SAND2019-6258C

Digital Volume Correlation with Fragile Speckle Patterns: Damage in Syntactic Foams

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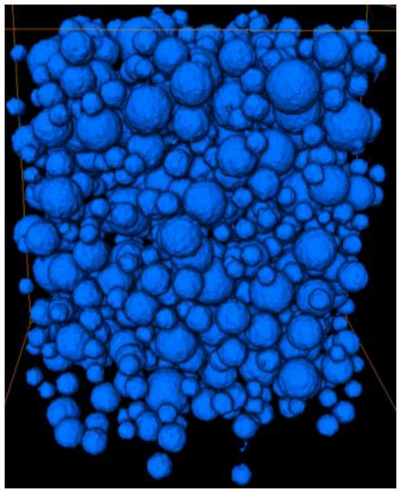
This research is supported by Sandia National Laboratories. Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC., a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA-0003525.

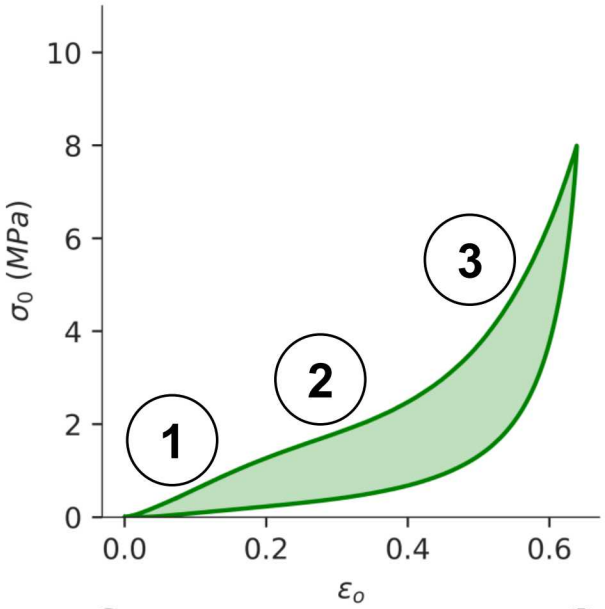
Introduction

Syntactic foams, DVC, and Sources of DVC error

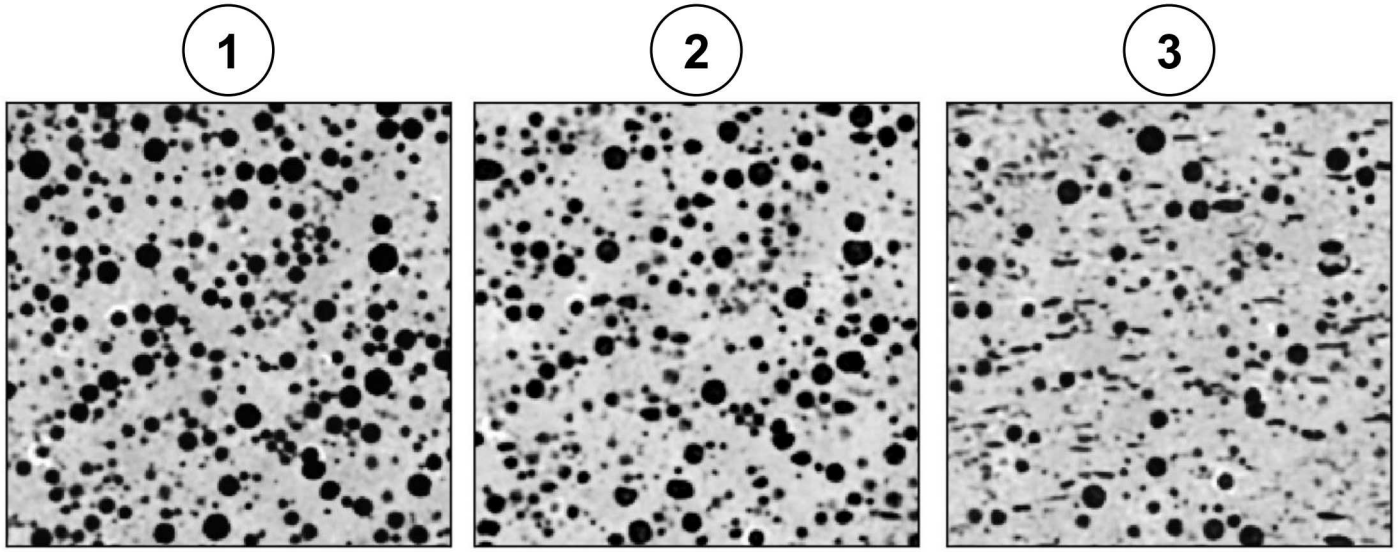
Syntactic Foams



500 μm

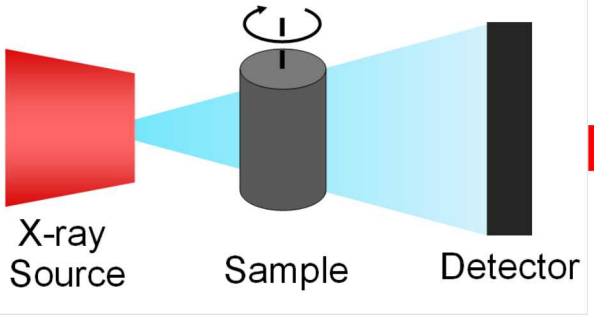


500 μm

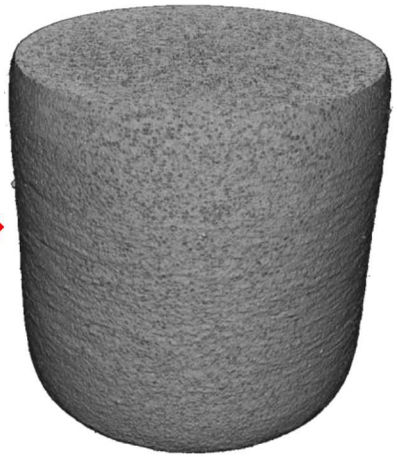


Digital Volume Correlation

In situ X-ray Computed Tomography



3D image



DVC

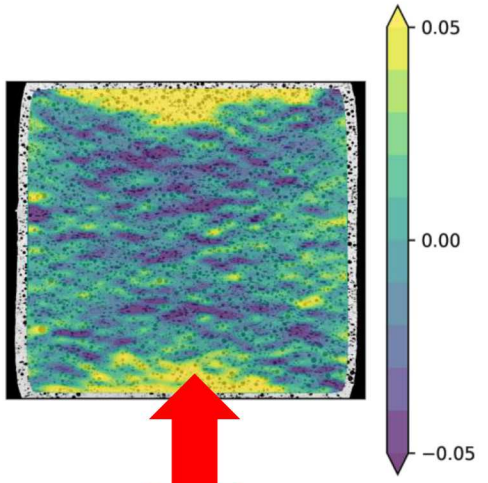
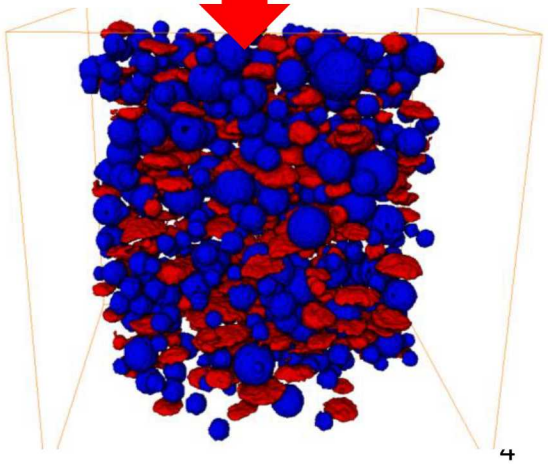
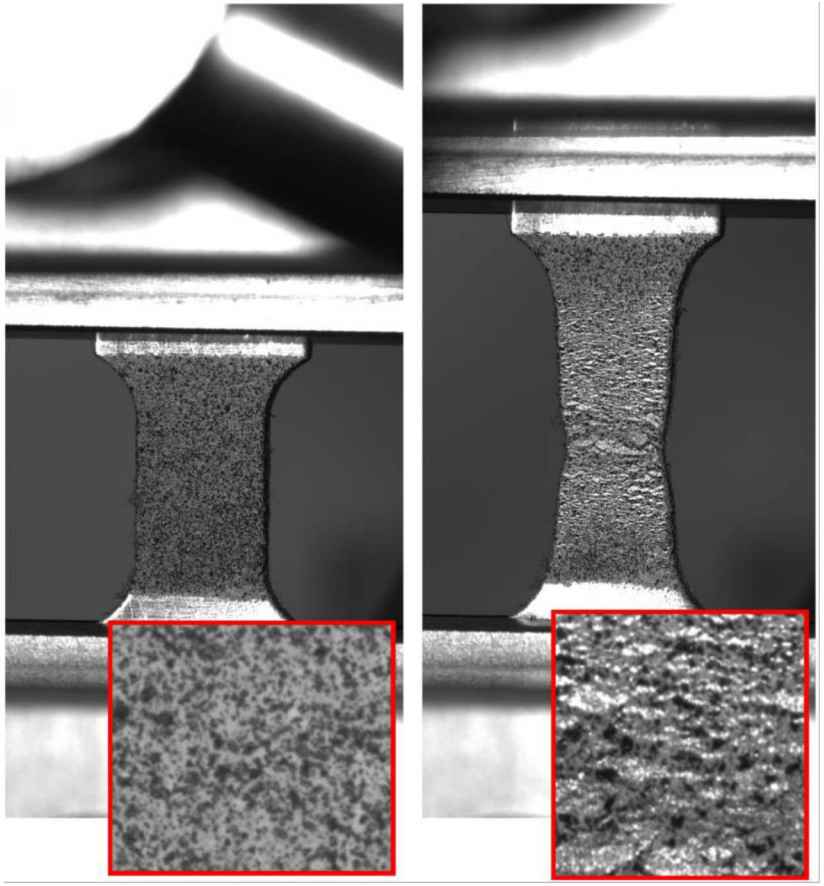


