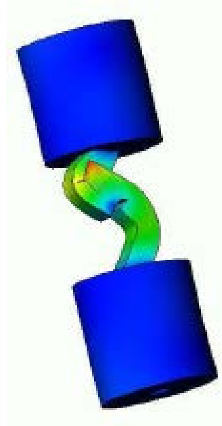
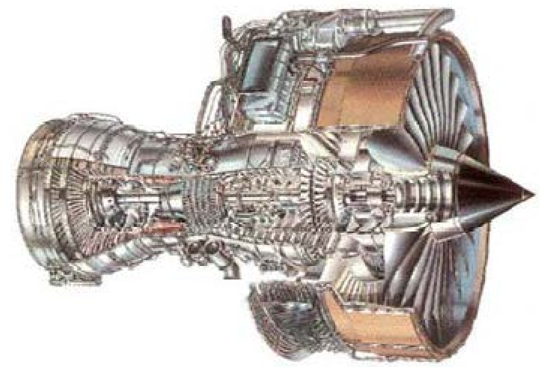
Exceptional service in the national interest





Indentation of Porous Materials: Factors Affecting the Indentation Results and a Comparison to Bulk Material Testing

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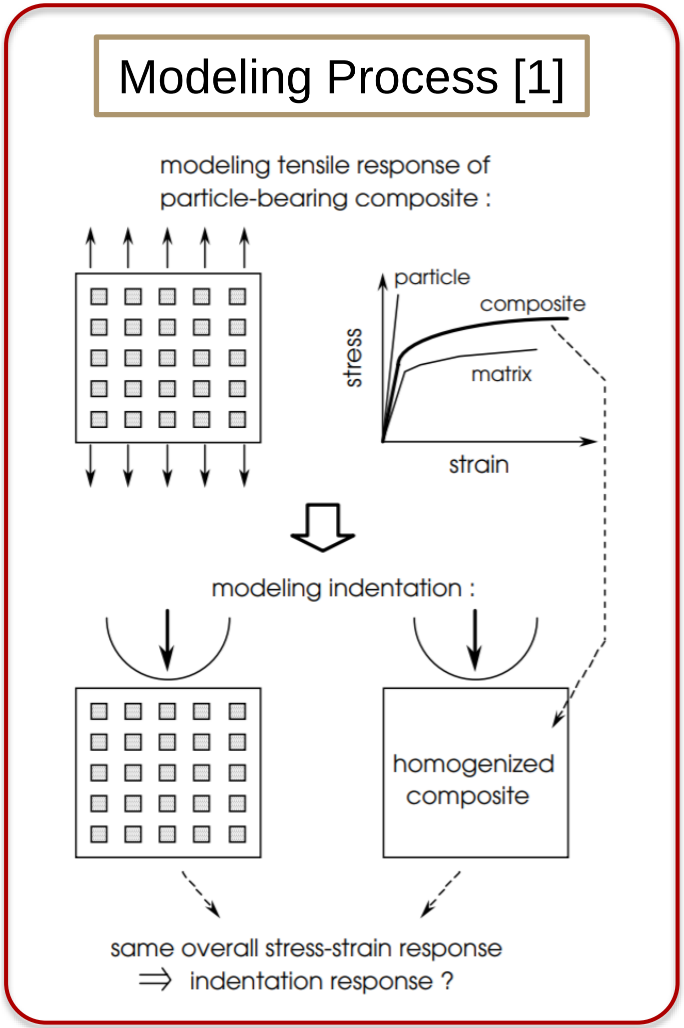
SAND2019-8709 PE

Introduction/Motivation



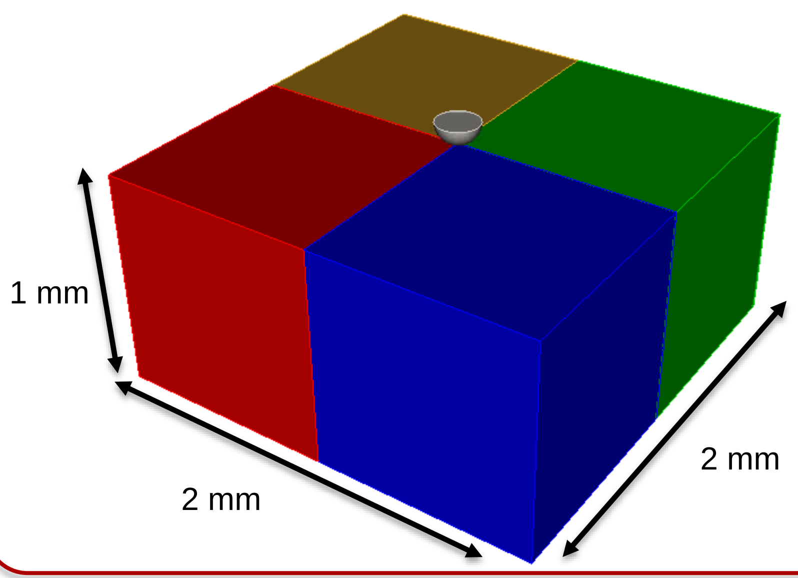
- In modeling the mechanical behavior of heterogeneous materials, distinct microstructural features are often homogenized so the material can be treated as a continuum and the problem becomes less computationally demanding
- It is well known that indentation probes are local measurements of mechanical properties and sensitive to heterogeneous nature of the material tested
- The goal of this project is to study the correlation between the indentation-derived material properties with the overall (macroscopic) mechanical properties for materials containing microscopic constituents with distinctly different mechanical features

[1] Y-L. Shen and Y. L. Guo, "Indentation modelling of heterogeneous materials," *Modelling Simul. Mater. Sci. Eng.*, vol. 9, pp. 391-398, Aug. 2001.

Model Descriptions

- Indenter Properties
  - Spherical, rigid indenter
  - Radius: 0.1 mm
  - 40μm indentation depth
- Material Properties
  - Isotropic
  - Young's modulus: 207 GPa
  - Poisson's Ratio: 0.3
  - Flow stress: 210 MPa
- Void Volume fractions: 5%, 10%, 15%
- Spatial Distributions: simple cubic, body centered cubic, random
- All compression tests were performed up to 0.1 strain
- Model is elastic-plastic
  - Gives perfect elastic/plastic behavior

Material block with symmetry lines and indenter

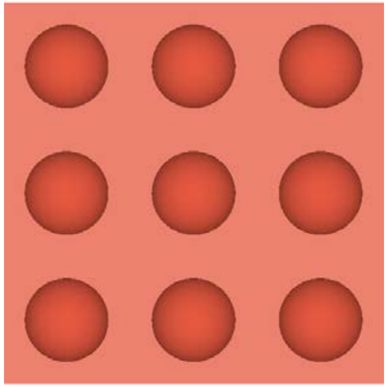


Geometry

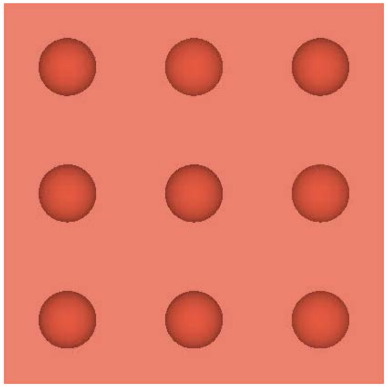
Block geometry is 1mm x 1mm x1 mm

Simple Cubic

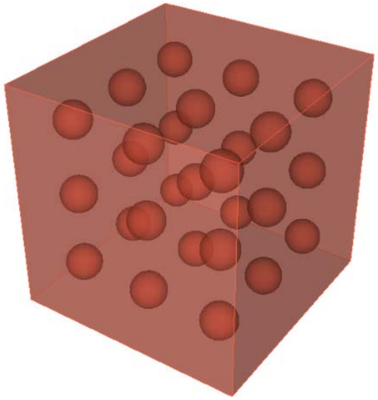
Configuration consists of 27 voids



15% Porosity (Front View)



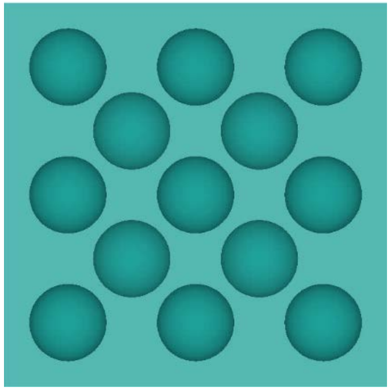
5% Porosity (Front View)



