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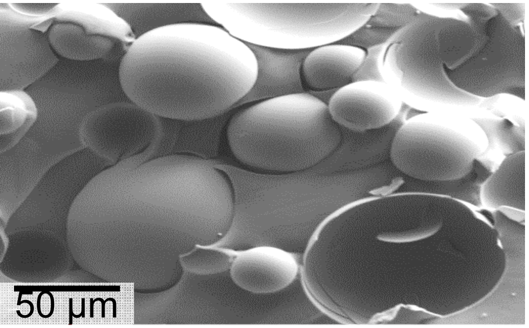

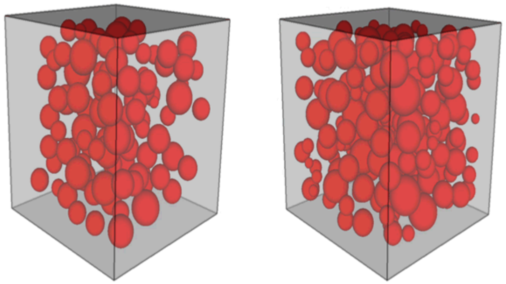

Micromechanics of Damage in Glass Microballoon Filled Syntactic Foams

Judith A. Brown, Kevin N. Long, Bradley Huddleston, Helena Jin, Jay Carroll

ASME IMECE

November 17, 2016

Exceptional service in the national interest

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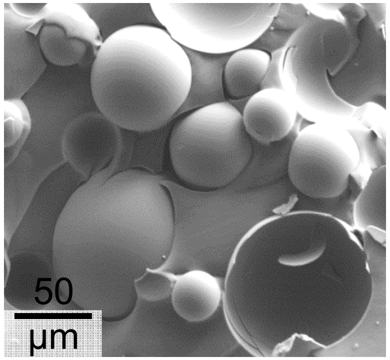
Polymeric Syntactic Foams

- Heterogeneous composite materials—hollow particles embedded in matrix material

Images: Gupta et. al., JOM, Vol. 66, No. 2, (2014)

Applications:
*Deep sea vehicles
*Aircraft radar encapsulation
*Blast mitigation
*Potting/protective layers

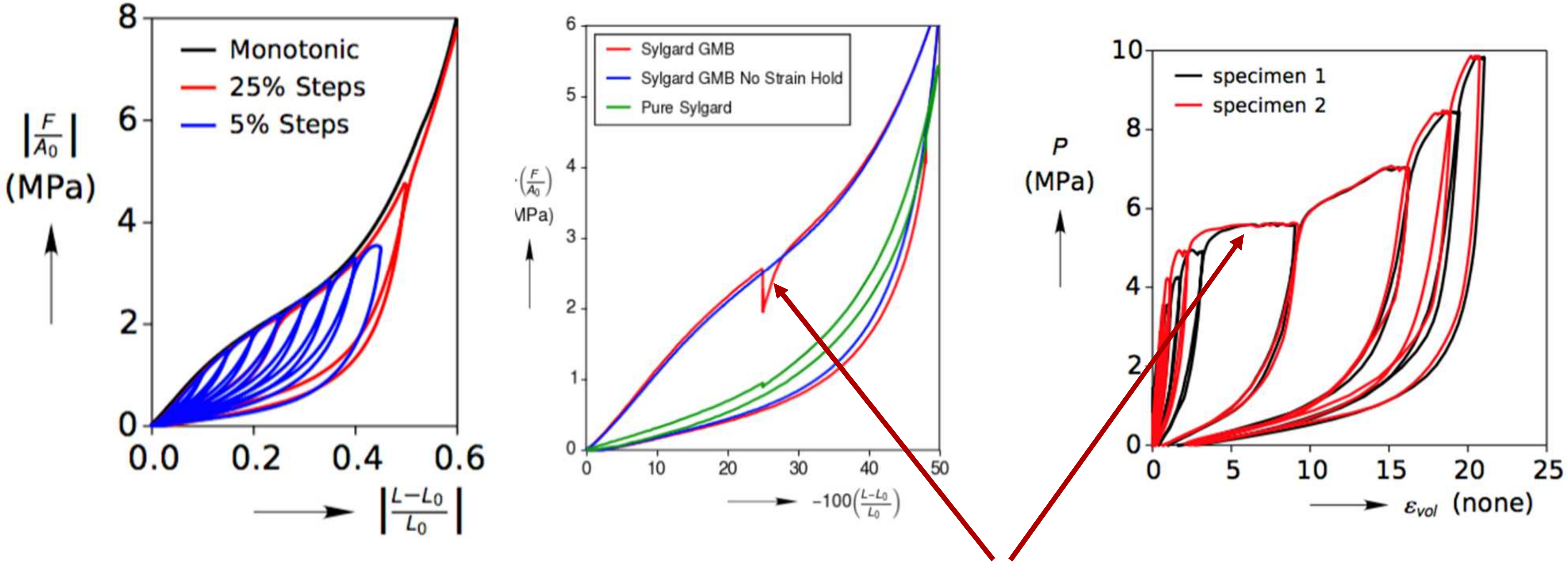
- Sylgard Elastomeric Matrix + Hollow Glass Microballoon Fillers
- Why add Glass Microballoons (GMBs)?
  - Lower thermal expansion coefficient
  - Lower cure shrinkage (mismatch strains)
  - Increase specific modulus
  - Increase energy dissipation



Macroscale Response of Sylgard/GMB

Macroscale compression

Hydrostatic Pressurization

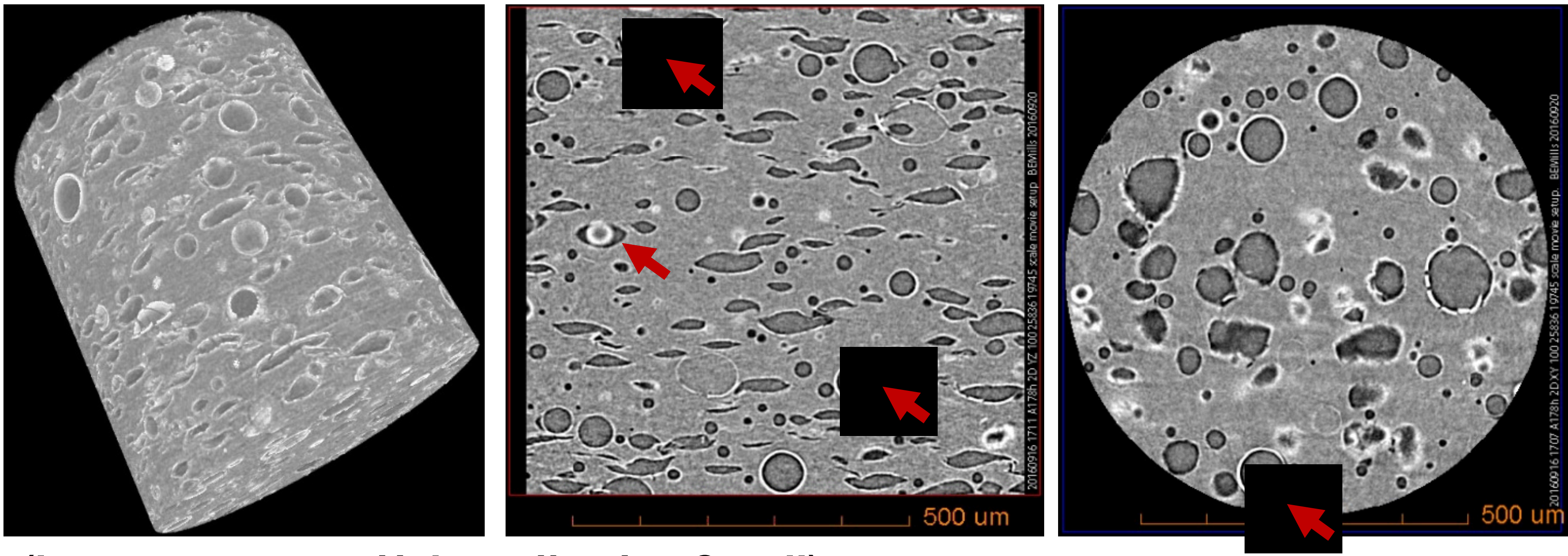


Time Dependent Damage Observed

- Need understanding of microstructure behavior to identify role of damage mechanisms and inform macroscale constitutive model

Possible Damage Mechanisms

X-ray CT Images at 25% global compression



(Images courtesy Helena Jin, Jay Caroll)

Observations:

1. Some GMBs completely crushed, others mostly intact
2. A few GMBs are debonded

Research Objectives

- What are the macroscale effects of each damage mechanism?
  - First order homogenization to study macroscale elastic properties of materials with each type of damage
  - Analytic Composite Theory
- Develop numerical modeling platform that can be used to study microstructural behavior of Polymeric Syntactic Foams
  - Explicitly resolve local stresses in components of the microstructure under various loading conditions
  - Small strain and finite deformation regimes
  - Supplement experimental efforts to understand role of various damage mechanisms
- Use knowledge gained to inform engineering length scale constitutive models

Approach to Study Microstructure

- How do GMB delamination and breakage affect the macroscale elastic constants?

How to represent various damage states?

