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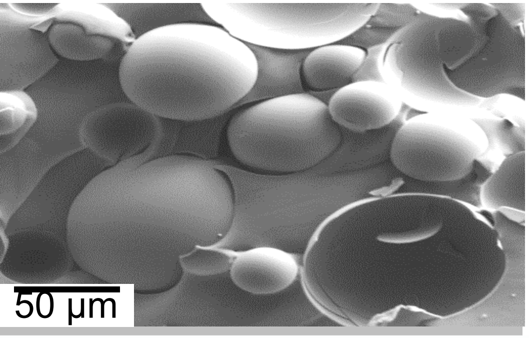

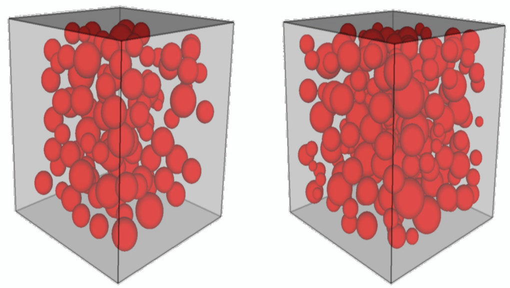

Modeling Damage Evolution in Glass Microballoon Filled Syntactic Foams Under Large-Strain Confined and Unconfined Compression

Judith Brown, Kevin Long, Jay Carroll, Helena Jin

ASME International Mechanical Engineering Congress & Exposition

Nov 8, 2017

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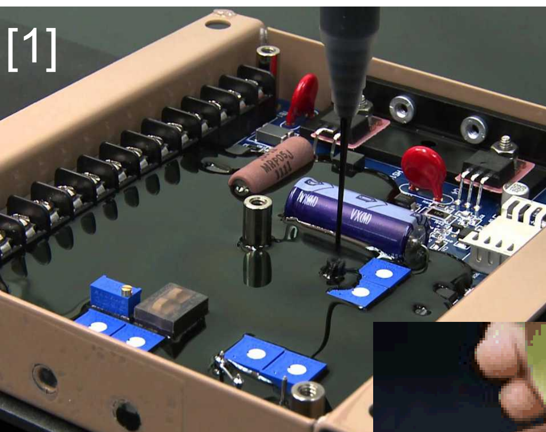
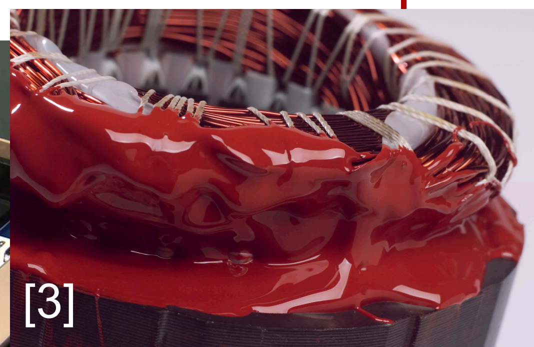
Syntactic Foams for Potting and Encapsulation

Sandia National Laboratories

Potting and Encapsulation

- Vibration dampening
- Electrical & environmental insulation

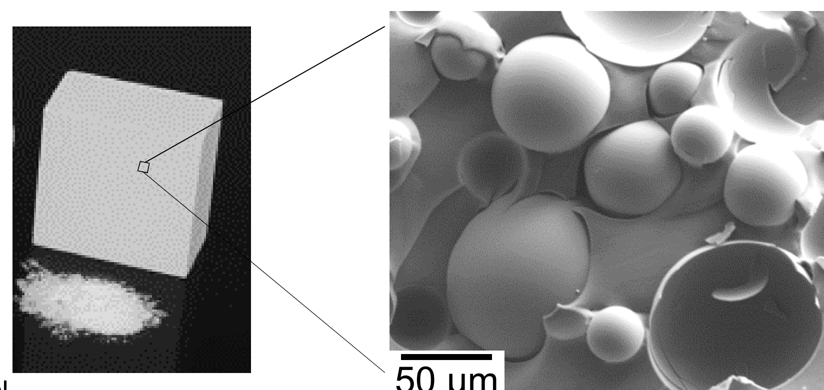




Sylgard/GMB Syntactic Foam

Sylgard® 184 (PDMS) matrix with embedded Glass Microballoons (GMBs) (3M® A16/500)

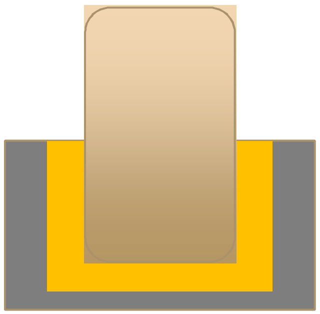
- Crushable foam
- Increased stiffness
- Low Density
- Reduced thermal expansion



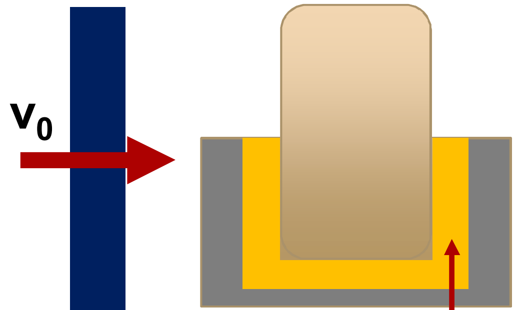
[1] http://www.ecopoxy.com/epoxy-casting-system-for-electronics-encapsulation/
[2] https://www.masterbond.com/tds/ep17ht-100
[3] http://www.directindustry.com/prod/star-technology/product-114815-1369531.html

Need to Develop a Constitutive Model of Sylgard GMB

Encapsulated Component



Environmental Insult



Component Testing ($$$)

FEA Analysis ($)

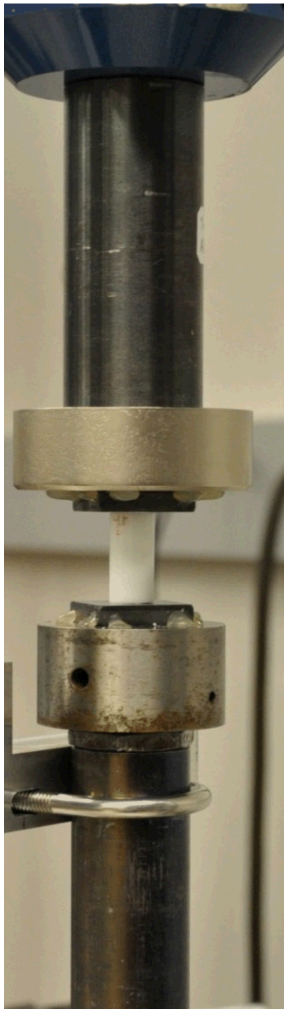
Macroscale Constitutive Model for Elastomeric Syntactic Foams

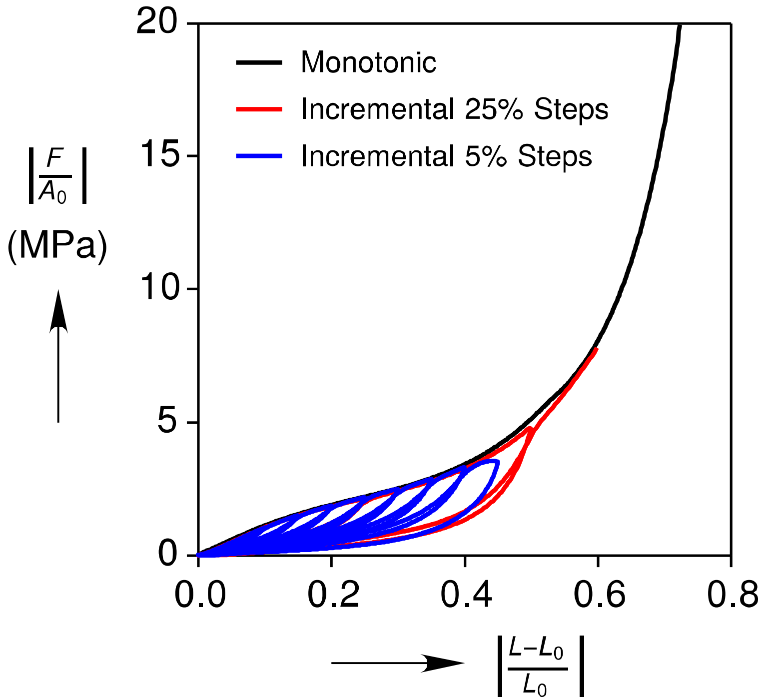
Model Requirements

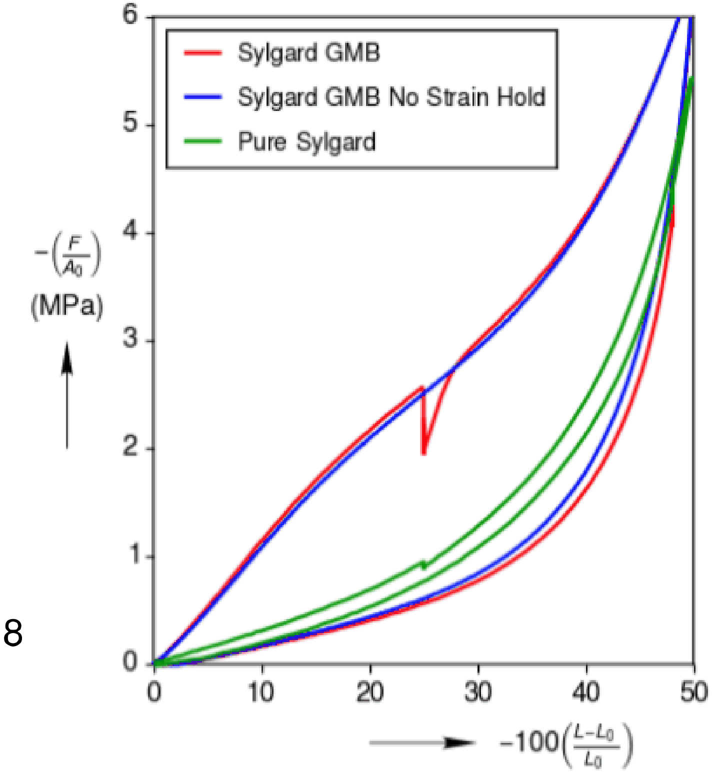
- Large Deformation
- Rate, Temperature, and Time Dependence

A High Fidelity Constitutive Equation Requires A Detailed Understanding Of Damage in the Microstructure and a Representation for the Effects at the Macroscale

