MIT EARTH RESOURCES LABORATORY
ANNUAL FOUNDING MEMBERS MEETING 2020

Fracture deformation and its effects on flow - experiments and simulations

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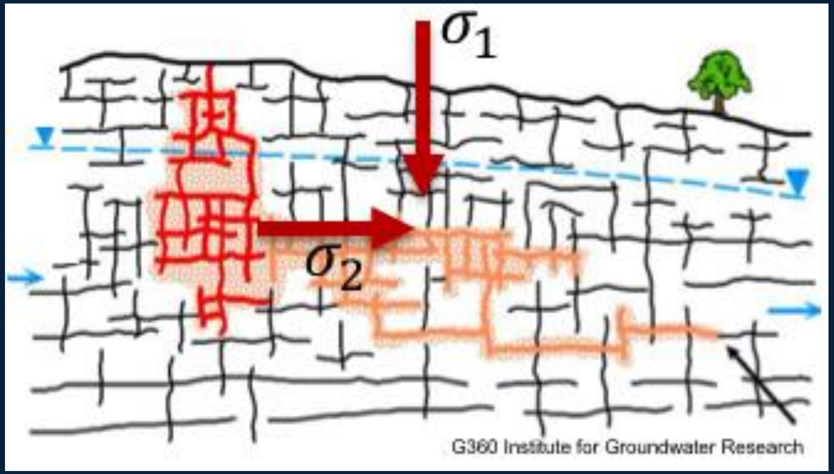
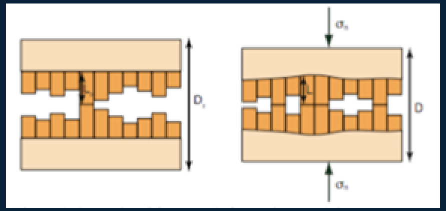
GRADUATE STUDENTS [CIVIL AND ENVIRONMENTAL ENGINEERING]

Supervised by Prof. Herbert Einstein.

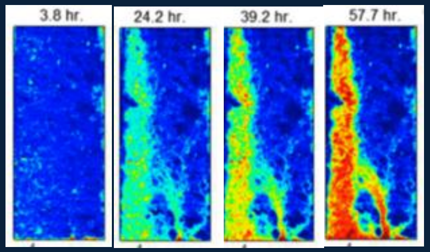
Introduction



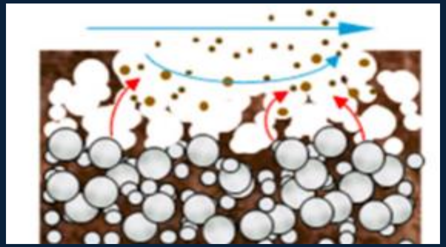
σ_1, σ_2 = far-field stresses



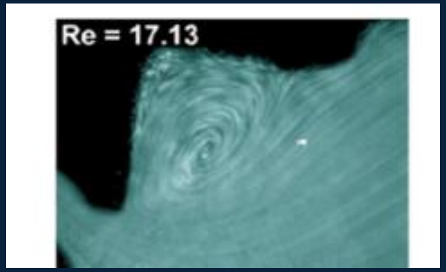
Detwiler & Morris. (2014)



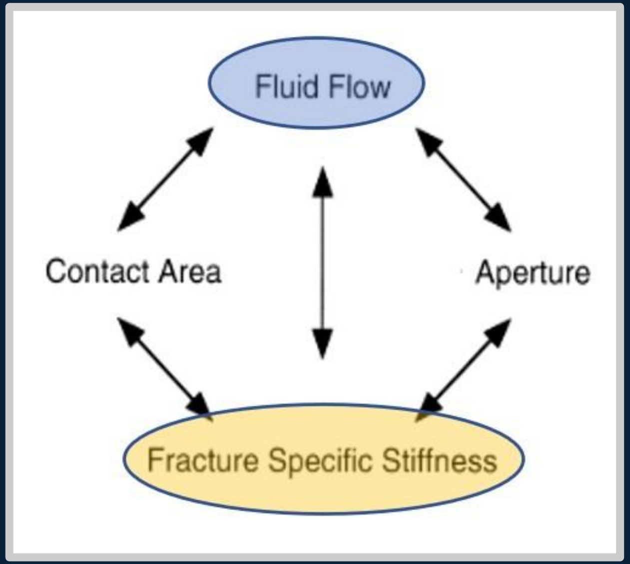
Deng et al. (2015)



Deng et al. (2015)



Lee et al. (2015)

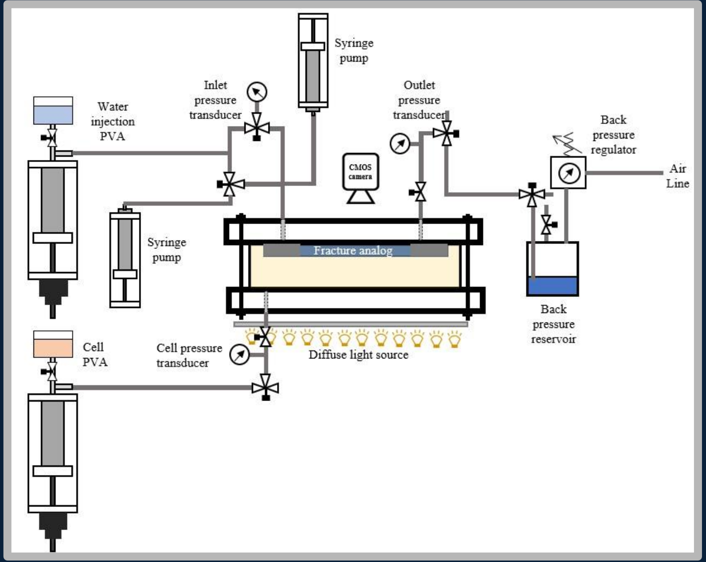


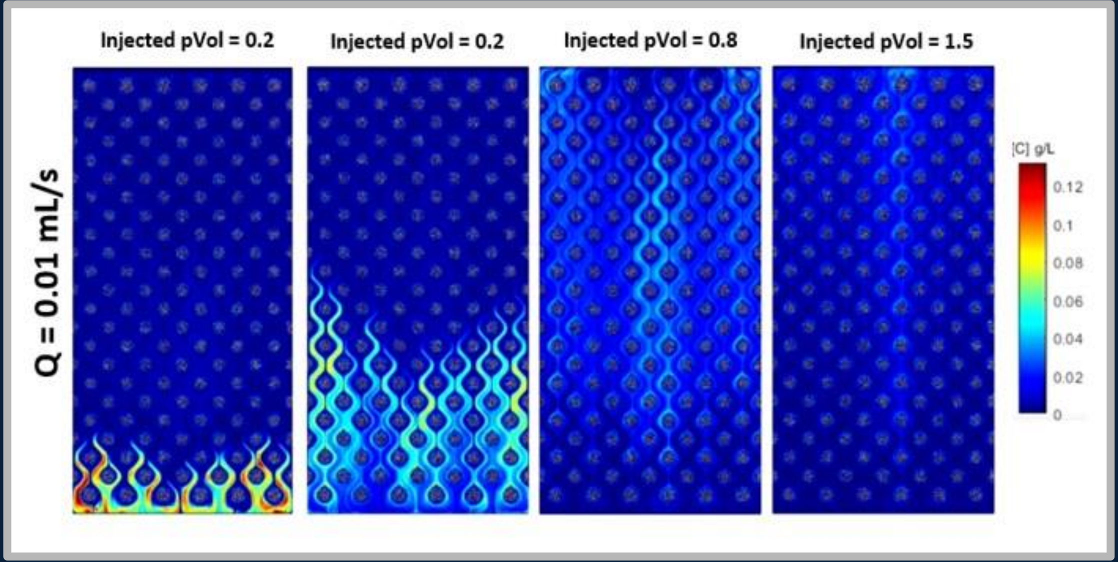
Outline

- ❖ Part A: **Experimental Investigations**
  - ➢ Experimental setup
  - ➢ Specimen design + fabrication
  - ➢ In-situ aperture + concentration fields
  - ➢ Flow measurements
  - ➢ Flow and fracture deformation
- ❖ Part B: **Numerical simulations**
  - ➢ Methodology
  - ➢ Micro-indentation experiments
  - ➢ Abaqus simulations
- ❖ **Conclusions**