Generate Synthetic Microstructure Model (SVE)

Mesh Generation

FEA Analysis for suite of boundary value problems

Elastic Constants

Repeat over many SVE Realizations to find effective properties

Bonded Intact GMBs: → determine equivalent solid sphere properties

Fully Broken GMBs: → approximate as voids

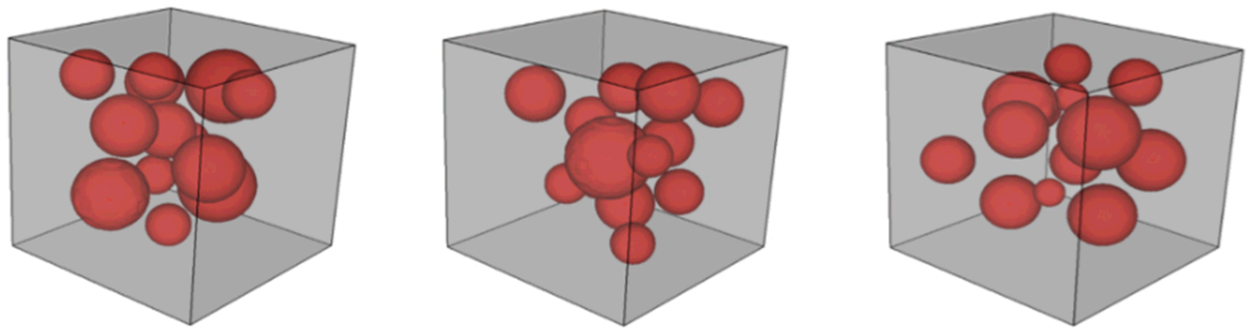
Christensen Micromechanics Composite Theory

Elastic Constants

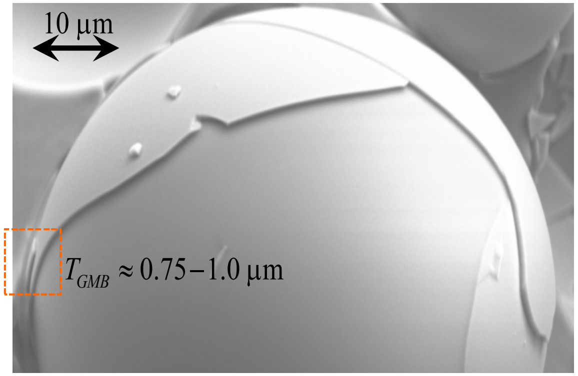
Microstructure Model Generation

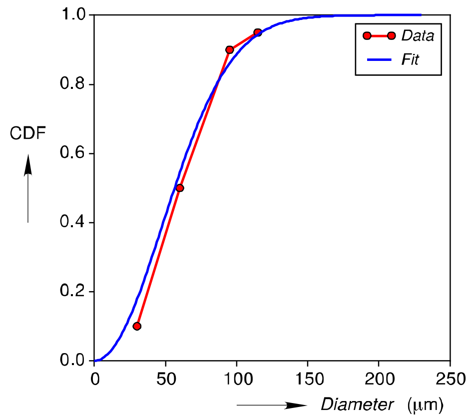
- Generate Stochastic Volume Element (SVE) models of Sylgard/GMB microstructure

- GMB Thickness: 1 μm
- Average GMB Diameter: 60 μm



Estimate Characteristic GMB Thickness:





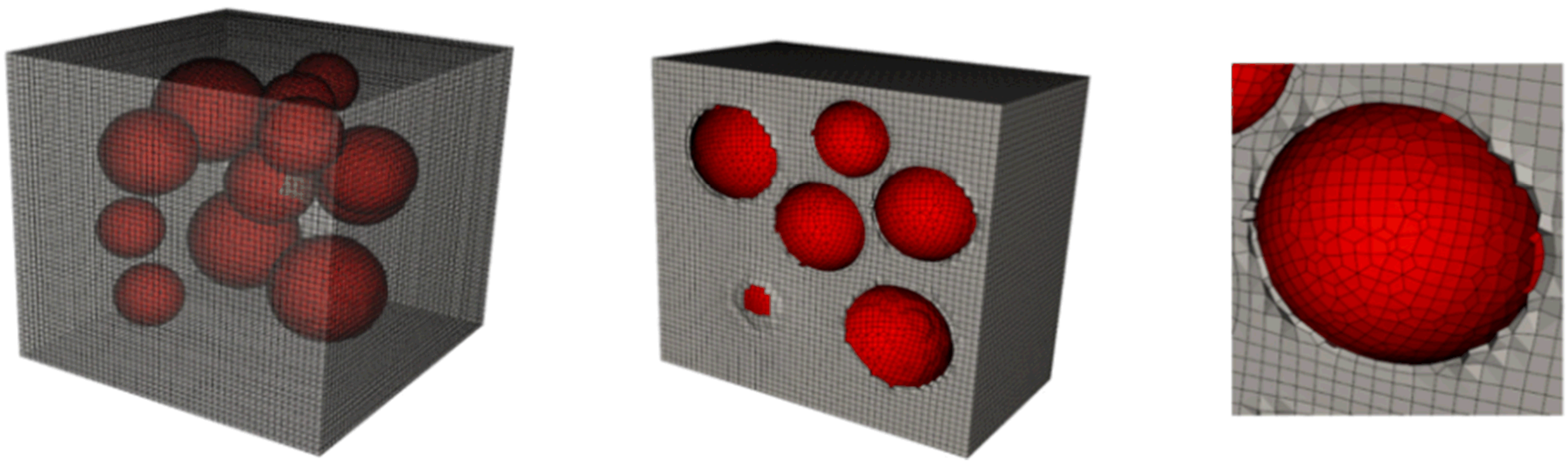
Manufacturer's (3M®) Cumulative Distribution Data for A16/500 GMB

Microstructure Model Generation

- 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)]

  - Borosilicate glass GMBs: 4-node quadrilateral shell elements
    - Linear Elastic material model
    - Properties estimated from (http://www.engineeringtoolbox.com/modulus-rigidity-d_946.html)

(a) (b) (c)



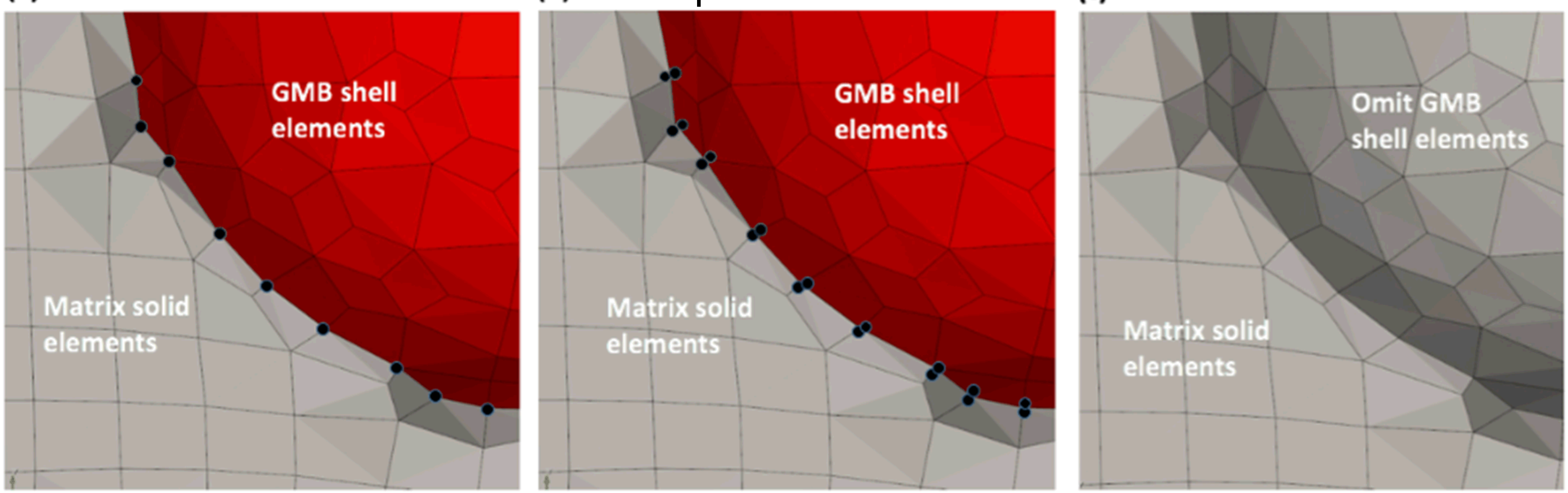
Mesh Design for GMB/Matrix Interface

- How to represent various damage mechanisms?

(a) Perfectly Bonded: Shared Nodes

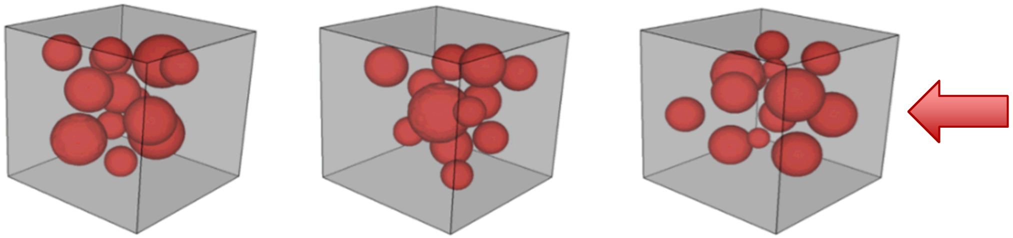
(b) Fully Debonded: Duplicate Nodes

(c) Fully Broken: Omit GMB elements



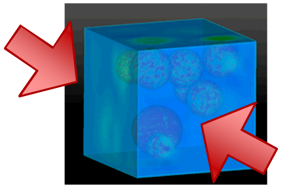
First Order Homogenization of Elastic Constants

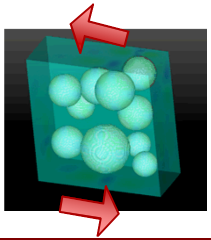
- Generate Stochastic Volume Element (SVE) models of Sylgard/GMB microstructure



15 Realizations of SVE with VF = 20% 20 GMBs each

- Six Independent Boundary Value Problems to recover elastic stiffness tensor

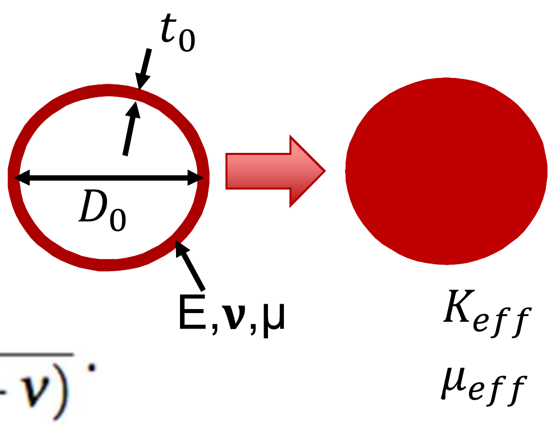




  - KUBC: Specify Displacement BC to achieve known, uniform macroscale strain $\langle \boldsymbol{\varepsilon} \rangle$ $\{u\} = [E]\{x\},$
  - Recover volume average stress response from SVE $\langle \boldsymbol{\sigma} \rangle = \frac{1}{\Omega_v} \int_{\Omega_v} \boldsymbol{\sigma}(x) d\Omega$
  - Stiffness Tensor recovered from Hooke's Law $\langle \boldsymbol{\sigma} \rangle = \mathbb{C} \langle \boldsymbol{\varepsilon} \rangle.$
  - Sierra Solid Mechanics Finite Element Analysis Software used for all numerical BVP

Analytic Composite Theory for Elastic Constants

- Adapt composite theory of Christensen to study Sylgard/GMB syntactic foams: [R.M. Christensen, *Mechanics of Composite Materials*, (2005)]
  - Calculate elastic constants for solid sphere that has same structural response at its outer boundary as hollow GMB
  - Assume thin shell description of GMB $D_0 >> t_0$