Macroscale Behavior: Cyclic Uniaxial Compression



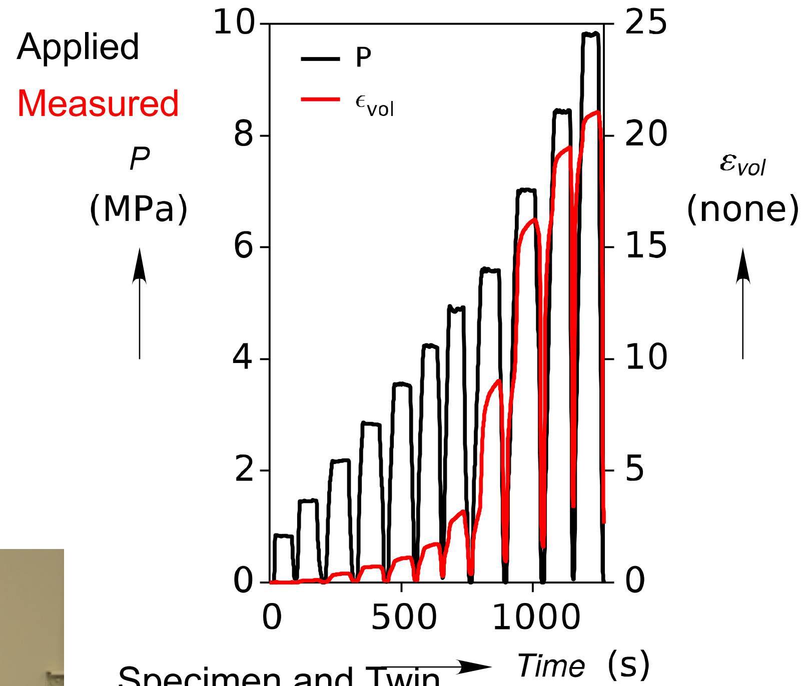


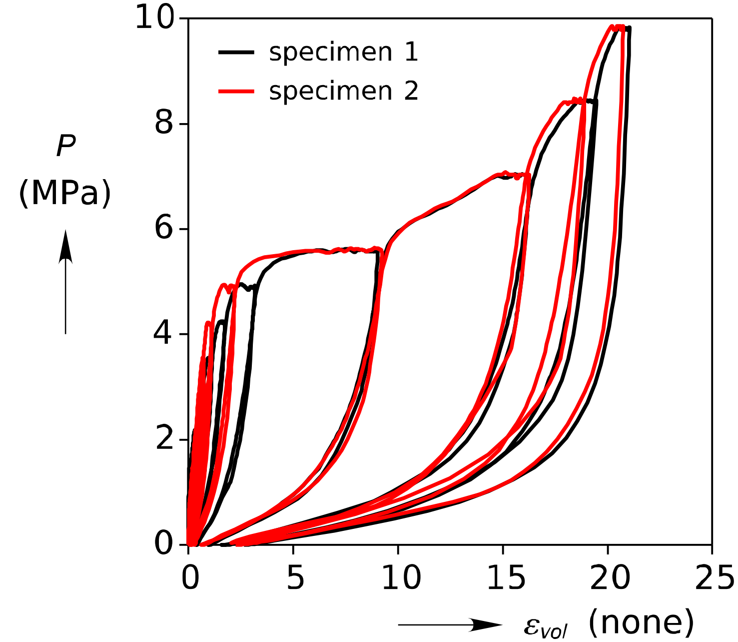


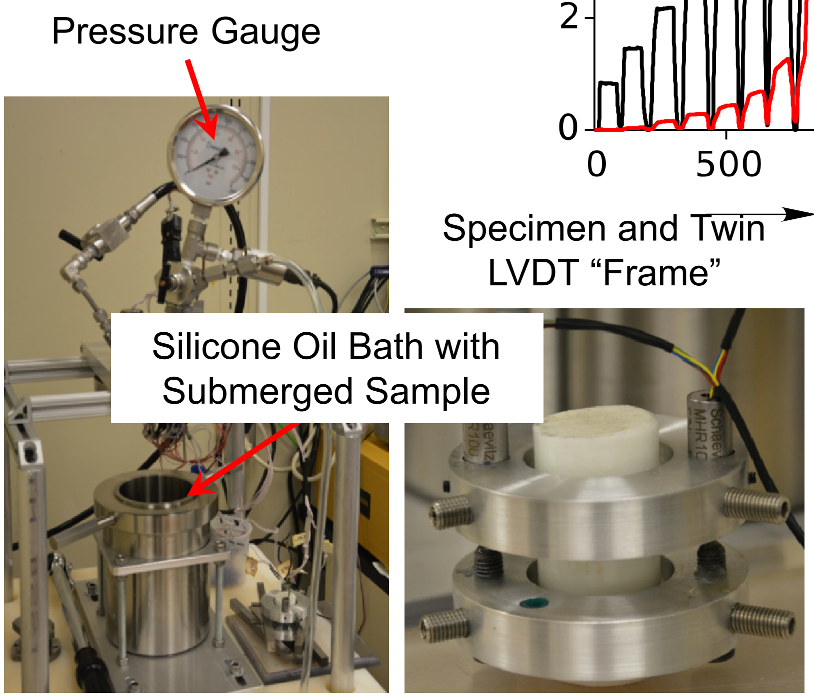
"Mullins Effect"—Like Hysteresis Indicated Damage

Time Dependent Stress-Relaxation

Macroscale Behavior: Hydrostatic Pressurization



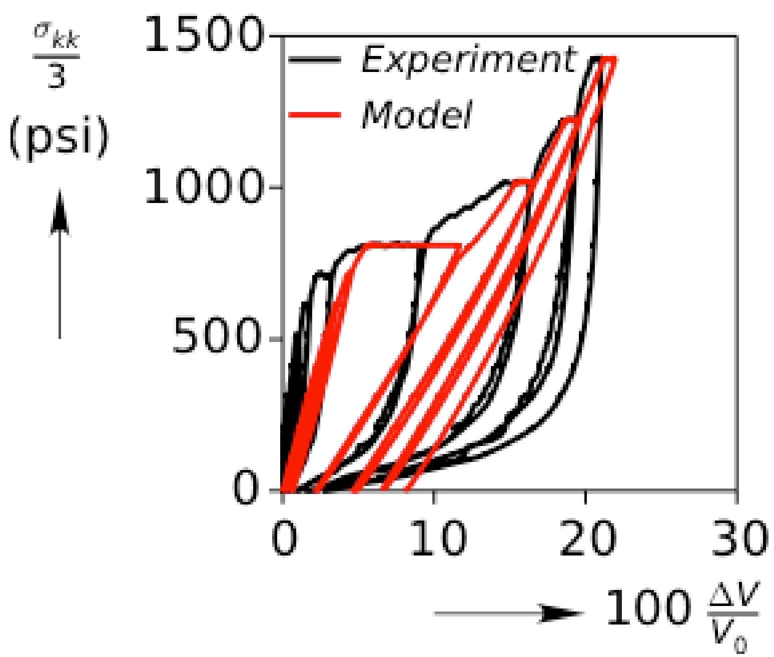


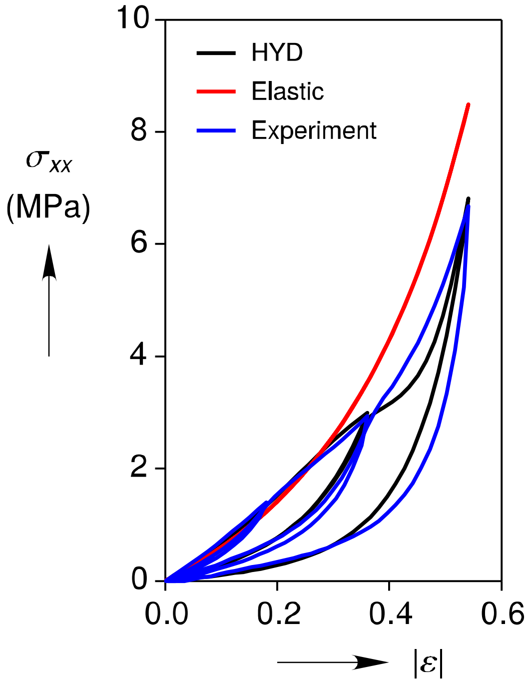


- <u>More</u> damage than compression or torsion
- Threshold pressure prior to damage
- Time dependent damage
- Fully damaged response is a foam response

Simple Macroscale Constitutive Modeling Is Unsuccessful

- Hyperelastic Yeoh Model with Isotropic-Kachanov Style Damage
- Quasi-Linear Viscoelasticity Does Not Help



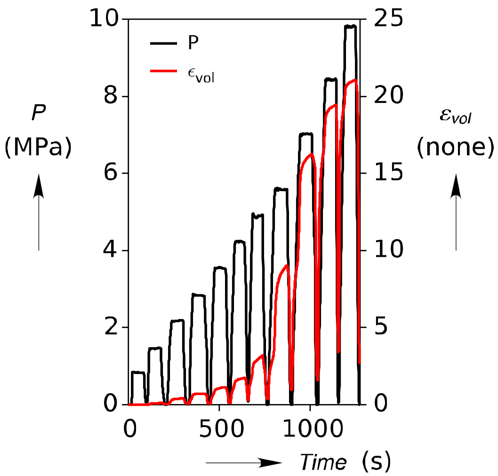


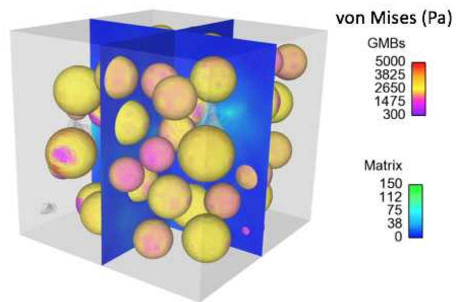
HYD model does not fit the hydrostatic pressurization data well

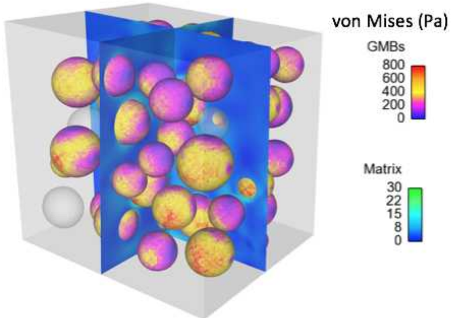
Model reasonably fits the uniaxial compression data (Mullins Effect)

Simple phenomenological efforts fail to capture bulk behavior—We Need a Detailed Understanding of the Damage Behavior

Project Structure and Contributors

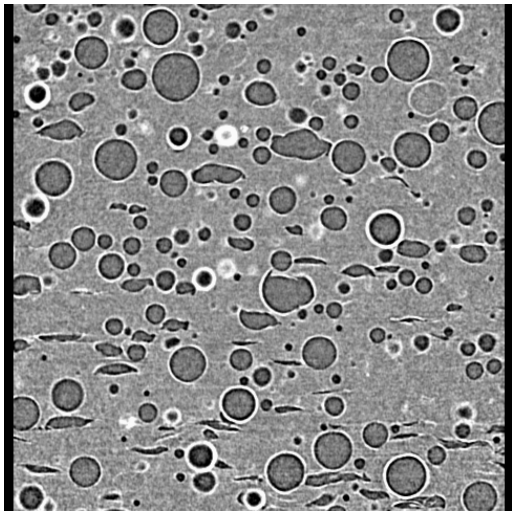






Elastomeric Syntactic Foam Mechanics

- **Modeling**
  - Kevin Long (PI): Macroscale Constitutive Modeling
  - Judith Brown: Micromechanics FEA
  - Dan Bolinteneau: Data Sciences
- **Experiments**
  - Helena Jin: In-Situ X-Ray CT
  - Jay Carroll: Macroscale Testing
  - Rong Long (CU Boulder): Micromechanics, Failure, Torsion

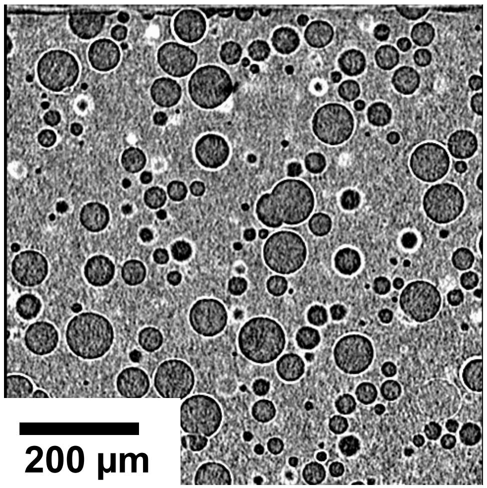


Research Objectives

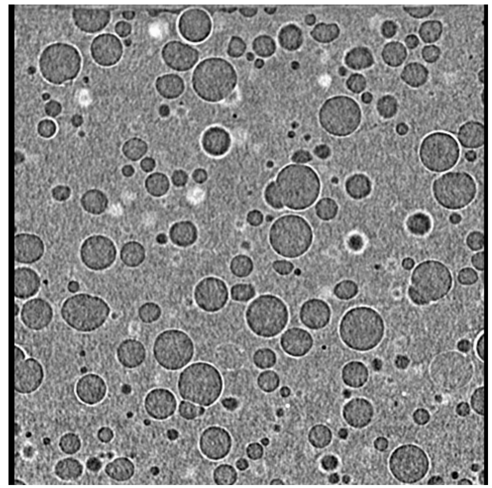
- Global Project Goal: Use knowledge gained to inform physics inspired engineering length scale constitutive models
- Presented in this talk:
  - Understand damage mechanisms in Sylgard/GMB
  - Study microstructural behavior of Polymeric Syntactic Foams through numerical meso-scale models

High Magnification X-ray CT, in-situ Compression

0% Strain

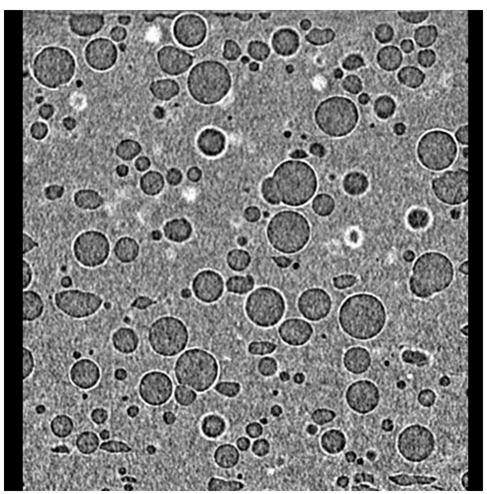


10% Strain

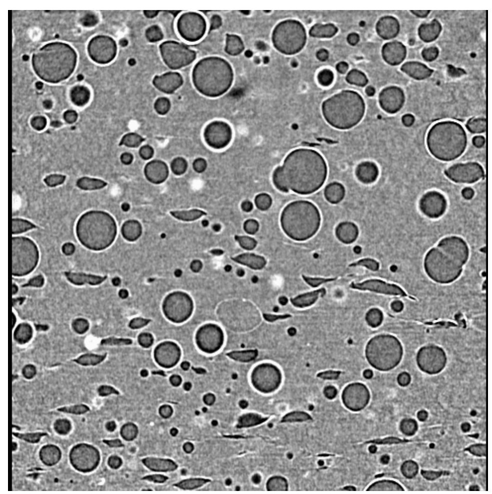


- Up to 10% strain, very few broken GMBs
- At 40% strain, some GMBs still intact!!