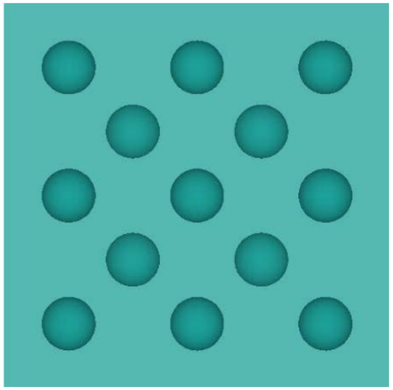
5% Porosity (Isometric View)

Body Centered Cubic

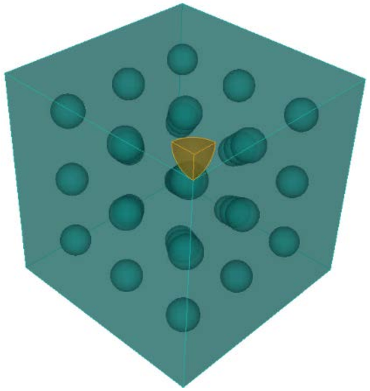
Configuration consists of 35 voids



15% Porosity (Front View)



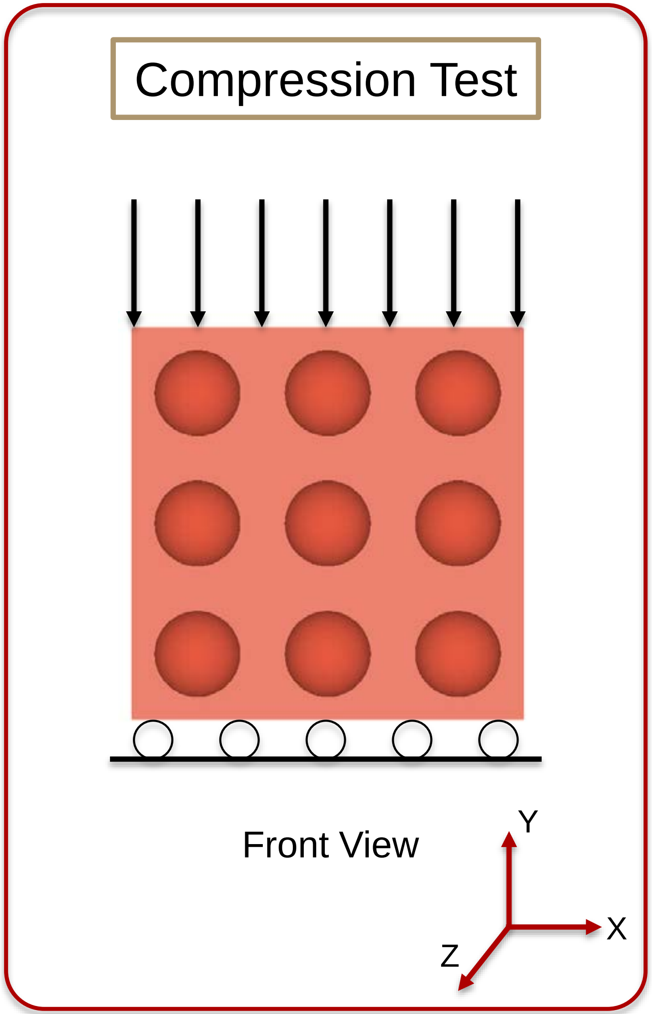
5% Porosity (Front View)

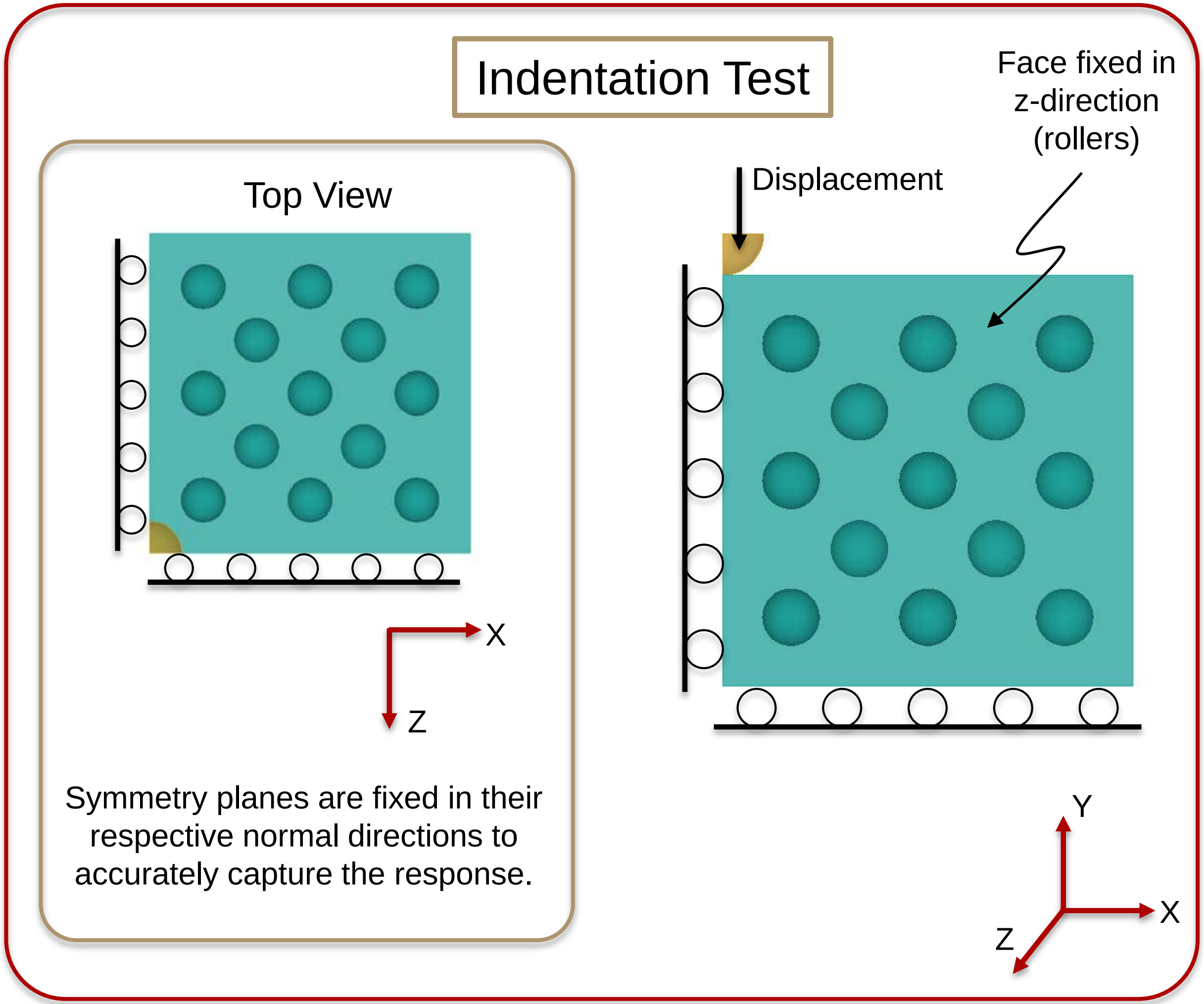


5% Porosity (Isometric View)

Models were created in CUBIT using a script to control the different parameters for each case.