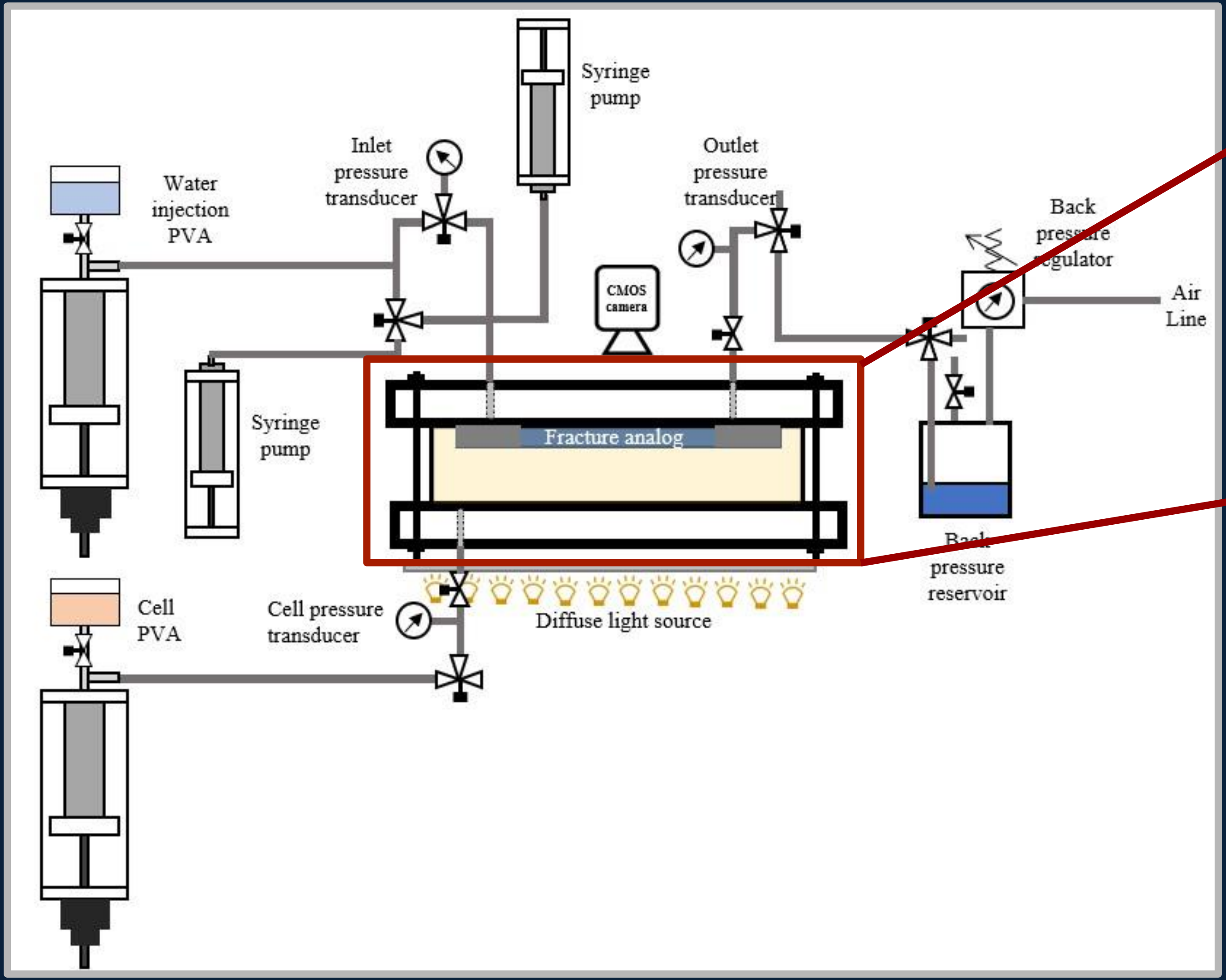
Part A:

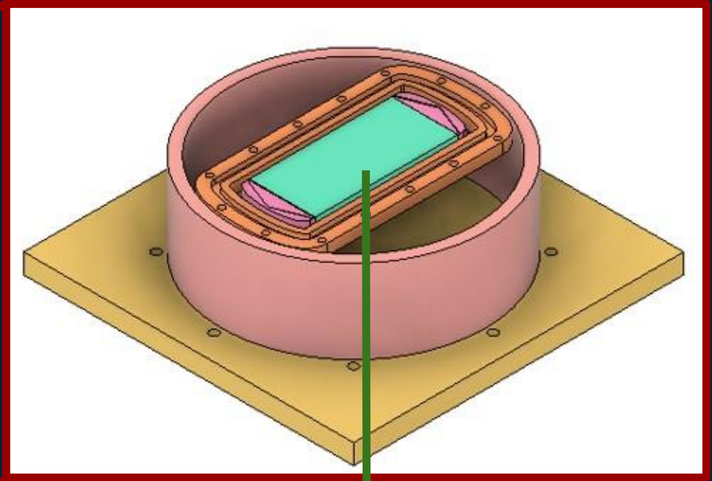
Experimental Investigations

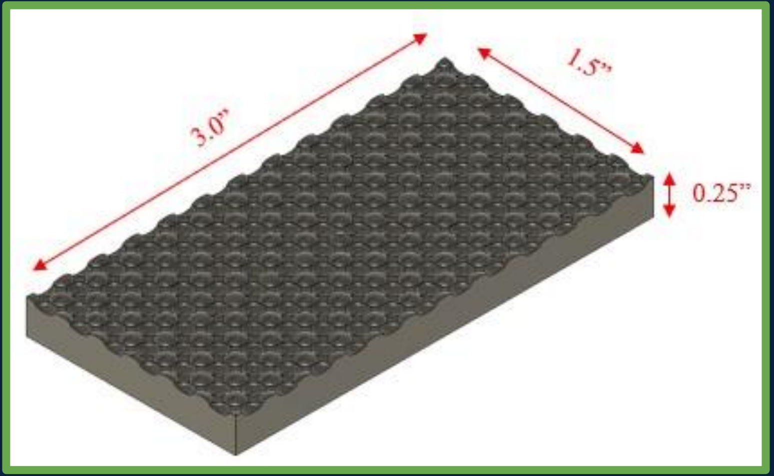




Part A: Experimental Setup



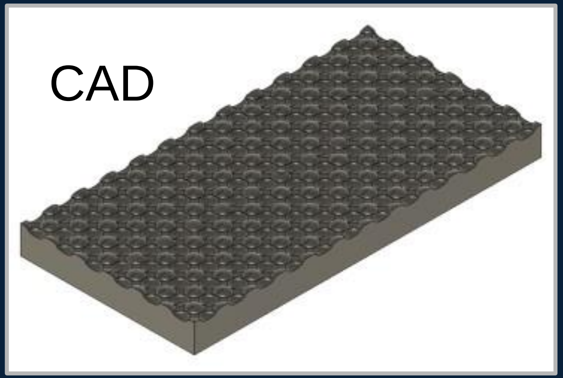




Part A: Specimen Design + Fabrication

Workflow

- ➢ Geometry control
- ➢ Material properties



e.g. STL

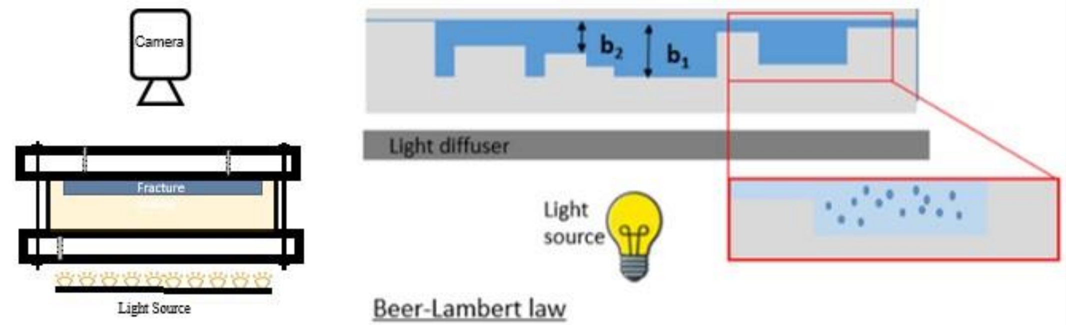
- CNC machining
- Molding & Casting
- 3D-printing

Computer-generated geometry

Digital Fabrication

Part A: In-situ Aperture + Concentration Fields

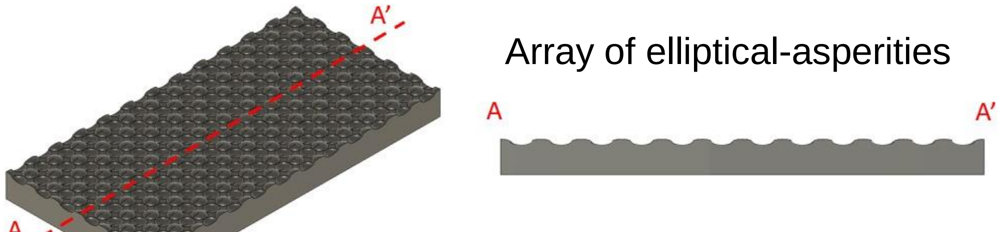
Light Transmission Technique



Beer-Lambert law

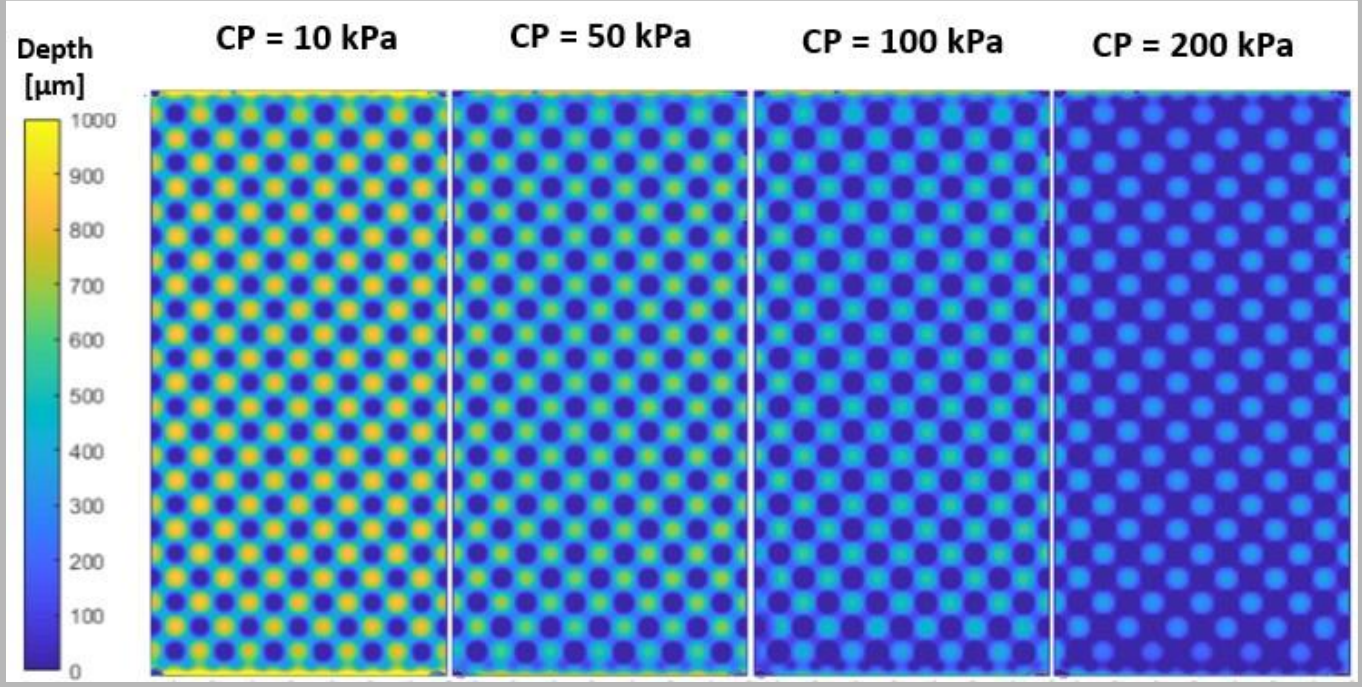
$$I(x,y) = I_0(x,y)e^{-\varepsilon C(x,y)b(x,y)}$$