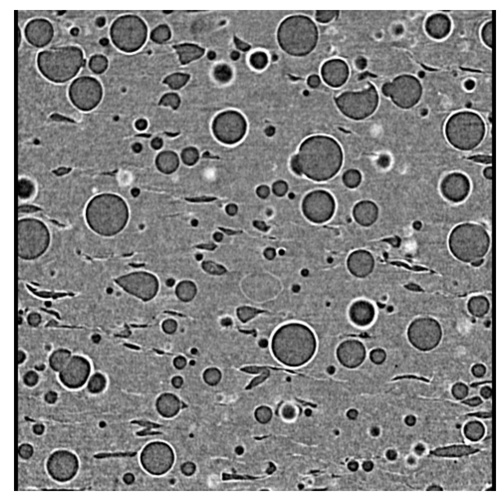
20% Strain



30% Strain



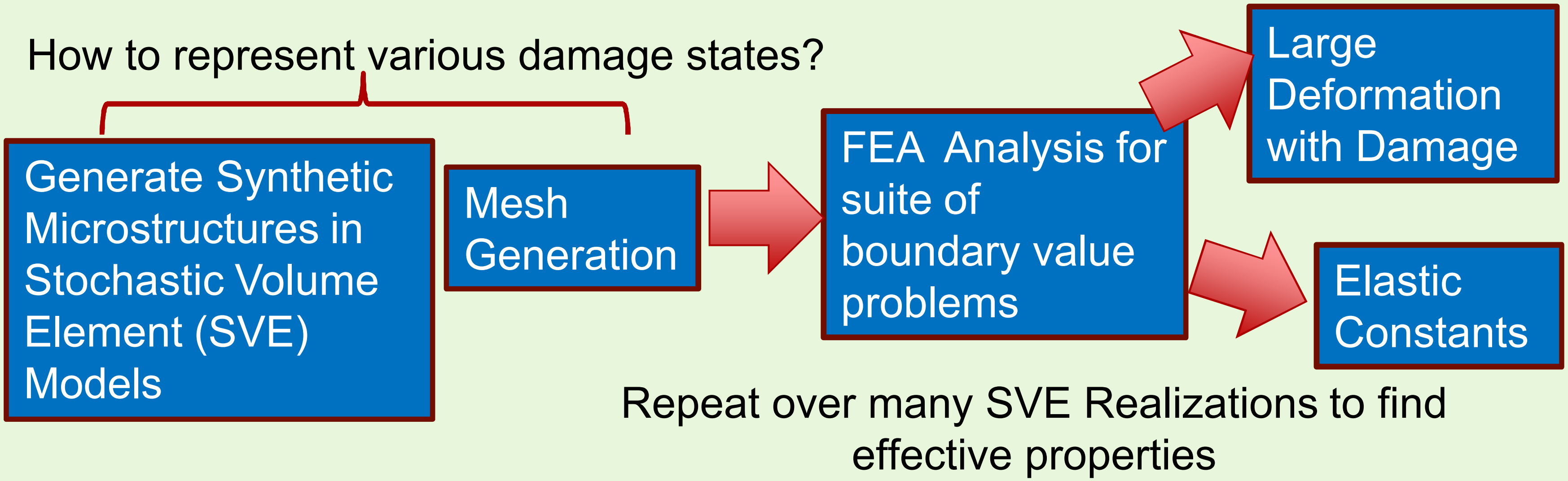
40% Strain



Meso-scale Modeling Approach

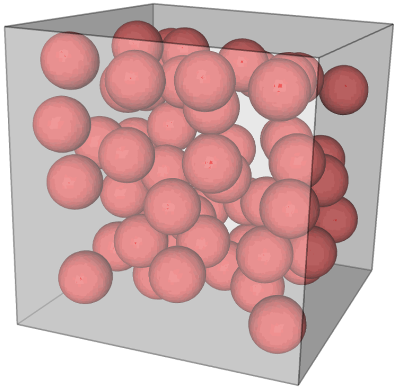
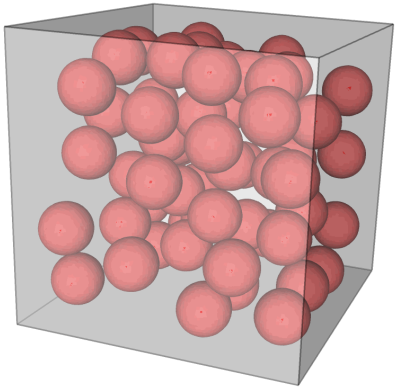
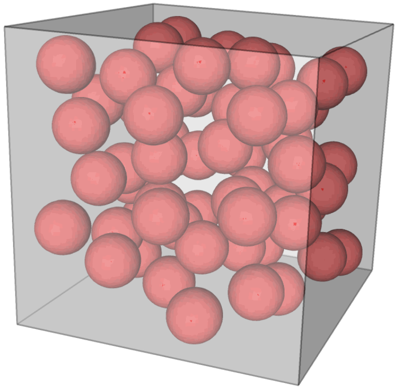
- How does GMB breakage affect the macroscale behavior?

Finite Element Studies

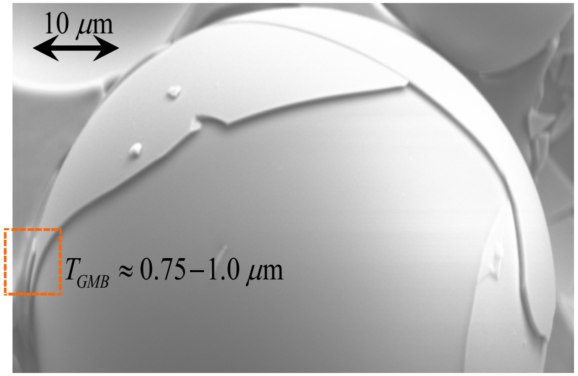


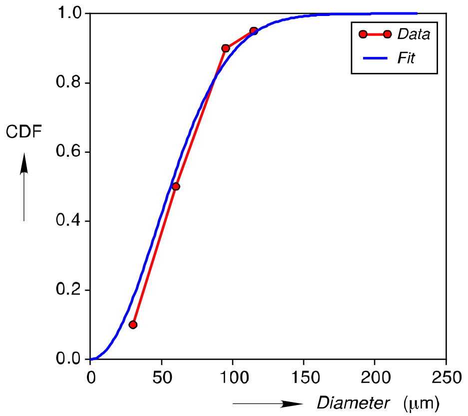
Synthetic Microstructure Generation

- Generate Stochastic Volume Element (SVE) models of Sylgard/GMB microstructure

Estimate Characteristic GMB Thickness: 1 µm





Manufacturer's (3M®) Cumulative Distribution Data for A16/500 GMB

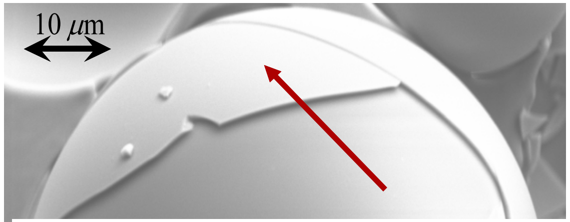
Average GMB Diameter: 60 µm

Failure Model for GMBs

Borosilicate Glass Wall Material:

- Elastic Properties[1]:
  E_{glass} = 61 GPa, ν_{glass}=0.19

- Characteristic wall thickness
  - T_{wall} = 1 μm



Smooth GMB surface does not appear to have many flaws

Estimate flaw size ~ 0.2μm

Failure Criteria Estimate:

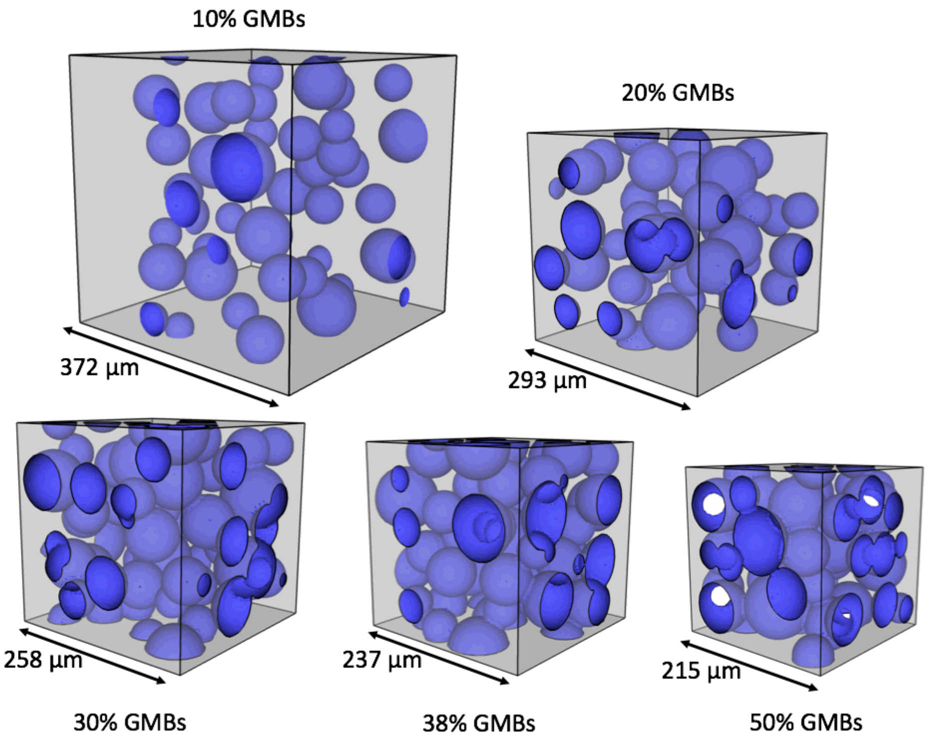
- Fail individual shell elements (element death) when max principal stress = failure stress

  - LEFM approach to estimate failure stress

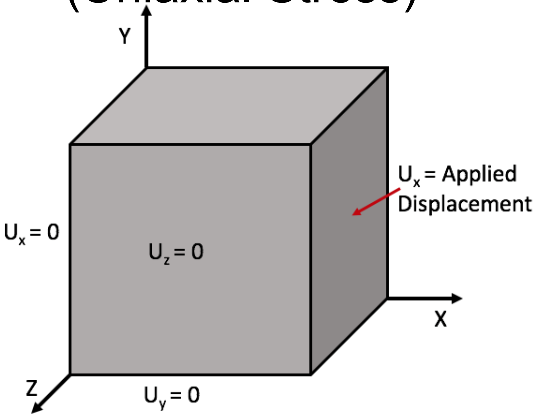
1.X. Nie and W.W. Chen. *Journal of the American Ceramic Society*, 90(8):2556–2562, 2007

Boundary Value Problems

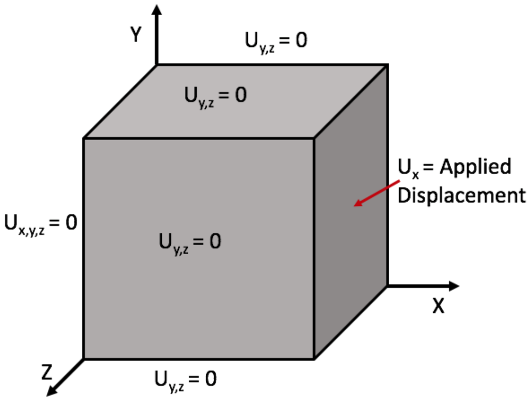
Five different GMB Volume Fractions



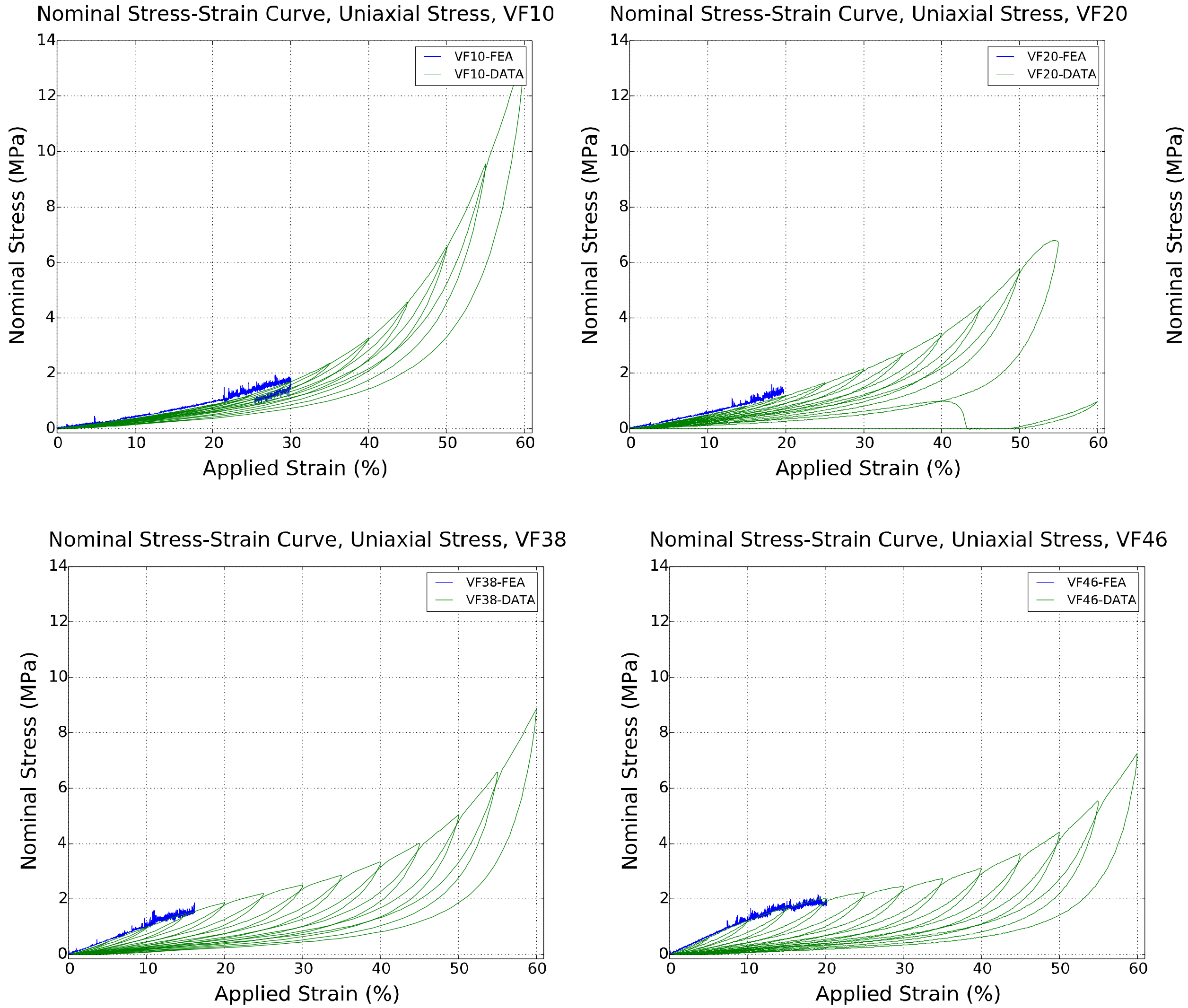
Unconfined Compression (Uniaxial Stress)