Test Setup

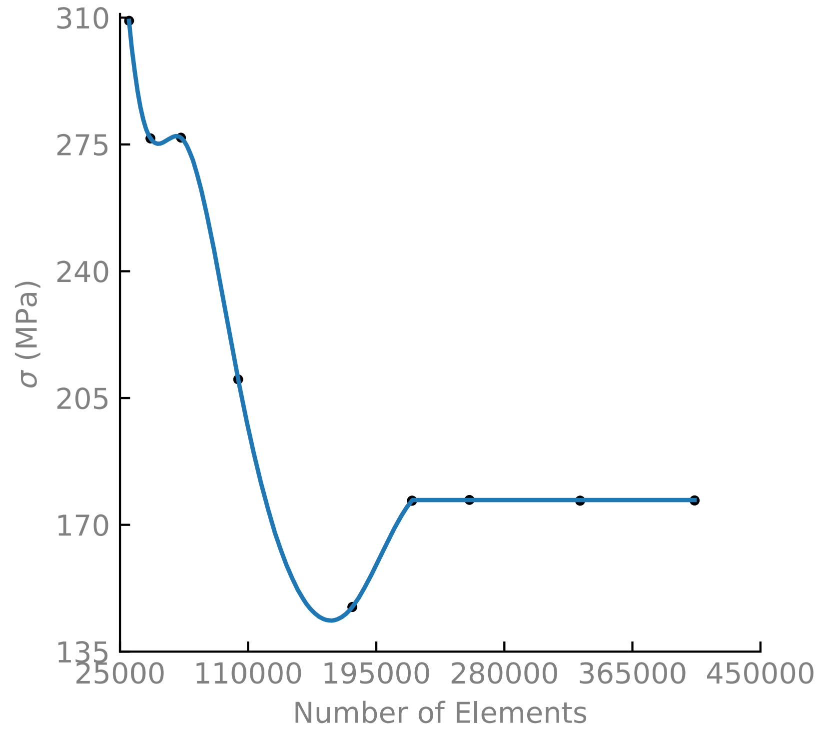

Compression Test
Front View
Y
X
Z


Indentation Test
Top View
X
Z
Symmetry planes are fixed in their respective normal directions to accurately capture the response.
Displacement
Face fixed in z-direction (rollers)
Y
X
Z

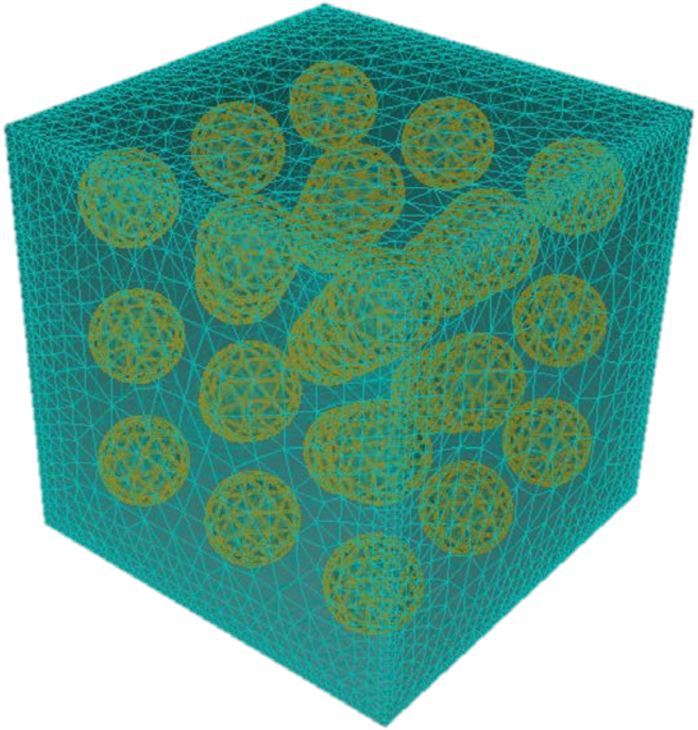
Compression Model Meshing

For the compression tests, the material block was meshed with quadratic 10-node tetrahedron elements in CUBIT. A mesh convergence study was conducted to determine mesh independence.

h-Refinement on Compression Model



Compression model mesh

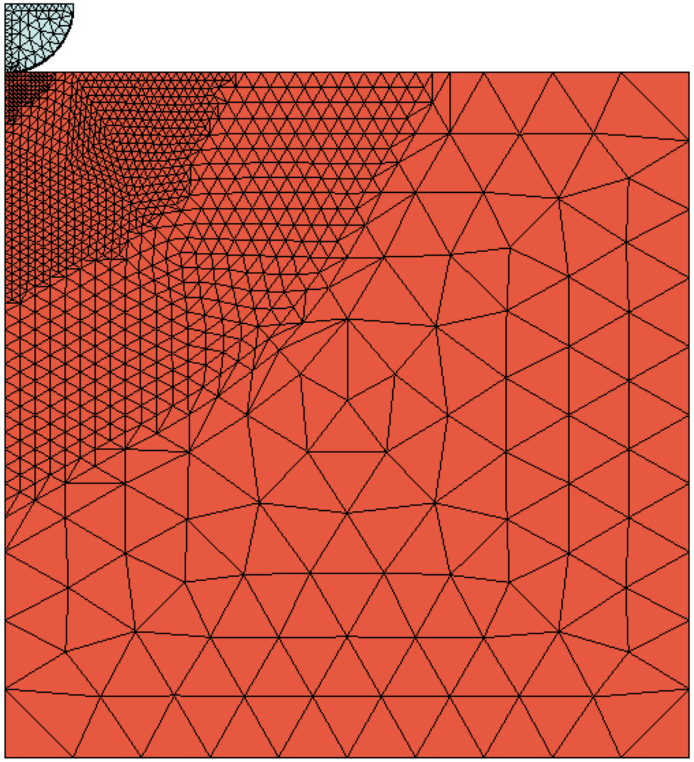


Indentation Model Meshing

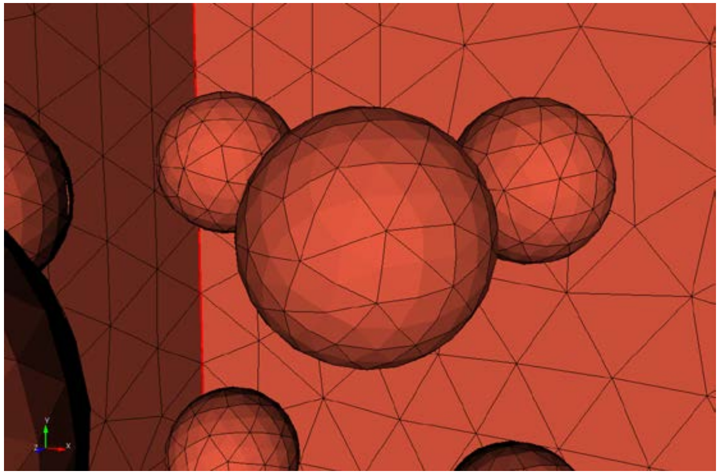
The indenter and material block were meshed with quadratic 10-node tetrahedron elements in CUBIT. Three different parameters were specified for the mesh:

- Size at the vertex of indenter contact
- Size of the elements on the void surfaces
- Overall mesh size

