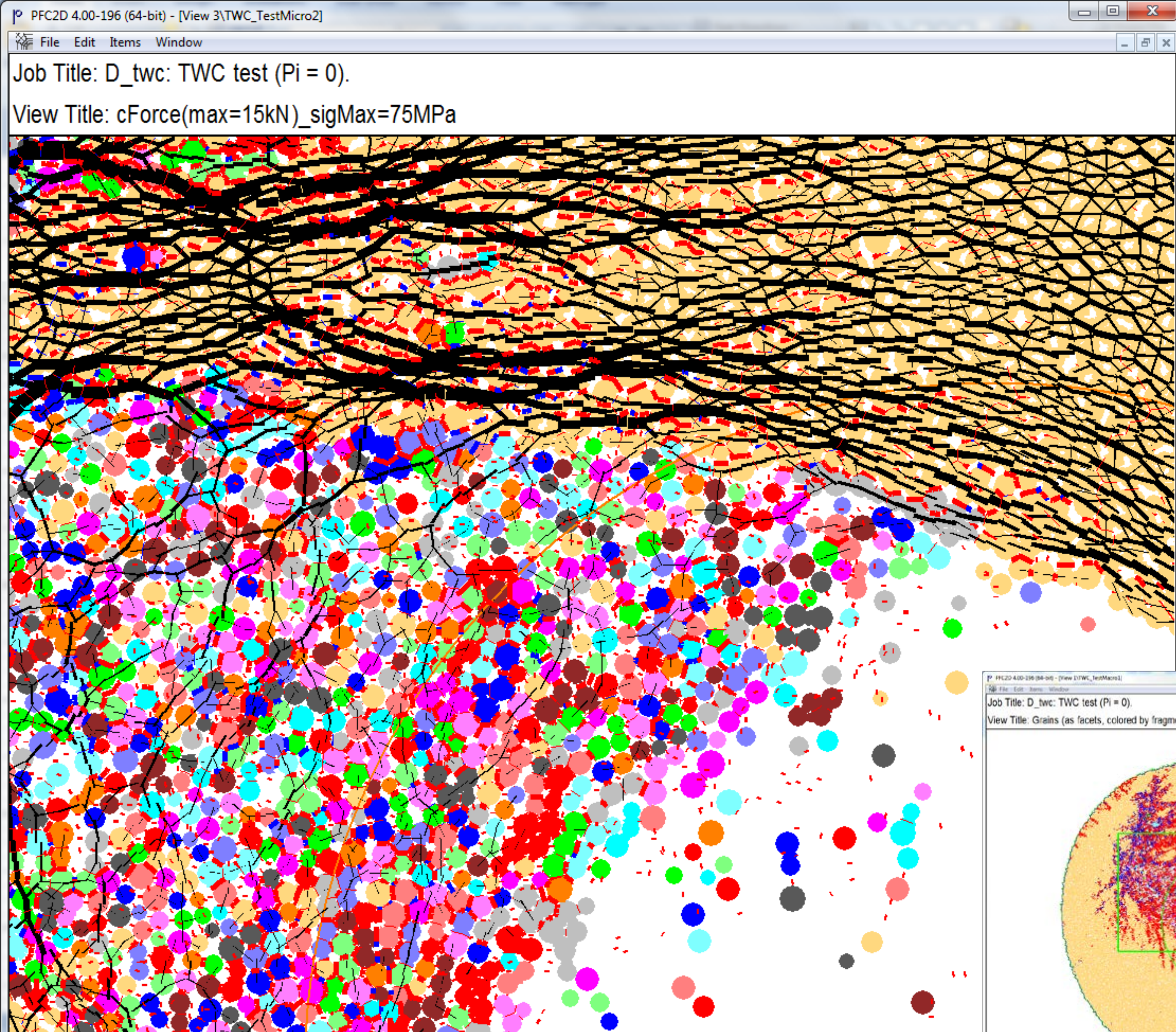
$P_o = 20.5$ MPa $\left(\text{plus45k-twc41f}\right)$