- Equivalent Solid Sphere Bulk Modulus:

$$\frac{d\varepsilon_{\text{vol}}}{dp_0} = K_{\text{eff}}^{-1} \rightarrow K_{\text{eff}} = \frac{4Et_0}{3D_0(1-\nu)}.$$

- Equivalent Solid Sphere Shear Modulus:

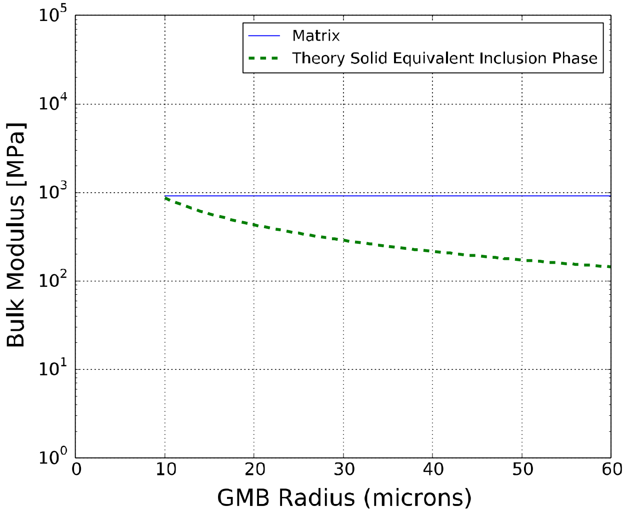
$$\mu_{\text{eff}} = \mu\,(1-f_0)\,.$$

Danielsson et. al.,Mech.of Mater., (2004)

Analytic Composite Theory for Elastic Constants

- Composite Bulk Modulus:
  - Christensen, composite spheres model

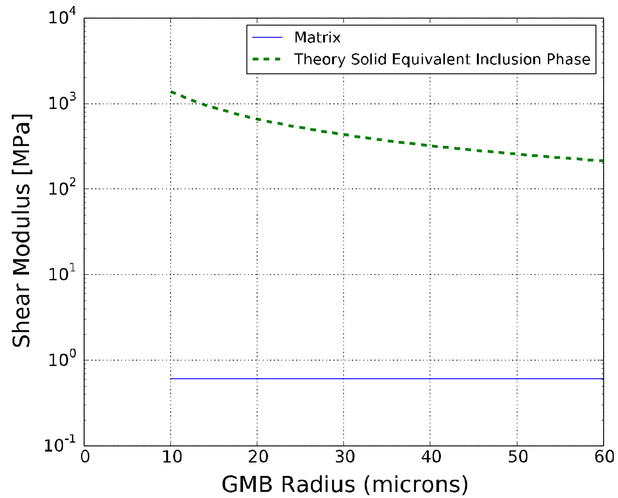
$$K_{\text{composite}} = K_m + \frac{f_i (K_i - K_m)}{1 + (1 - f_i)\left[(K_i - K_m)/(K_m + 4\mu_m/3)\right]}.$$



- Composite Shear Modulus:
  - Match energy associated with deforming single matrix/inclusion to equivalent homogeneous medium

$$A\left(\frac{\mu}{\mu_m}\right)^2 + 2B\left(\frac{\mu}{\mu_m}\right) + C = 0.$$

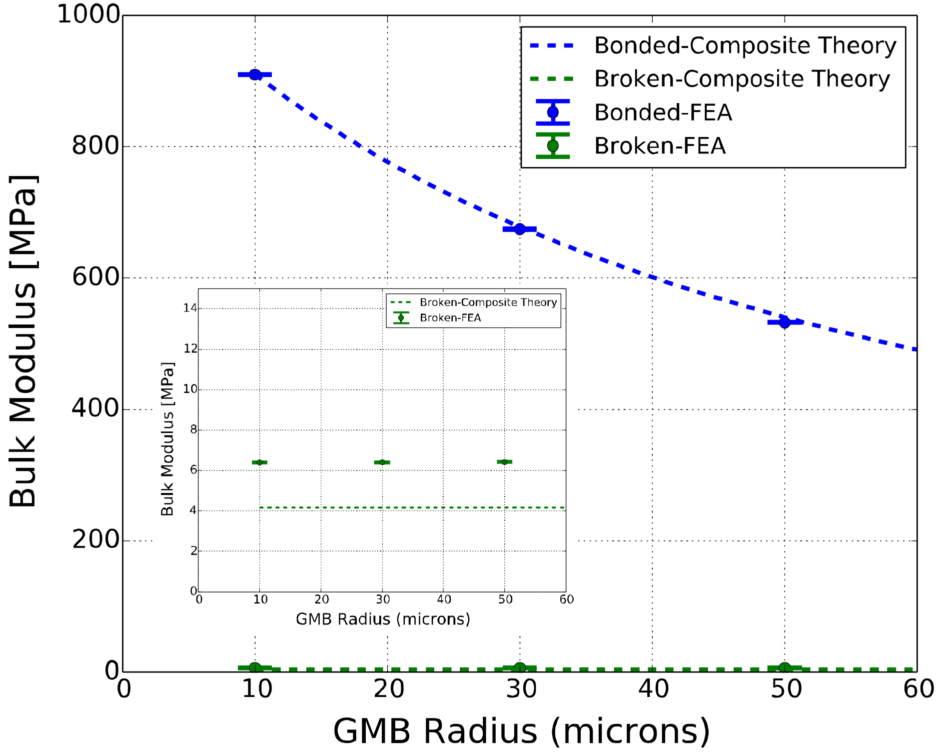
  - A,B,C, are functions of matrix & inclusion properties

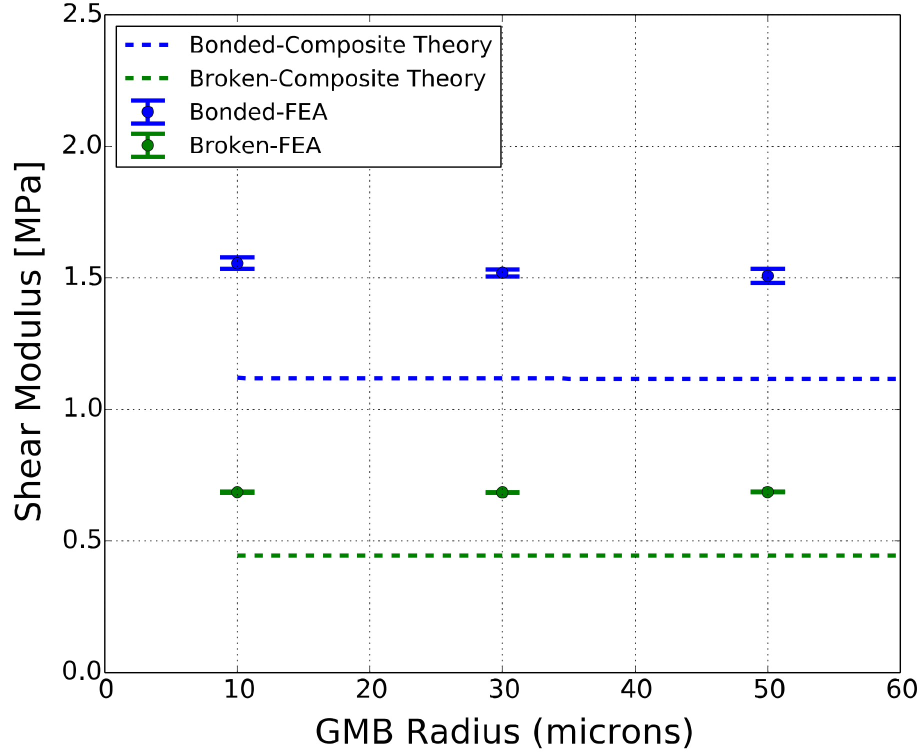


[R.M. Christensen, *Mechanics of Composite Materials*, (2005)]

Effect of GMB Radius

- Uniform distribution of GMBs, mean VF = 20%
- Each FEA point is averaged from 15 SVE microstructure realizations





- Bulk Modulus is only sensitive to inhomogeneity size when GMBs are in virgin, bonded state
- Shear modulus is not sensitive to inhomogeneity size for either bonded or broken state

Effect of GMB Volume Fraction

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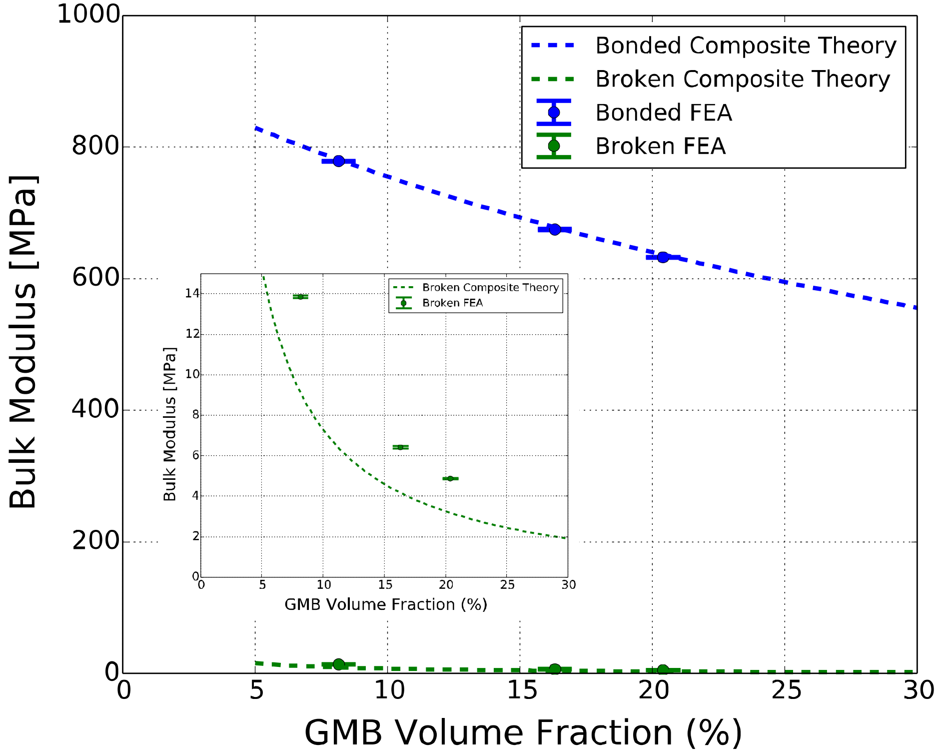
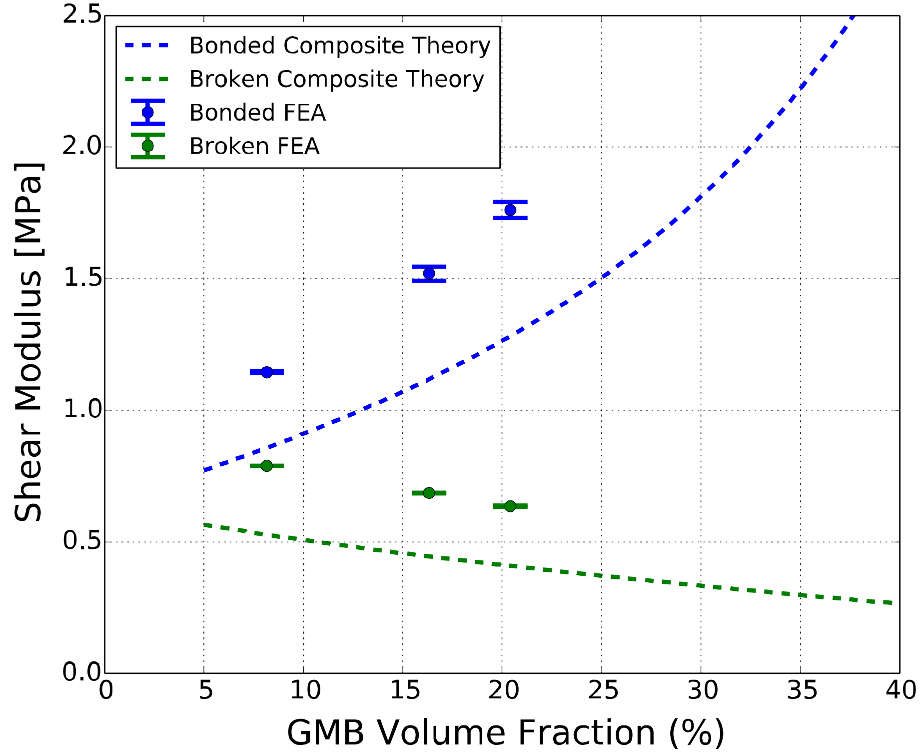
- Uniform distribution of GMBs, mean radius = 30µm
- Each FEA point is averaged from 15 SVE microstructure realizations