Block and indenter mesh

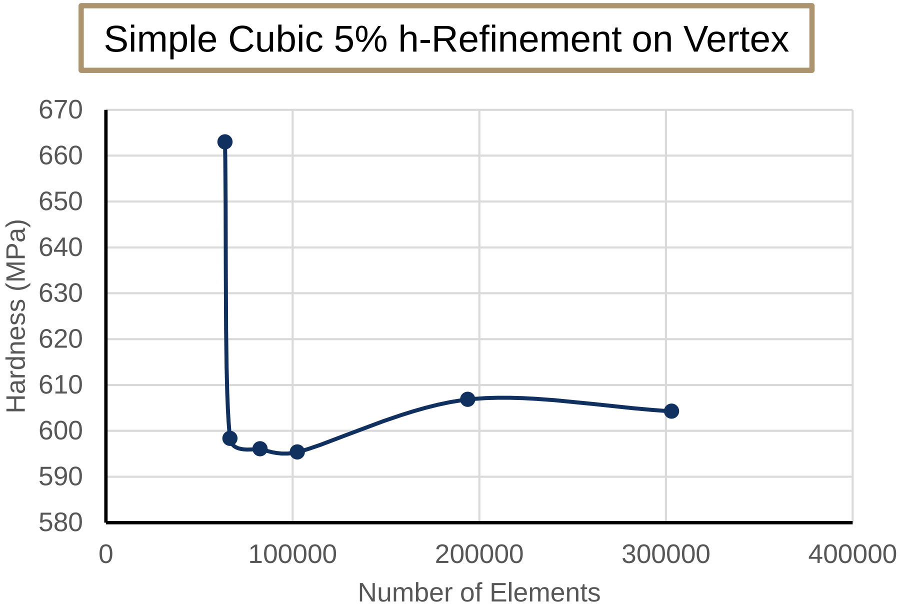


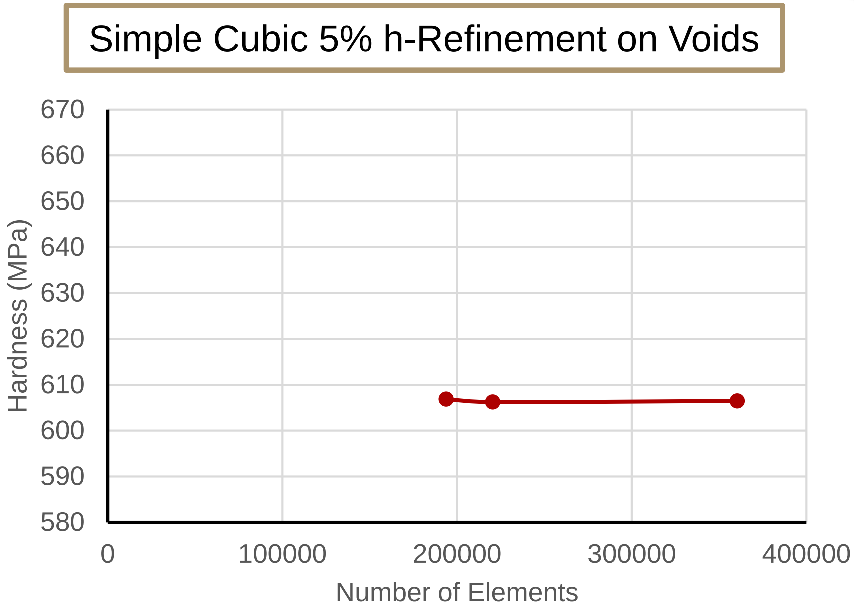
Mesh on surfaces of the voids



Mesh Refinement

A mesh refinement study was conducted on the simple cubic model in order to determine which areas of the model had the most effect on the result. Parameters were extrapolated from this study for use throughout the other models.



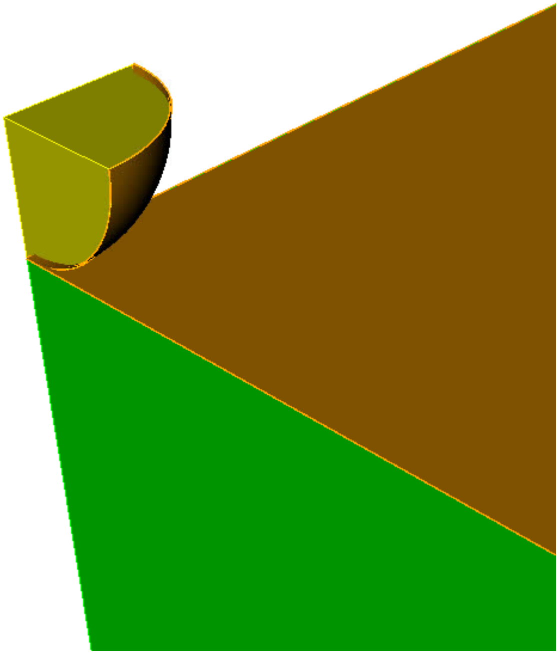


Refining the mesh on the vertex had the most effect on the resulting hardness. Changing the mesh on the surface of the voids had a negligible effect on the result by comparison

Contact

Contact was defined between the top surface of the material and the outer surface of the indenter. A friction coefficient of 0.1 was assigned to the interaction. The solver settings were adjusted until convergence was reached.

Contact Surfaces Highlighted

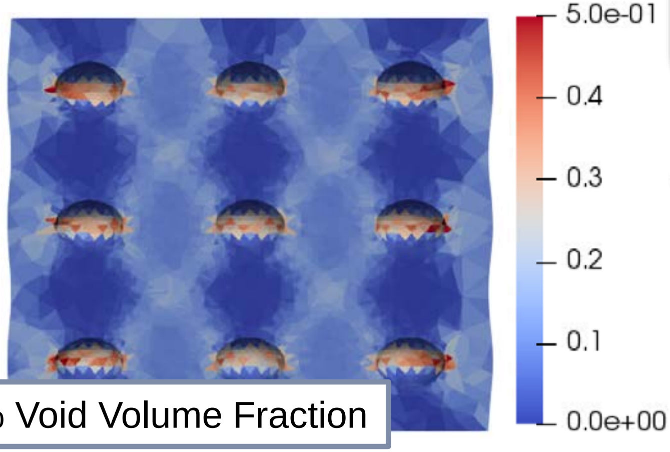


Contact Definitions in SIERRA Input File

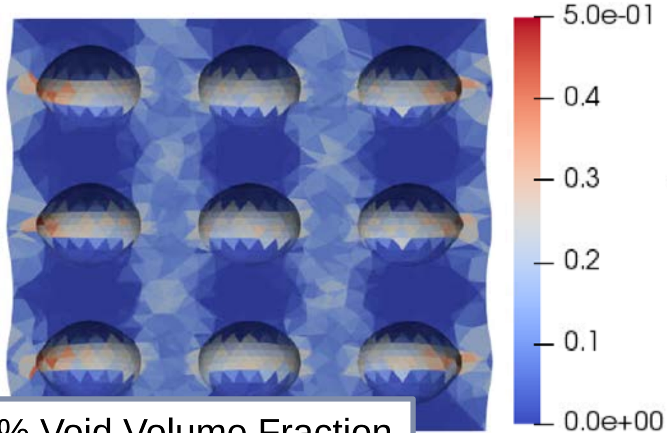
```
begin contact definition indenter_contact
        contact surface indent contains indenter_contact_surf
        contact surface top_face contains top_contact

        begin constant friction model fric_1
                friction coefficient = 0.1
        end

        begin interaction defaults
                general contact = on
                friction model =  fric_1
        end interaction defaults

end contact definition indenter_contact

begin control contact
        acceptable residual = {tr*10}
        acceptable relative residual = {trr*10}
        target residual = {tr}
        target relative residual = {trr}
        maximum iterations = 200
        minimum iterations = 1
        lagrange adaptive penalty = uniform
end control contact
```