Image Processing

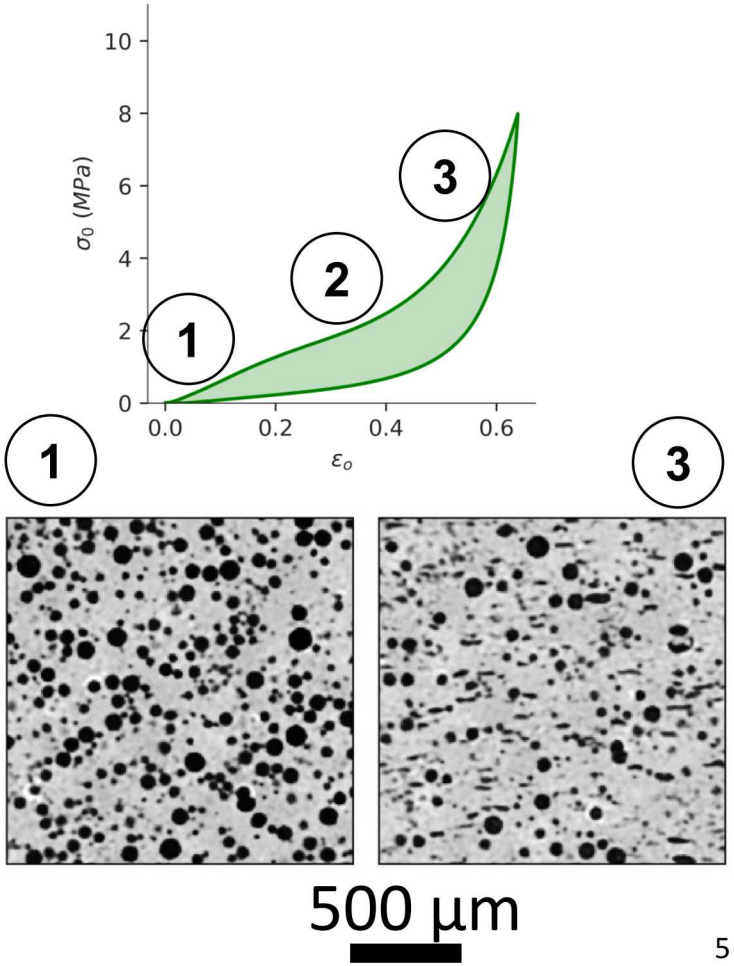


DVC in fragile speckle patterns

DIC tension of pure aluminum

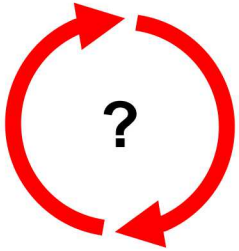


DVC compression test of syntactic foam



DVC in fragile speckle patterns

DVC tracks
deformation due to
damage mechanisms



Damage hinders
accurate DVC

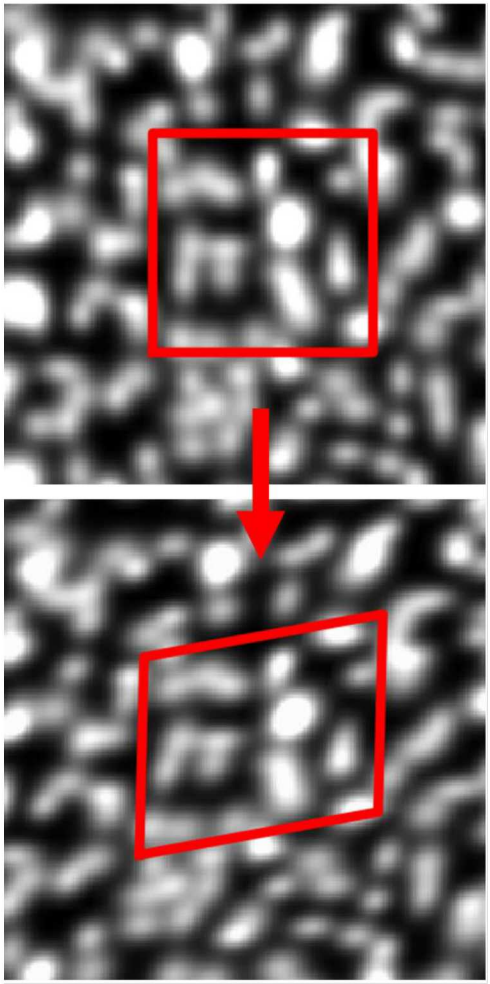
DVC in fragile speckle patterns

Objectives:

1. How sensitive are displacement + strain measurements to damage / decorrelation?
2. How can we improve the *robustness* of DVC measurement to damage?
3. Use DVC to quantify the damage mechanics of syntactic foams

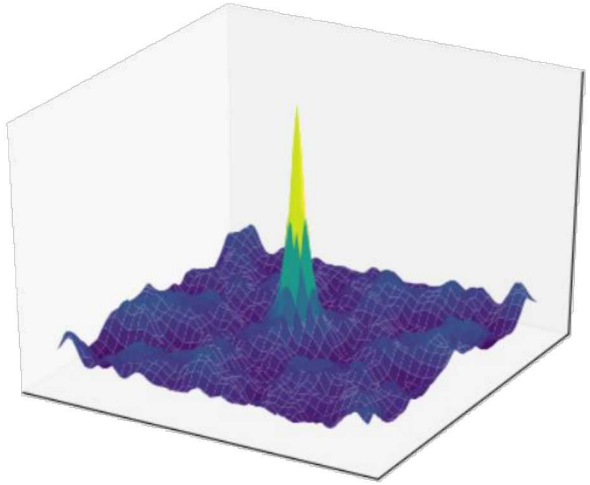
Digital Volume Correlation

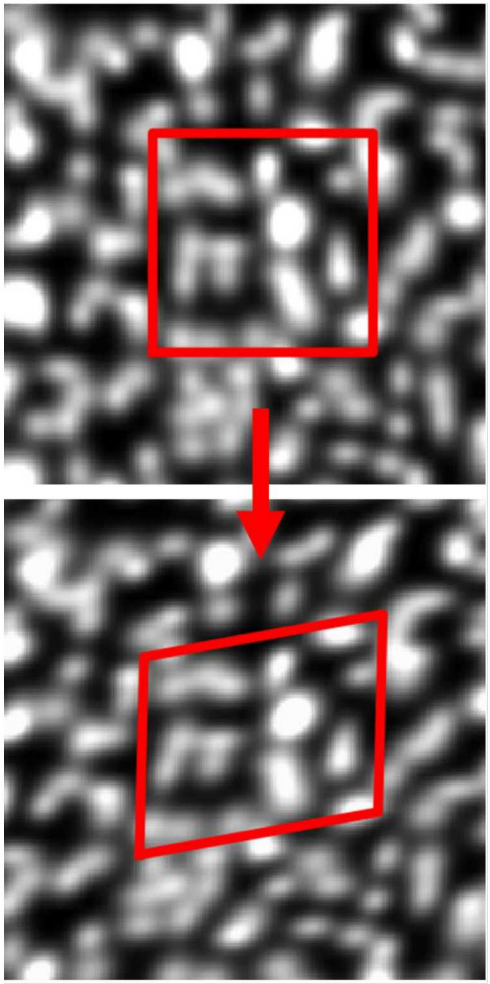
DVC is a texture-tracking operation



Digital Volume Correlation

$$\chi(\boldsymbol{x}) = \frac{1}{N} \sum_{\boldsymbol{x} \in S} \left(F(\boldsymbol{x}) - G\left(\boldsymbol{x} + \boldsymbol{u}(\boldsymbol{x})\right) \right)^{\mathbf{2}}$$

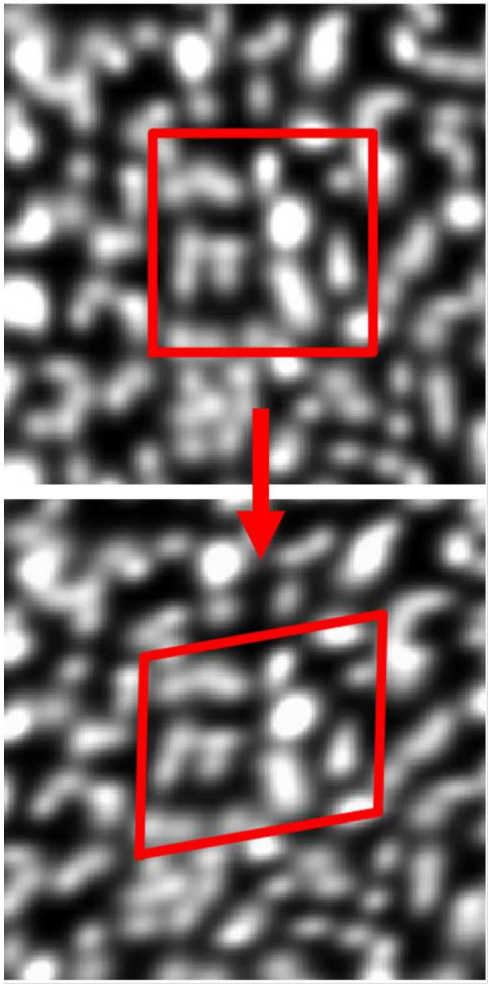




Digital Volume Correlation

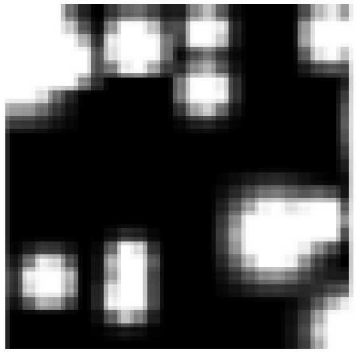
Microstructure should be:

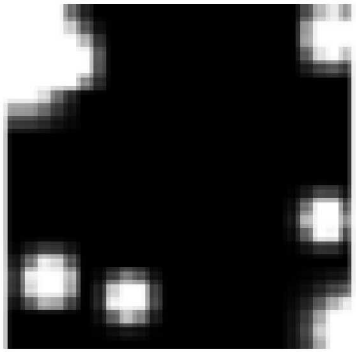
- Random
- High contrast
- Isotropic
- Durable



Digital Volume Correlation

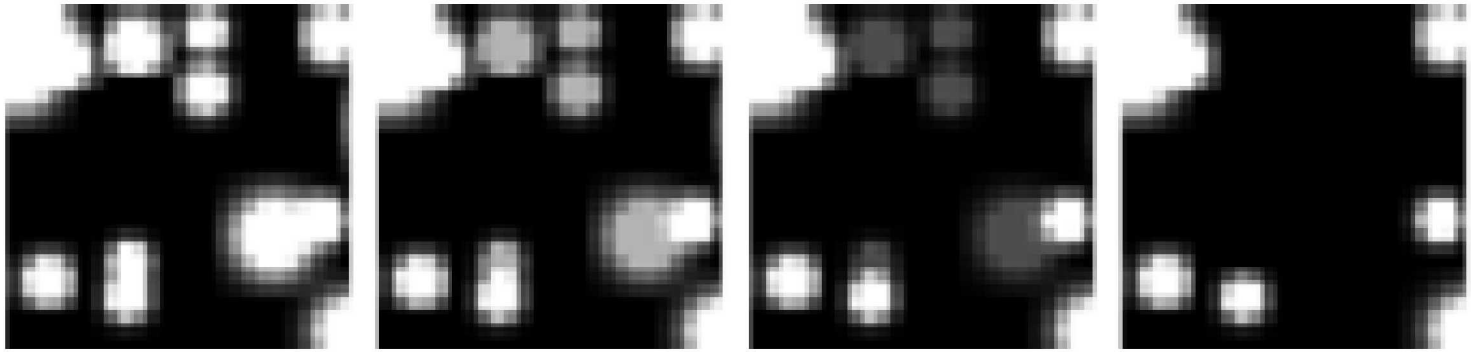
How confident are we that these are the same subset?





Digital Volume Correlation

How confident are we that these are the same subset?



Increasing Damage

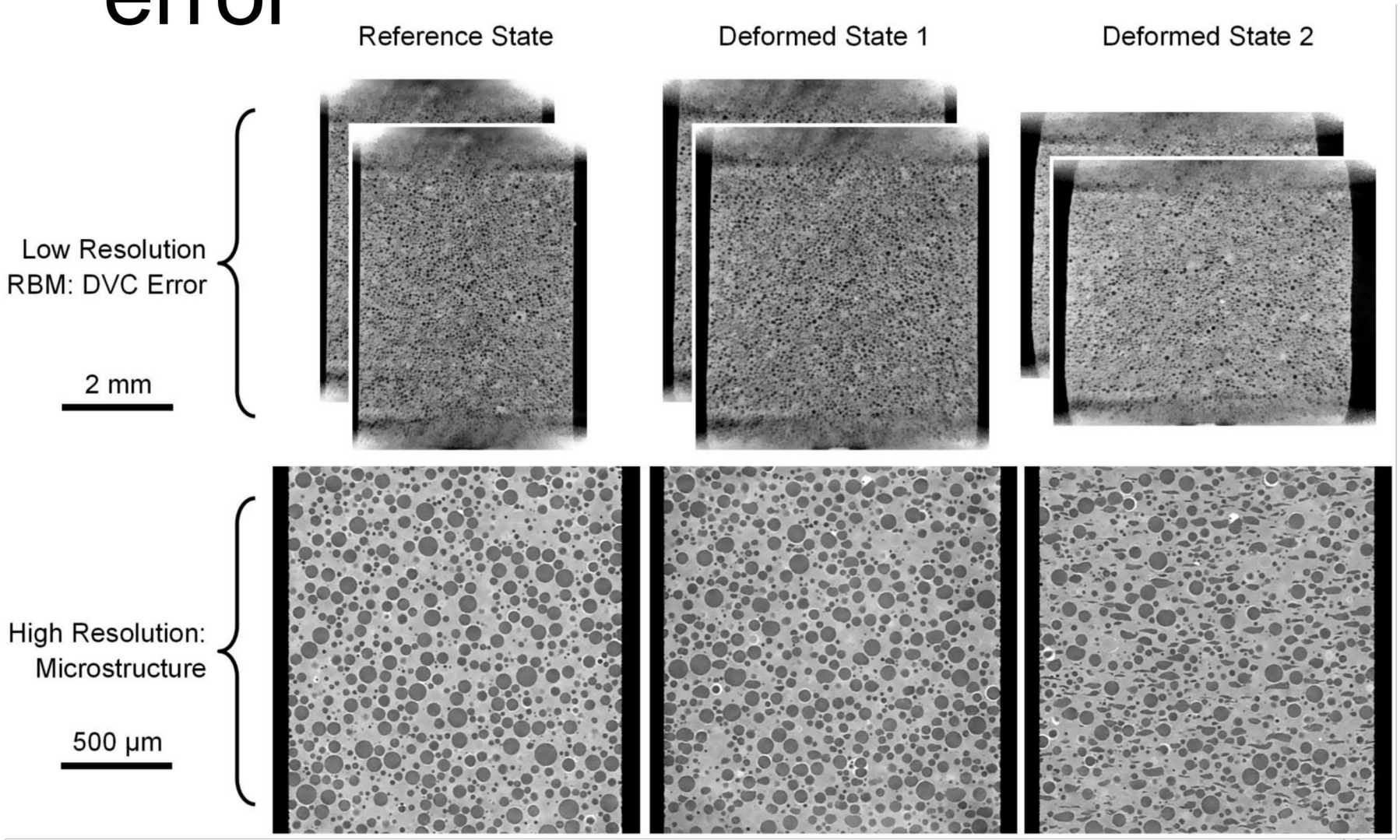
DVC accuracy with fragile speckle patterns

Research approach

1. Experimental: Rigid body motion experiments
2. Theoretical: Reconcile with error models
3. Numerical: Generate images with controlled damage (not included)