I = light intensity @ concentration C
I_0 = light intensity @ zero concentration
ε = tracer absorptivity
b = fracture aperture (solution thickness)



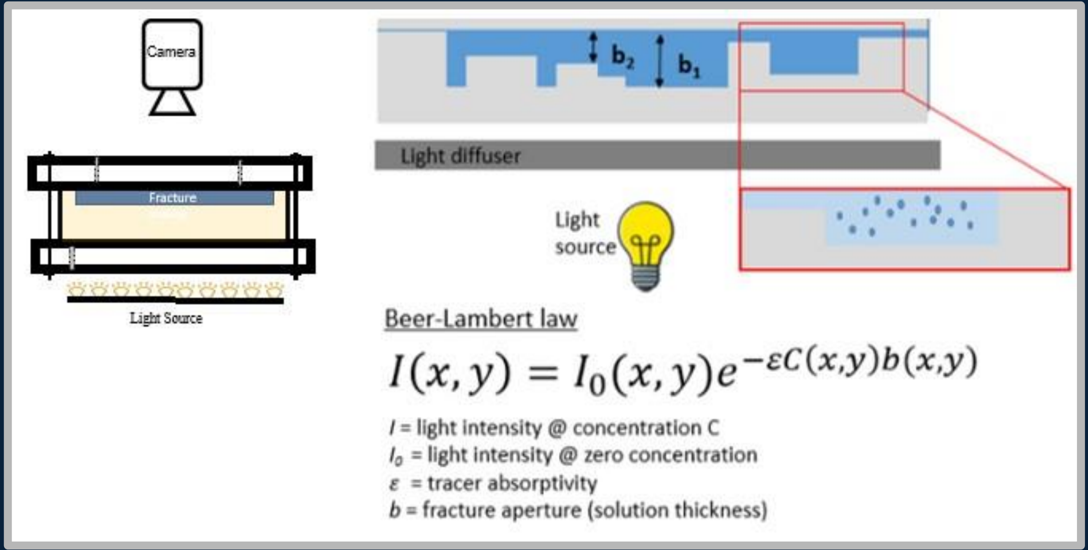
Asperity height ~ 500 microns
Material: PDMS