Deformation from Compression Tests

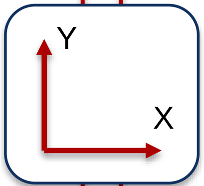
Simple Cubic
Equivalent Plastic Strain



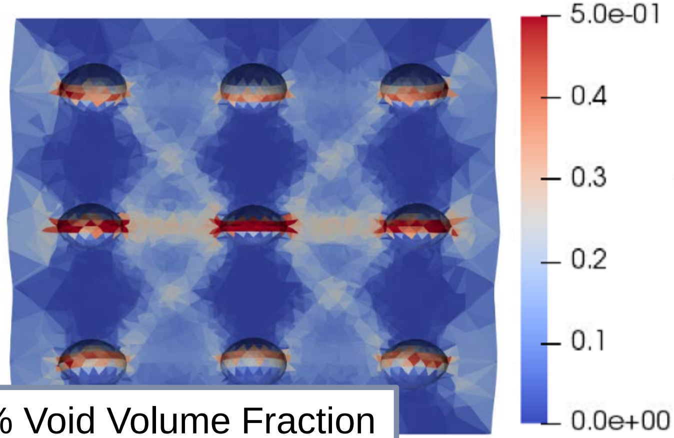
5% Void Volume Fraction



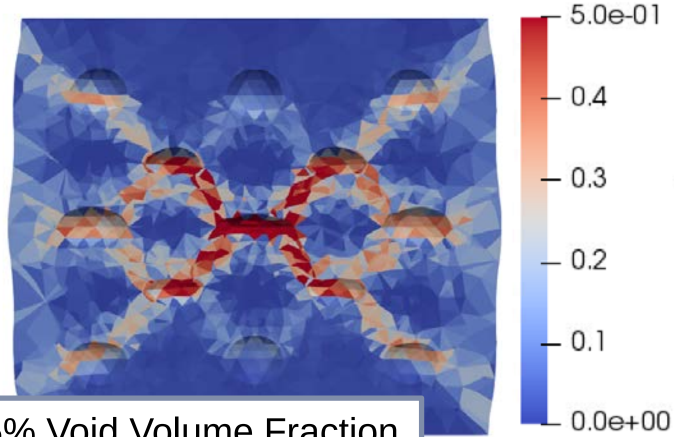
15% Void Volume Fraction



Body Centered Cubic
Equivalent Plastic Strain

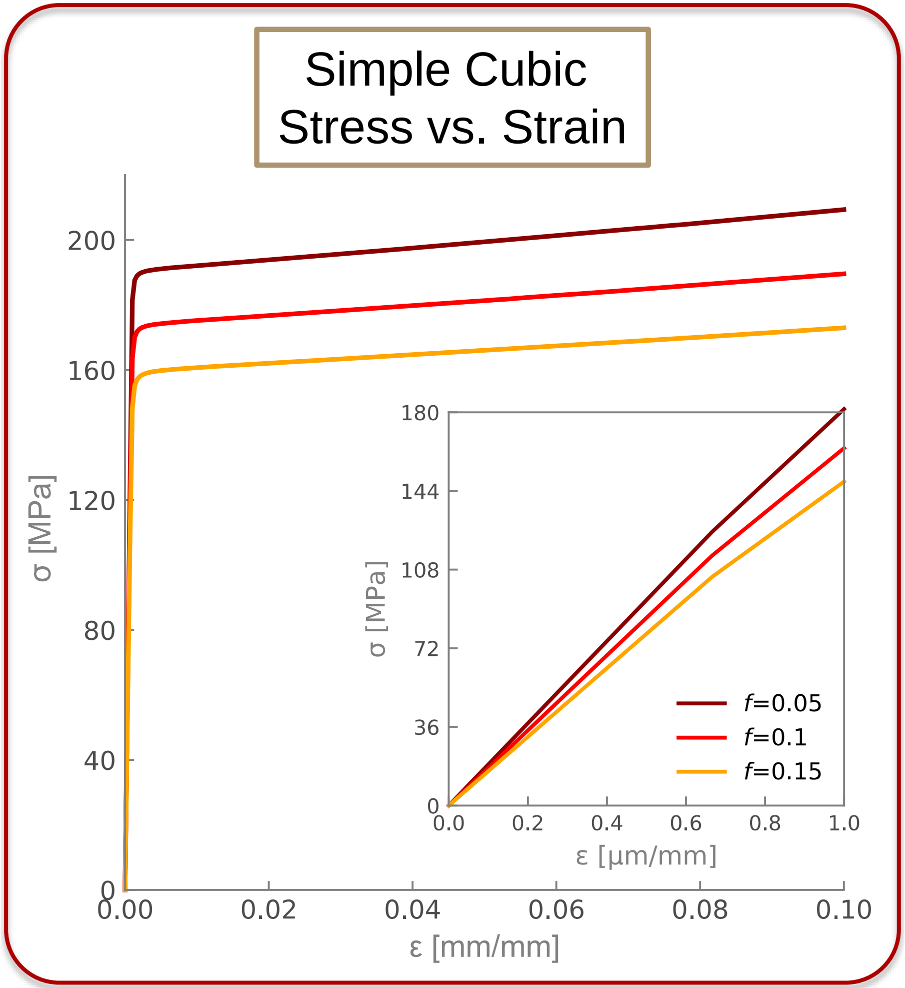


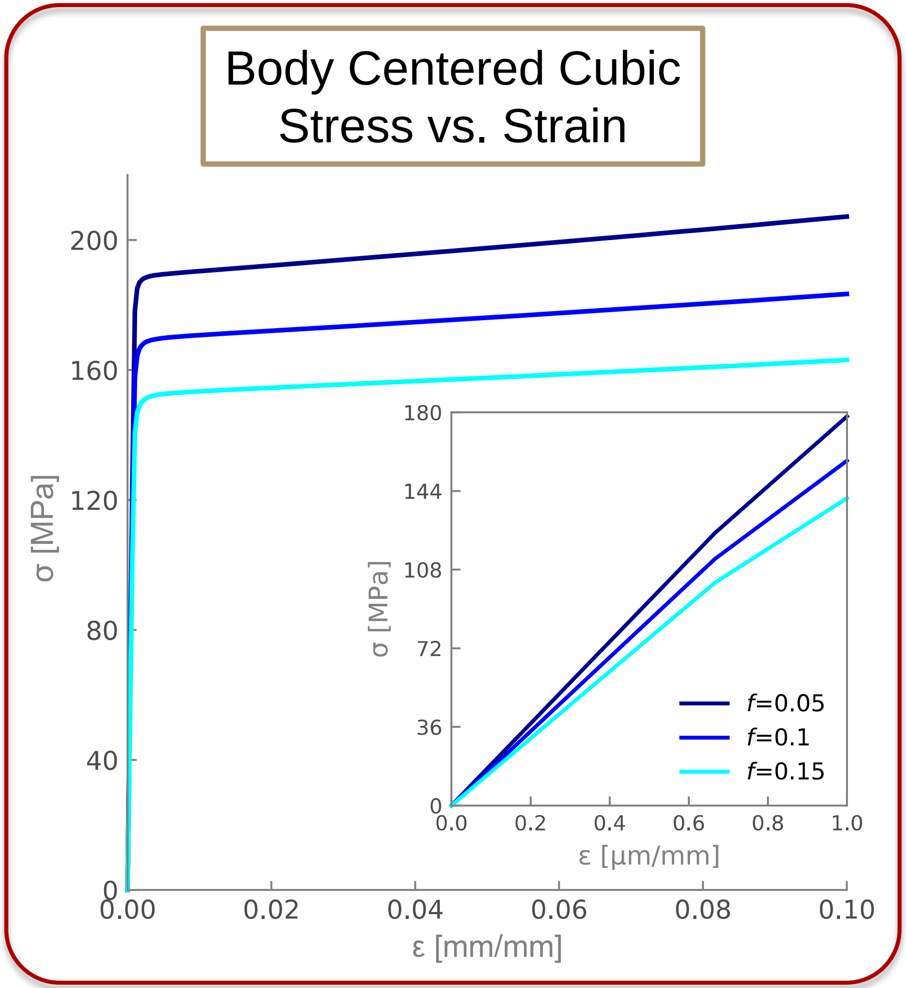
5% Void Volume Fraction



15% Void Volume Fraction

Compression Test Stress-Strain Results

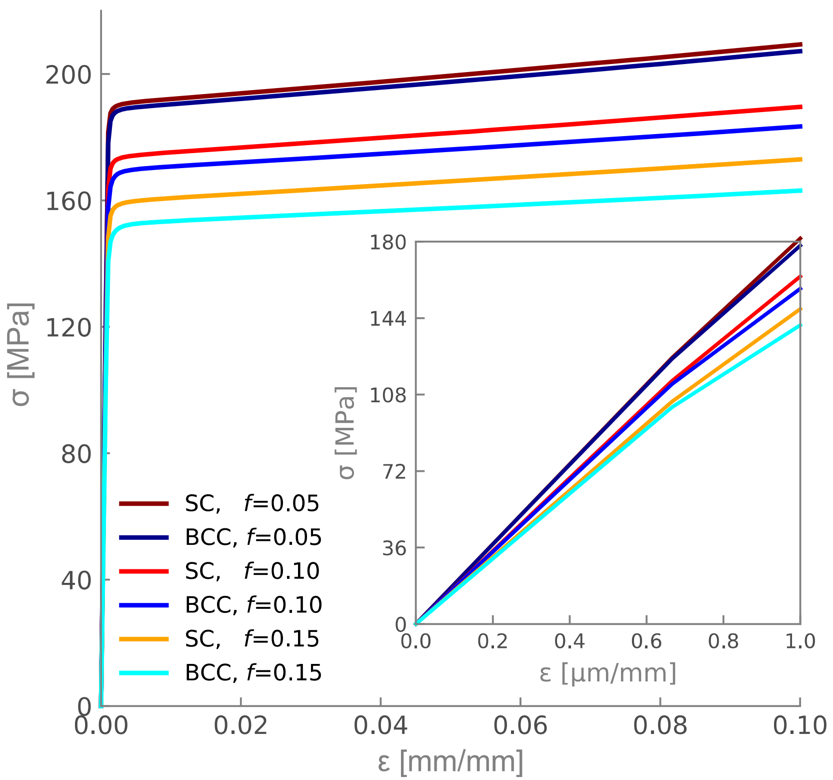




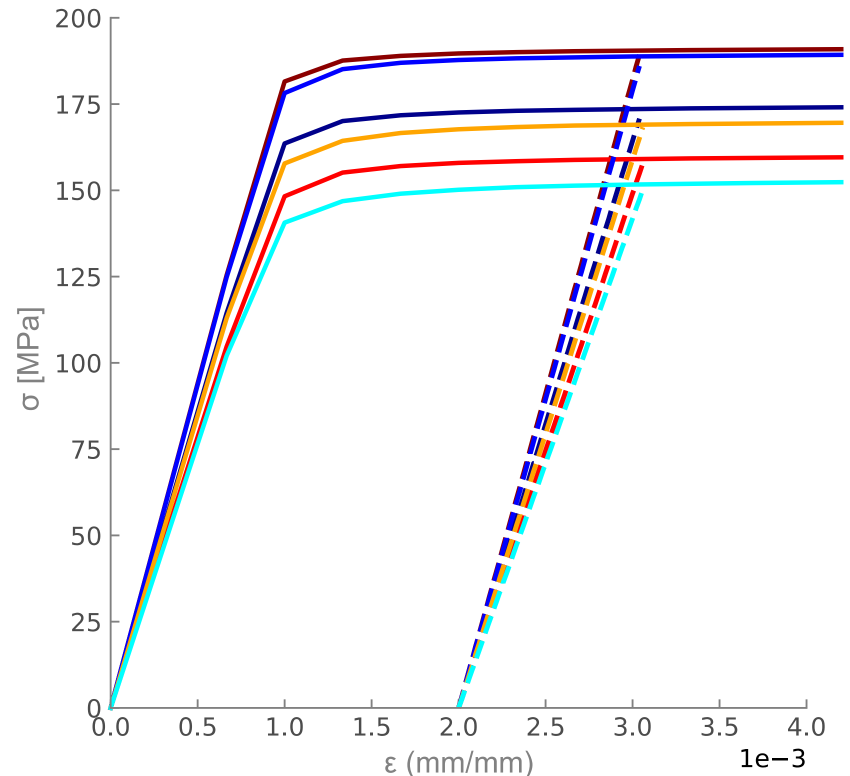
Stress-strain curves show expected behavior as void volume fraction increases

Compression Test Stress-Strain Results

Combined SC and BCC Stress vs. Strain



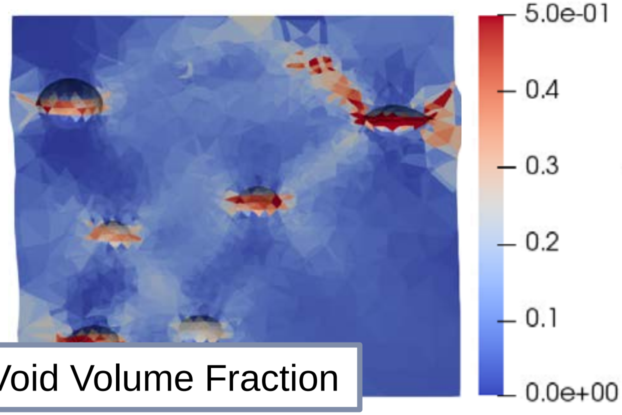
0.2% Offset Method for Yield Stress



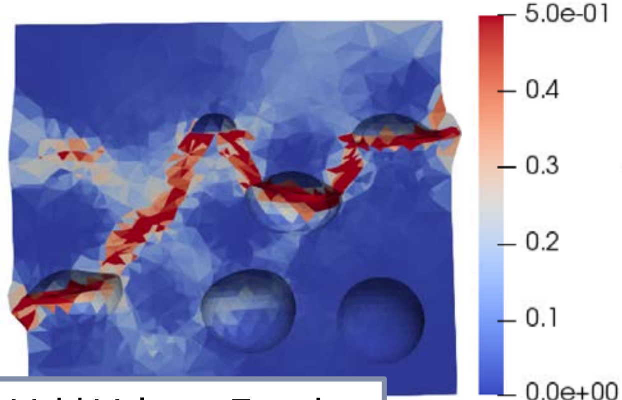
Body centered cubic yield stress shows a "softer" reponse than the corresponding simple cubic structure for a given void volume fraction