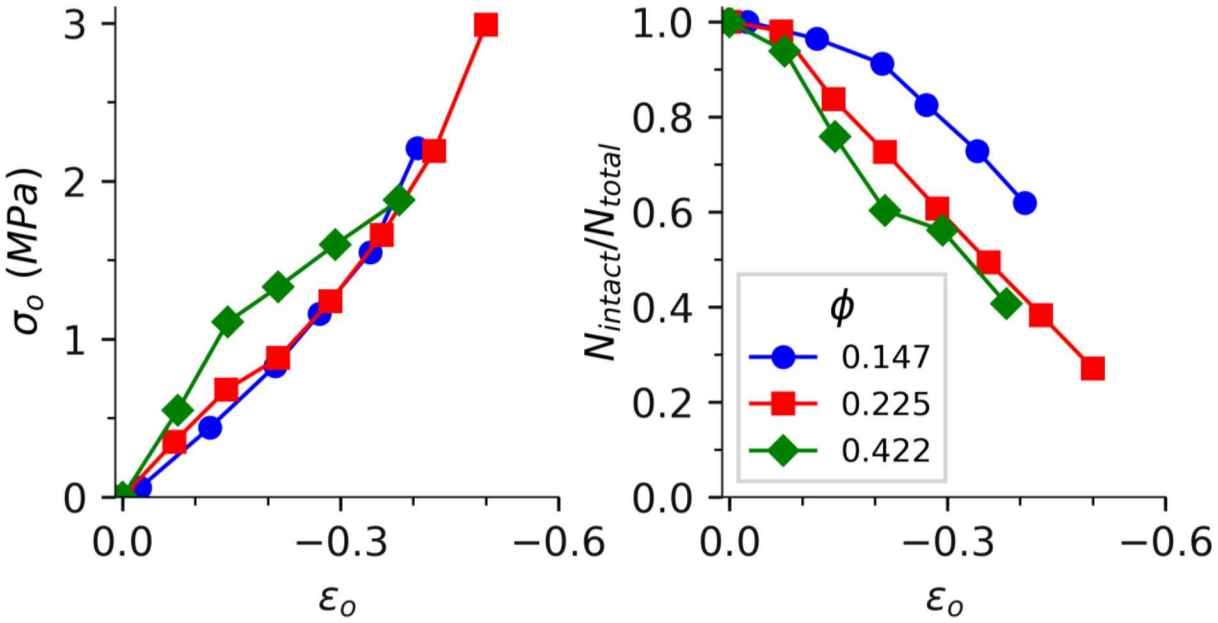
Experimental error assessment

Experimental assessment of error



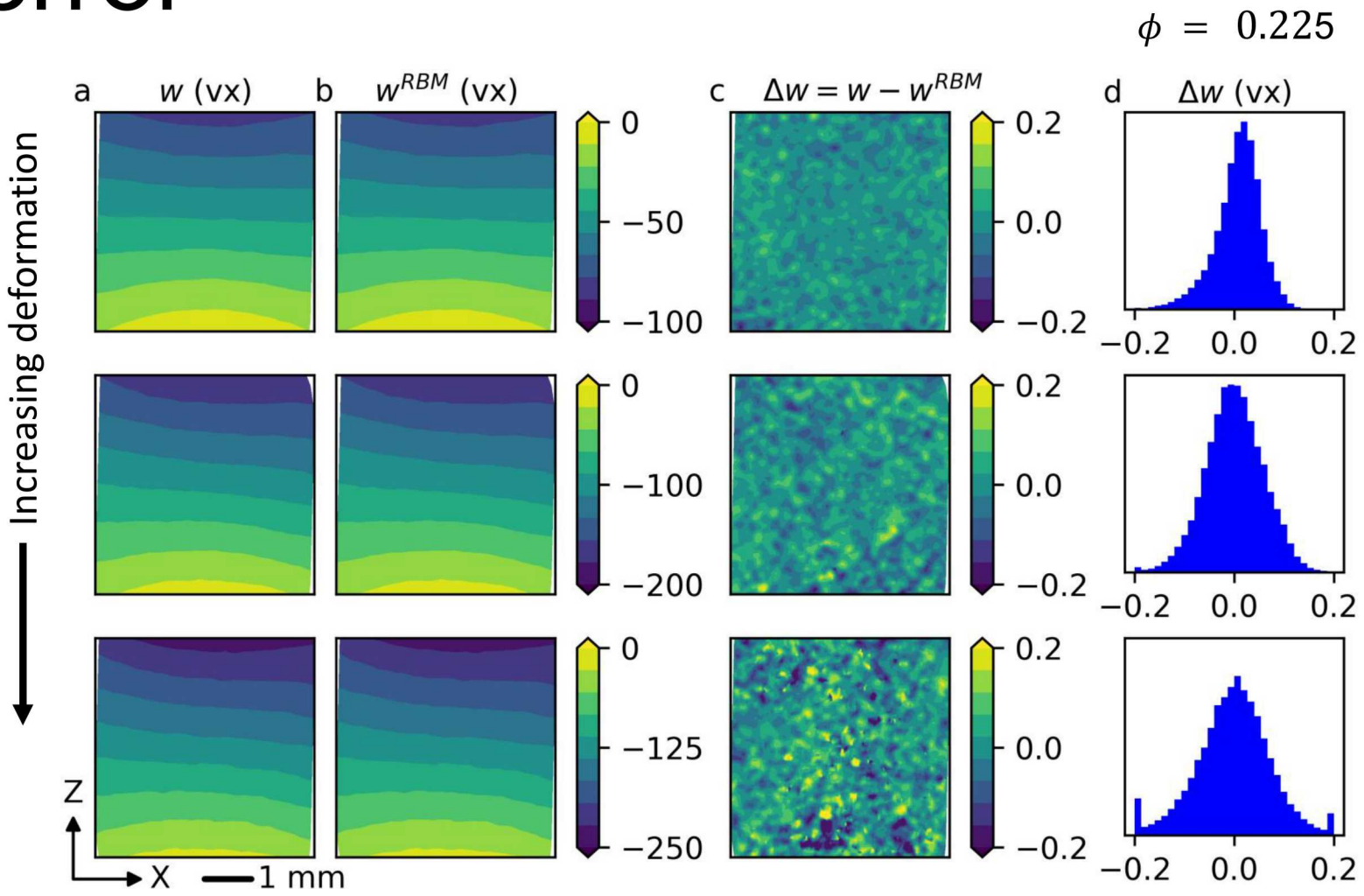
Experimental assessment of error

ϕ = Volume Fraction



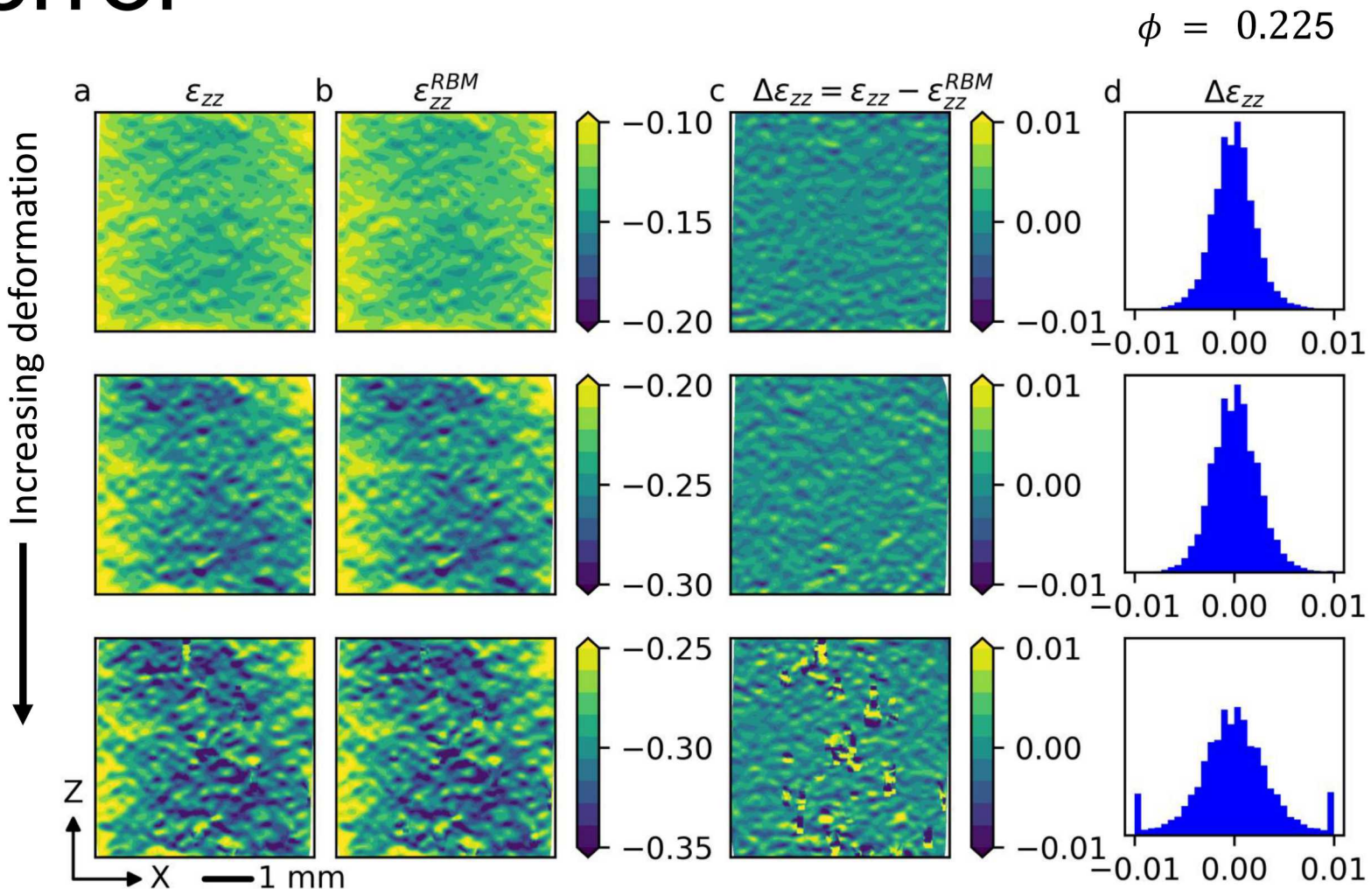
Croom, *Experimental Mechanics*, in press