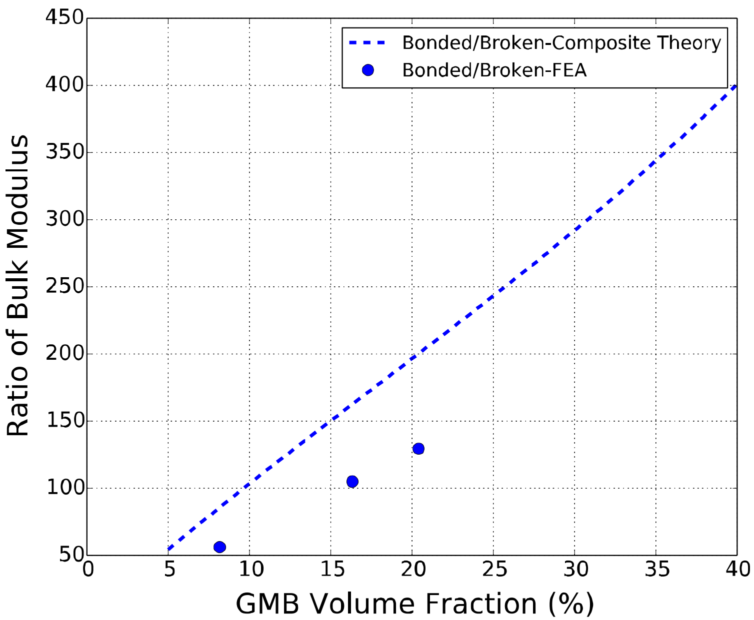


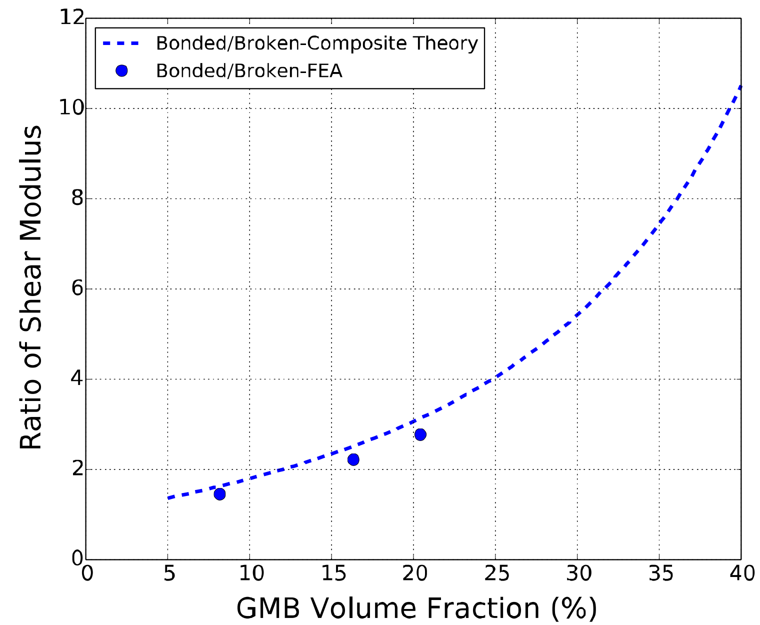


- Bulk Modulus AND Shear modulus in both virgin state (bonded GMBs) and fully damaged states (broken GMBs) are sensitive to GMB volume fraction
- Excellent agreement between Composite Theory and FEA

Effect of Broken GMBs

- Uniform distribution of GMBs, mean radius = 30µm
- Each FEA point is averaged from 15 SVE microstructure realizations





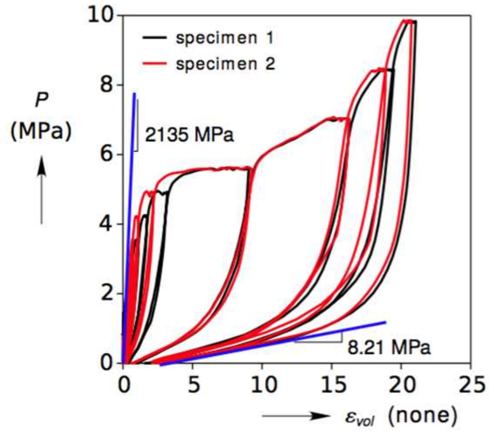
- Good agreement between Composite Theory and FEA

Comparison with Macroscale Data

GMB VF = 37%

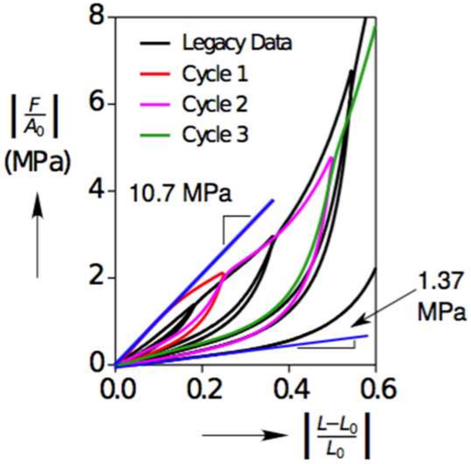
Bulk Modulus (MPa)

	Comoposite Theory	Macroscale Experiment
Virgin State	508	2135
Fully Damaged	1.39	8.21
Ratio	**366.1**	**260.0**



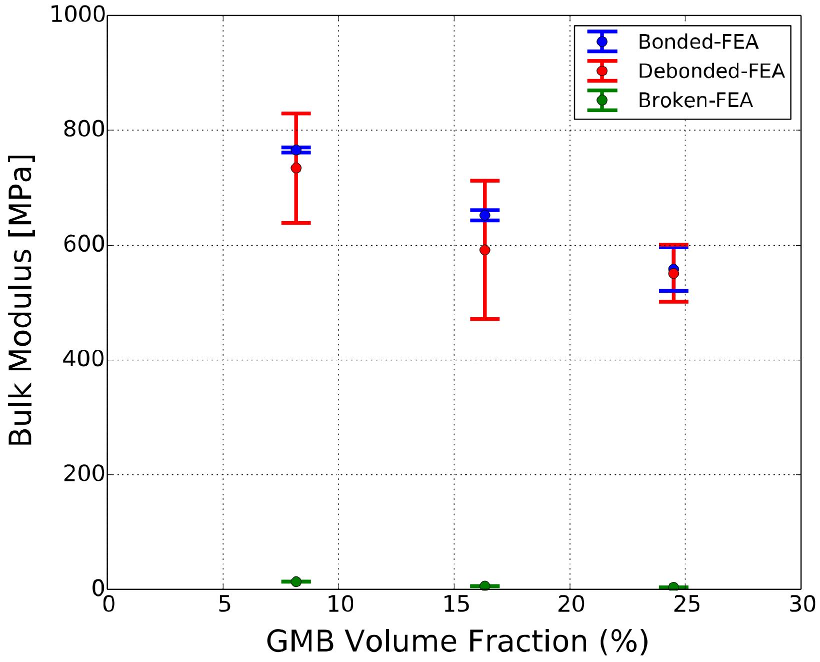
Young's Modulus (MPa)

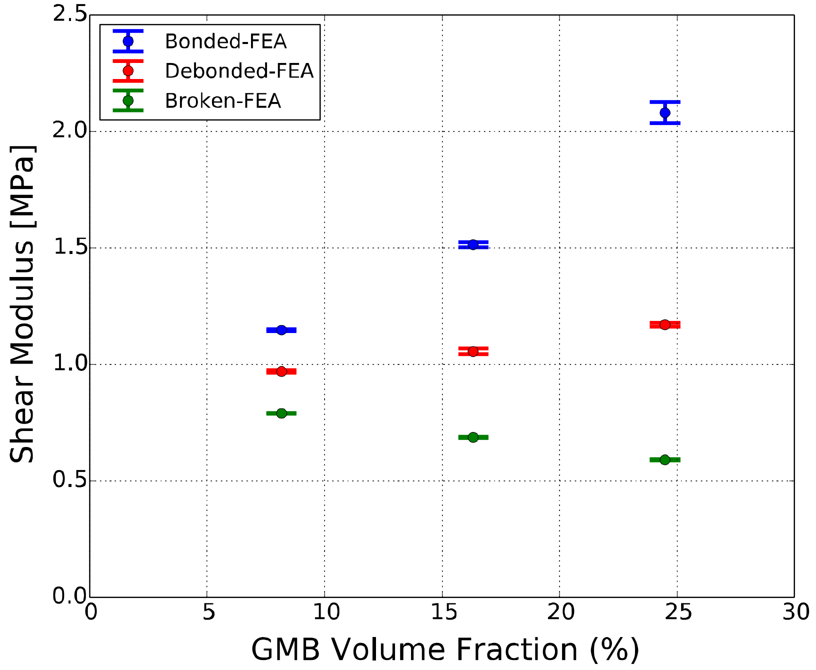
	Comoposite Theory	Macroscale Experiment
Virgin State	7.26	10.7
Fully Damaged	0.80	1.37
Ratio	**9.09**	**7.81**



