New Ways to Look at the Fracture Processes in Concrete

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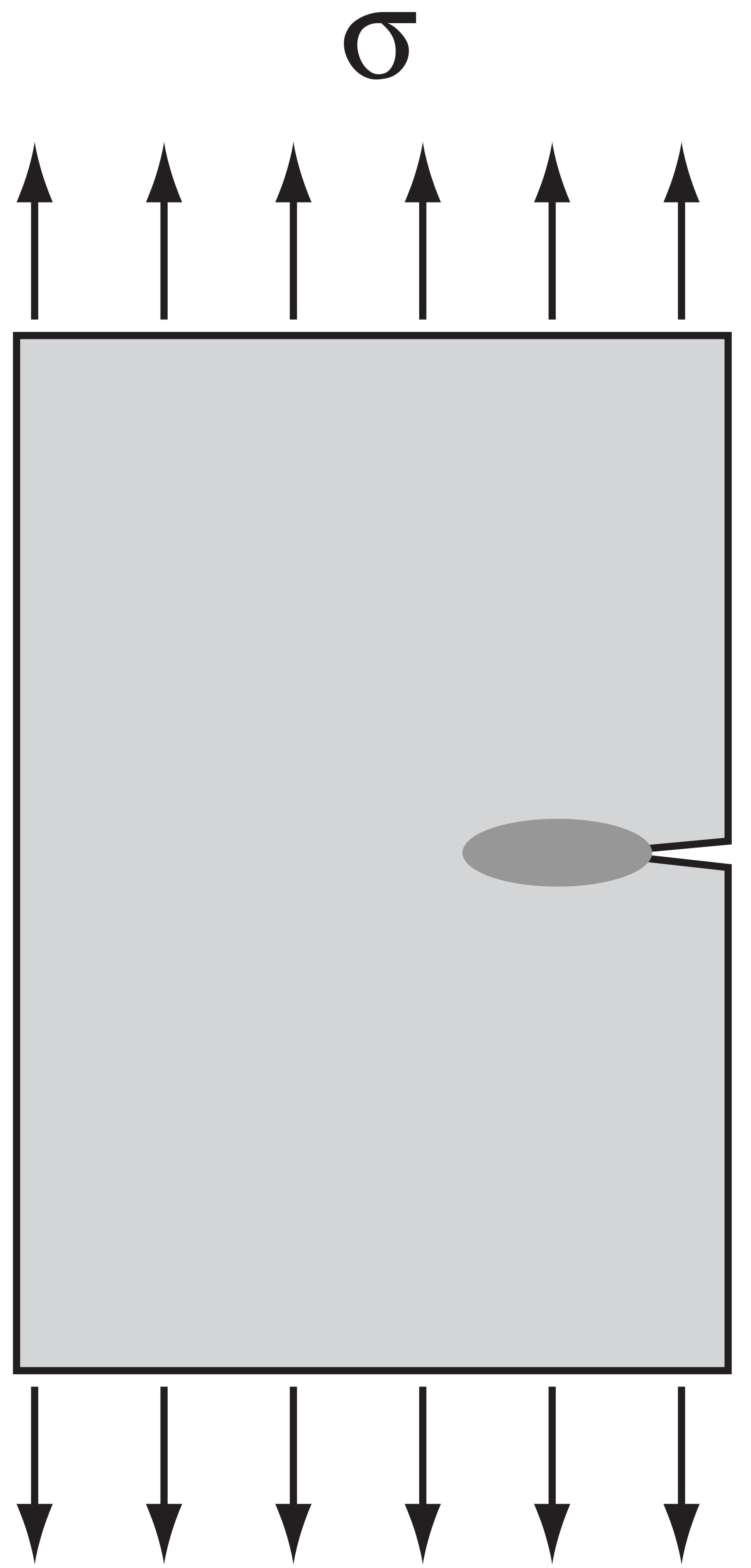
École des Ponts ParisTech