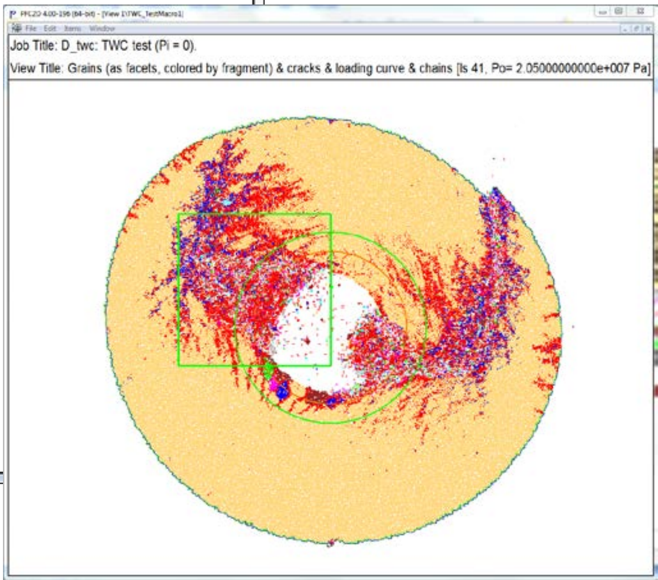




CG_a1

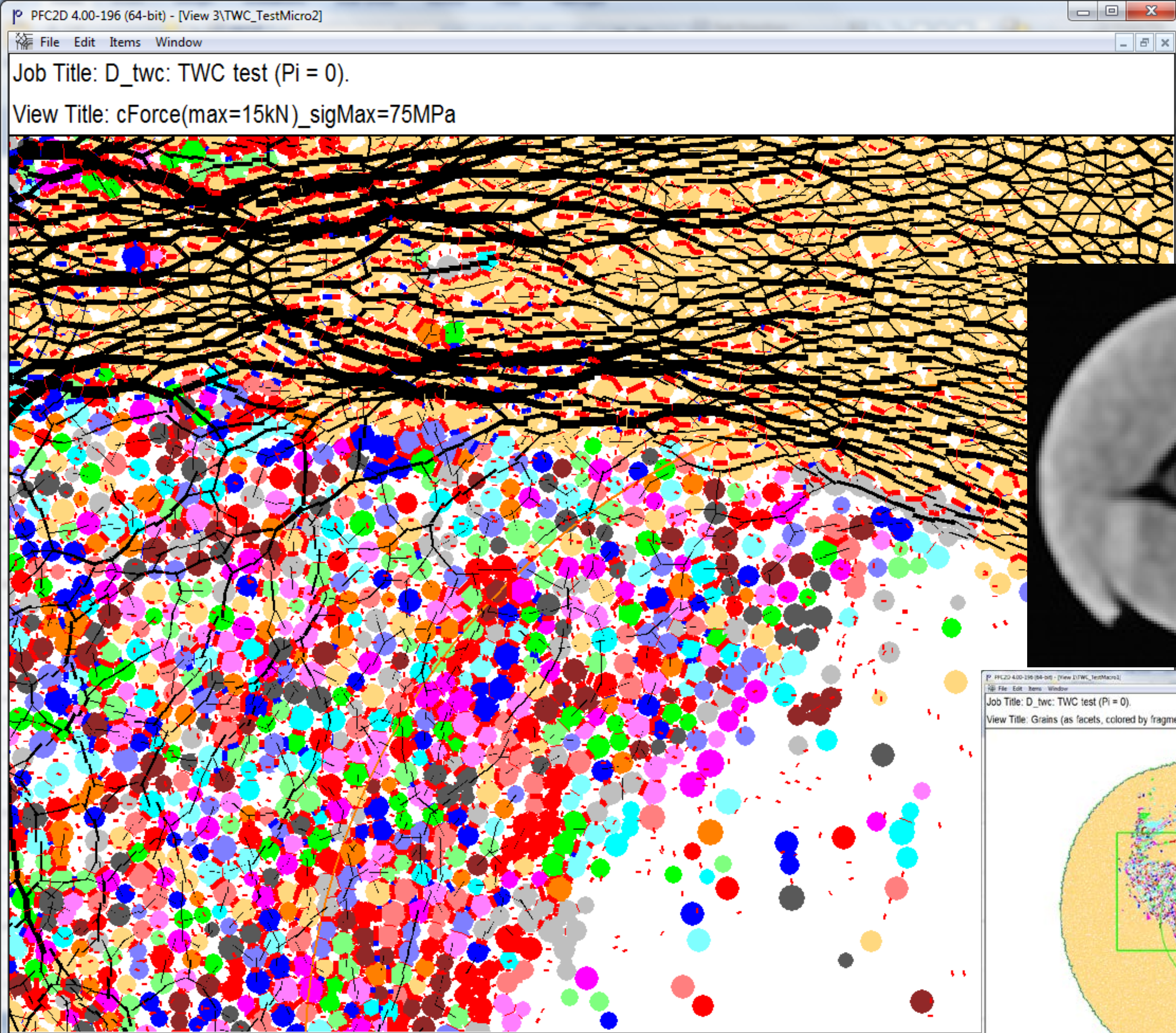
$P_o = 20.5$ MPa (plus50k-twc41f)