Effects of GMB Debonding

- Weibull distribution of GMBs, mean radius = 30μm
- Each FEA point is averaged from 15 SVE microstructure realizations





- Bulk Modulus not sensitive to debonded GMBs but greatly reduced by broken GMBs
- Shear Modulus noticeably reduced by debonded GMBs and broken GMBs

Local Matrix Pressures: Uniaxial Strain

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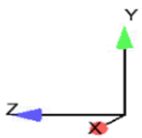
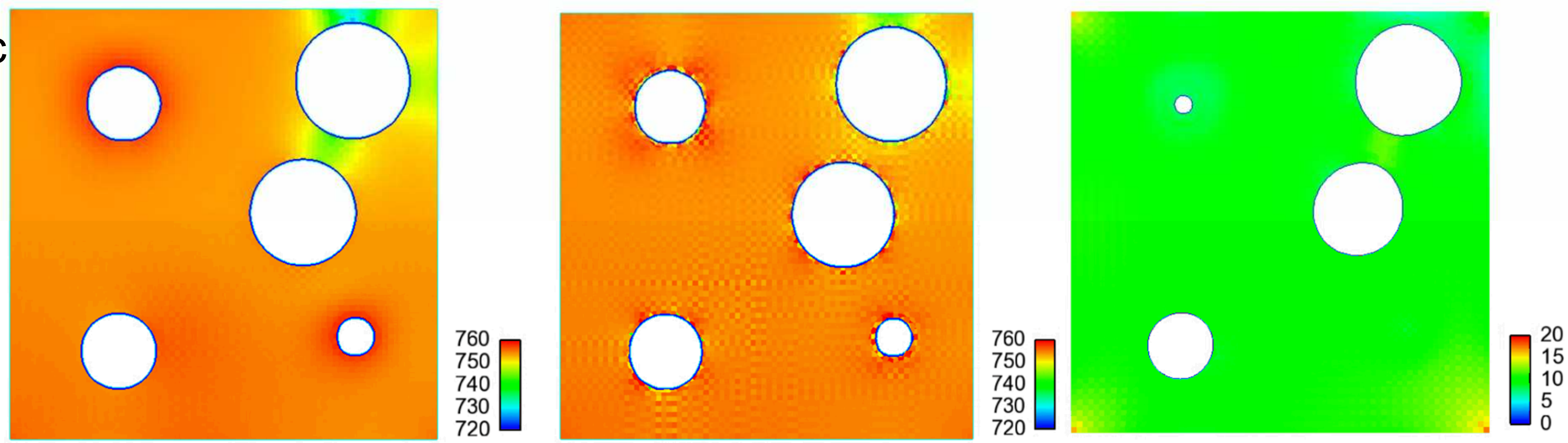
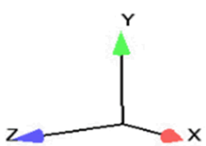
Fully Bonded **Fully Debonded** **Fully Broken**

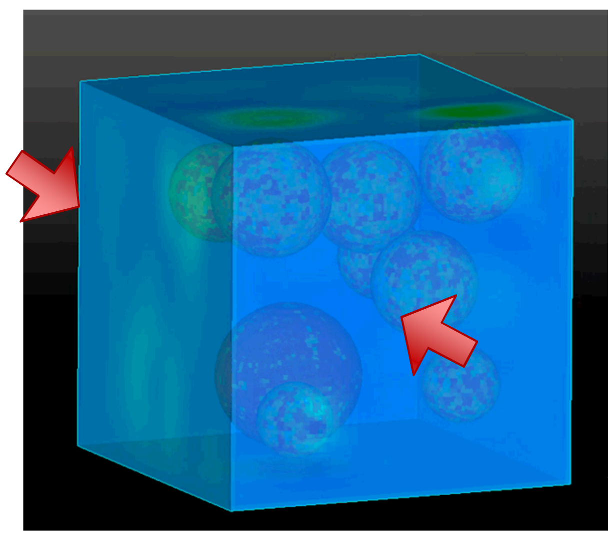
Hydrostatic Pressure
y-z plane at x=0

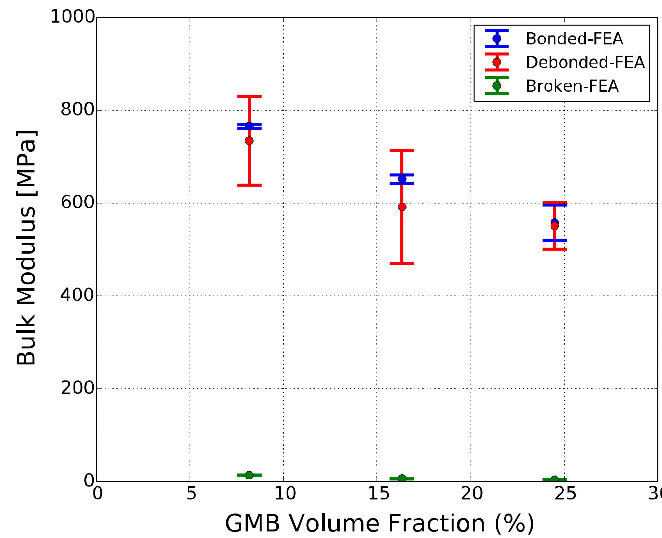




Macroscale Deformation



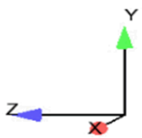


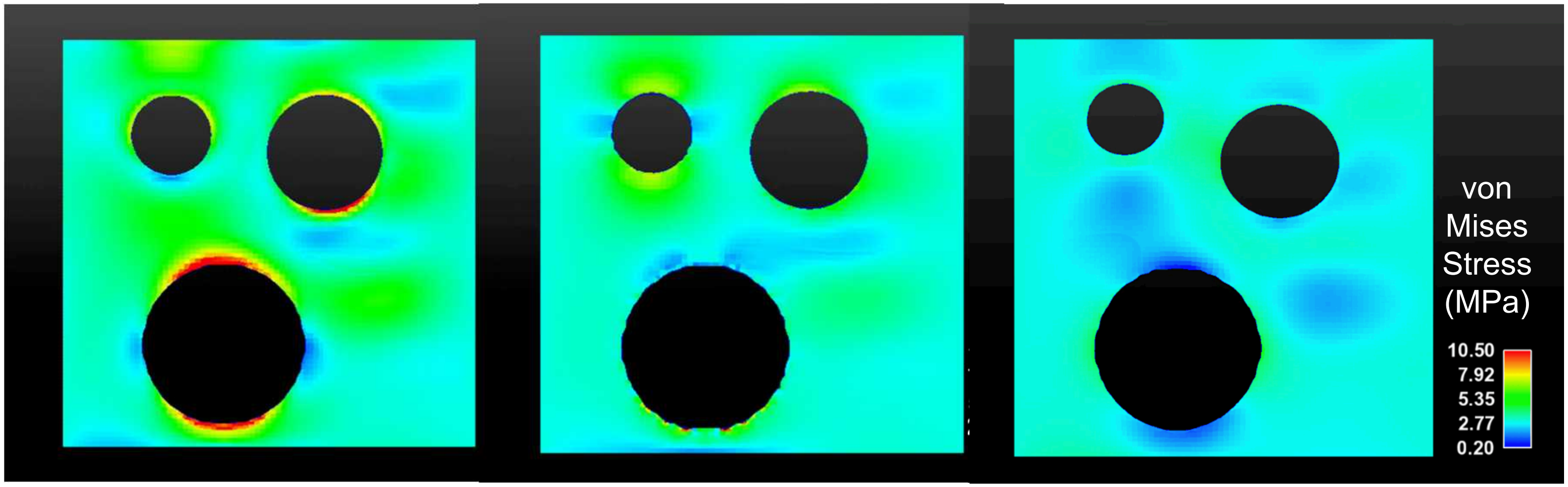


Local Matrix Stresses: Shear Strain

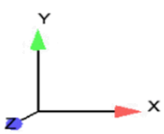
Fully Bonded | **Fully Debonded** | **Fully Broken**