Imaging of Construction Materials and Geomaterials
École des Ponts Paris Tech
7-8 July, 2016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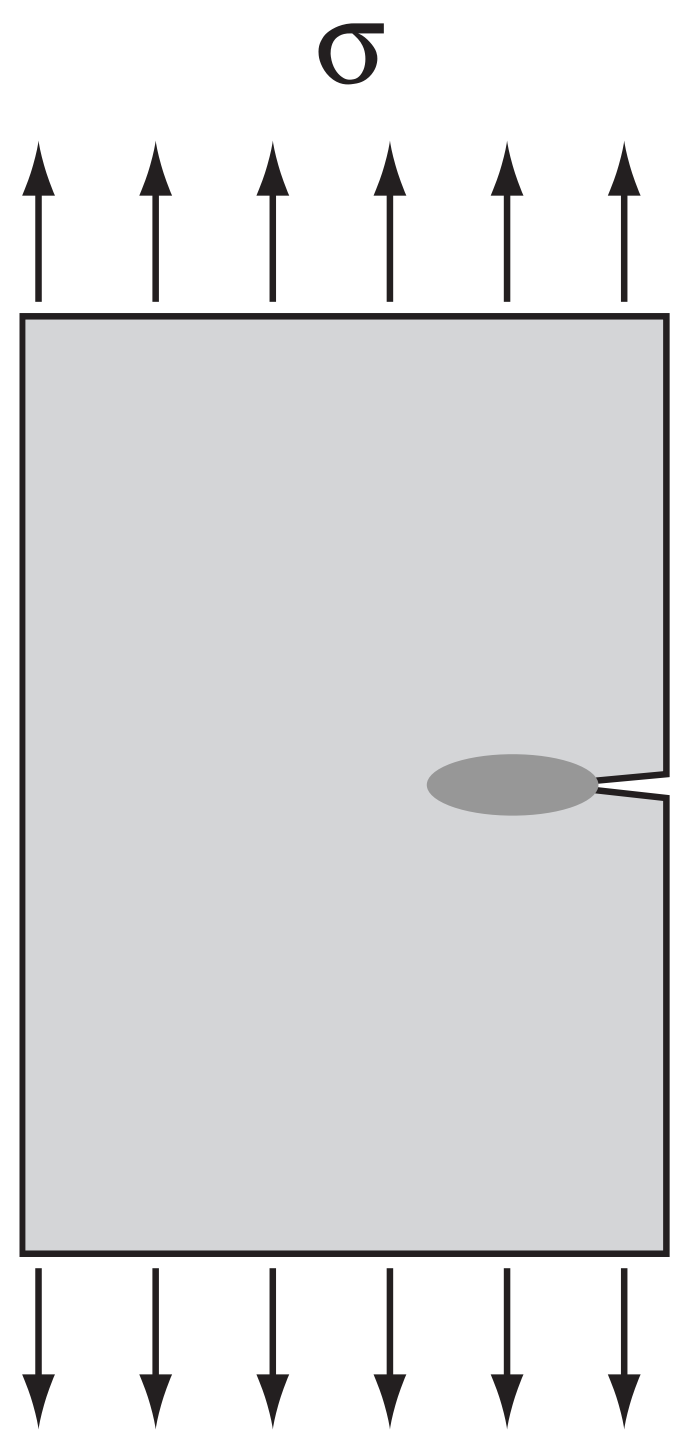
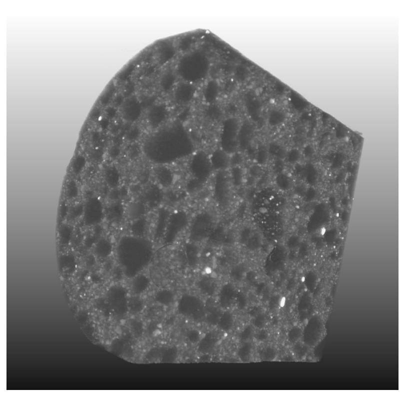
Fracture Process Zone Characteristics

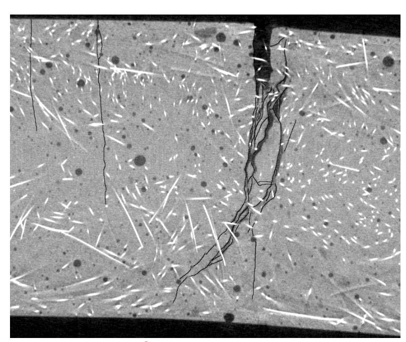
- Microcracking
- Aggregate interlocking
- Friction
- …