Aperture Fields

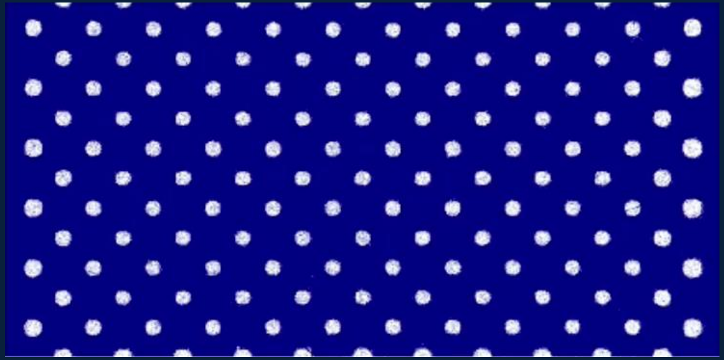


Part A: In-situ Aperture + Concentration Fields

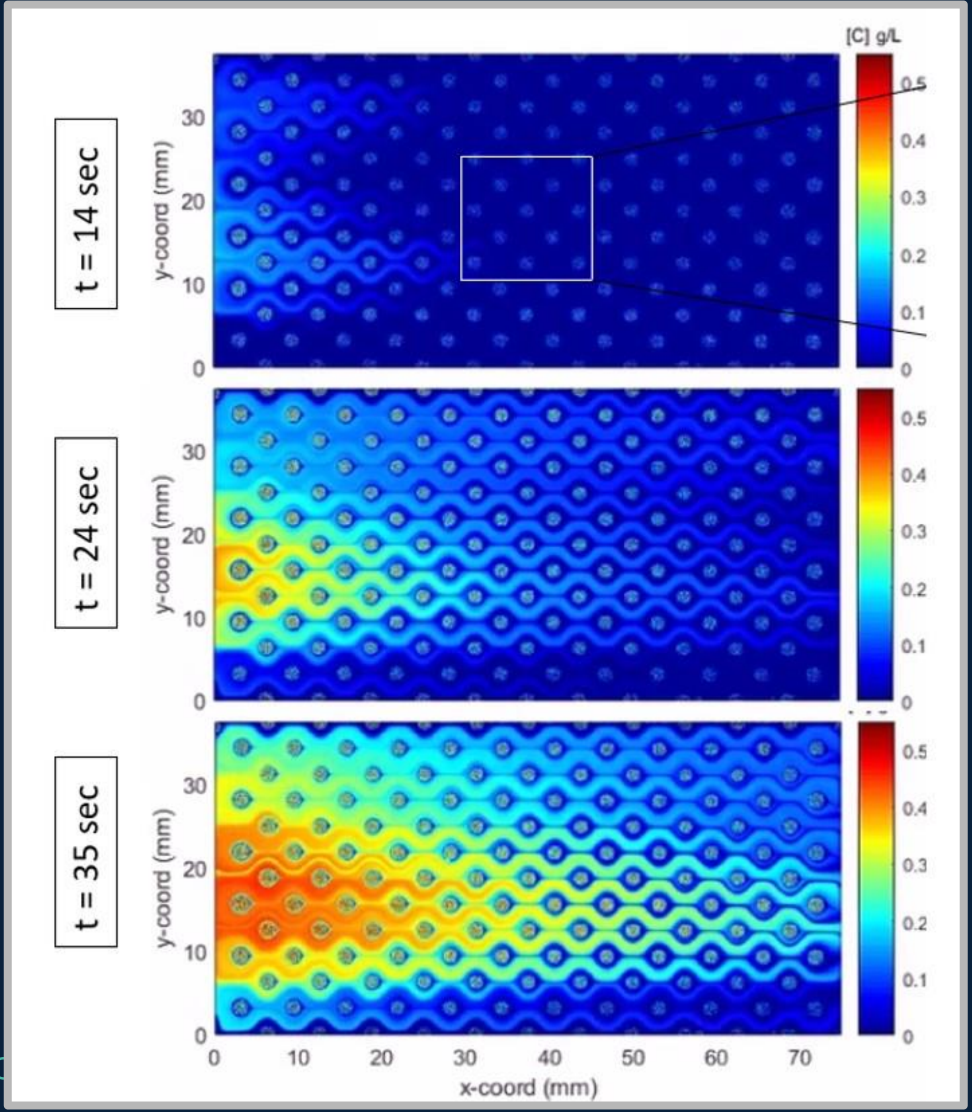
Light Transmission Technique



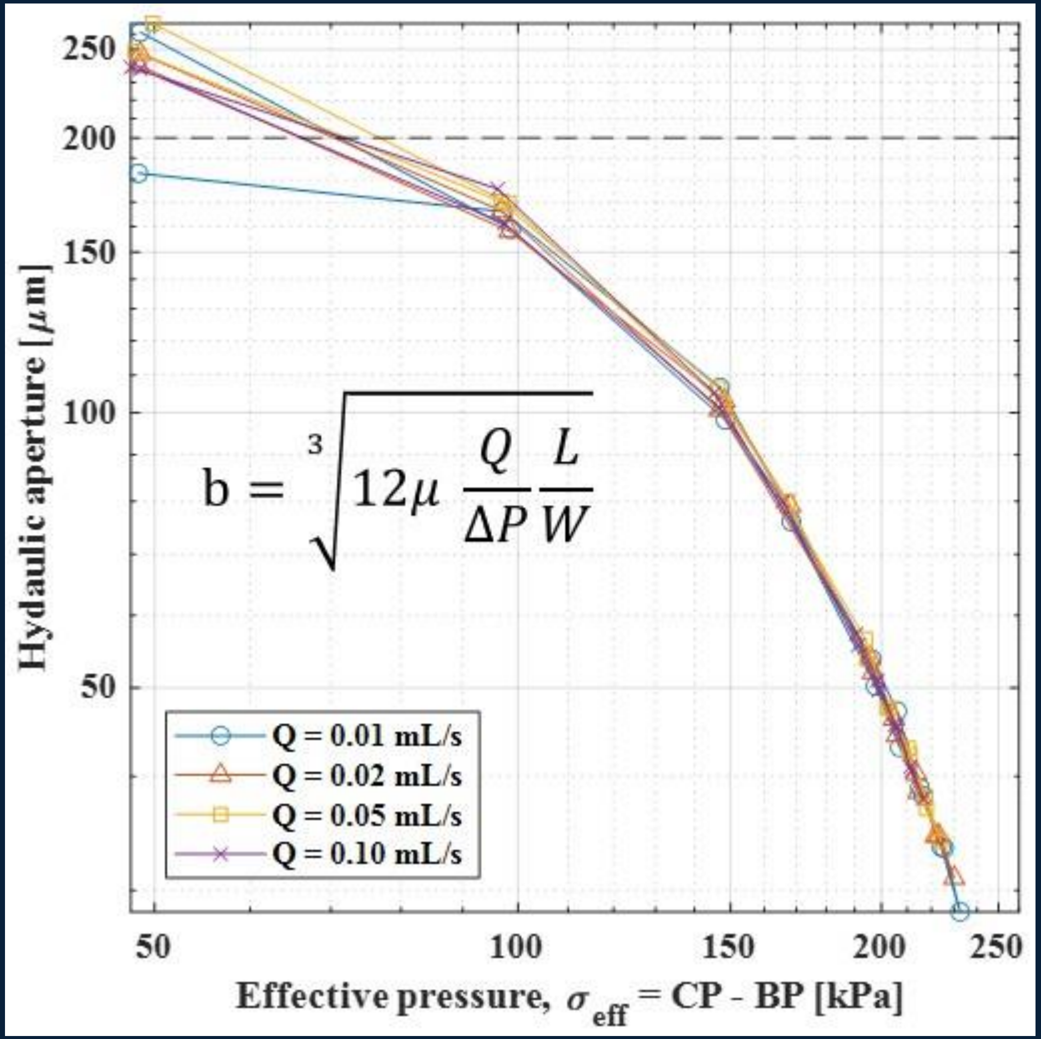
Flow

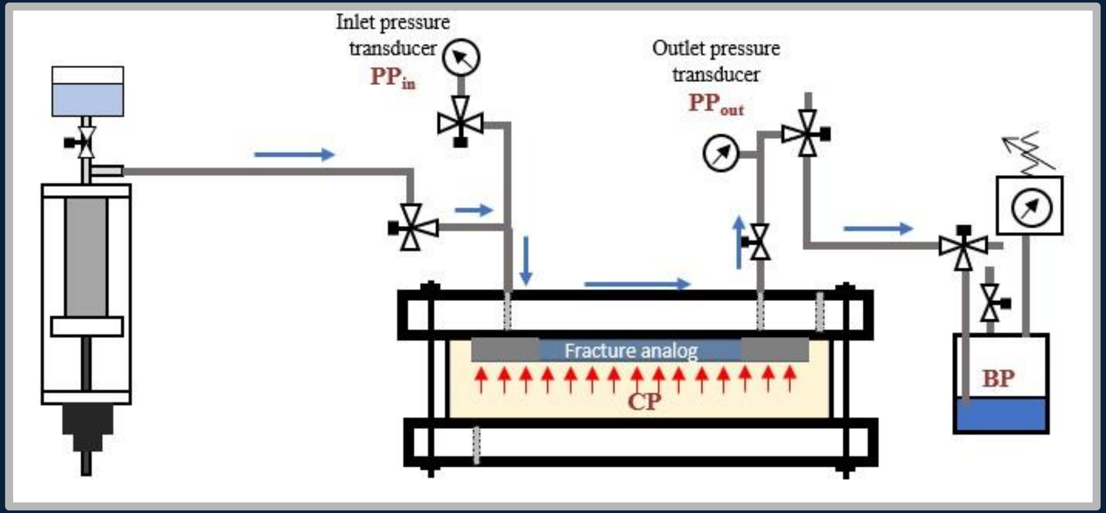


Concentration Fields

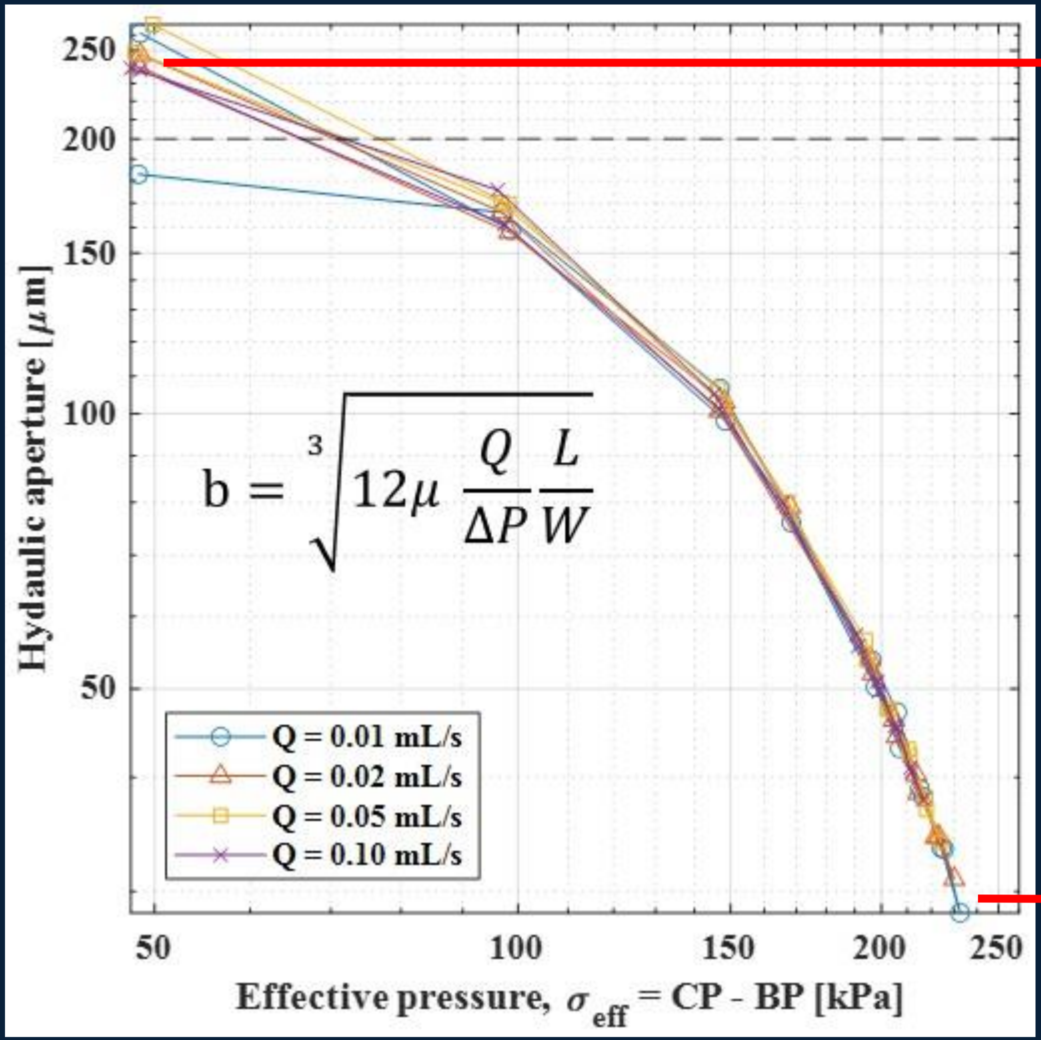


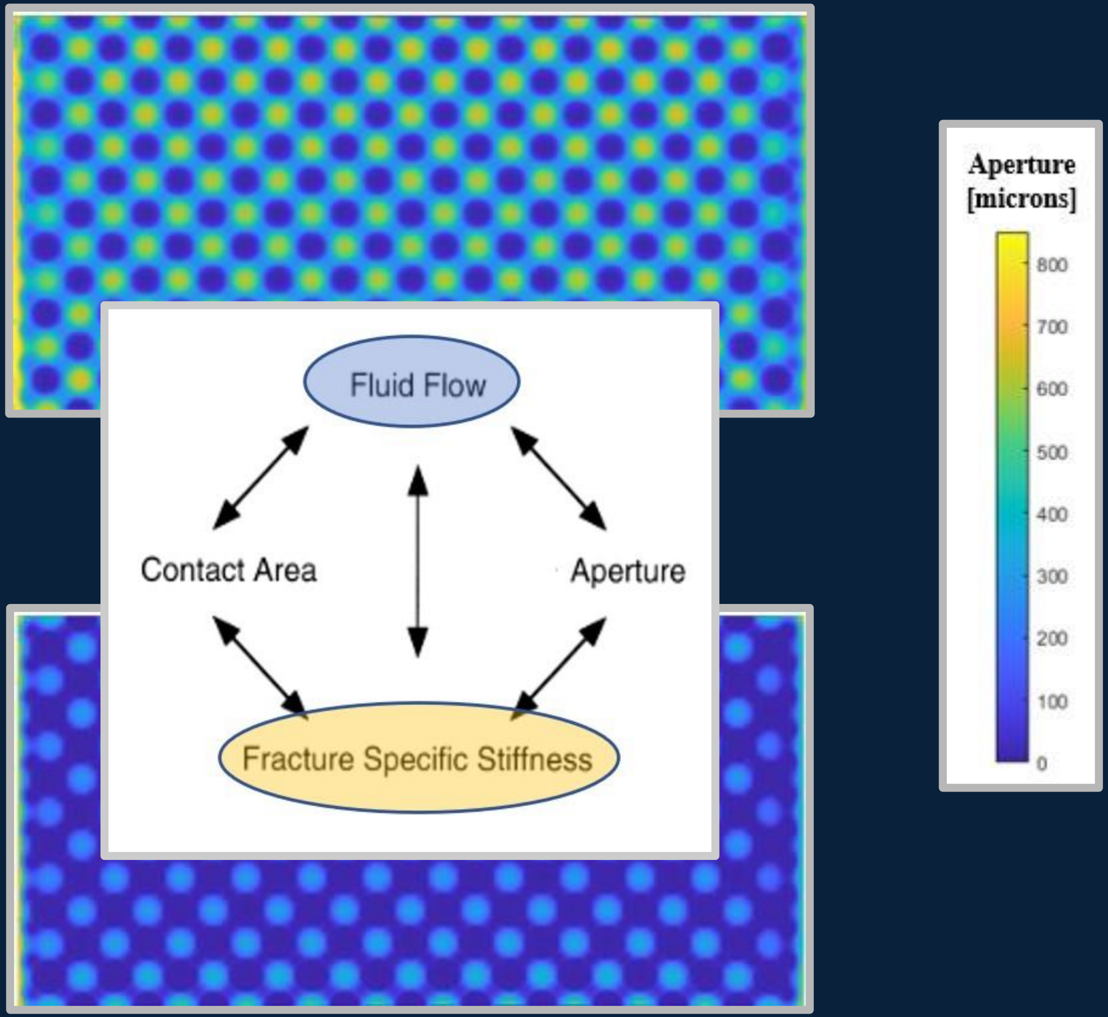
Part A: Flow measurements





Part A: Flow and fracture deformation





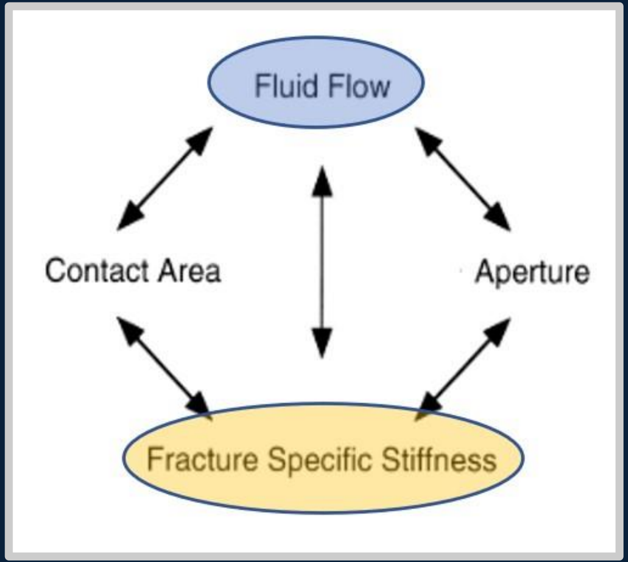
Part A: Current work + next steps

Current work:

- Stress-dependent permeability relationship

Next steps:

- Linear-nonlinear flow transition
- Interplay between fracture geometry, flow and transport



Part B:

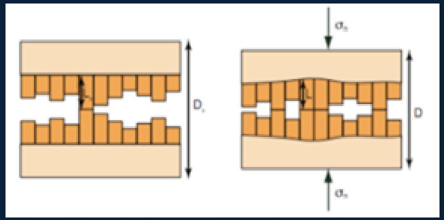
Numerical Simulations

Part B: Mechanical deformation simulation

Key motivation

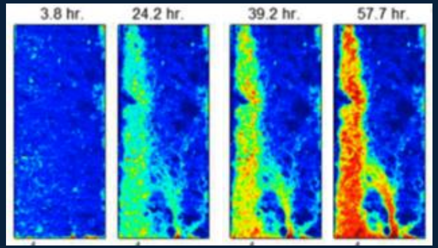
Factors affecting aperture change:

Mechanical deformation



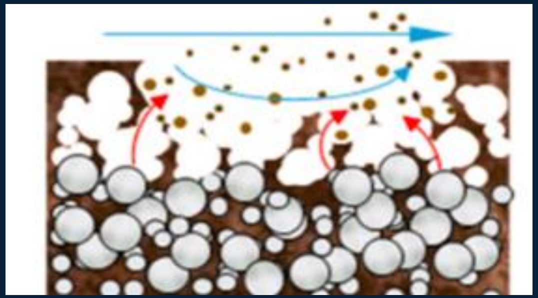
Detwiler & Morris. (2014)

Dissolution



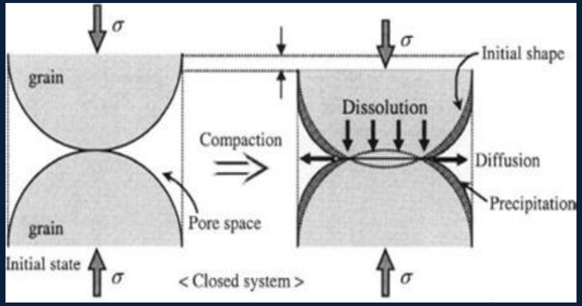
Deng et al. (2015)

Erosion



Deng et al. (2015)

Pressure solution:



Polak et al. (2004)

- The mechanical deformation (elasto-plastic defor. and creep) is significant, but it has not been accurately simulated.
- Start with elasto-plastic deformation of Musandam limestone fractures. Also working on the creep.

Part B: Mechanical deformation simulation

Overview of methodology

Final goal: ABAQUS simulation for fracture mechanical deformation

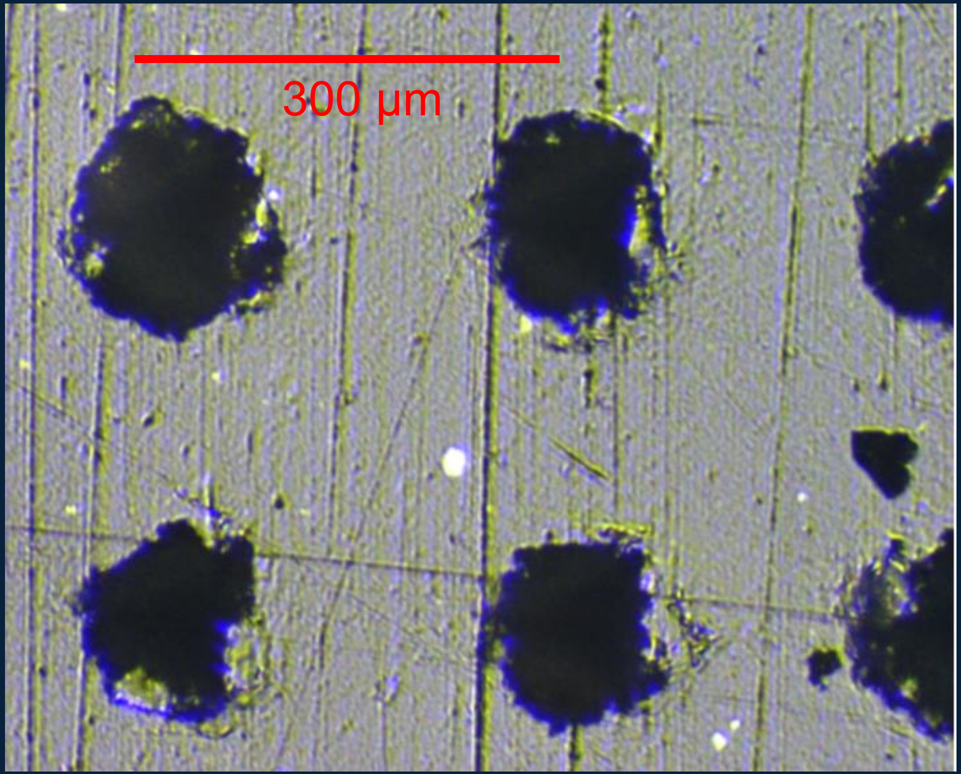
Question: How to verify the correctness of the simulation methods?

Method: Use experimental micro-indentation data to calibrate ABAQUS simulation

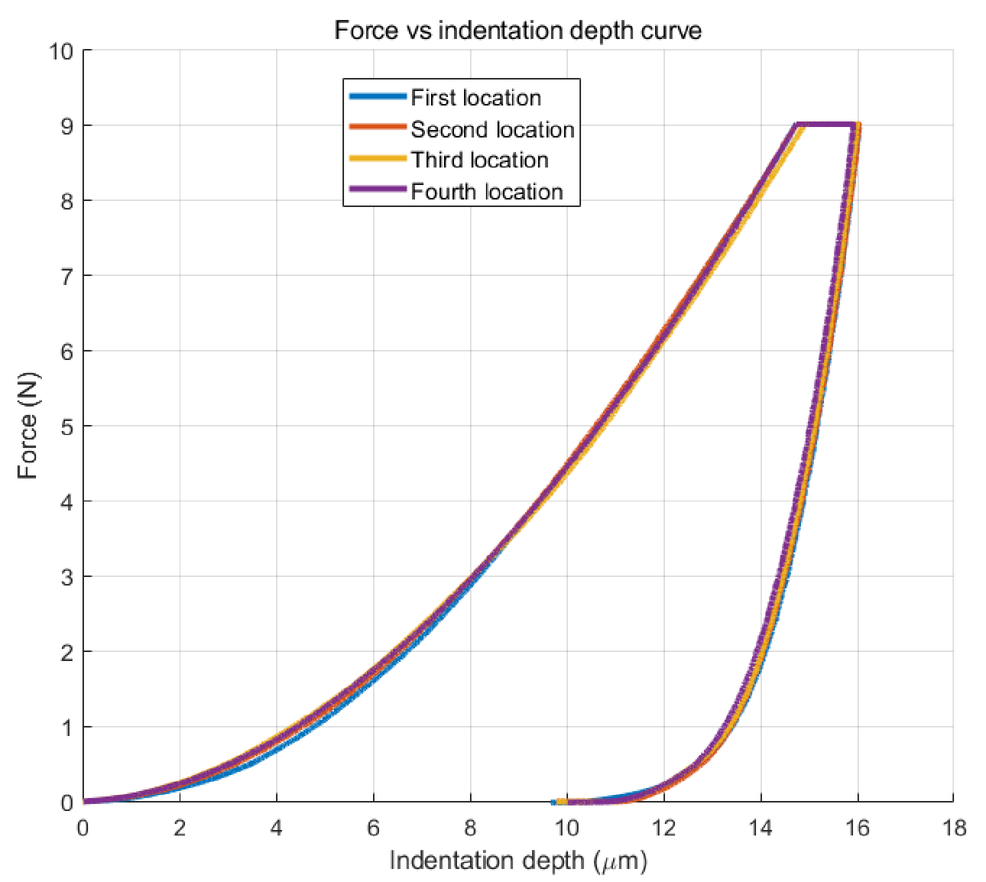
- Why choose micro-indentation data: similar size and stress states compared with fracture contacting asperities.