Confined Compression (Uniaxial Strain)

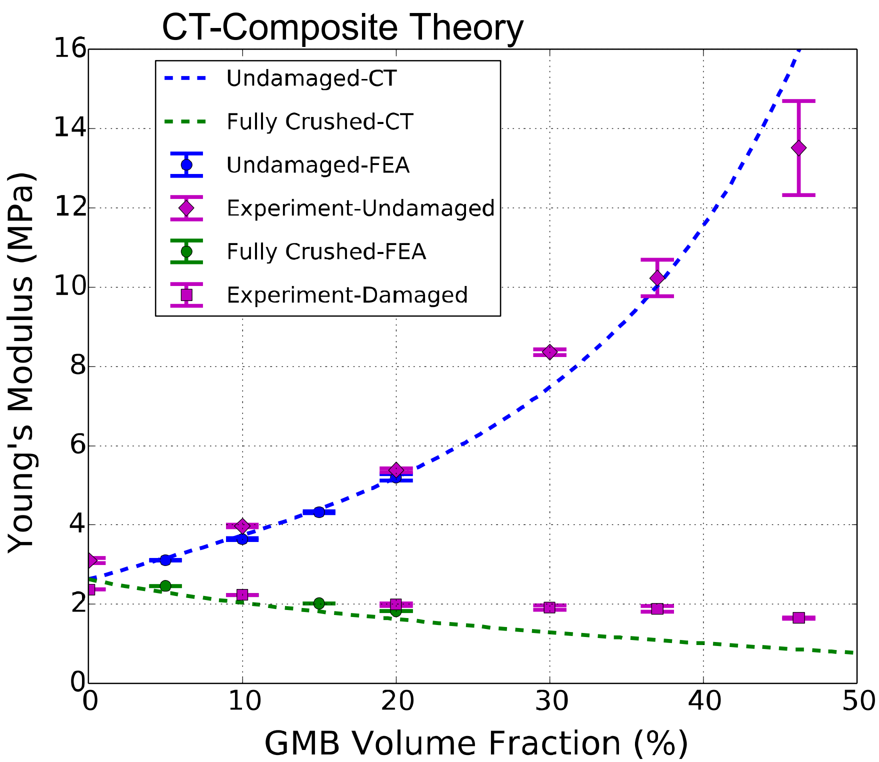


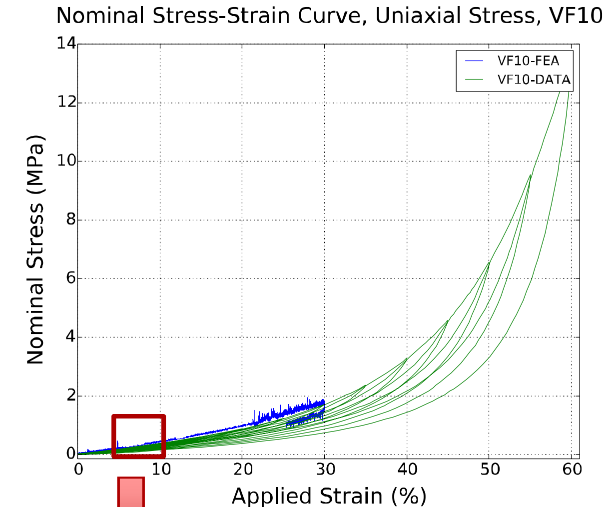
Uniaxial Compression Behavior

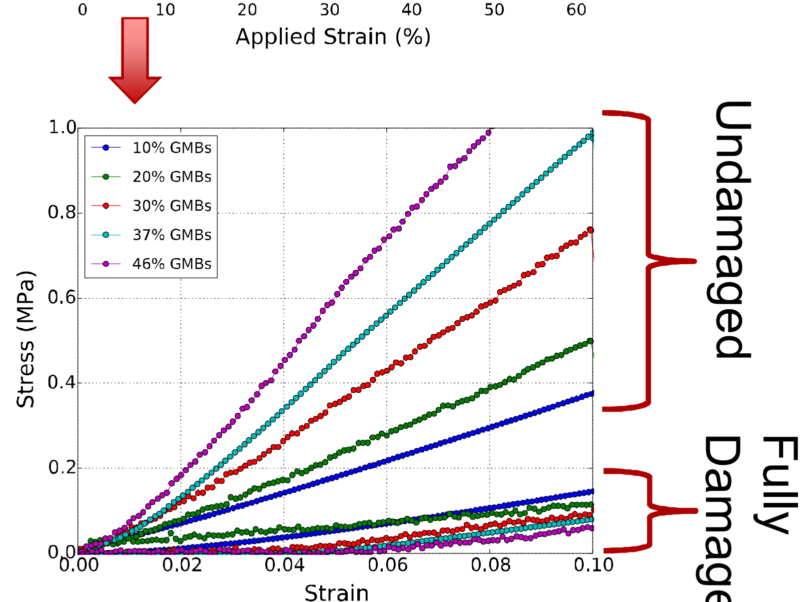


Transition from concave-up stress-strain curve to plateau-like behavior with increasing GMB volume fraction

Effect of Volume Fraction on Young's Modulus



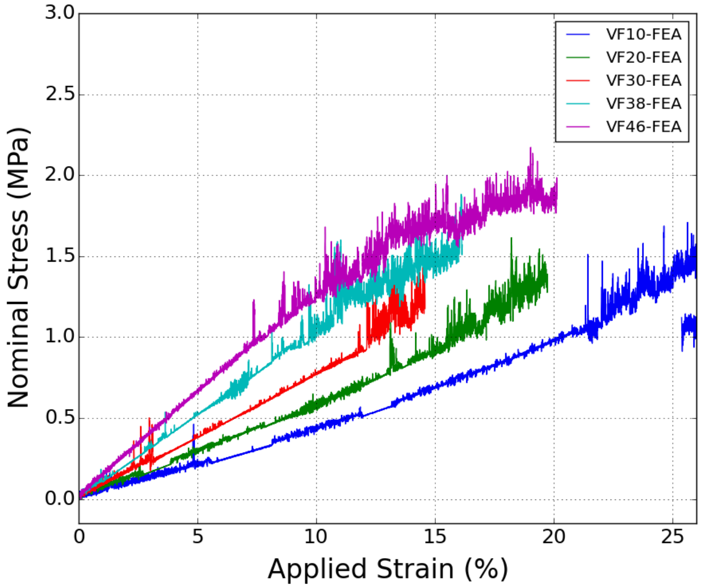


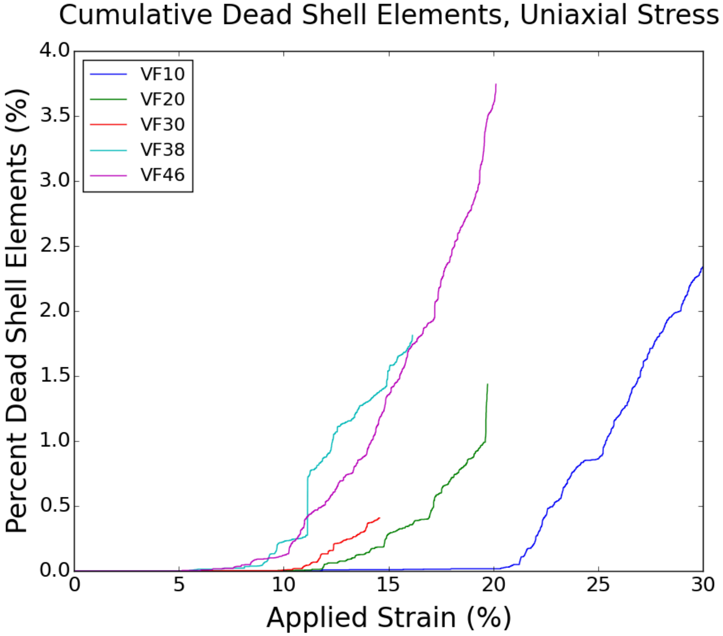


Increasing GMB Volume Fraction also increases the initial composite Young's Modulus

--Well predicted by FEA and composite theory

Effect of Volume Fraction on GMB Breakage





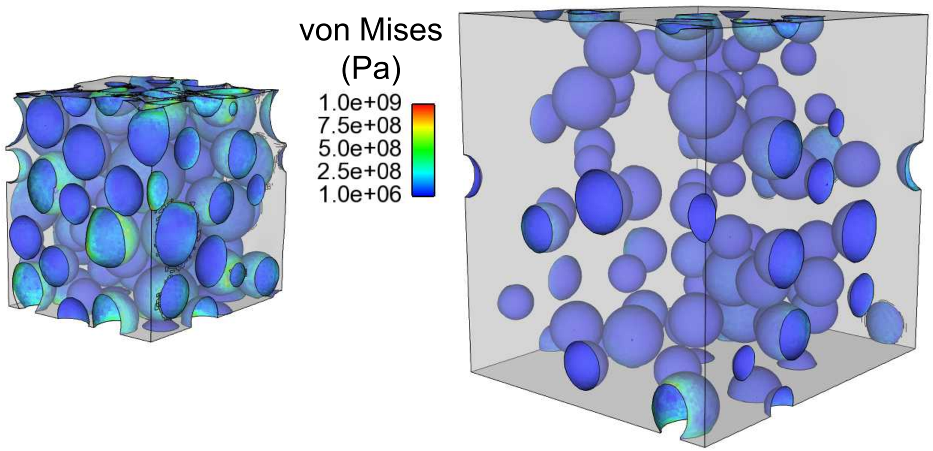
Volume Fraction	Strain at Initial GMB Breakage
Pure Sylgard	N/A
10% GMBs	11.8%
20% GMBs	9.7%
30% GMBs	6.4%
38% GMBs	5.4%
46% GMBs	5.1%