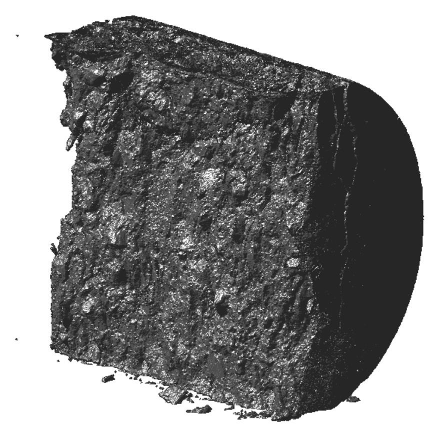


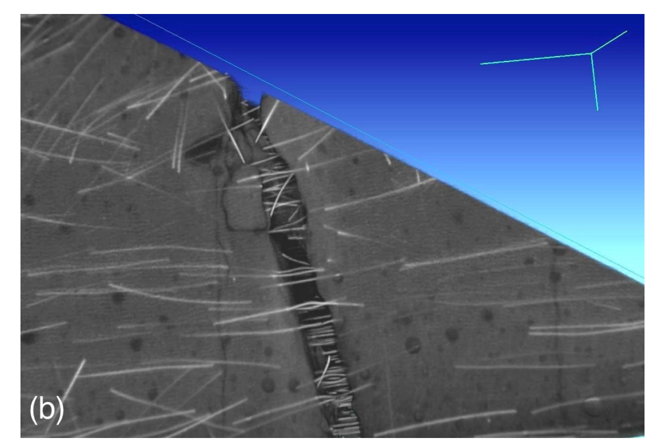
Aim of Work

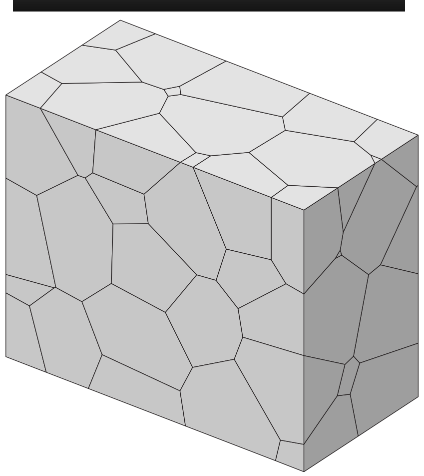
- Use our 3D "x-ray vision" to measure fracture processes that affect toughness (i.e. the fracture process zone).
  - *Measurements should be in form suitable for incorporation into mesoscale computational models.*