Part B: Mechanical deformation simulation

Micro-indentation experiments



Microscope image of indents



Force – indentation depth curves for four selected locations

Part B: Mechanical deformation simulation

ABAQUS simulation method for micro-indentation

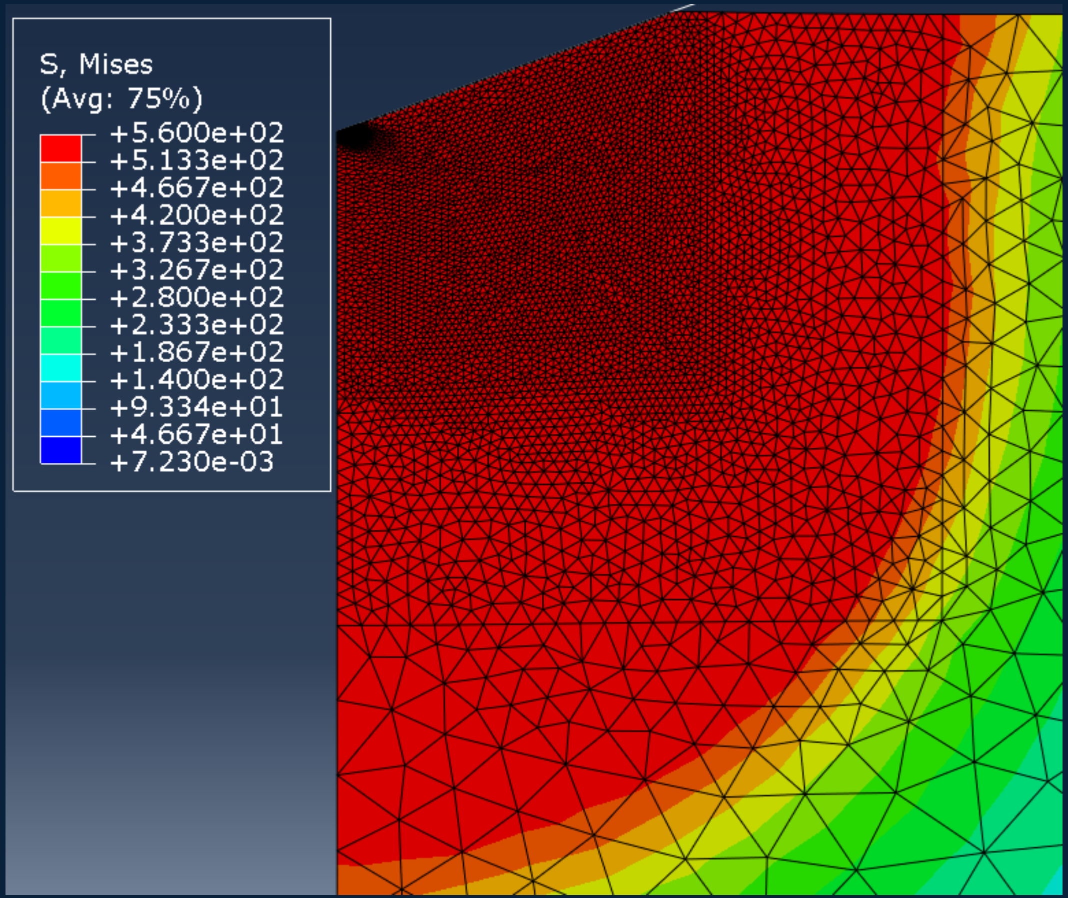
Elastic parameters (from triaxial tests):
- E = 67 GPa, v = 0.30

Plastic model: Mises yielding model

- Reason: at indentation / fracture asperity scale, the yield strength is not strongly pressure-dependent. Difficult to converge in Coulomb.

- Choose yielding strength σ_y = H / 3, where H is the indentation hardness. H = 1680 MPa, so σ_y = 560 MPa.

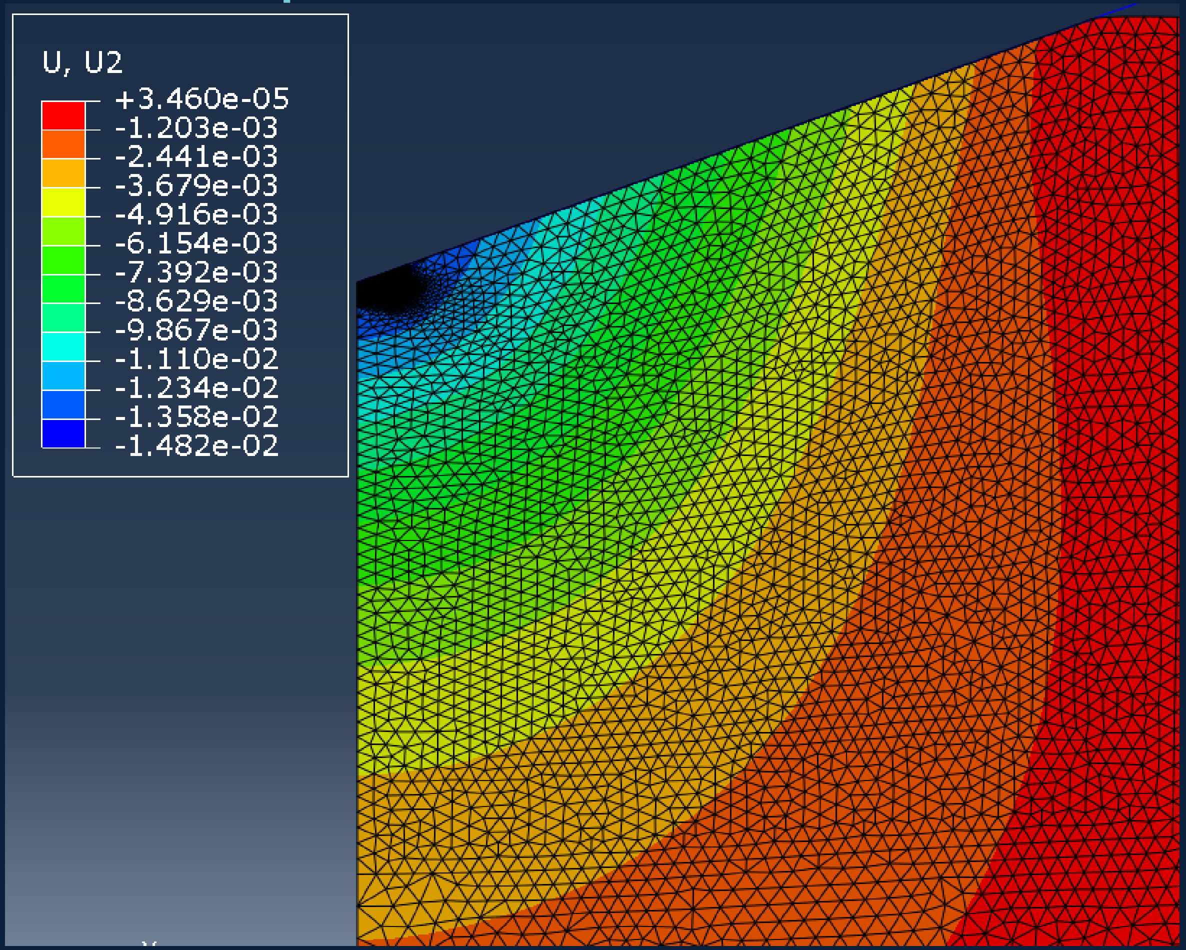
Mesh and Mises stress distribution:



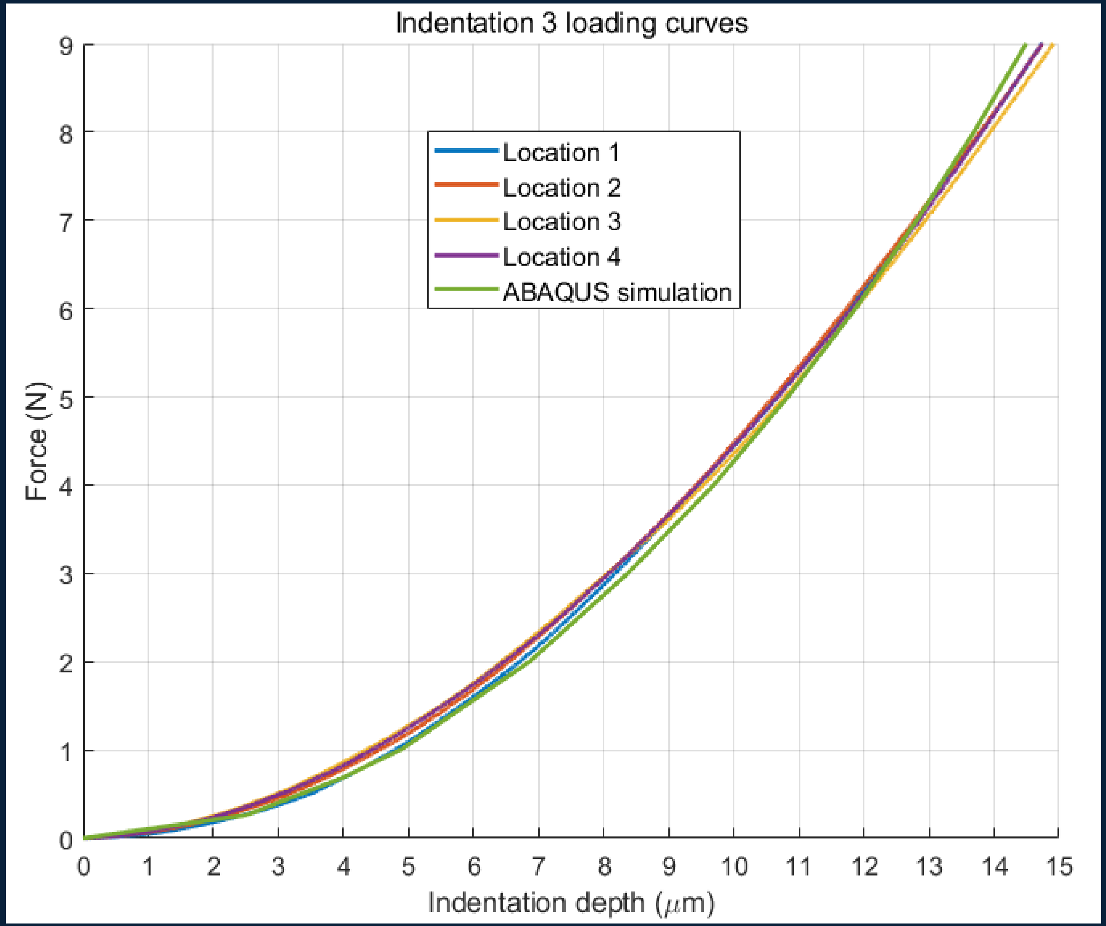
Part B: Mechanical deformation simulation

ABAQUS simulation results for micro-indentation

Vertical displacement:



Simulated force – depth curves:



Part B: Mechanical deformation simulation

ABAQUS simulation motivation for fracture surface asperity interaction

Reality:

In real fracture surfaces, multiple asperities with different heights and shapes.