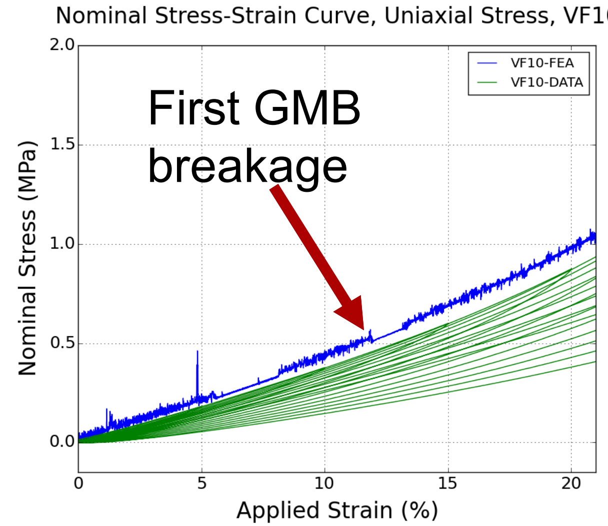
Microstructure Stresses

46% GMBs

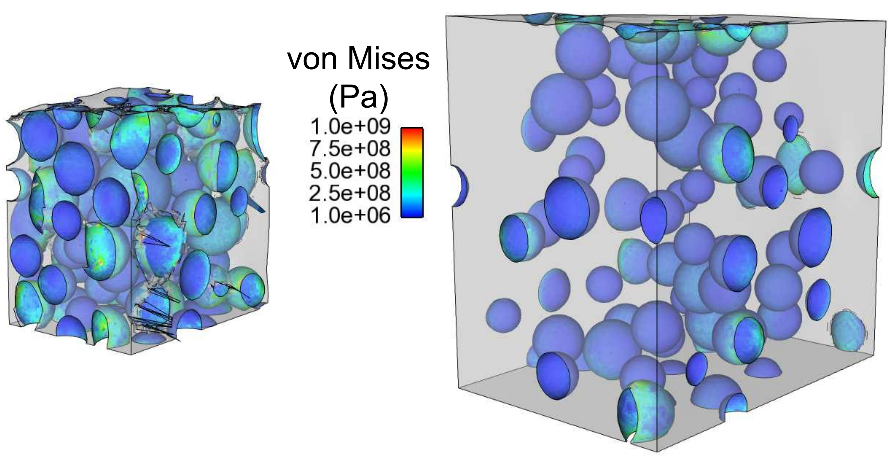
10% GMBs

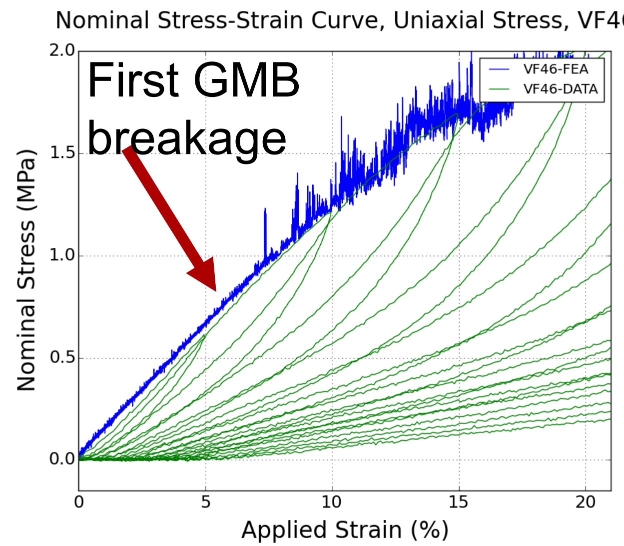
10% strain





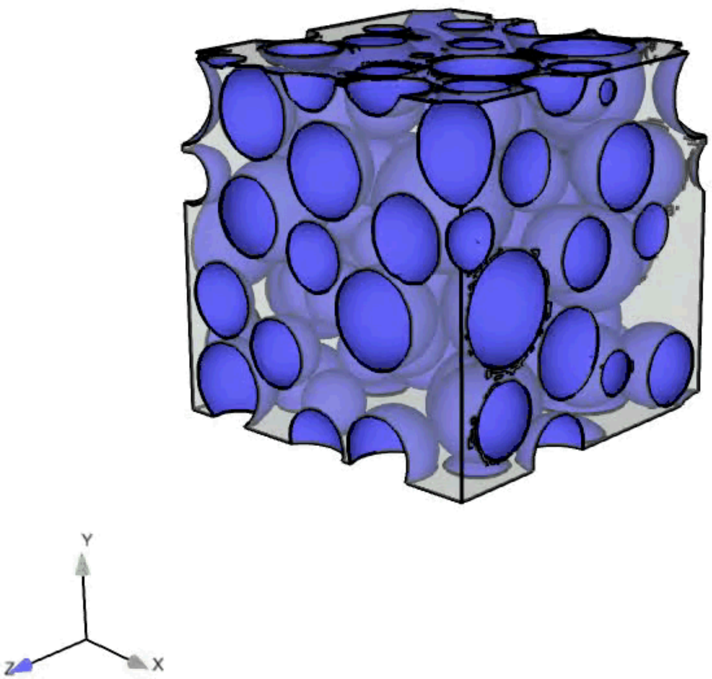
20% strain



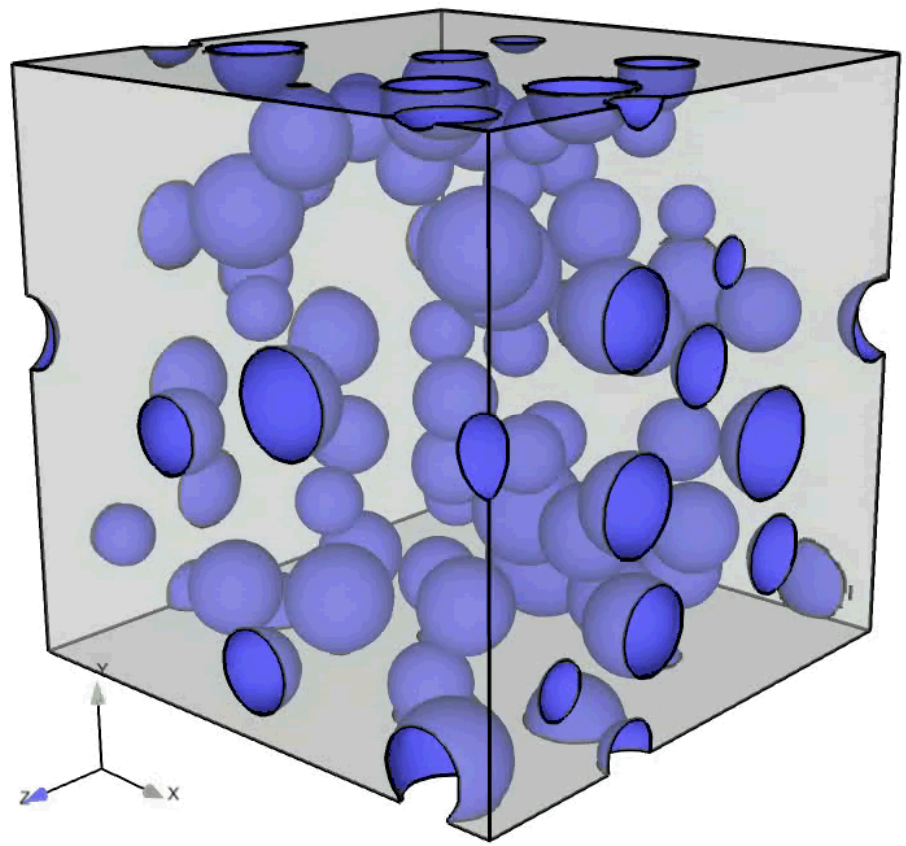


Uniaxial Compression up to 20% Strain

46% GMB
Volume Fraction

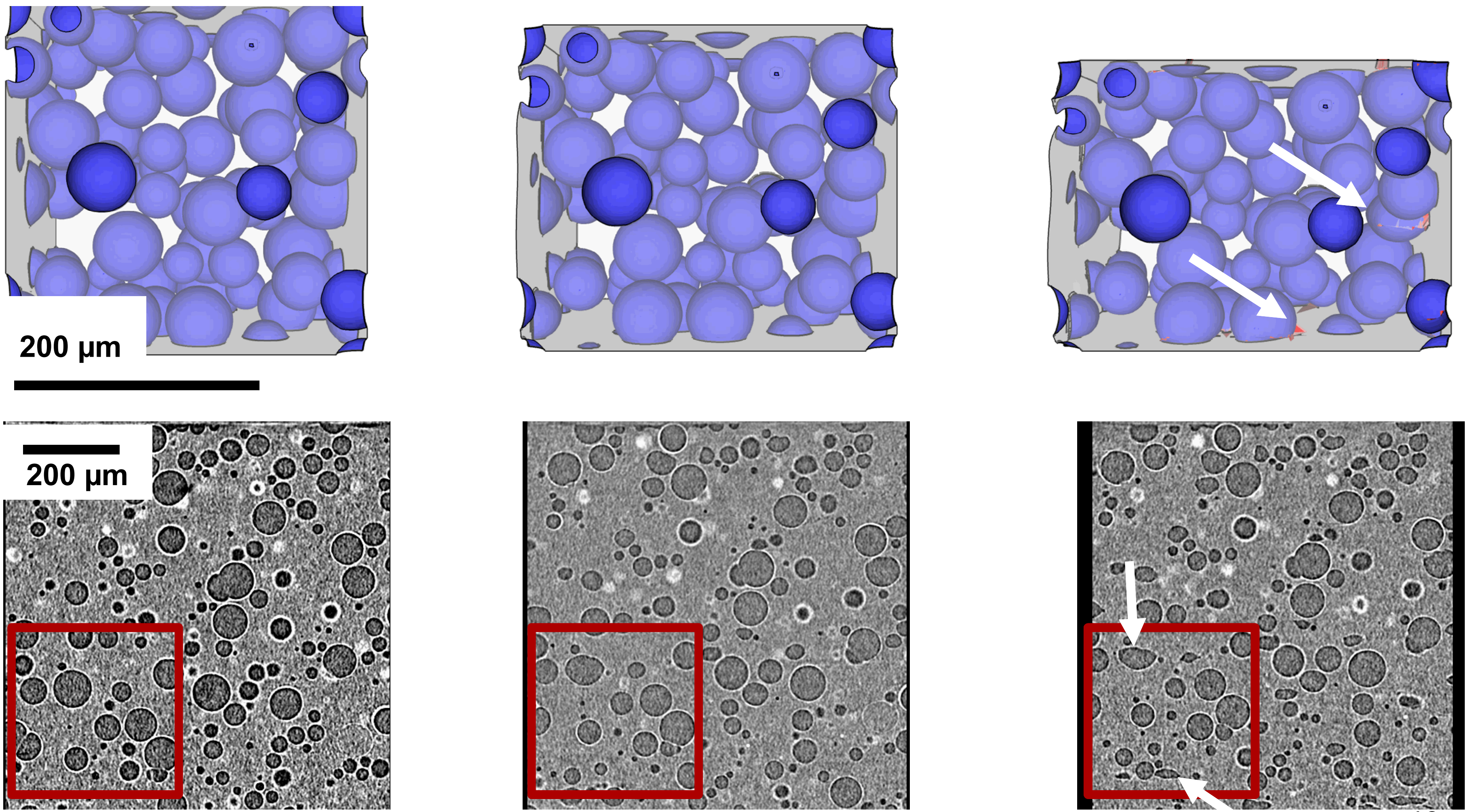


10% GMB
Volume Fraction

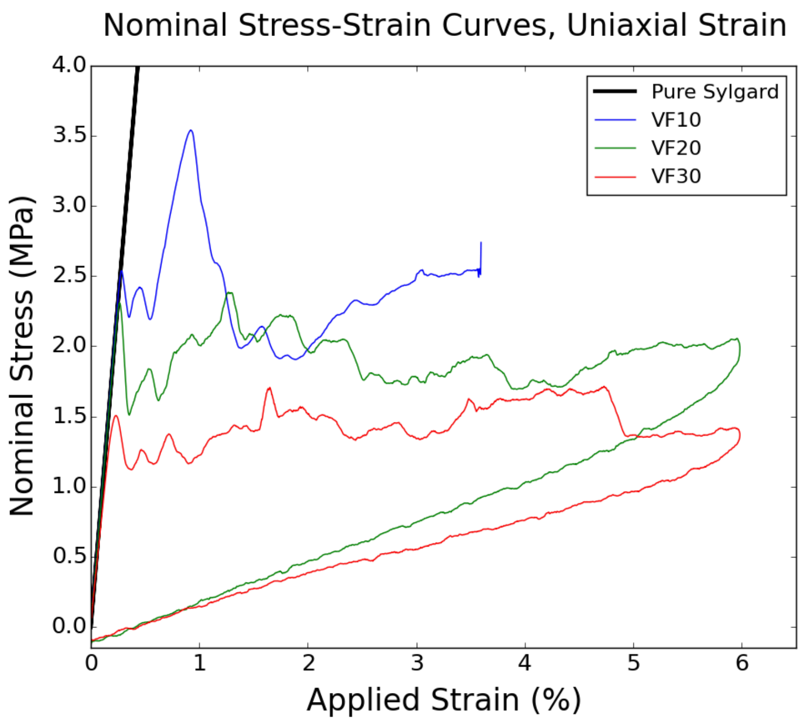


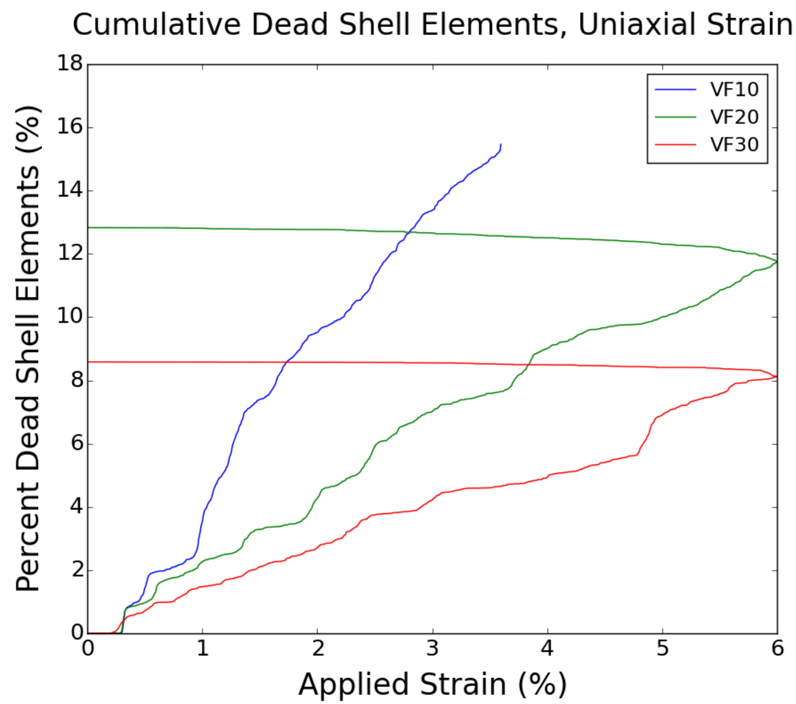
Comparison with X-Ray CT, 20-25% GMBs

Undeformed | 10% Strain | 20% Strain



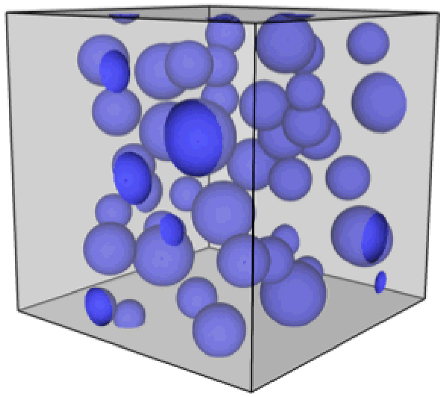
Finite Deformation Uniaxial Strain



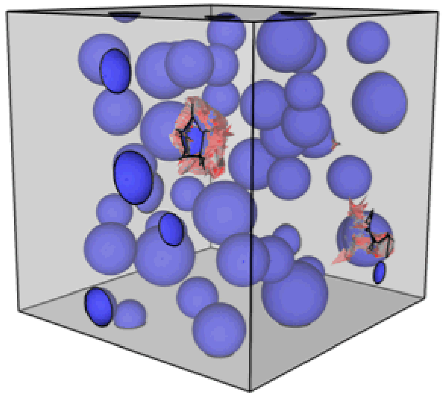


Volume Fraction	Initial Loading Slope (MPa)	Unload Slope (MPa)	Plateau Stress (MPa)	Strain at Initial GMB Breakage
Pure Sylgard	905.7	905.7	--	N/A
10% GMBs	933.5	Simulation failed before unload	~2.4	0.294%
20% GMBs	912.4	25.5	~1.9	0.283%
30% GMBs	770.3	17.5	~1.4	0.202%