Experimental assessment of error



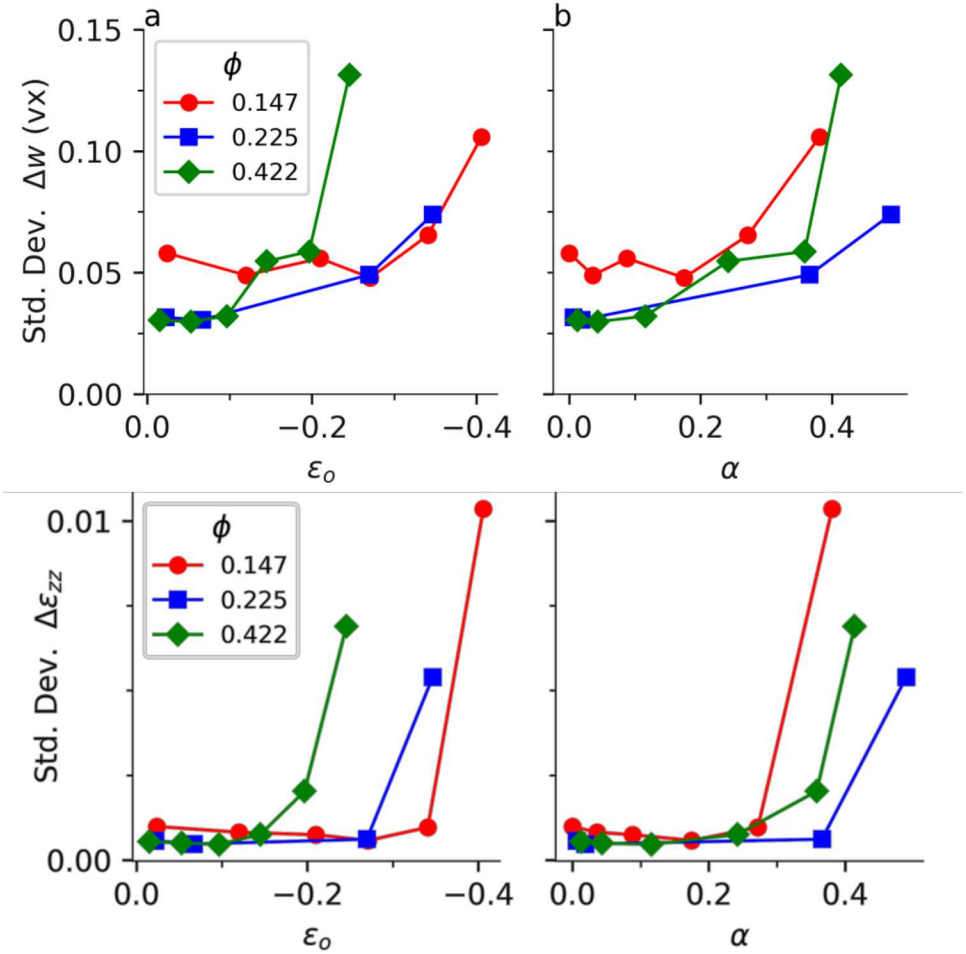
Croom, *Experimental Mechanics*, in press

Experimental assessment of error



Croom, *Experimental Mechanics*, in press

Experimental assessment of error



ϕ = Volume Fraction
α = % damaged speckles

Croom, *Experimental Mechanics*, in press

Experimental conclusions

- Error nonlinearly depends on speckle pattern damage
- Error decreases with increasing *volume fraction* (more speckles = better)

Theoretical error assessment

Theoretical error assessment

Can we reconcile with common DIC/DVC error models?

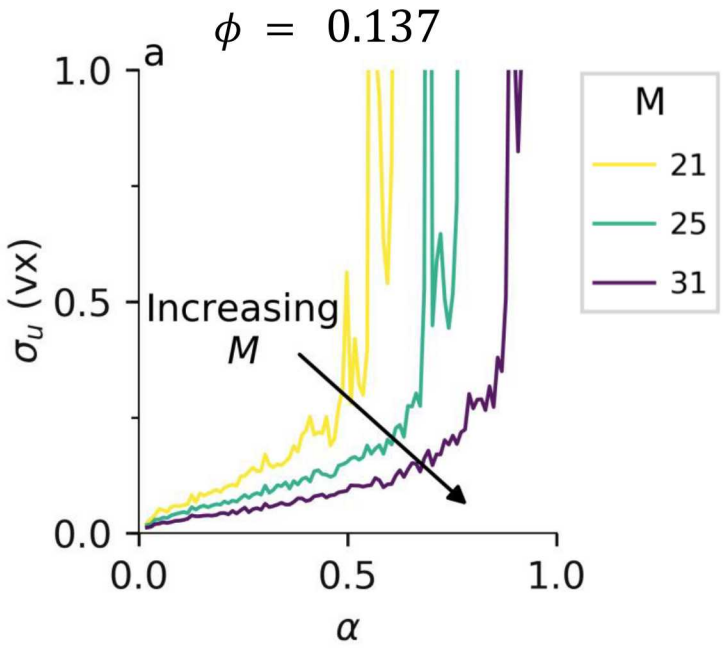
SSSIG metric
(Subset sum of squared intensity gradient)

$$\sigma_{u_i} \propto \left(\frac{D(\eta)}{\Sigma_S \left(\frac{\partial G}{\partial x_i} \right)^2} \right)^{0.5}$$

Pan, *Optics Express*, 2008

Theoretical error assessment

- SSSIG asserts similar relationships with subset size M and volume fraction ϕ



$$\sigma_{u_i} \propto \left(\frac{D(\eta)}{\sum_S \left(\frac{\partial G}{\partial x_i} \right)^2} \right)^{0.5}$$

Theoretical error assessment

Can we reconcile with common DIC/DVC error models?

Assumptions:

- Uniform speckle size, shape and contrast
- Non-overlapping speckles
- Uniform spacing of speckles can be characterized by a wavelength λ
- Cubic subsets of size M
- Consistent, independent noise for each voxel

$$\sum_S \left(\frac{\partial G}{\partial x_i}\right)^2 = N_{intact} \cdot \mathcal{G}_i$$

$$N_{particles} = \left(\frac{M}{\lambda}\right)^3$$

$$N_{intact} = (1-\alpha)\left(\frac{M}{\lambda}\right)^3$$

$$\mathcal{G}_i = \sum_S \left(\frac{\partial I_{speckle}}{\partial x_i}\right)^2$$

Theoretical error assessment

Can we reconcile with common DIC/DVC error models?

$$\sigma_u \propto \left(\frac{D(\eta)}{\sum_S \left(\frac{\partial G}{\partial x_i} \right)^2} \right)^{0.5} = \left(\frac{D(\eta)}{N_{intact} \cdot \mathcal{G}_i} \right)^{0.5}$$

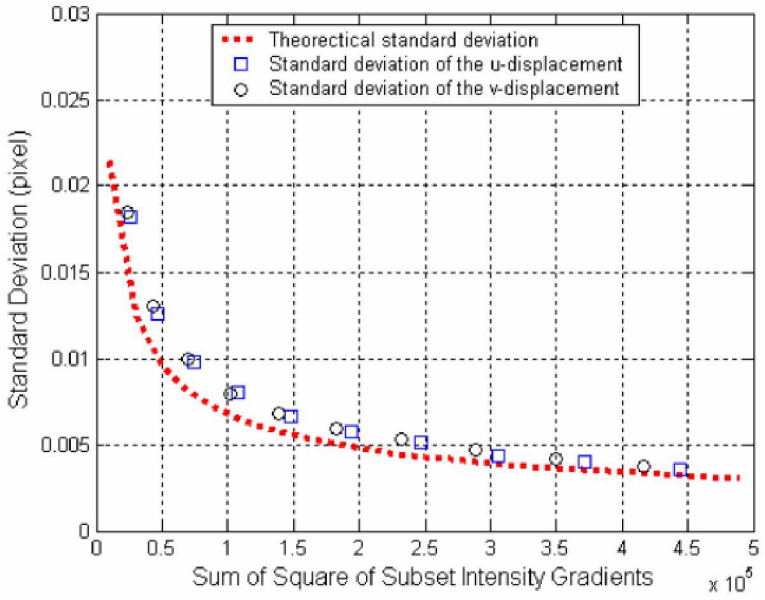
Error solely as a function of N_{intact}

- Independent of damage, subset size and volume fraction

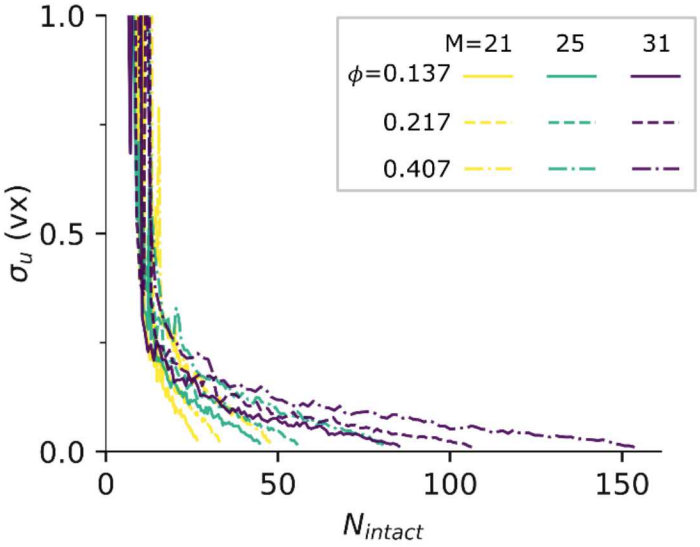
Theoretical error assessment

$$\sigma_u \propto \left(\frac{D(\eta)}{\sum_S \left(\frac{\partial G}{\partial x_i} \right)^2} \right)^{0.5} = \left(\frac{D(\eta)}{N_{intact} \cdot \mathcal{G}_i} \right)^{0.5}$$

ϕ = Volume Fraction
M = Subset Size



Pan, *Optics Express*, 2008



Croom, *Experimental Mechanics*, in press

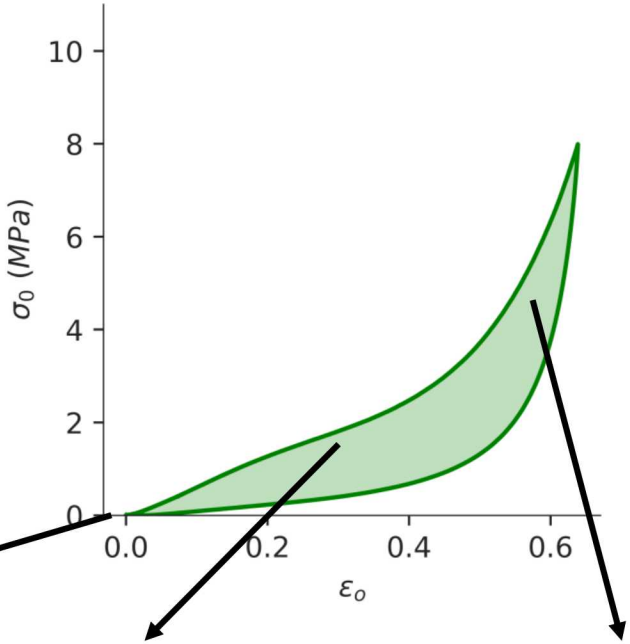
Theoretical

- Accurate DVC *is possible* in fragile microstructures
- Discovered two domains for DVC calculation:
  - Small damage = Stable = Near noise floor
  - Large damage = Unstable = Large error
- Reconciled with theories of DVC error (SSSIG metric)