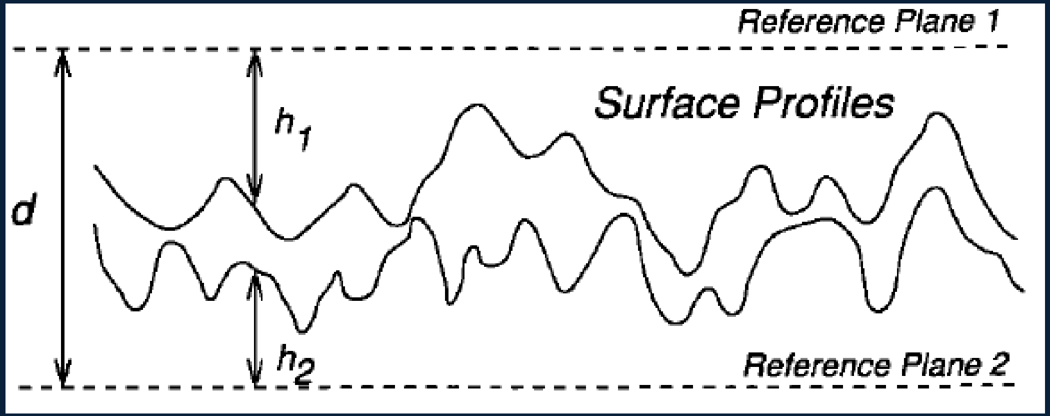
Question:

How to understand the interaction between different asperities?

Method:

ABAQUS simulation

Multiple asperities:



Brown et al. (1995)

Part B: Mechanical deformation simulation

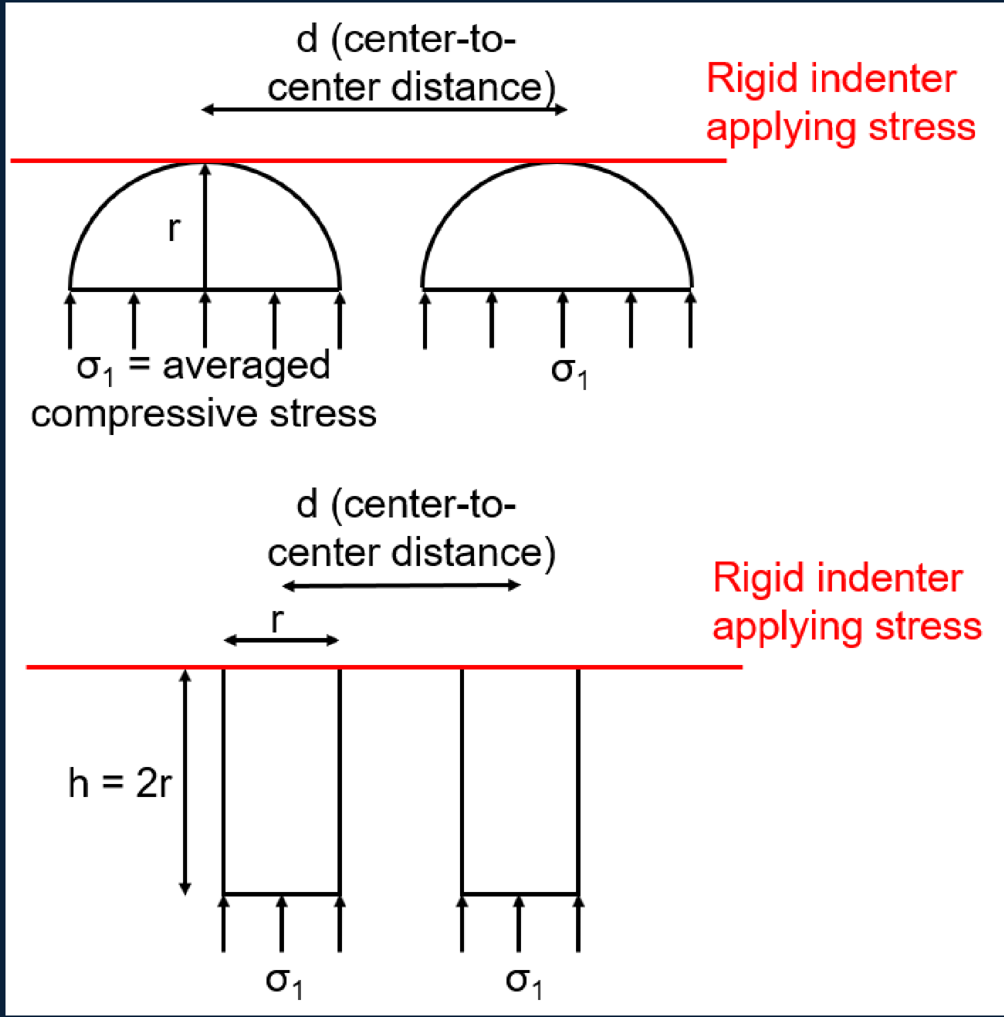
ABAQUS simulation methods for fracture surface asperity interaction

Overview: compare the indenter displacements under the same σ_1 (averaged compressive stress). Change the d / r, asperity shape, and No. of asperities.

Constitutive model: same as indentation simulation.

Summary:

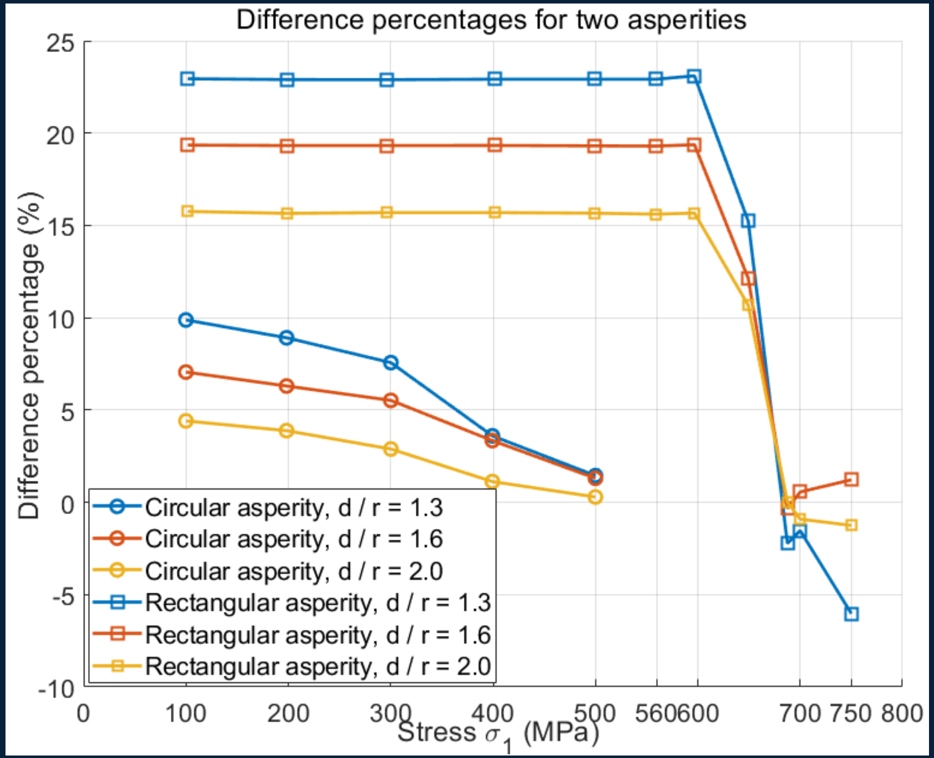
Asperity shape	d / r ratios	No. of asperities
Circular	1.3, 1.6, and 2.0	1, 2, and 5
Rectangular	1.3, 1.6, and 2.0	1, 2, and 5



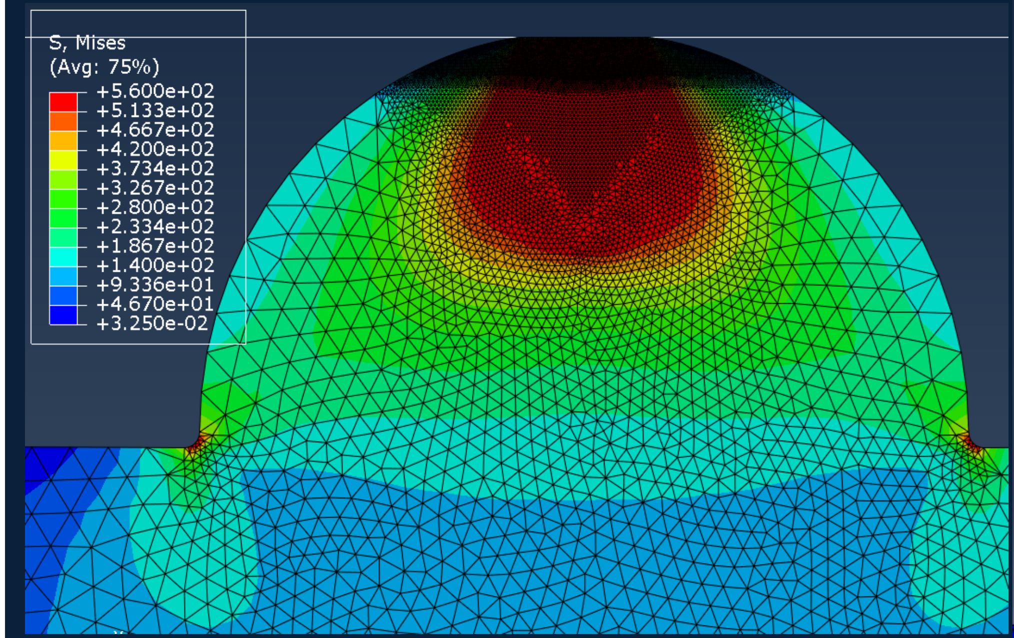
Part B: Mechanical deformation simulation