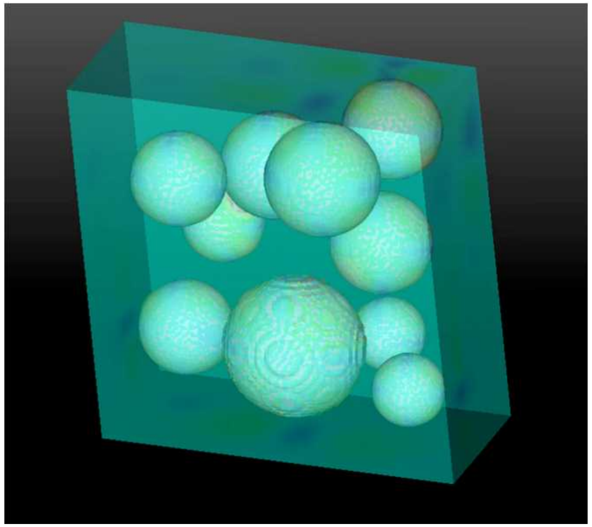
y-z plane
at x=0

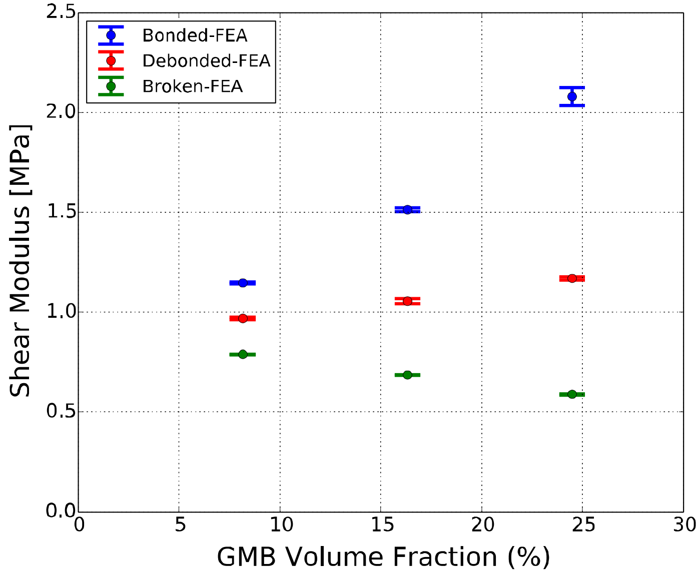




Macroscale
Deformation







Conclusions

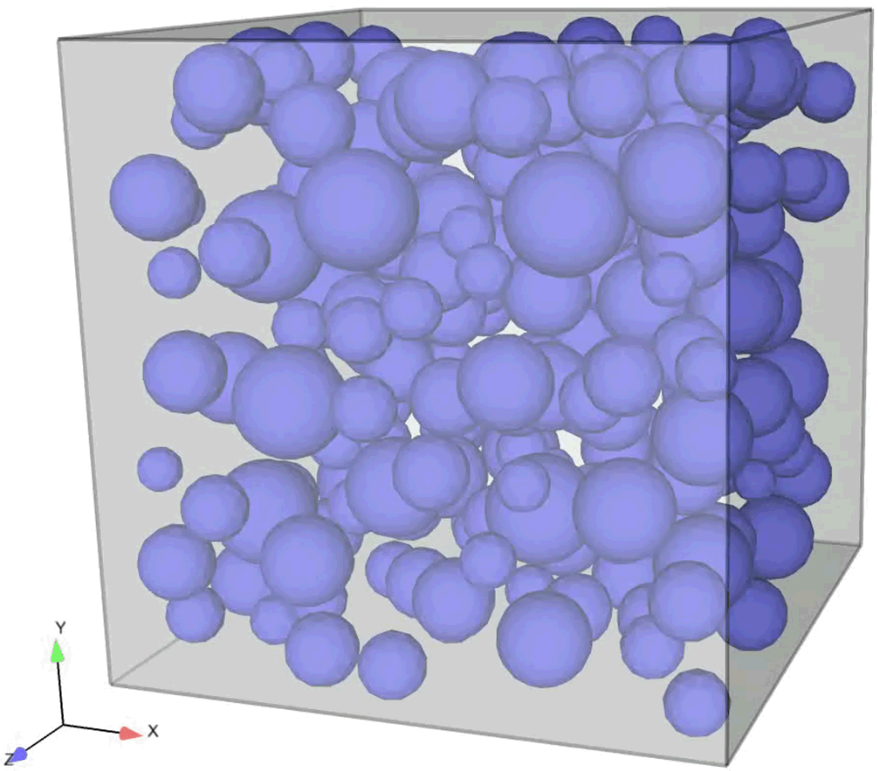
- Balloon Breakage vs. Delamination Affect Macroscale Elastic Constants in Different Ways:
  - The bulk modulus is greatly reduced by Broken GMBs but not by debonding
  - Both damage mechanisms reduce the shear modulus

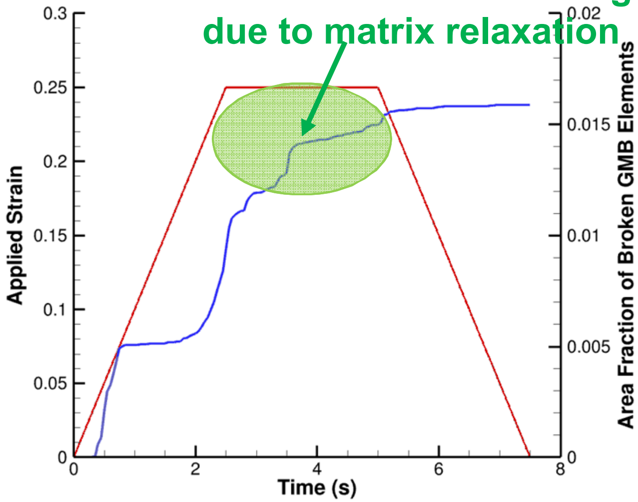
- Analytic Composite Theory and FEA homogenization agree

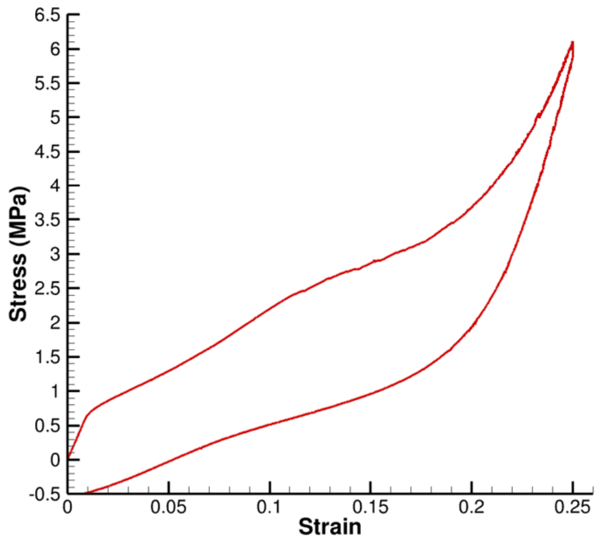
- Future Work: Damage Mechanisms and Time Dependence under large deformations

Finite Deformation: Uniaxial Strain

- Uniaxial strain to 25%



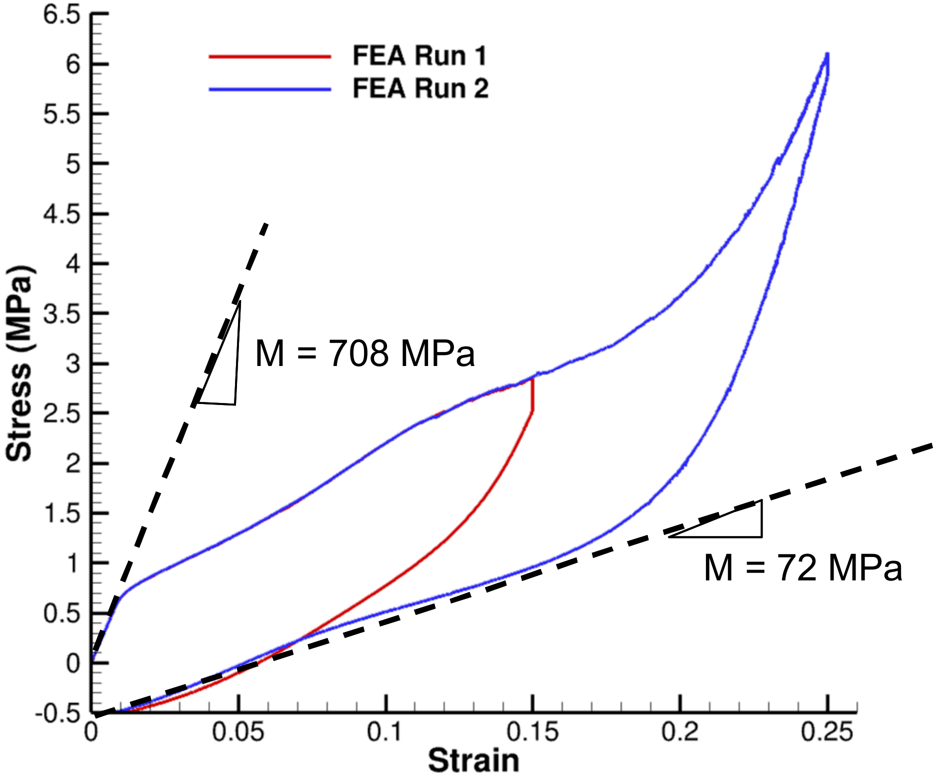




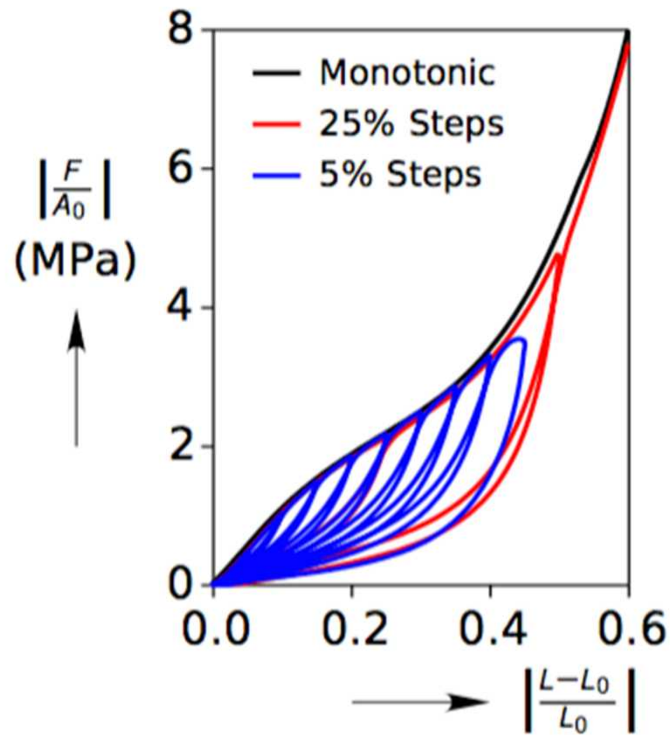
GMB Failure Criteria: Max Principal Stress
Matrix Properties: Linear Viscoelastic
Sylgard 184

Finite Deformation: Uniaxial Strain

FEA
Uniaxial Compressive Strain



Experiment
Uniaxial Compression



- **Qualitative Similarity to Macroscale Experimental Response**
- Time-dependent breakage of GMBs as viscoelastic matrix relaxes locally

Thank You!

QUESTIONS?

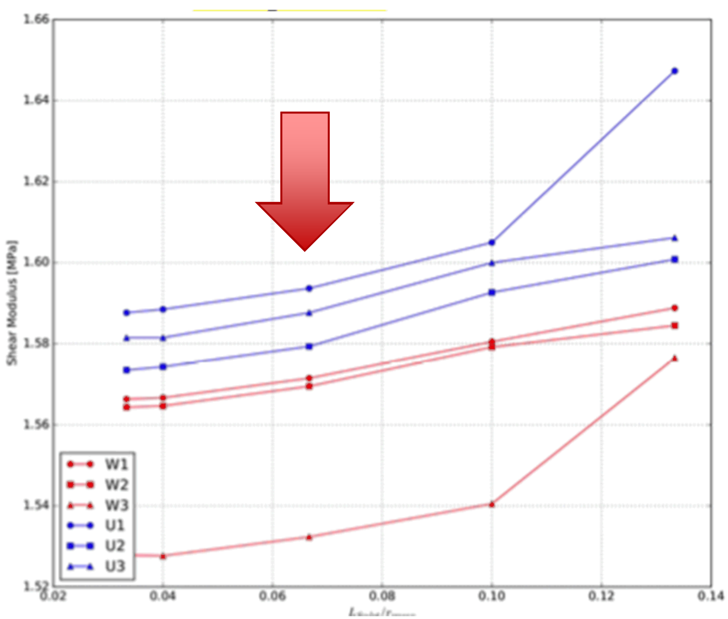
We would also like to acknowledge Dr. Joe Bishop for his help with FEA homogenization methods.