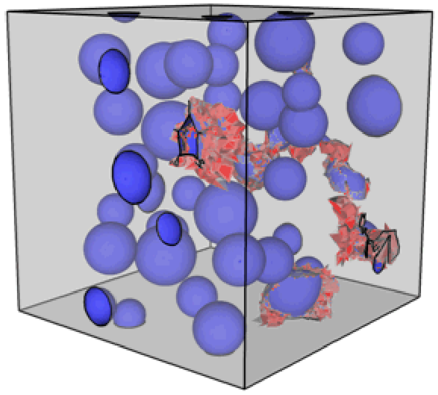
Finite Deformation Uniaxial Strain, 10% GMBs



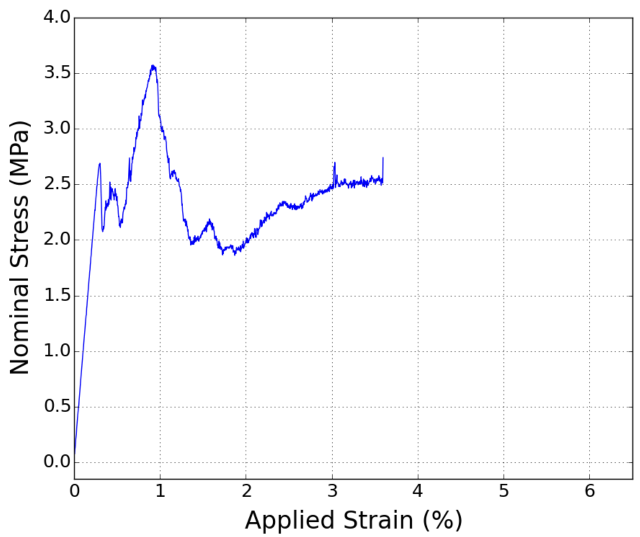
0 % Applied Strain

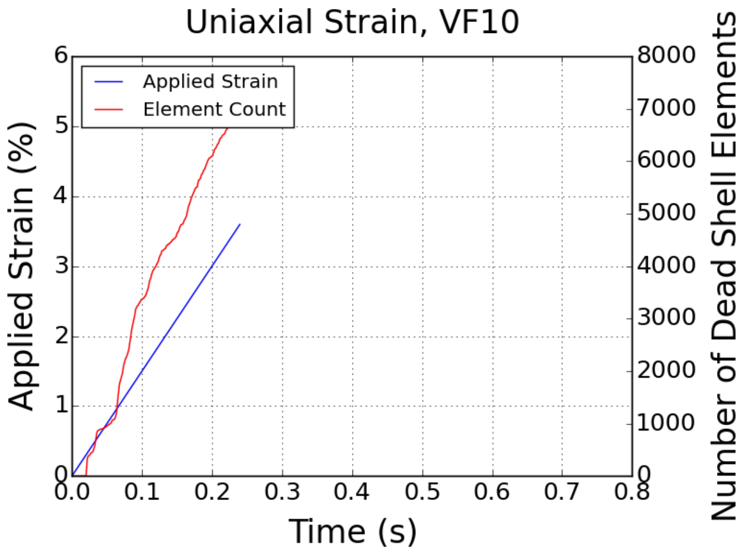


1 % Applied Strain



3 % Applied Strain





Conclusions

- GMB breakage is the primary damage mechanism
  - However, some GMBs remain intact!

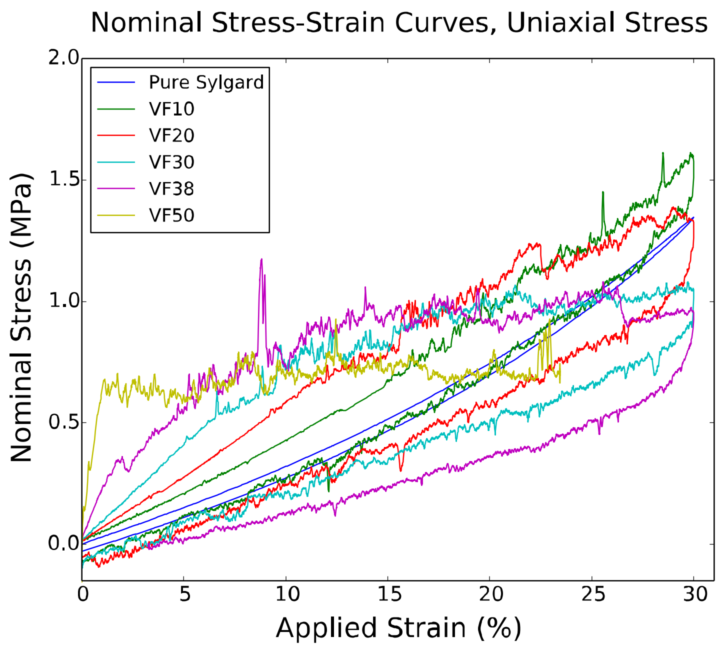
- Higher volume fractions of GMBs provide greater initial stiffness, but also begin breaking at smaller strains

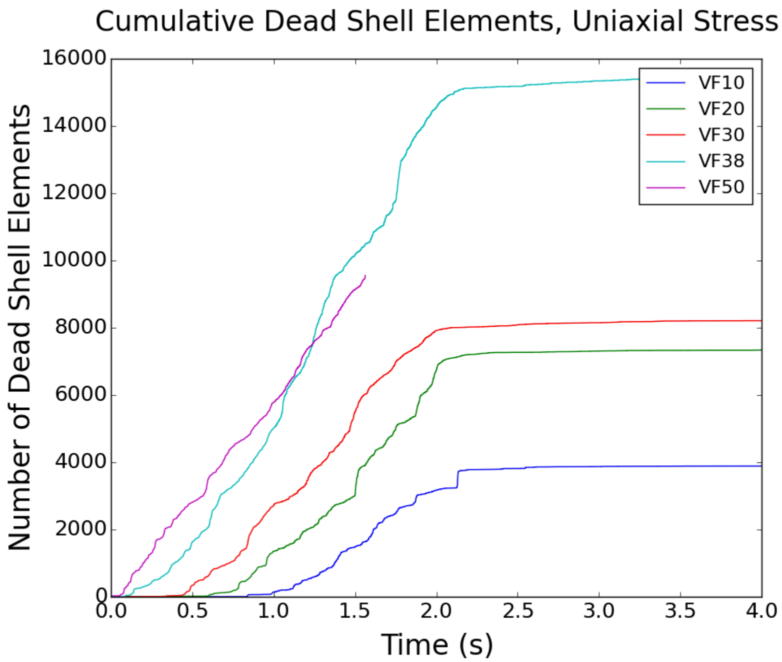
- Notable Difference in GMB breakage mechanism for Confined vs. Unconfined Compression

Thank You!

QUESTIONS?

Finite Deformation Uniaxial Stress

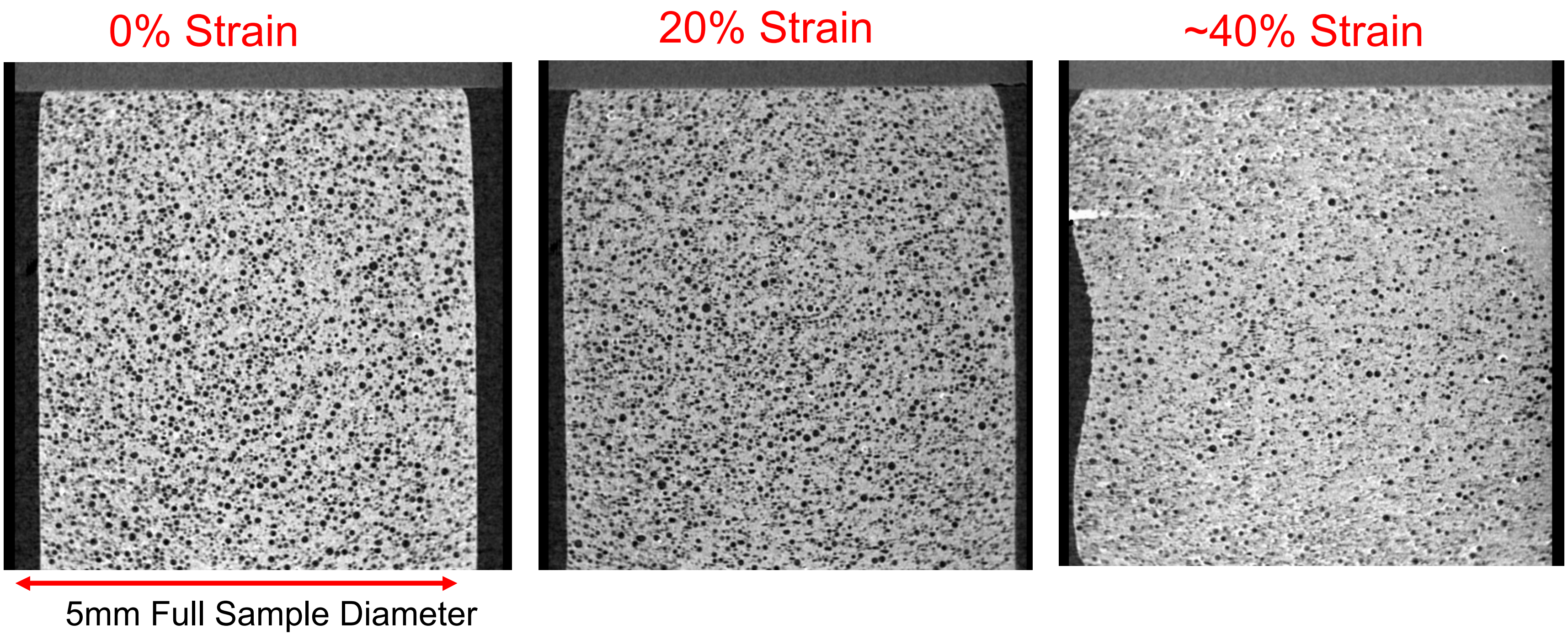




Volume Fraction	Initial Loading Slope (MPa)	Unload Slope (MPa)	Plateau Stress (MPa)	Strain at Initial GMB Breakage
Pure Sylgard	3.21	3.24	--	N/A
10% GMBs	7.21	5.1	--	12.49%
20% GMBs	8.92	3.3	--	4.65%
30% GMBs	11.25	3.0	~1.0	2.66%
38% GMBs	25.53	2.5	~0.9	1.23%
50% GMBs	69.15	Simulation Failed before unload	~0.65	2.5e-7%

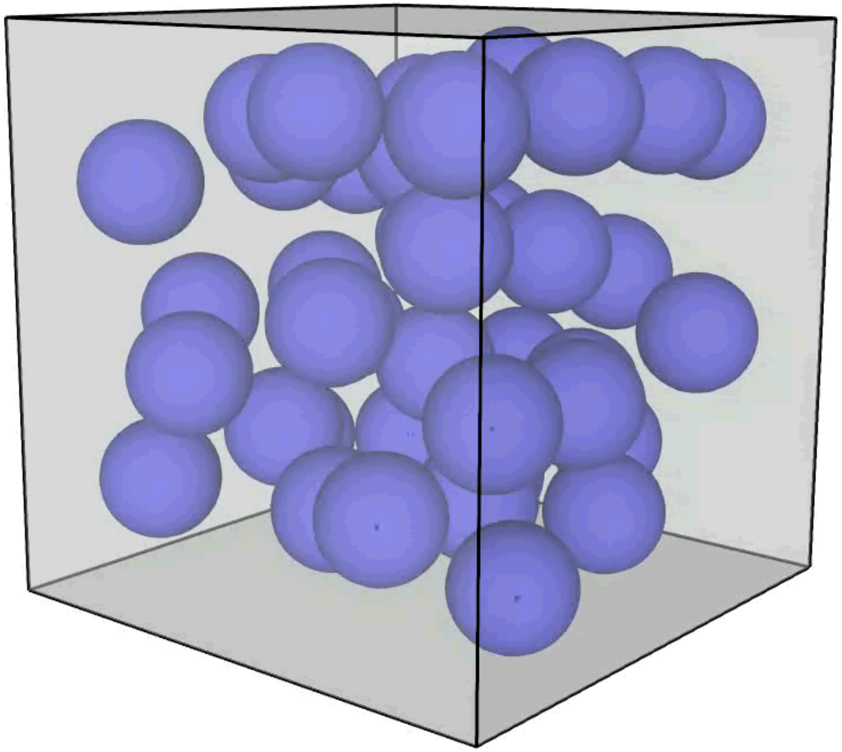
Low Magnification CT, in-situ Compression

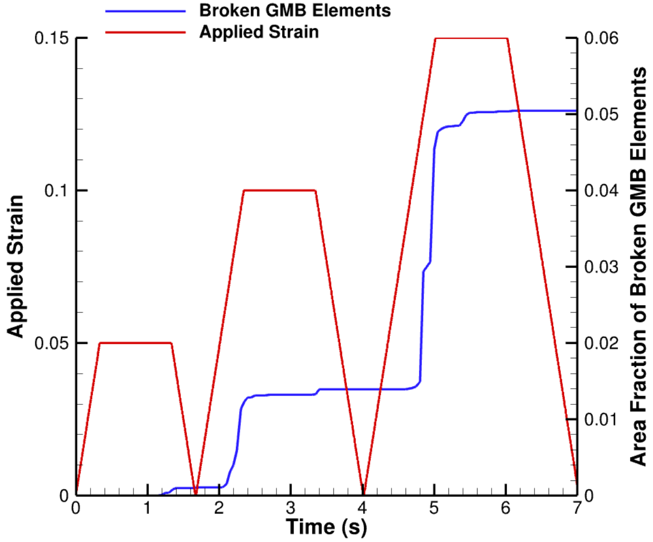
- Compressive load up to 40% strain, Imaged at 5% strain increments

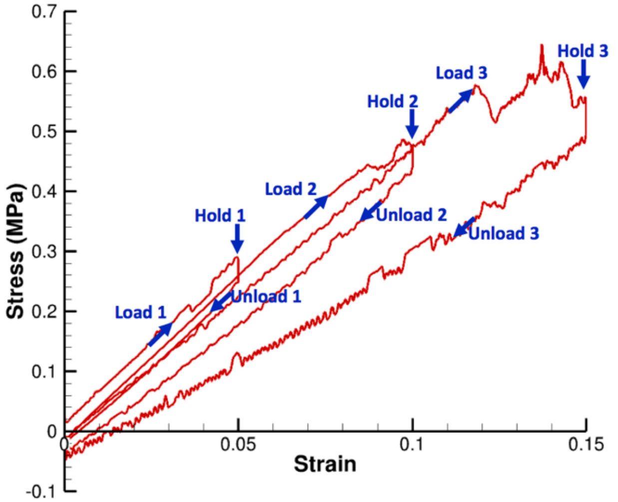


Cyclic Uniaxial Compression, 20% GMBs

Time dependent damage!