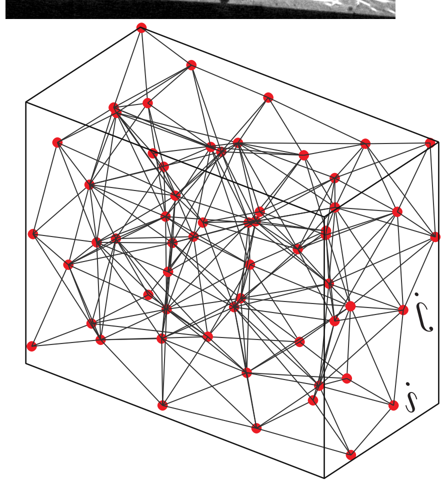




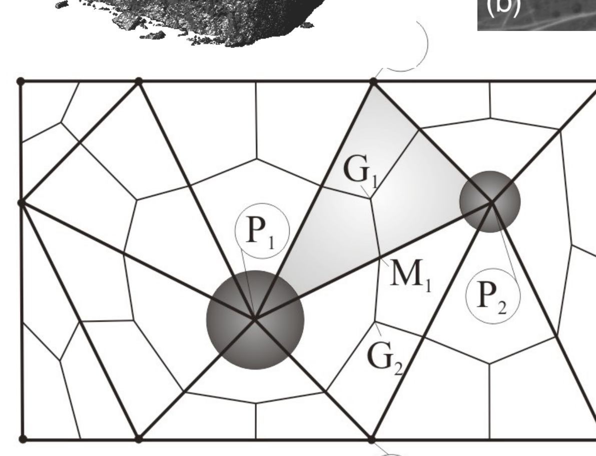




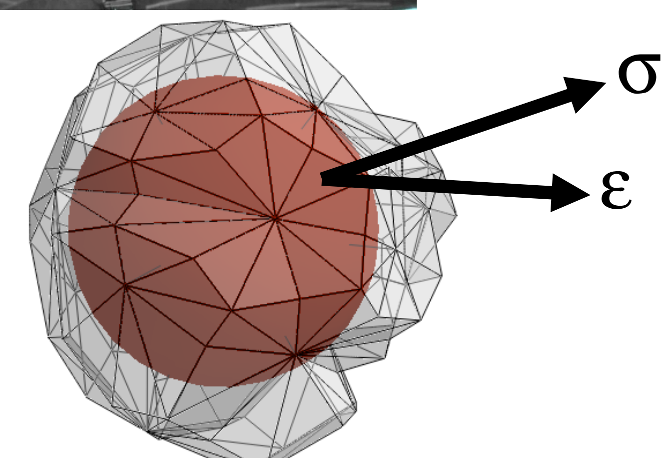




ref: John Bolander



ref: Gianluca Cusatis



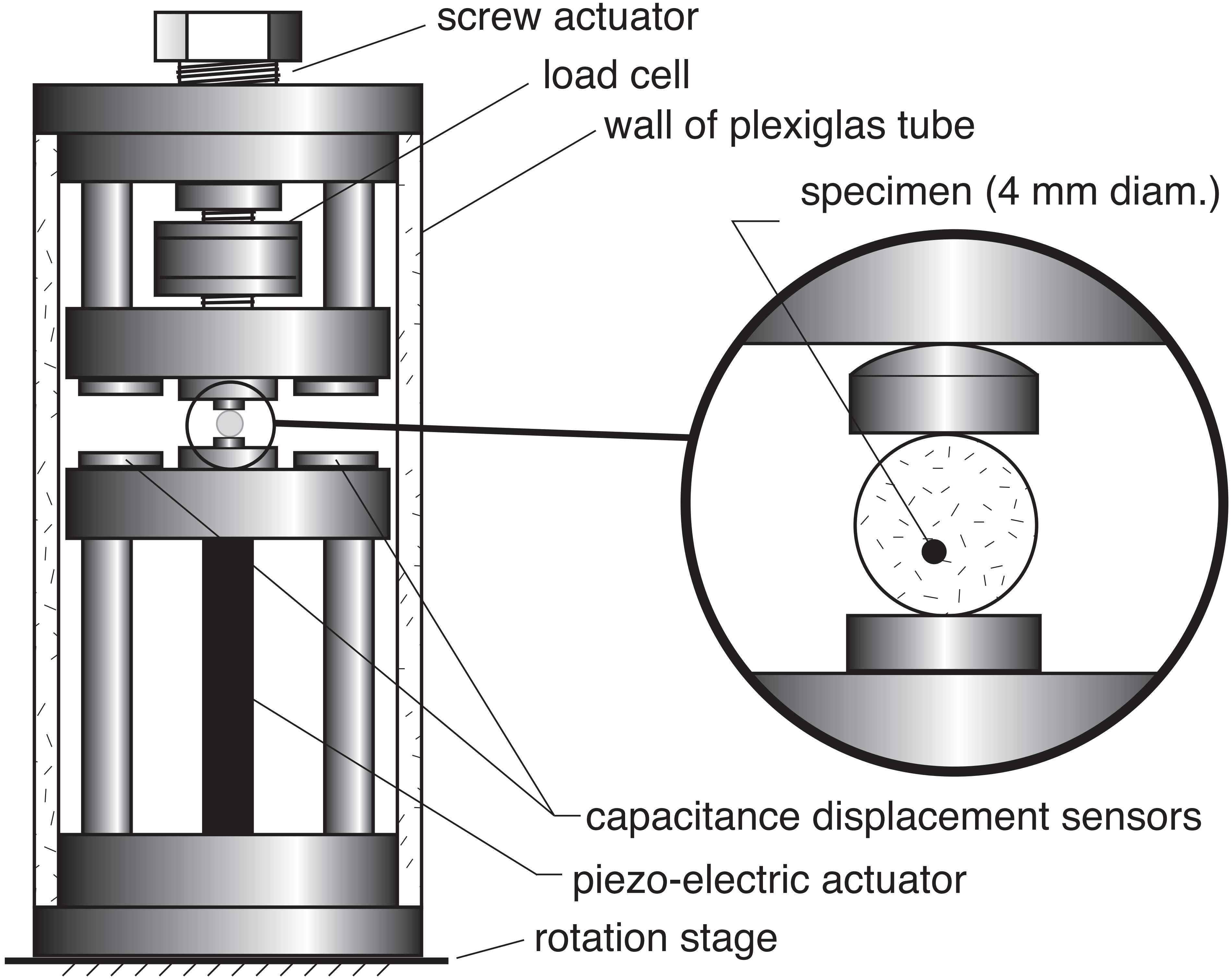
Outline

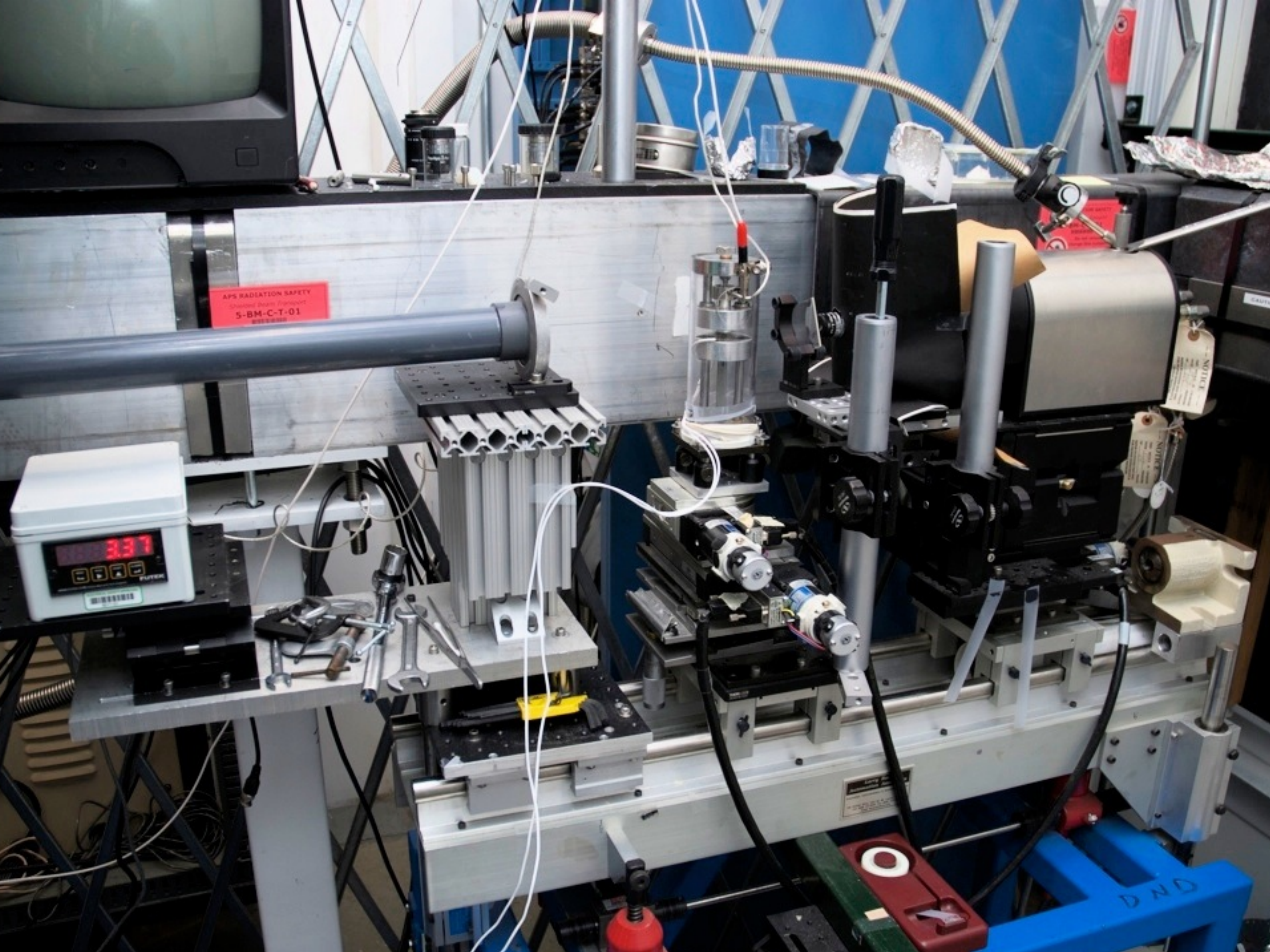
- Small scale *in situ* load tests of mortars using synchrotron source.
  - Alternate fracture energy measurements
  - Interfacial zone effects
- Mesoscale tests of fiber reinforced UHPC
  - Energy dissipation due to fiber presence