Deformation for Random Configuration

Random Void Configuration
Equivalent Plastic Strain

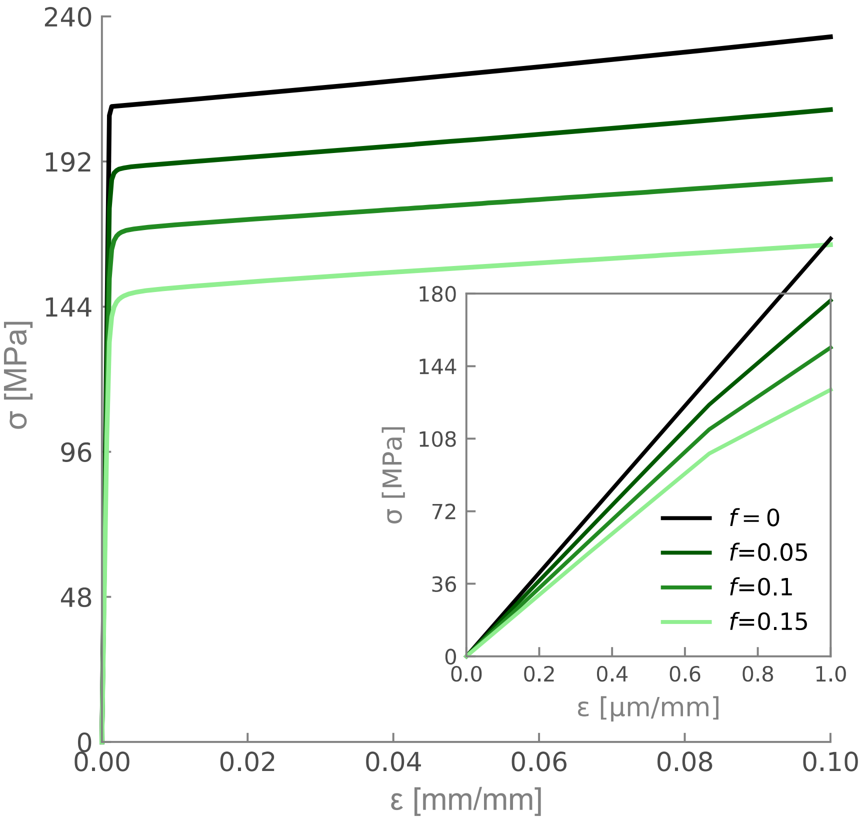


5% Void Volume Fraction



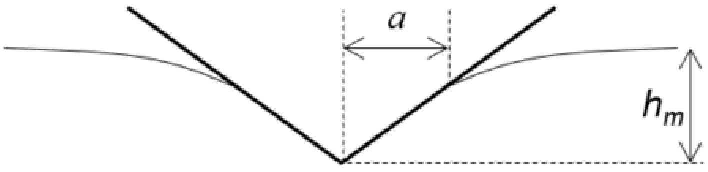
15% Void Volume Fraction

Random Void Configuration
Stress vs. Strain



Properties from Indentation Loading

Hardness



Hardness can be found by dividing the force exerted by the indenter by the projected contact area

Projected contact area $A = \pi a^2$

Hardness: $H = \dfrac{P}{A}$

Elastic Modulus

The effective elastic modulus can be found using the contact stiffness from the unloading section of the load-displacement curve:

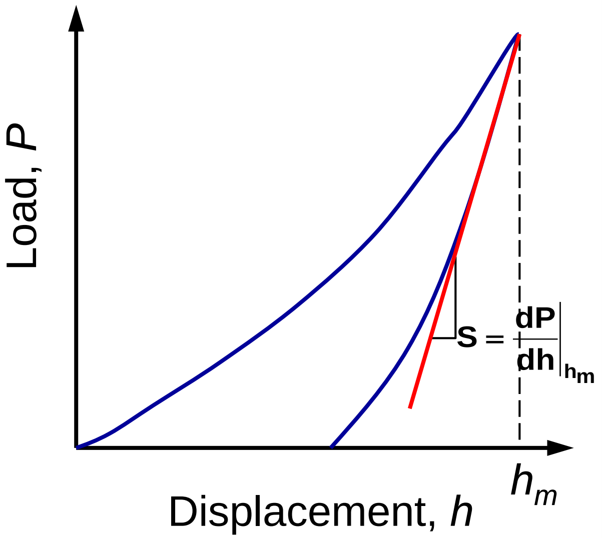
$$E_{eff} = \frac{\sqrt{\pi}}{2\beta}\frac{S}{\sqrt{A}}$$ where $\beta \approx 1$

This can then be used to find the elastic modulus:

$$\frac{1}{E_{eff}} = \frac{1-\nu^2}{E} + \frac{1-\nu_i^2}{E_i}$$

Zero, since indenter is rigid

A Poisson's ratio of 0.3 is assumed.