Mesh Convergence Study

- Governing features:
  - How well are GMBs resolved?
  - How many elements between GMBs?
- Results for Fully Bonded GMB Interface

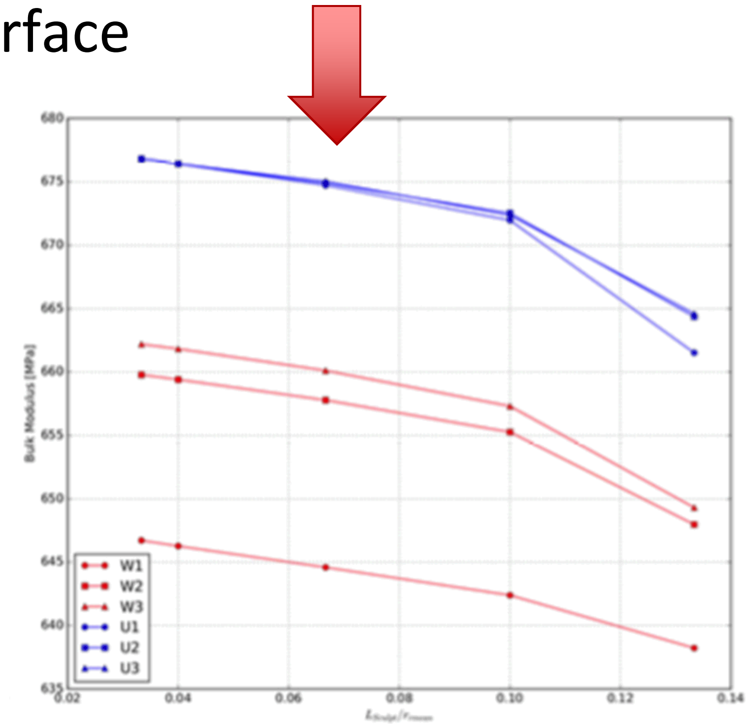
$$\frac{\mathit{Nominal\ Element\ Size}}{\mathit{GMB\ radius}} = 0.066$$

Shear Modulus (MPa)



$$\frac{\mathit{Nominal\ Element\ Size}}{\mathit{GMB\ radius}}$$

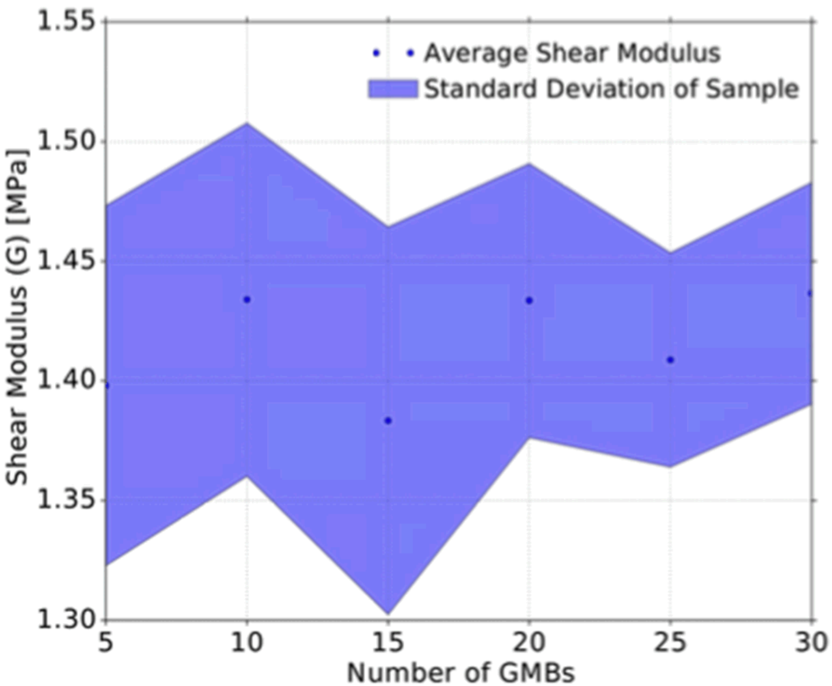
Bulk Modulus (MPa)

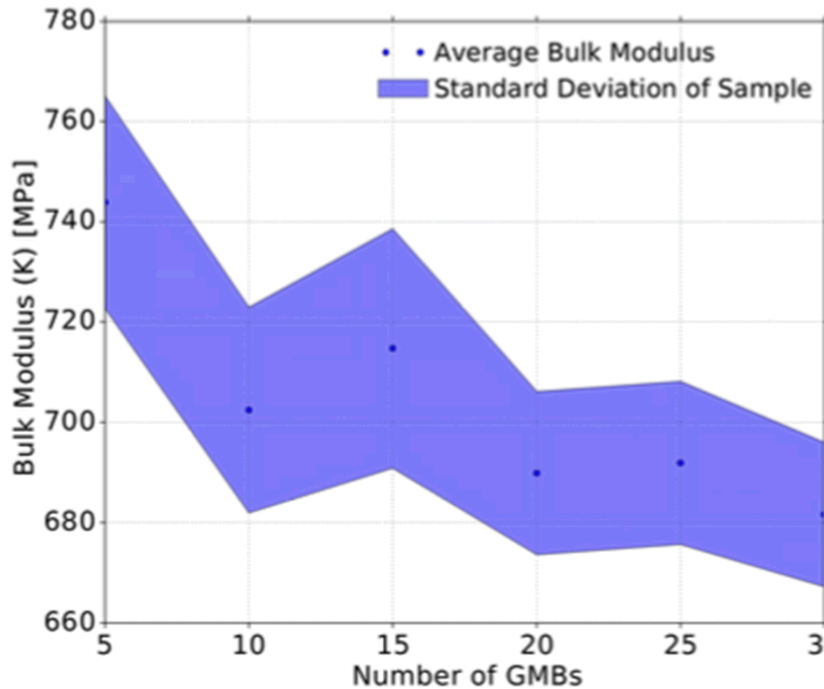


$$\frac{\mathit{Nominal\ Element\ Size}}{\mathit{GMB\ radius}}$$

Representative Volume Element Size

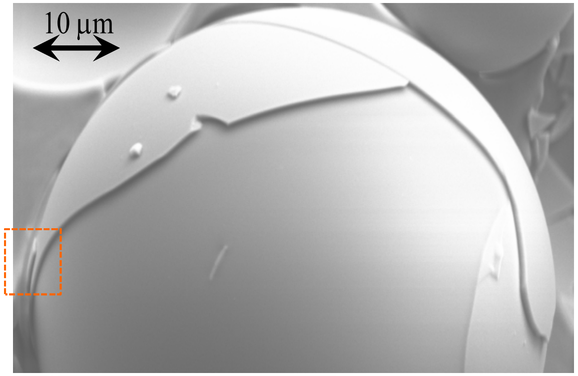
- GMB VF = 20%, Weibull distribution of GMBs, mean GMB radius = 30μm
- Average over 5 realizations at each SVE size (5 – 30 GMBs)





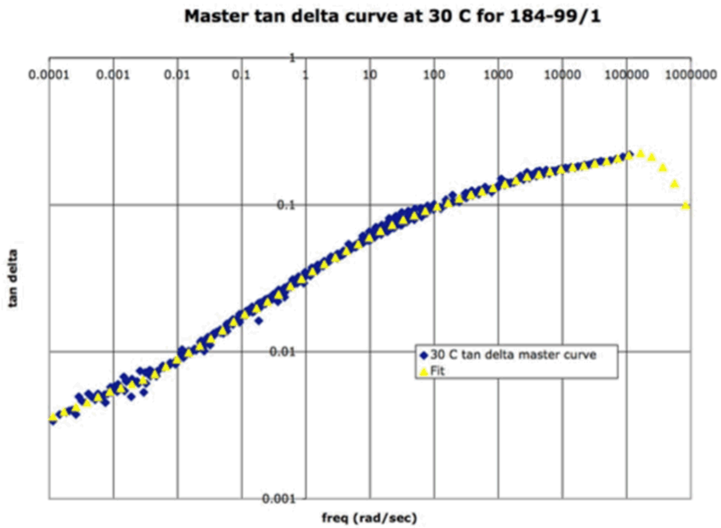
Constituent Material Properties: Borosilicate Glass

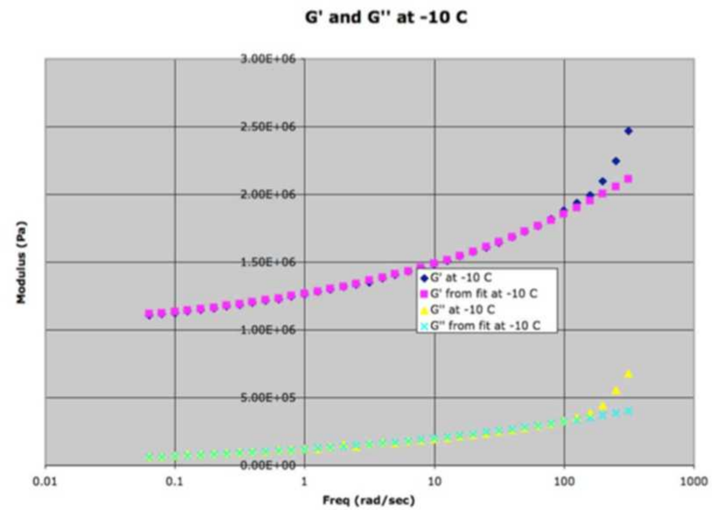
- Glass microballoons (GMBs): Borosilicate Glass
  - Young's modulus E_{glass} = 10.2 GPa
  - Shear modulus μ_{glass} = 4.2 GPa
  - Max principal stress at failure (estimated) = 100 Mpa
  - Properties estimated from (http://www.engineeringtoolbox.com/modulus-rigidity-d_946.html)



Constituent Material Properties: Sylgard 184

- Linear Viscoelastic Material Model used in FEA





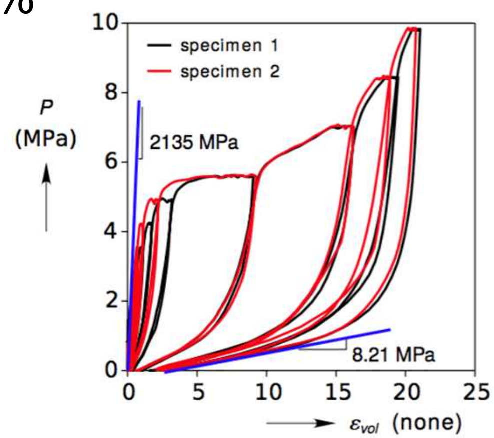
- Prony series fit (22 terms) and detailed material properties available in [M. Lewis et al, LA-UR-07-0298, (2007)]]