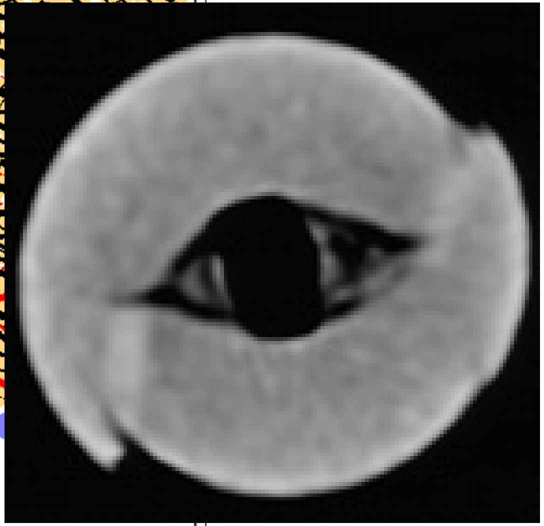


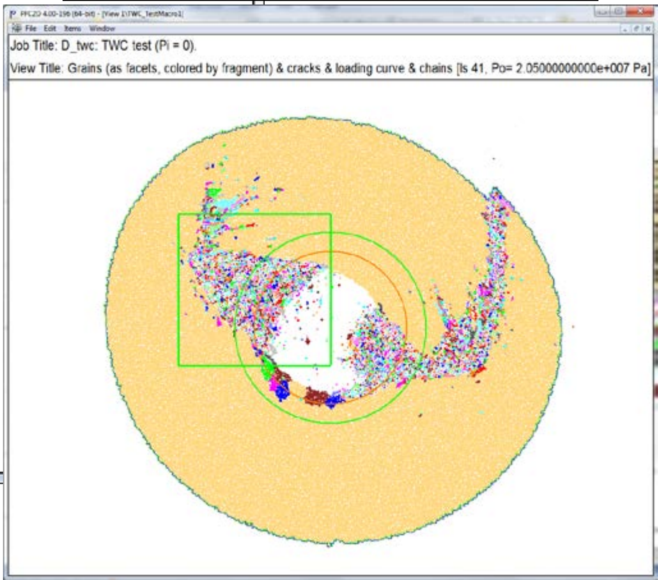


CG_a1

$P_o = 20.5\ \text{MPa}\ (\text{plus250k-twc41f})$







CG_a1

$$P_o = 20.5 \text{ MPa} \ (\text{plus250k-twc41f})$$