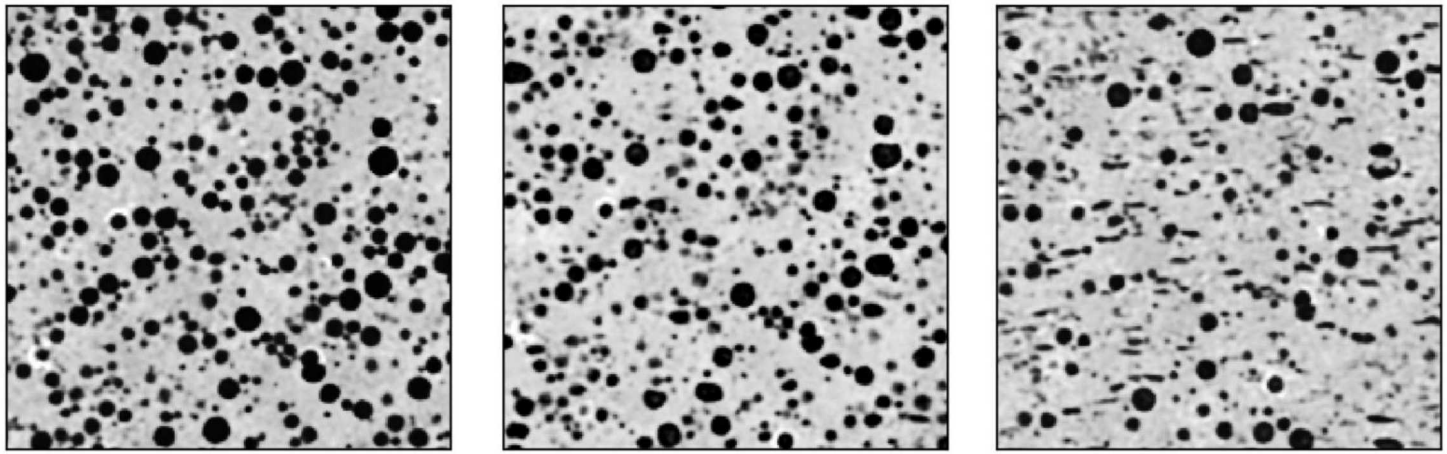
Damage micromechanisms in syntactic foams

Syntactic Foams

- GMB collapse causes three regions of deformation:
  - “Stiff” elastic region
  - “Plateau”
  - “Densification”



XCT slices:



500 µm

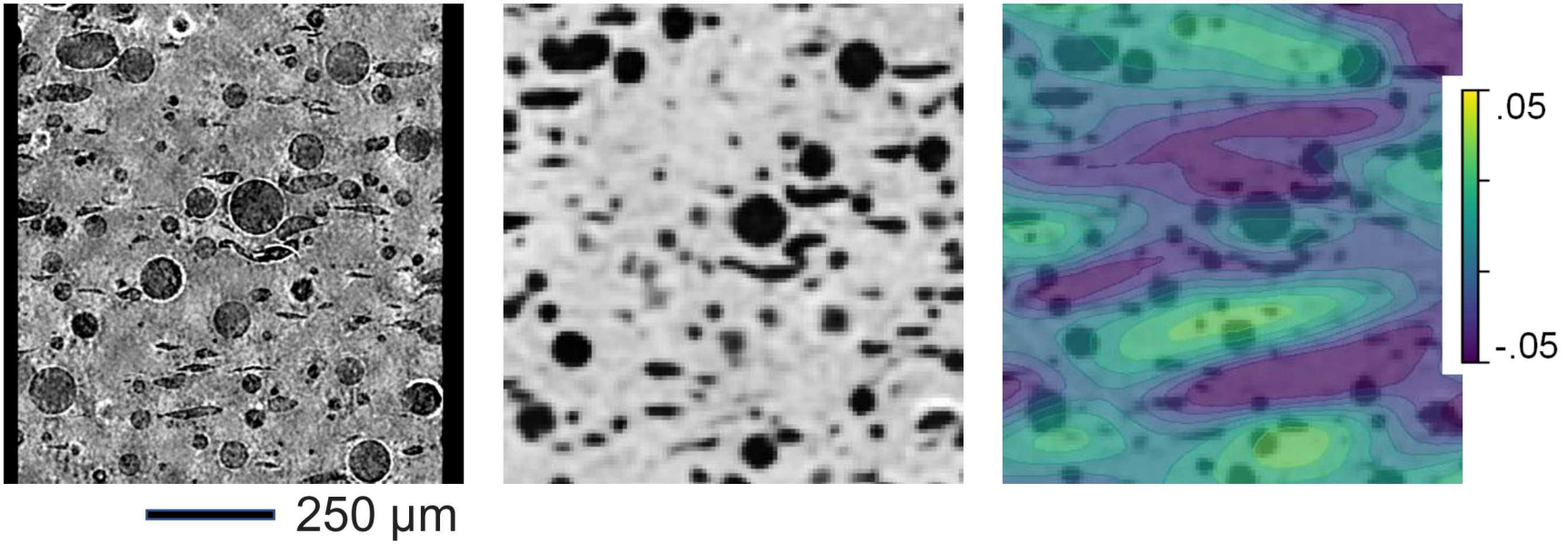
Research Questions

- When does damage initiate in the syntactic foam? How does damage propagate?
- What are the mechanisms of damage initiation and propagation?
- How does damage vary across specimen?

Relationship between DVC strain and GMB collapse

Mechanistically, GMB collapse reduces stiffness:

Results in locally amplified compression

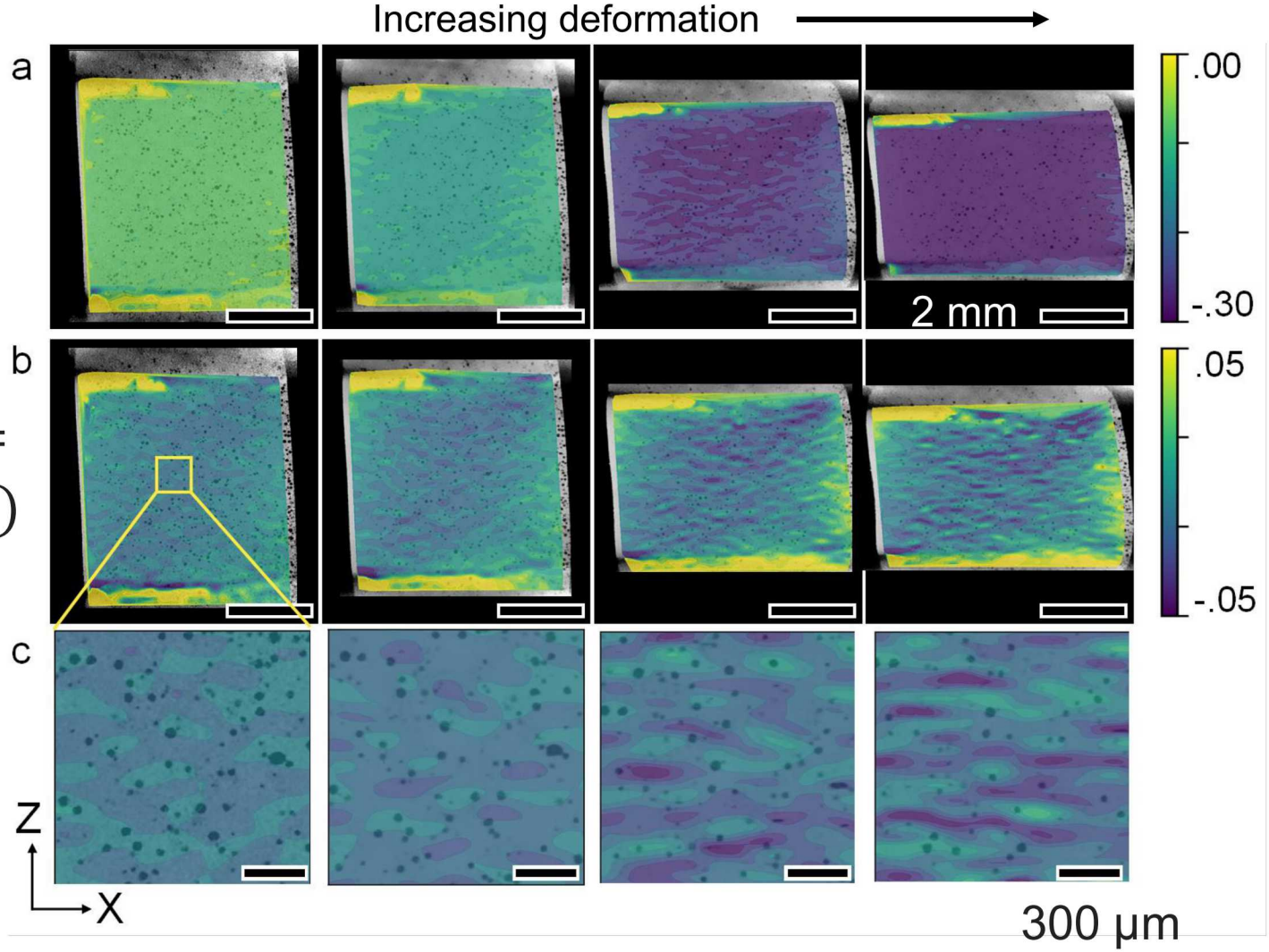


DVC results

$\phi = 0.10$

ε_{zz}

$\bar{\varepsilon}_{zz} = \varepsilon_{zz} - \mathrm{avg}(\varepsilon_{zz})$

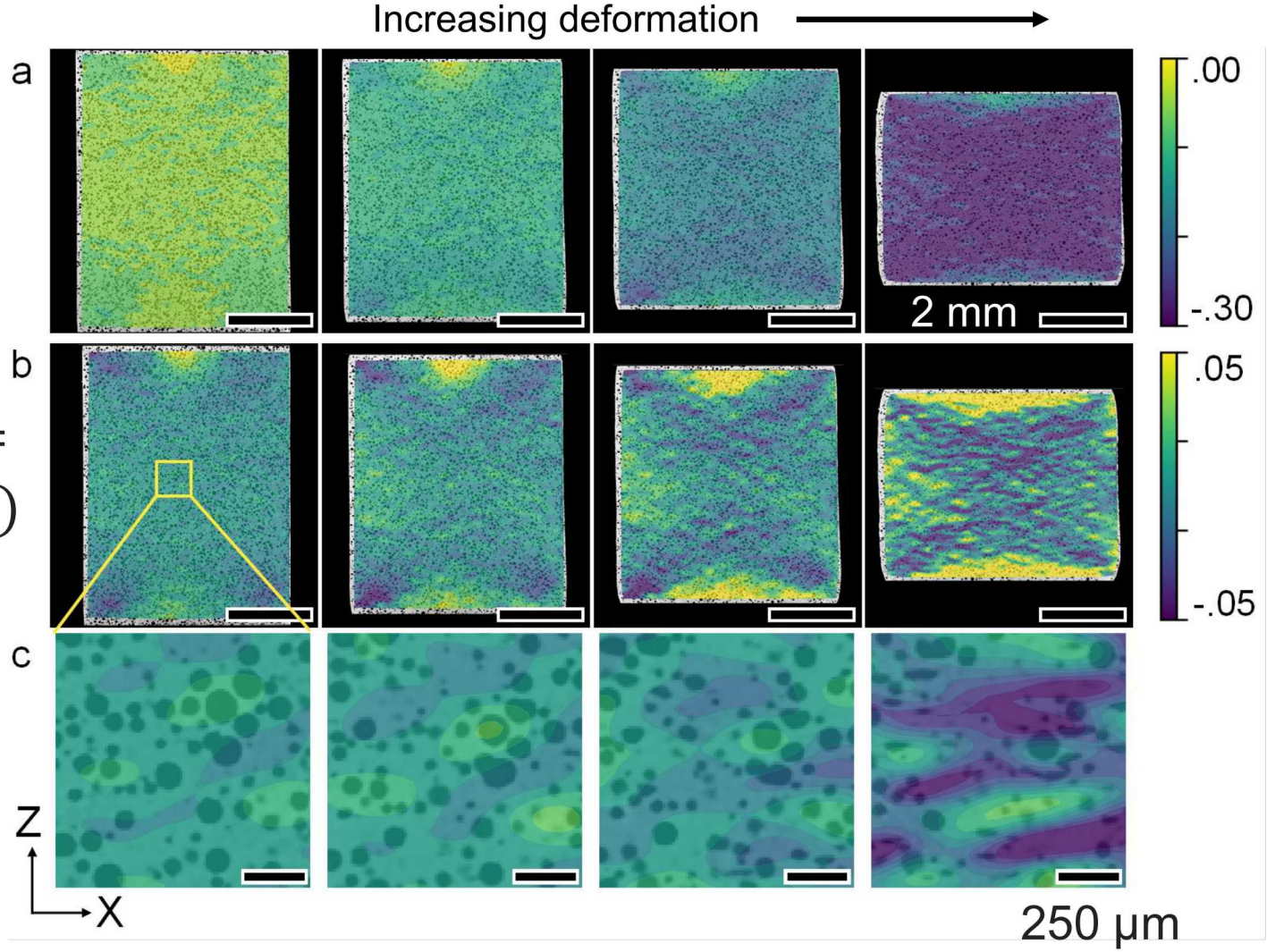


DVC results

$\phi = 0.37$

ε_{zz}

$\bar{\varepsilon}_{zz} = \varepsilon_{zz} - \mathrm{avg}(\varepsilon_{zz})$



Croom, *Comp. Sci. Tech*, 2019

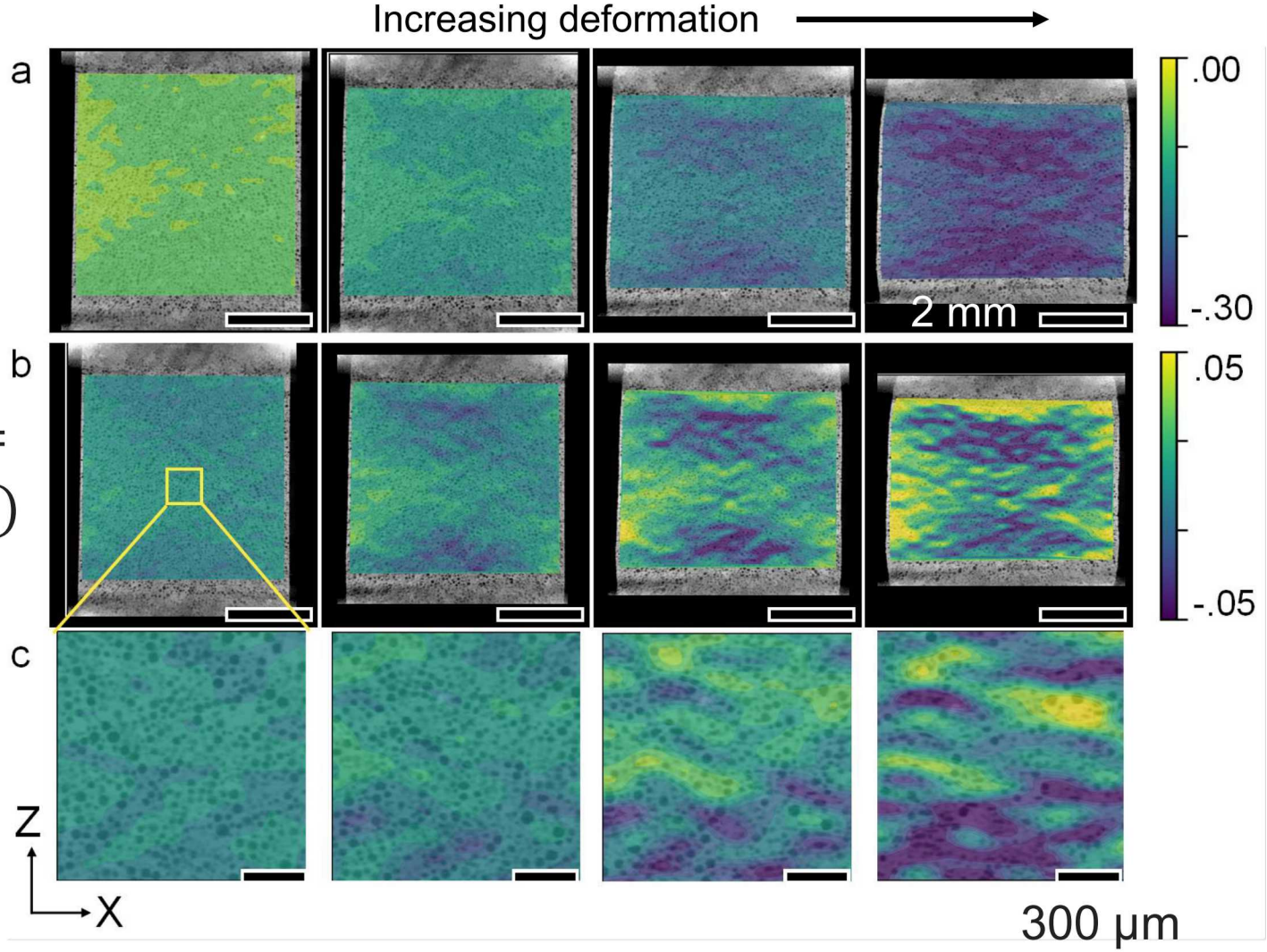
DVC results

$\phi = 0.46$

ε_{zz}

$\bar{\varepsilon}_{zz} = \varepsilon_{zz} - \mathrm{avg}(\varepsilon_{zz})$

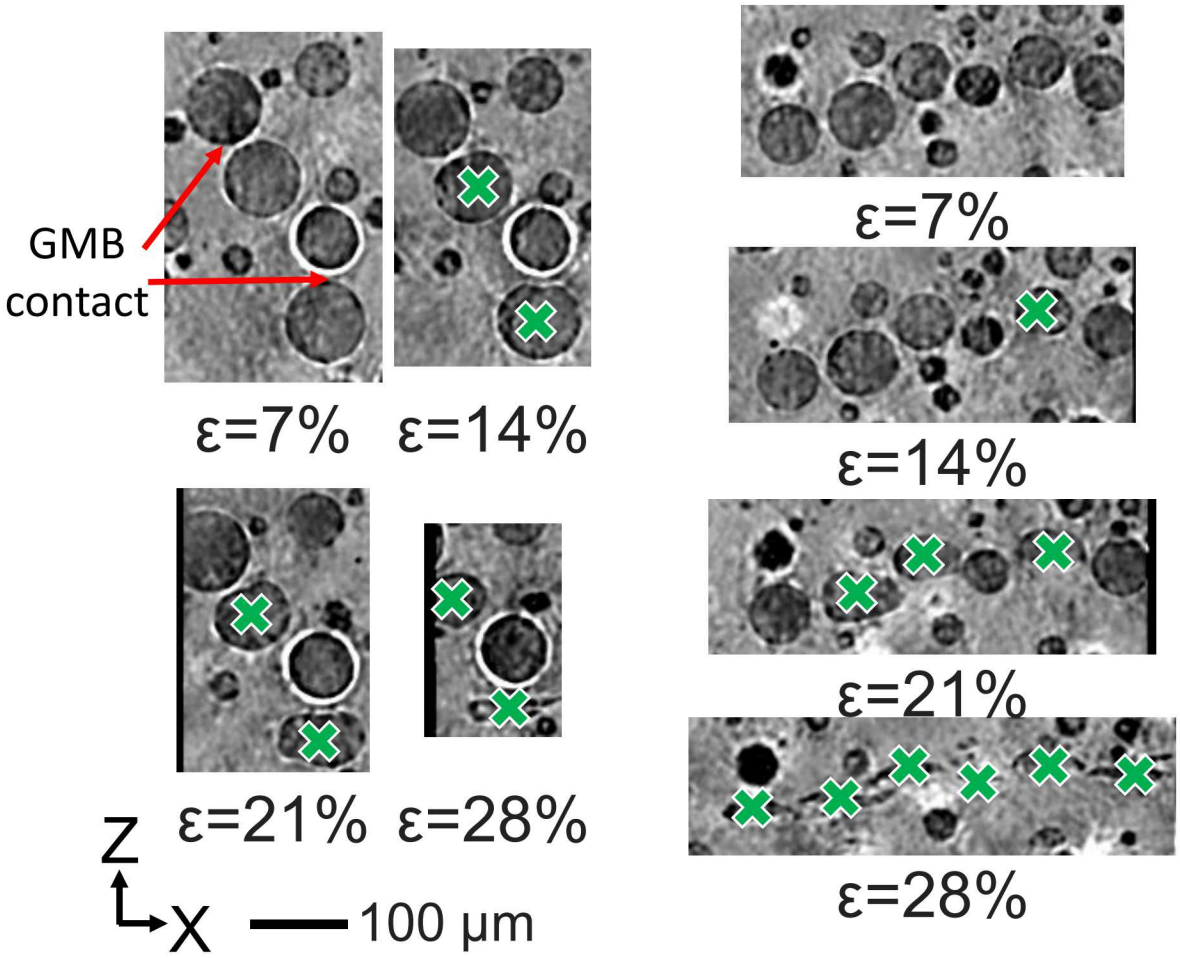
Strain variation is large in magnitude, forms large regions of GMB collapse



GMB Collapse: A closer look

$\phi = 0.37$

- Orientation of clusters DOES NOT affect damage ***initiation***