ABAQUS simulation results for fracture surface asperity interaction

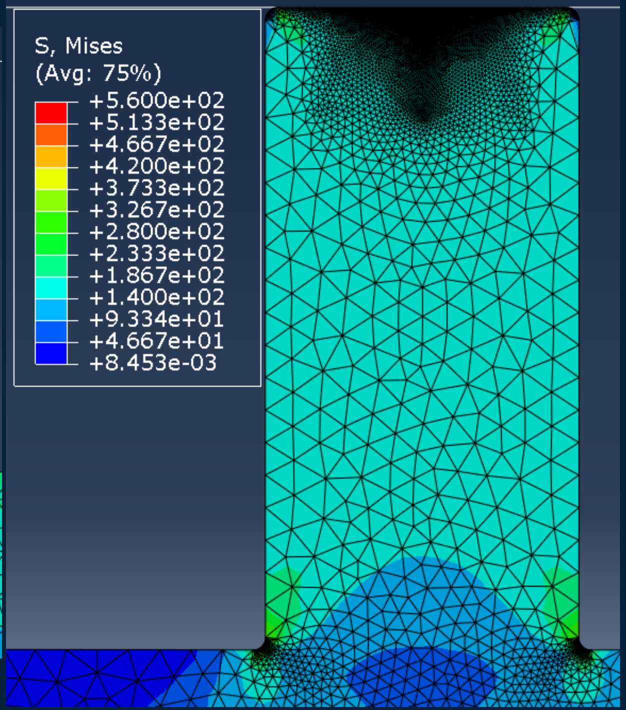
2 asperities (d / r is changed):



Mises stress for circular shape when σ_1 = 200 MPa:



Mises stress for rectangular shape when σ_1 = 200 MPa:



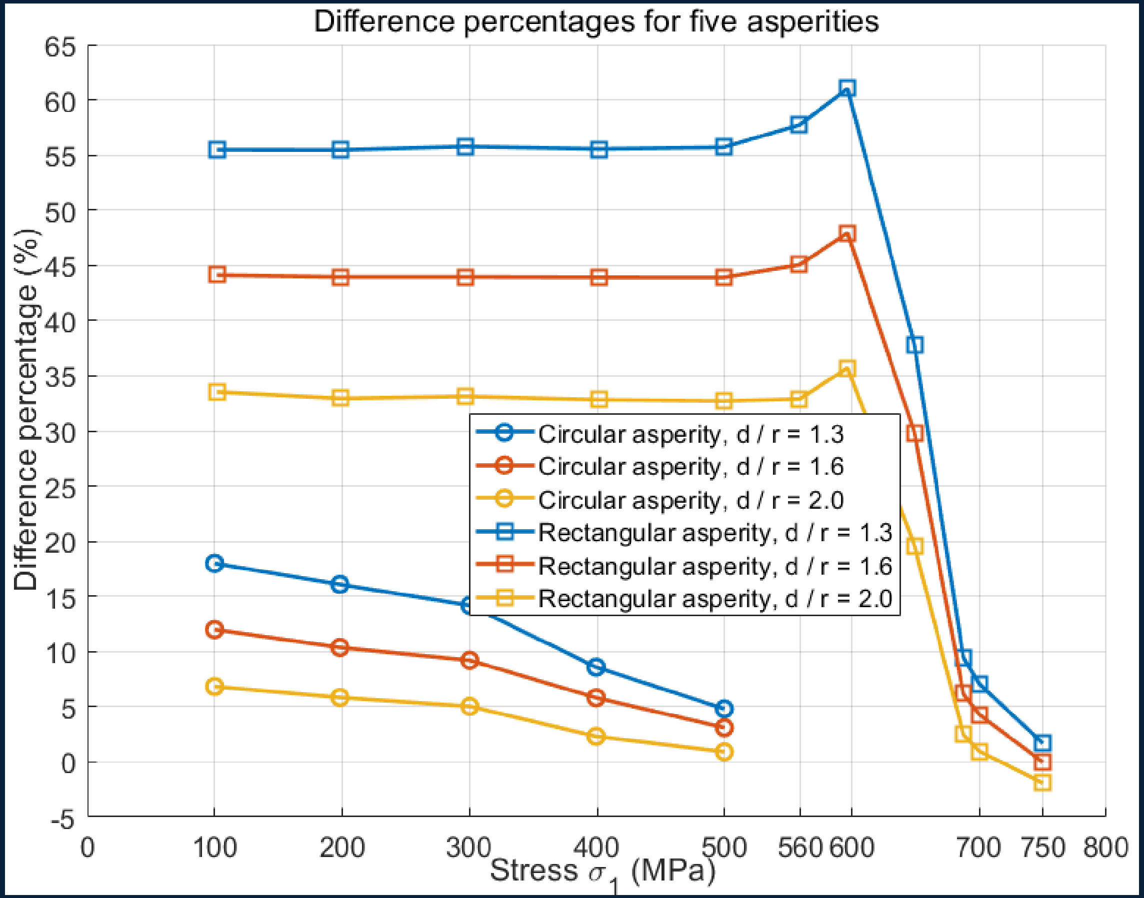
Note: $Difference\,percentage = \dfrac{\delta_{multiple\ asperities} - \delta_{single\ asperity}}{\delta_{single\ asperity}}$

When σ_1 < 500 MPa, plastic yielding is more significant in circular asperity.

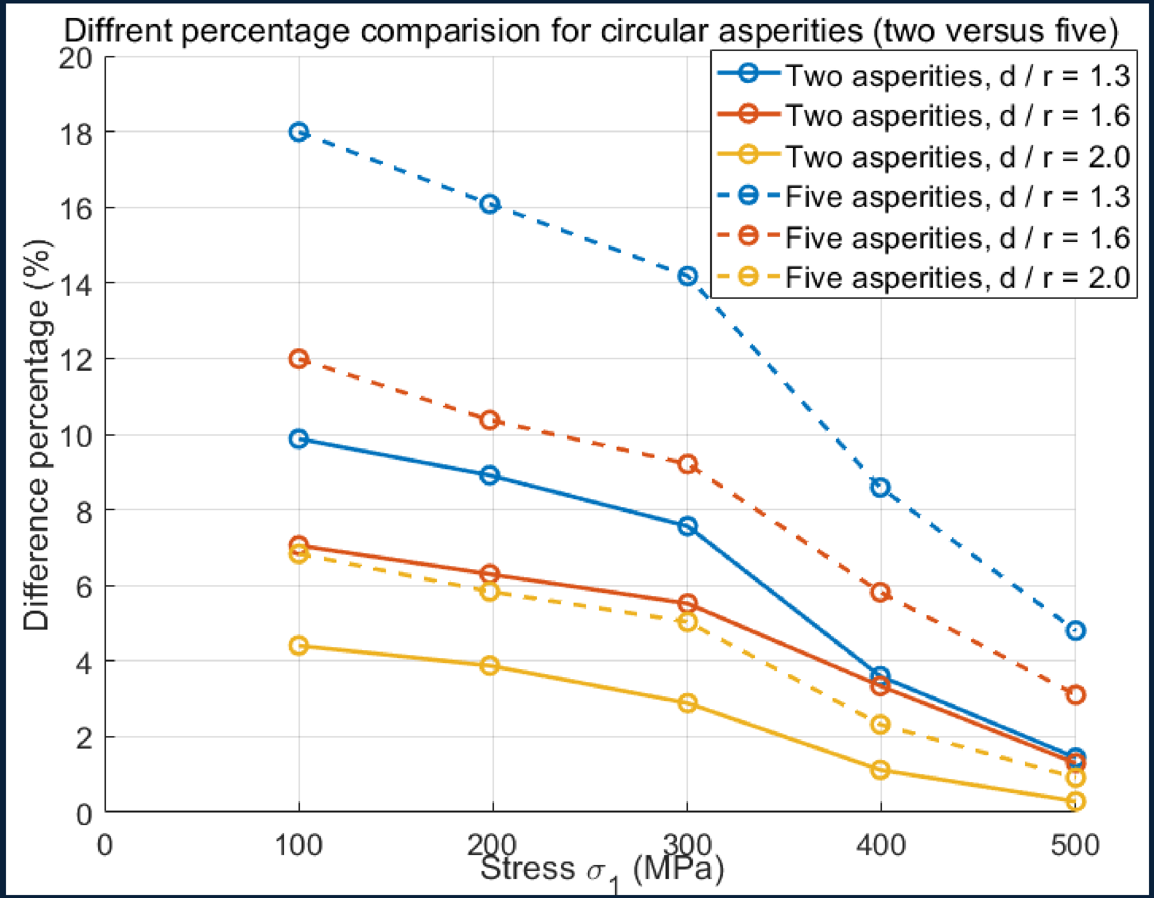
Part B: Mechanical deformation simulation

ABAQUS simulation results for fracture surface asperity interaction

5 asperities (d / r is changed):



Circular shape, two versus five asperities:



d / r is also changed.

Part B: Mechanical deformation simulation

Simulation conclusions and next steps for fracture surface asperity interaction

Conclusion:

- Mises yielding gives reasonably good fit between indentation simulations and measurements.
- Plastic yielding reduces the difference percentage. The difference percentage for circular asperity is smaller than that of rectangular.
- When the number of asperities increases, the difference percentage of rectangular asperity increases much faster than that of circular asperity.

Next steps:

- Find suitable description of fracture surface with multiple asperities. Implement it in ABAQUS (or other code) and conduct simulation.
- Extend the simulation to creep.

Conclusion

- Flow experiments on a pressure-controlled Hele-Shaw cell
  - *Develop a novel setup for flow and transport measurements*
  - *Direct observations of aperture fields under stressed conditions*

- Numerical simulation
  - *Mises yielding gives reasonably good fit between indentation simulations and measurements.*
  - *Plastic yielding reduces the difference percentage. The difference percentage for circular asperity is smaller than that of rectangular.*

Back-up slides

Mesh for five asperities interaction