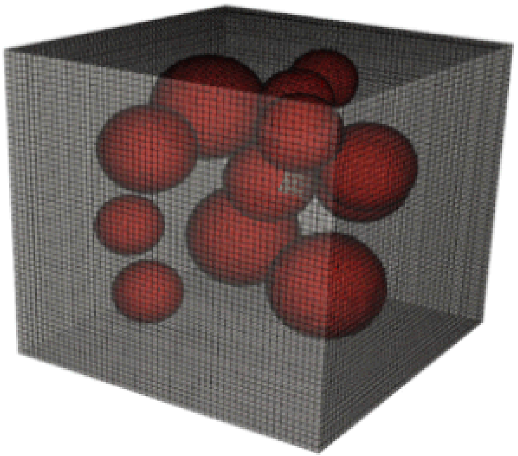
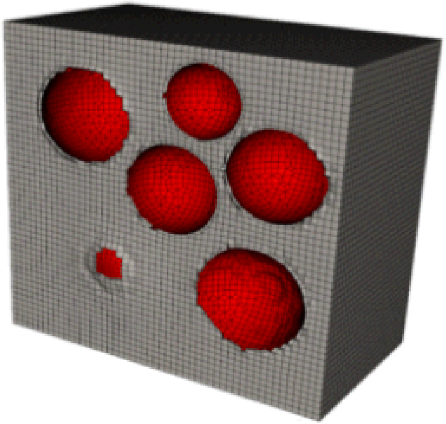
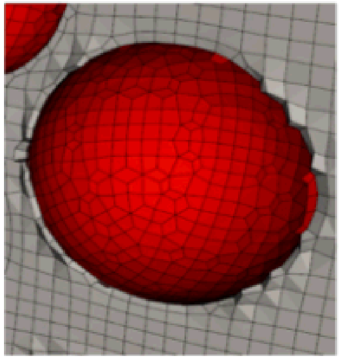






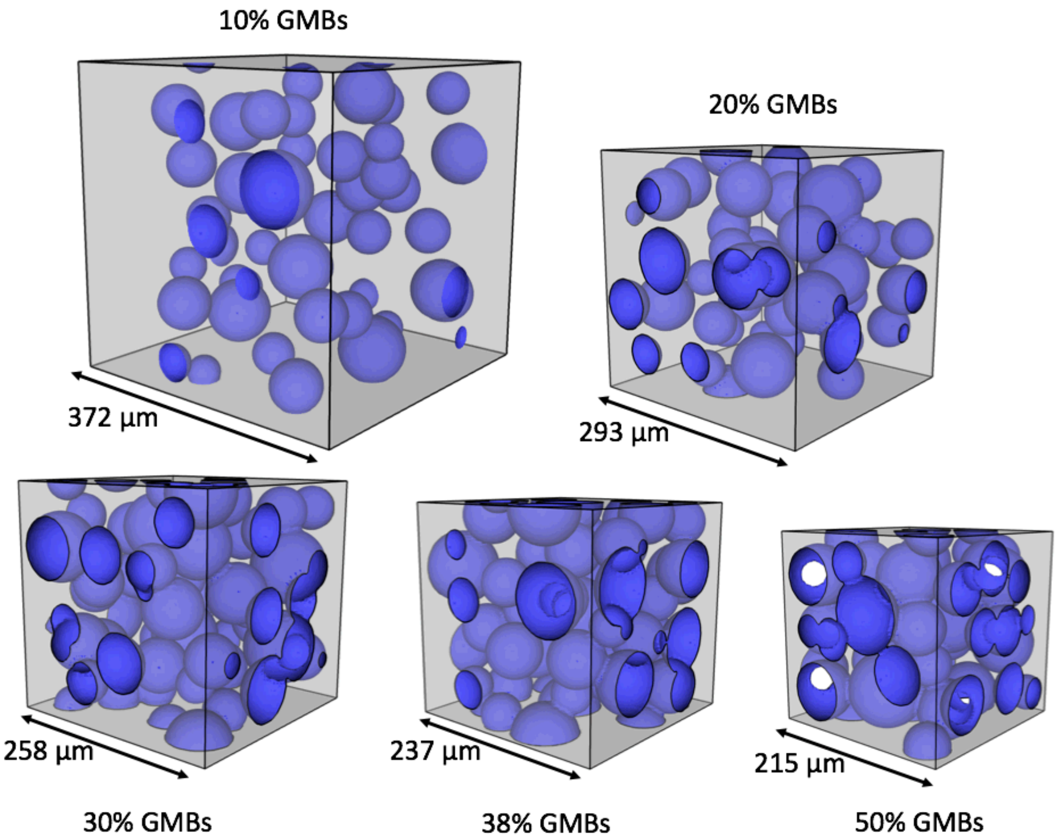
Microstructure Model Meshing & FE Simulations

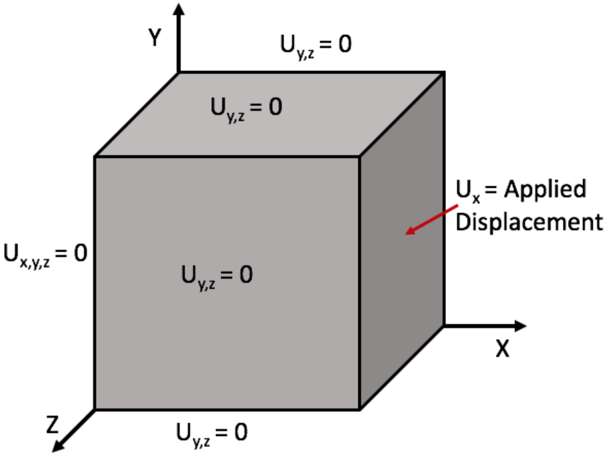
- Automated Meshing with SCULPT mesh tool:
  - Sylgard 184 Matrix: 8-node hexahedral elements
    - Linear viscoelastic material model, adopted from [M. Lewis et al, LA-UR-07-0298, (2007)]
  - Glass Microballoons (GMBs): 4-node quadrilateral shell elements
    - Linear Elastic material model, properties estimated as borosilicate glass
- Simulations run with Sierra SM, explicit quasistatic mode
  - Needed to simulate large time-scales (~s) with pervasive contact & GMB failure

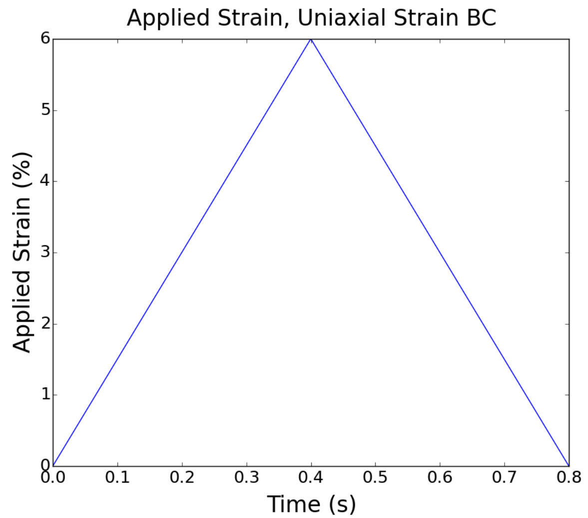




Confined Compression (Uniaxial Strain)

Five different GMB Volume Fractions

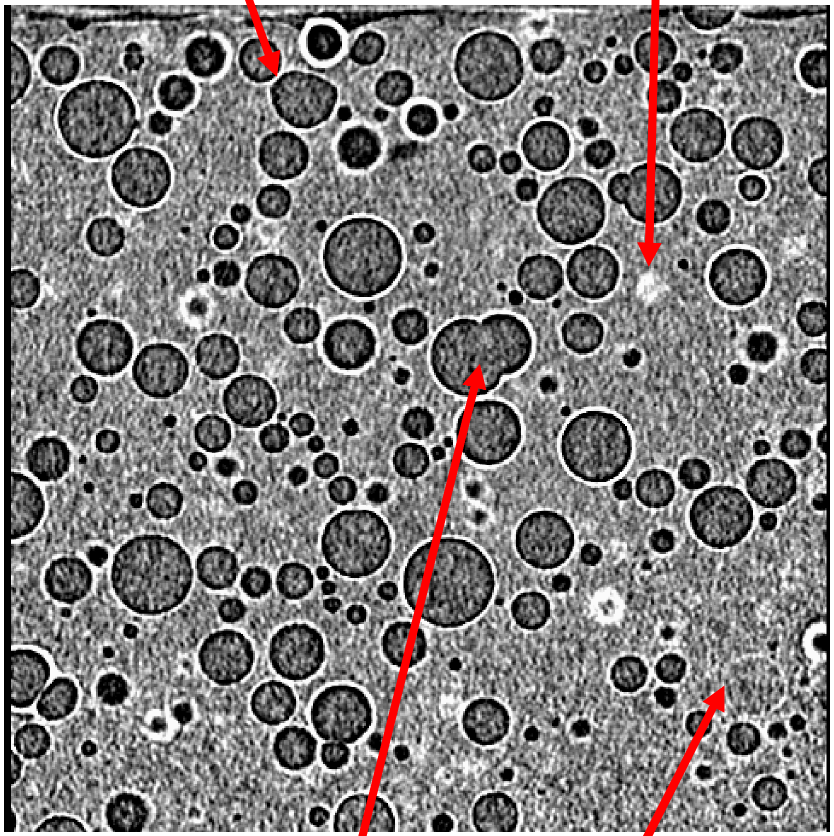






In Situ CT

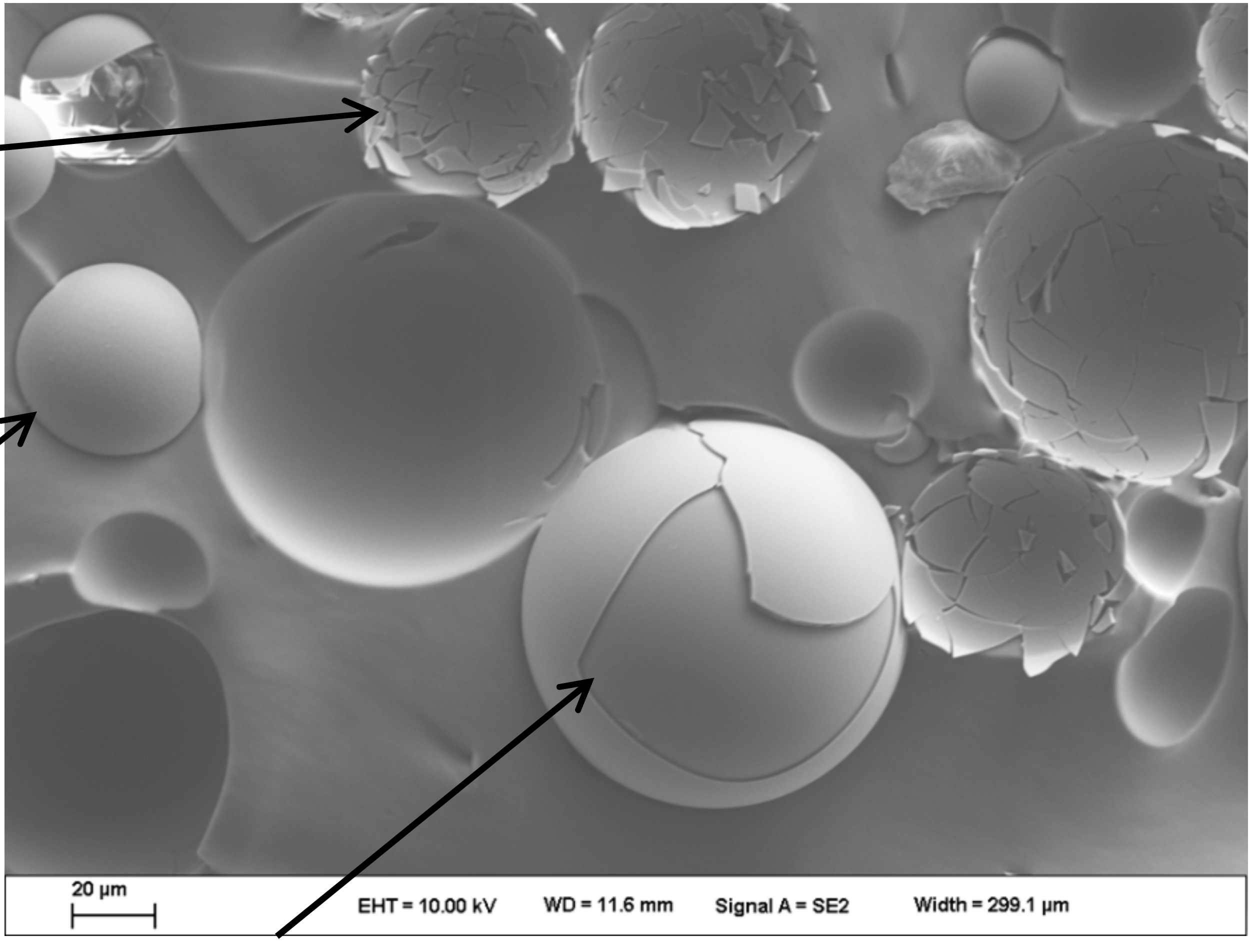
- Typical slice of pristine specimen.
  - Black = air,   White = glass,   Grey = Sylgard
- Observations
  - 3D size and proximity distributions of GMBs can now be measured and modeled accurately
  - GMB wall thicknesses can be estimated
  - Several "Twin" GMBs
  - Several filled-in GMBs. Broken before cure and filled with Sylgard in cure process (like hard boiled eggs, see slide 1)
  - Partially broken GMBs in pristine sample
  - Very few shards
  - Many GMBs directly touching one another at this high volume fraction. Small ones next to large ones.