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

Comparison with Macroscale Data

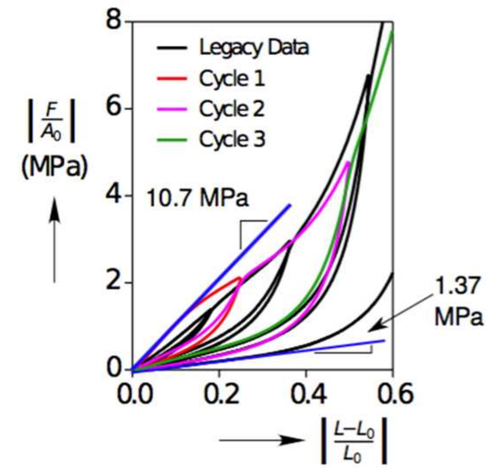
Bulk Modulus (MPa)

	GMB VF = 24.5% Comoposite Theory	GMB VF = 24.5% FEA Homogenization	GMB VF = 37% Macroscale Experiment
Virgin State	599	558	2135
Fully Damaged	2.513	3.858	8.21
Ratio	**238.4**	**144.6**	**260.0**



Young's Modulus (MPa)

	GMB VF = 24.5% Comoposite Theory	GMB VF = 24.5% FEA Homogenization	GMB VF = 37% Macroscale Experiment
Virgin State	4.424	6.229	10.7
Fully Damaged	1.072	1.681	1.37
Ratio	**4.127**	**3.705**	**7.81**

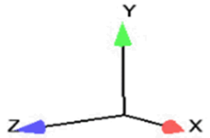


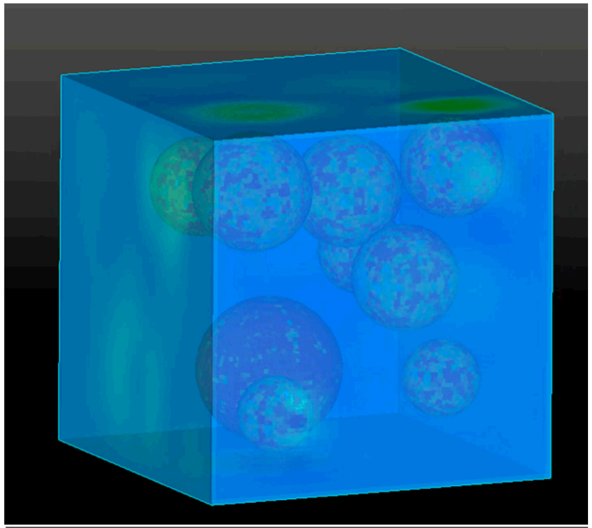
Local Stresses: Bonded GMBs

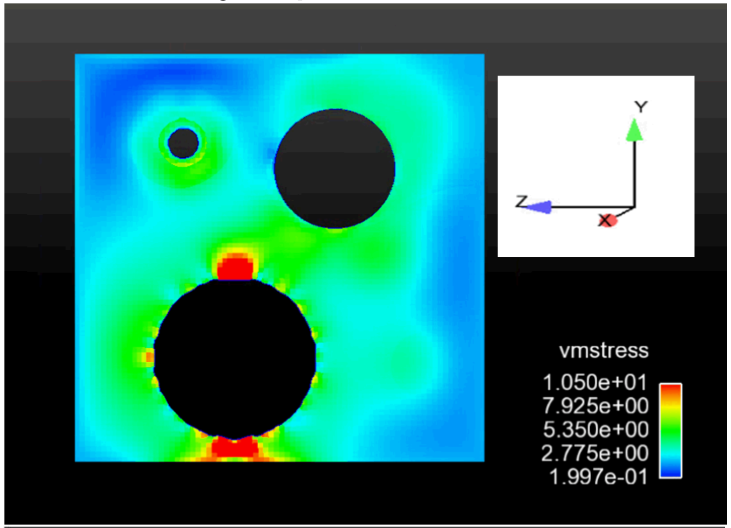
Matrix von Mises Stress--Macroscale

Matrix von Mises stress in y-z plane at x=0

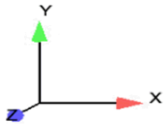
Uniaxial Strain in x-Direction

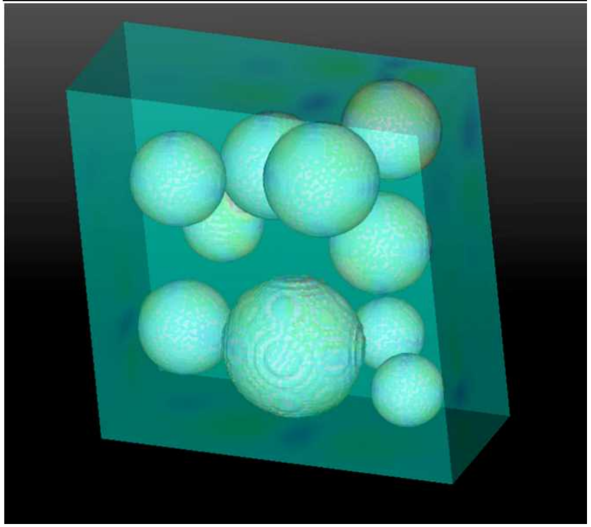


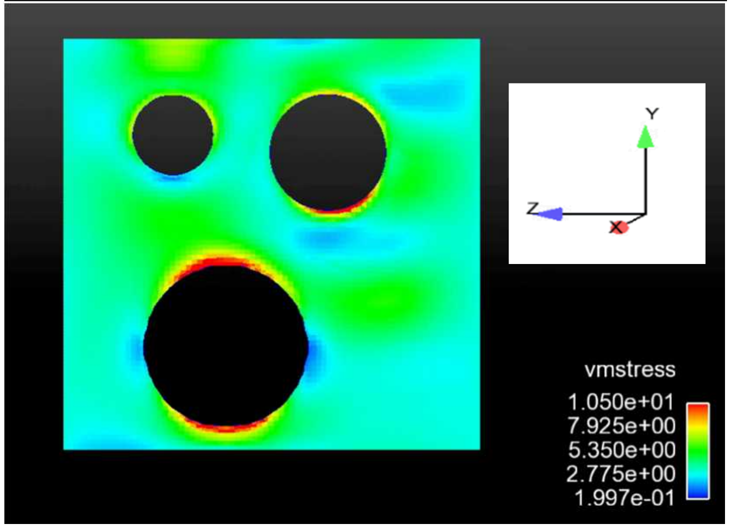




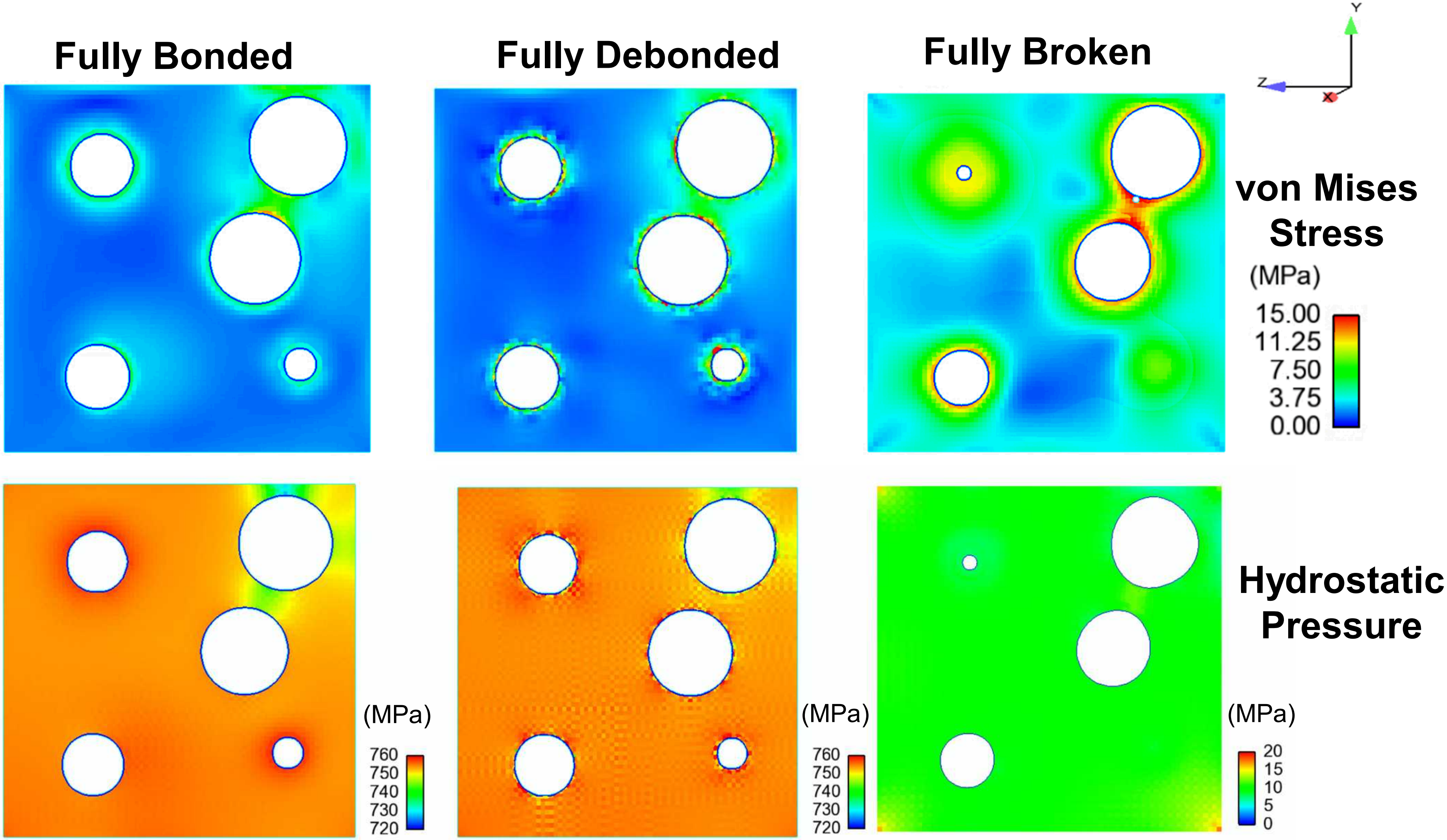
Shear in x-y Plane







Local Matrix Stresses: Uniaxial Strain



Deformed shapes amplified by 5×10^4 for visualization