Deformation from Indentation Tests

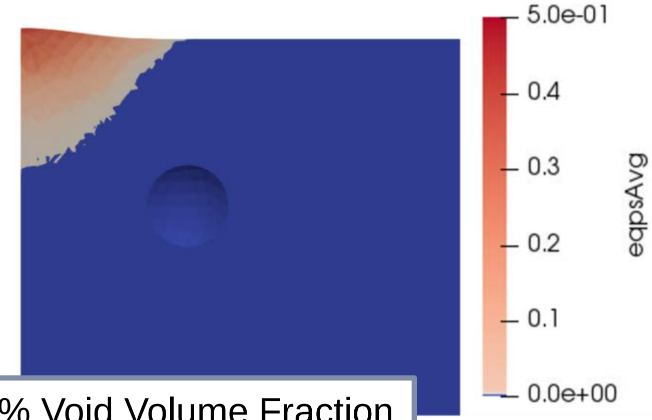
Indentation Direction

Simple Cubic Equivalent Plastic Strain

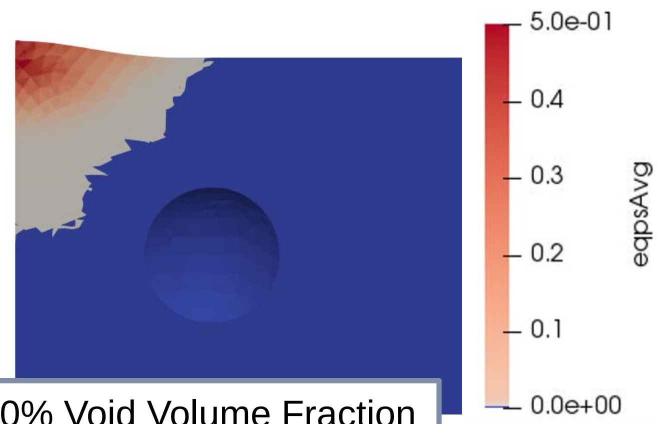
5% Void Volume Fraction

15% Void Volume Fraction

Body Centered Cubic Equivalent Plastic Strain

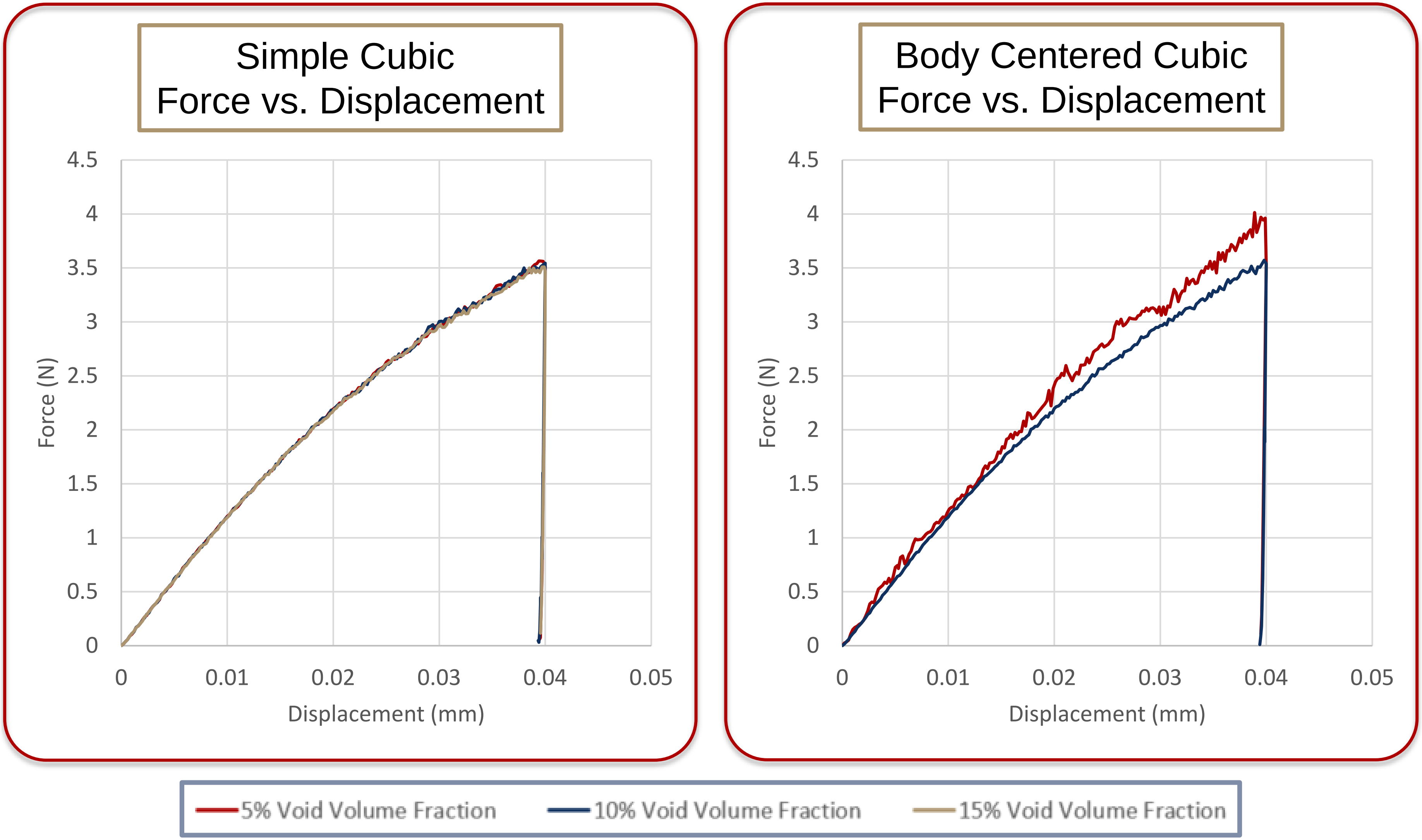


5% Void Volume Fraction



10% Void Volume Fraction

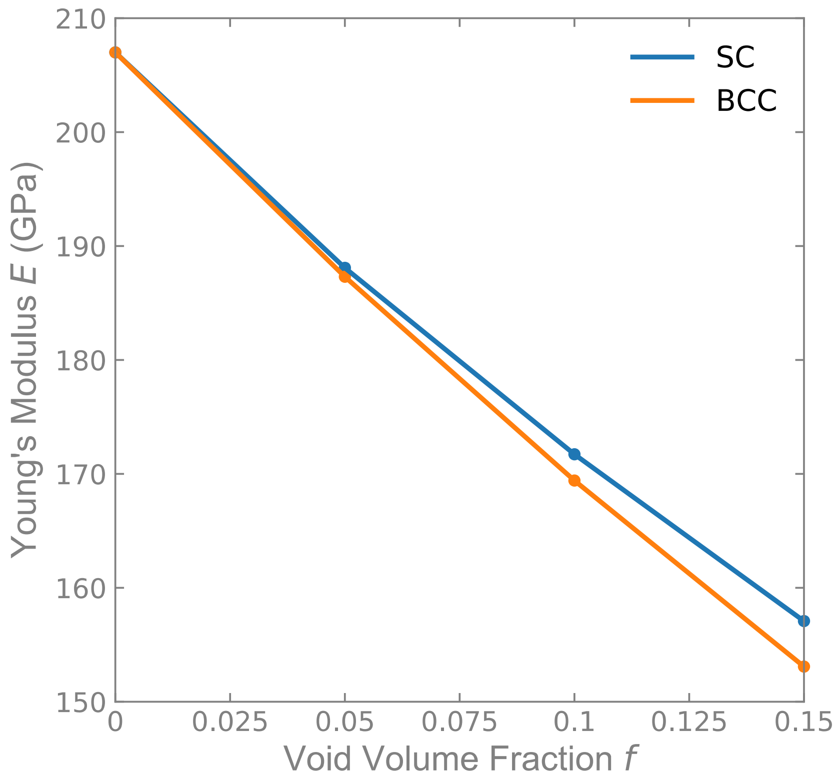
Indentation Load-Displacement Curves



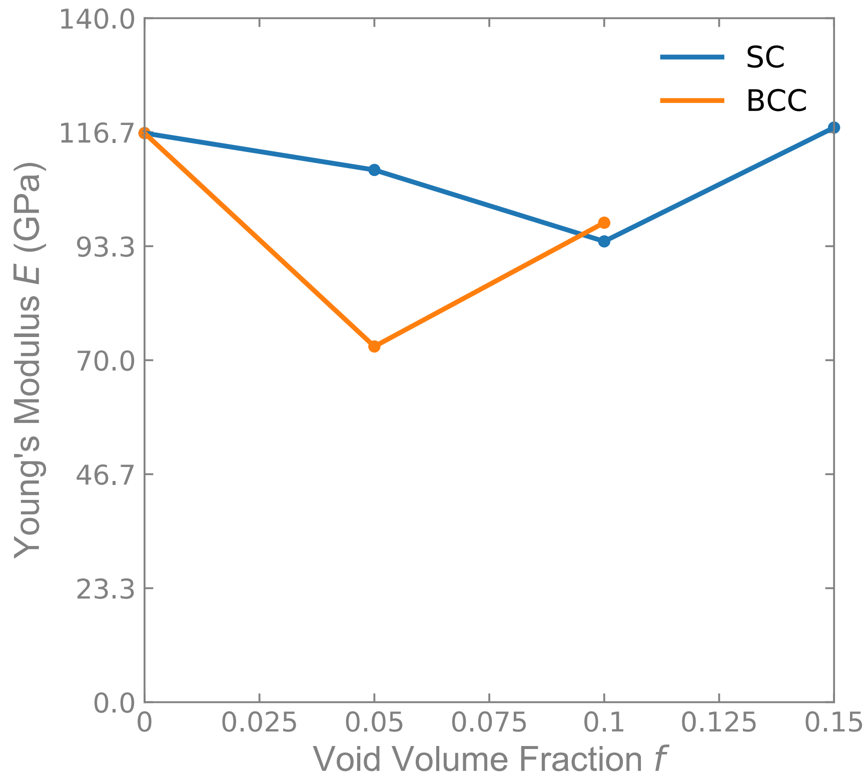
Contact is having trouble converging on some of the BCC simulations

Elastic Modulus Results

Compression Tests
(10% Strain)



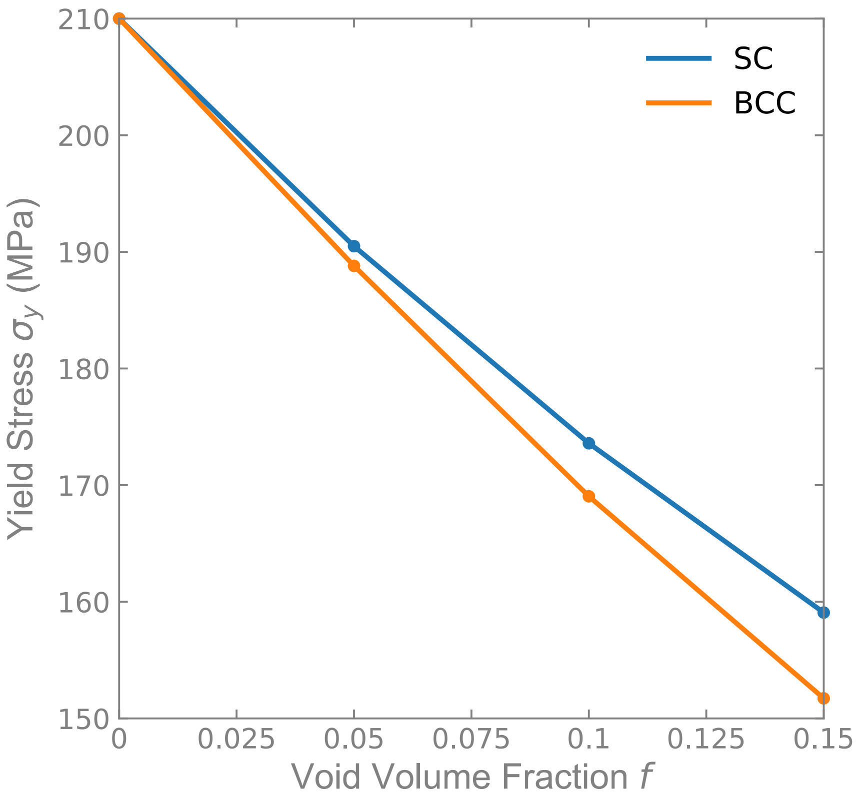
Indentation Tests
(40 μm Displacement)



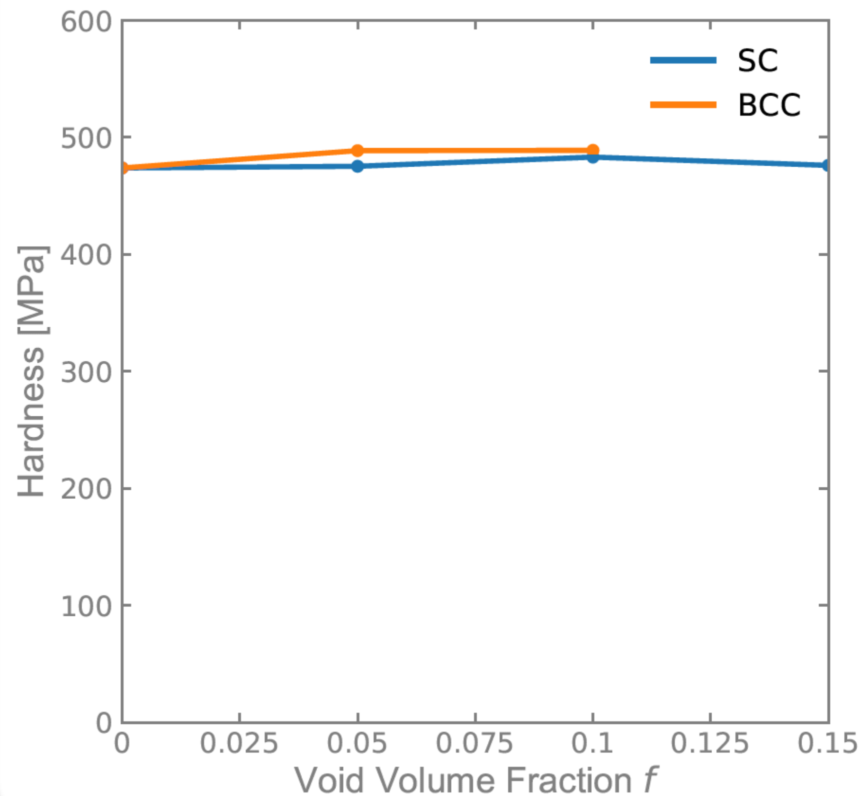
Unsure what is causing the indentation tests to incorrectly report the Elastic Modulus

Yield Stress & Hardness Results

Compression Tests
(10% Strain)



Indentation Tests
(40 μm Displacement)



The voids seem too far away to have a significant impact on the hardness results. Unsure what is causing the hardness to be significantly lower than expected.

Conclusions & Remaining Work

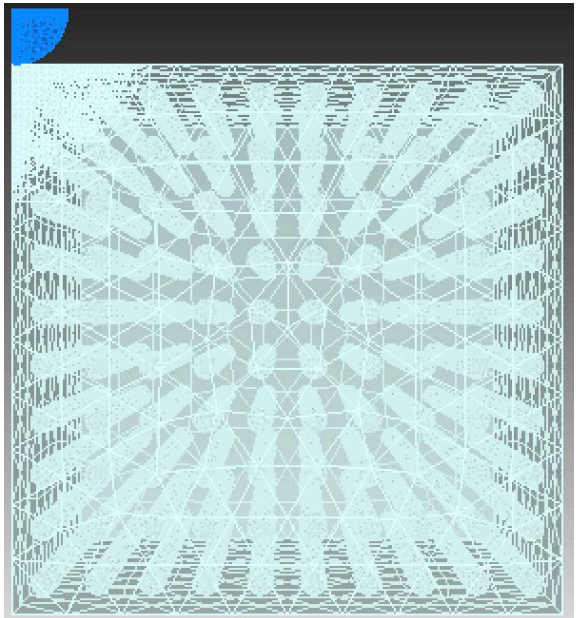
Resolving Ongoing Issues

- Current size and position of voids relative to the indenter is not able to sufficiently capture the effects of porosity.
  - Solution: Create higher-order matrices of voids (such as 10x10x10) and run indentation simulations on these instead.
- Hardness values and elastic moduli obtained from indentation results are too low.
  - Solution: Investigation into the cause of this disparity is ongoing.
- Contact is having trouble converging on some simulations.
  - Solution: Investigation into this issue is ongoing.

Conclusion

Once these issues are resolved, reliable and accurate results can be obtained and compared with the compression tests.

Larger Void Matrix for Future Simulations



Acknowledgements

- This research was conducted at the 2019 Nonlinear Mechanics and Dynamics Research Institute supported by Sandia National Laboratories and hosted by the University of New Mexico.
- Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC., a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA-0003525.
- A special thanks to all of the NOMAD staff, especially Rob Kuether and the mentors on this project.

Questions?