Post-Mortem SEM images provide insight

After compressive loading

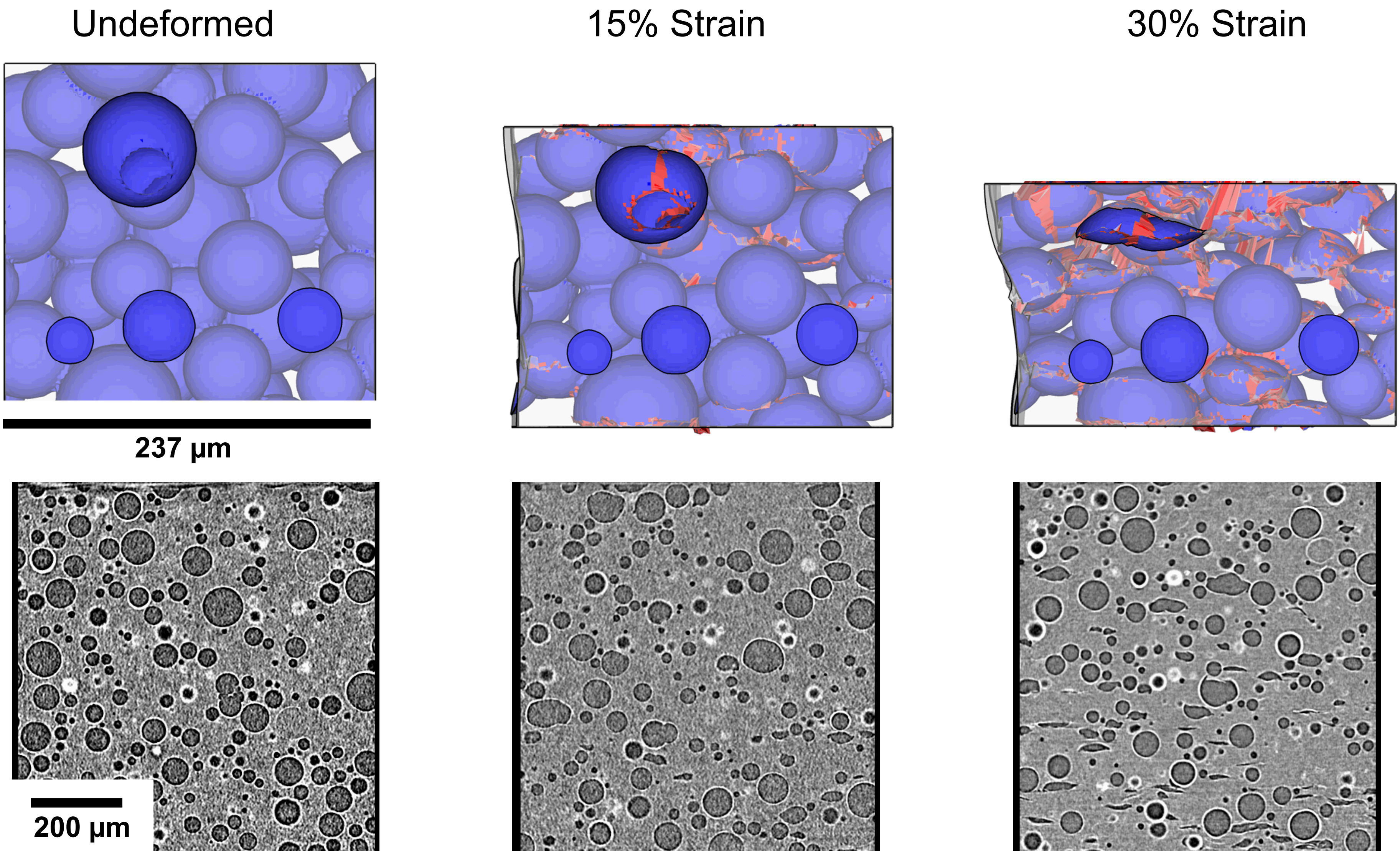
Shattered GMBs indicate fracture during loading



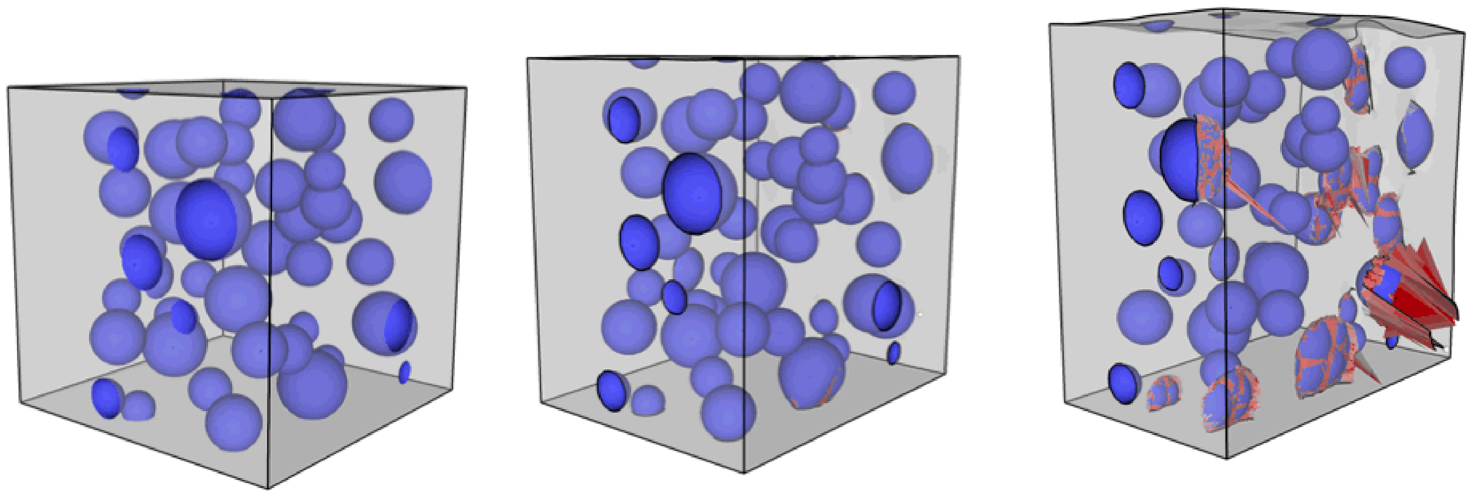
Intact GMBs indicate delamination

“Hard-boiled egg” structure indicates this GMB was broken before gel point. Sylgard flowed into GMB void.

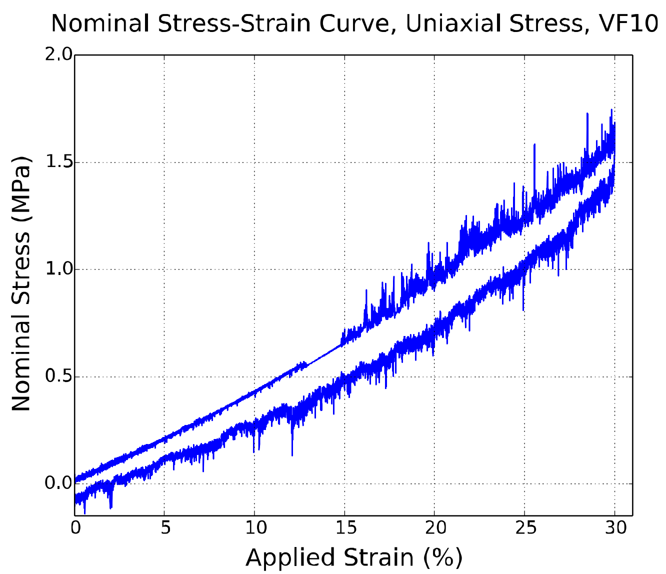
Comparison with X-Ray CT, 38% GMBs

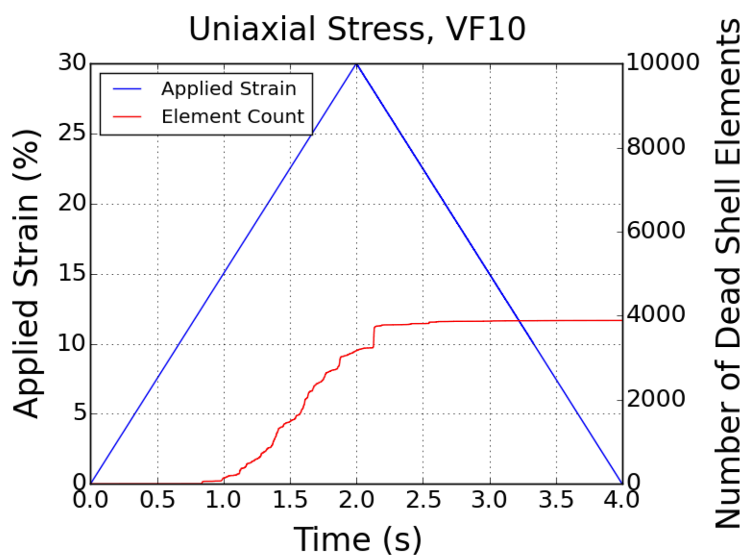


Finite Deformation Uniaxial Stress, 10% GMBs



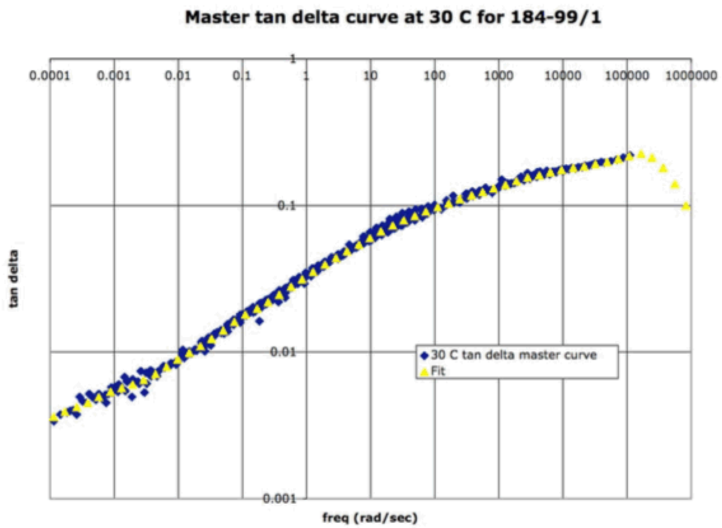
0 % Applied Strain   15 % Applied Strain   30 % Applied Strain

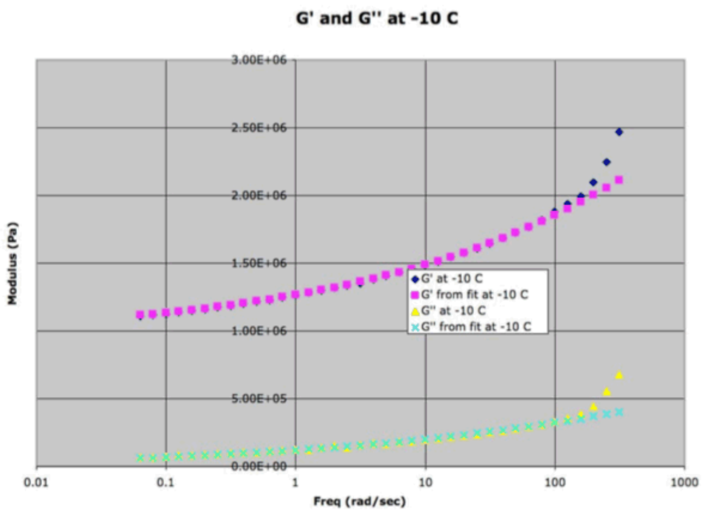




Constituent Material Properties: Sylgard 184

- Linear Viscoelastic Material Model used in FEA





- Prony series fit (22 terms) and detailed material properties available in [M. Lewis et al, LA-UR-07-0298, (2007)]]

- Elastic Properties used for composite theory:
  - Young's Modulus = 1.84 MPa
  - Shear Modulus = 0.61 MPa

Unconfined Compression (Uniaxial Stress)

Five different GMB Volume Fractions