- But does affect damage ***propagation***

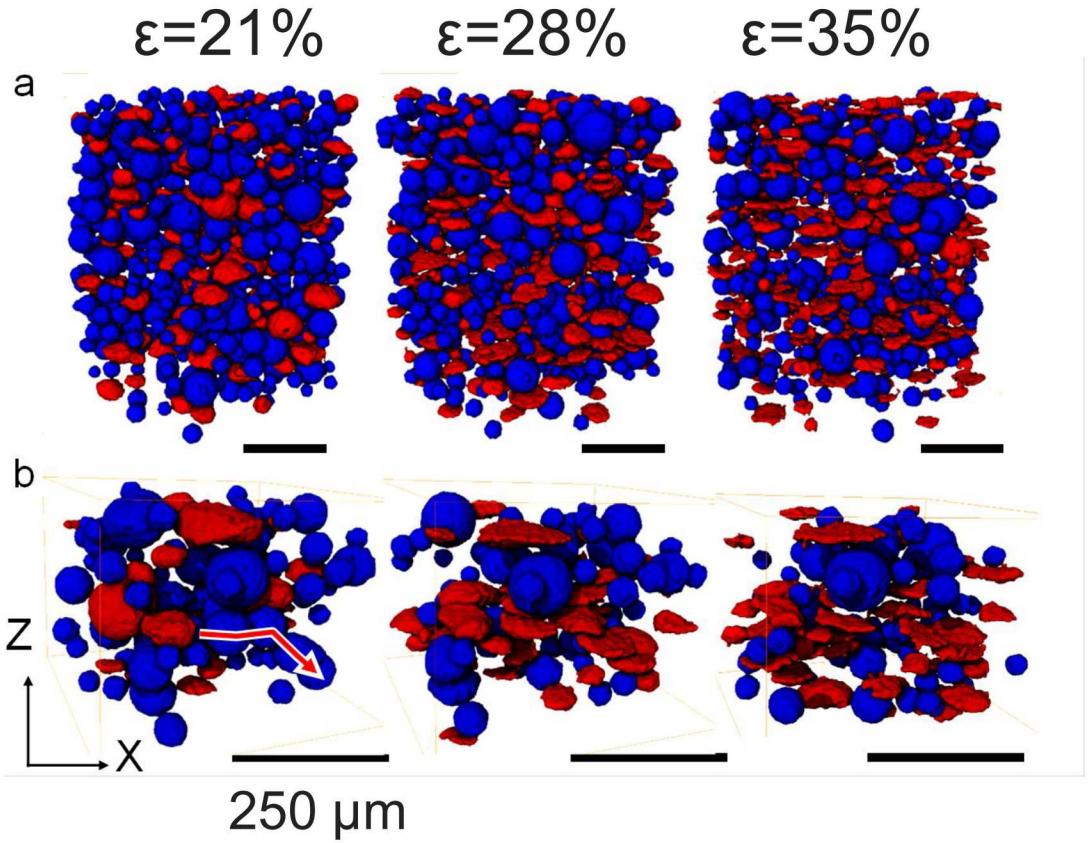


Croom, *Comp. Sci. Tech*, 2019

GMB Collapse: A closer look

$\phi = 0.37$

- Colored by Feret Shape (red = collapsed)



Croom, *Comp. Sci. Tech*, 2019

Mechanisms of damage propagation

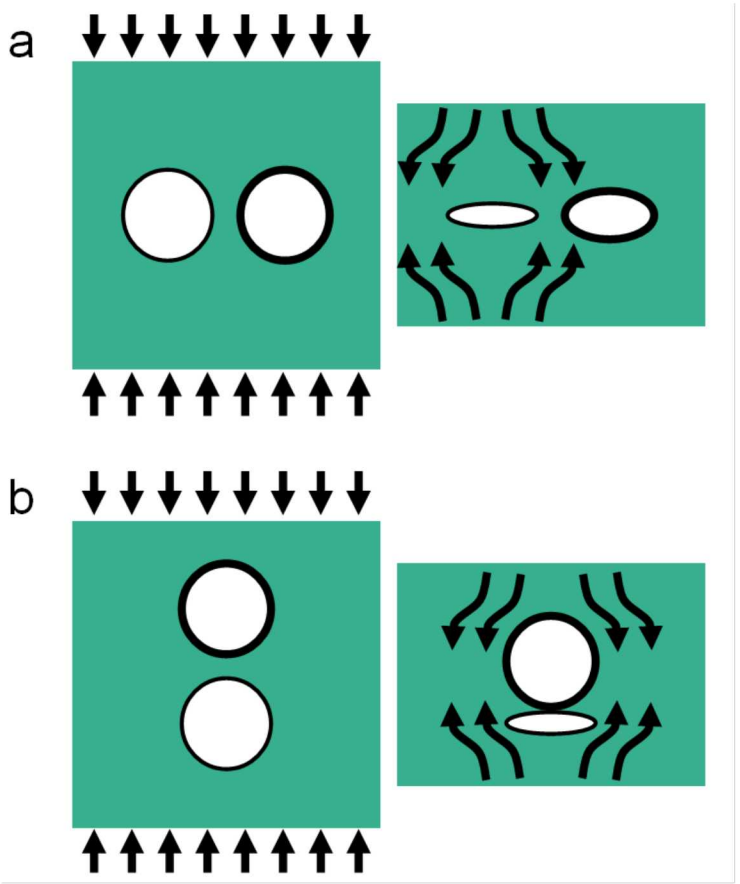
Orientation of nearest neighbors affects GMB damage:

Stress Intensifying

vs.

Stress Shielding

Do we observe these mechanisms at larger length scale?



Croom, *Comp. Sci. Tech*, 2019

Conclusions

- DVC is a quantitative tool to study long-range damage behavior in syntactic foams
- Complementary high-resolution scans reveal microscale GMB damage and collapse mechanisms
- *Stress intensifying* vs. *stress shielding* mechanism is postulated to form banded damage structures