Micro Scale Test Information

- Synchrotron sources:
  - NSLS/Brookhaven National Lab
  - APS/Argonne National Lab
- 30 keV monochromatic source
- Specimens:
  - nominal 4 mm x 4 mm fine mortar cylinders
  - specimens loaded in axial compression and split cylinder mode using *in situ* frame
  - 6 μm voxel size

In situ Loading

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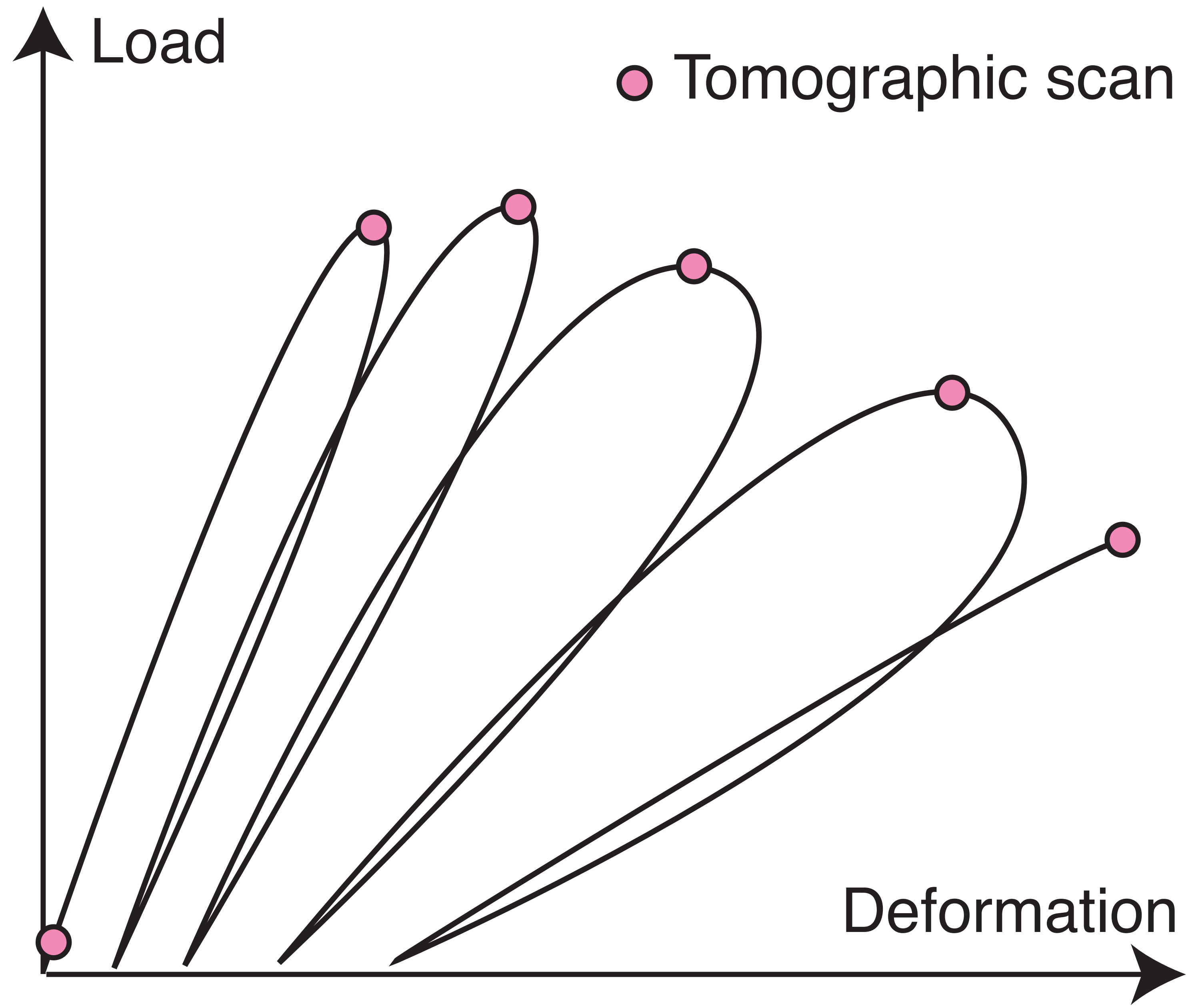
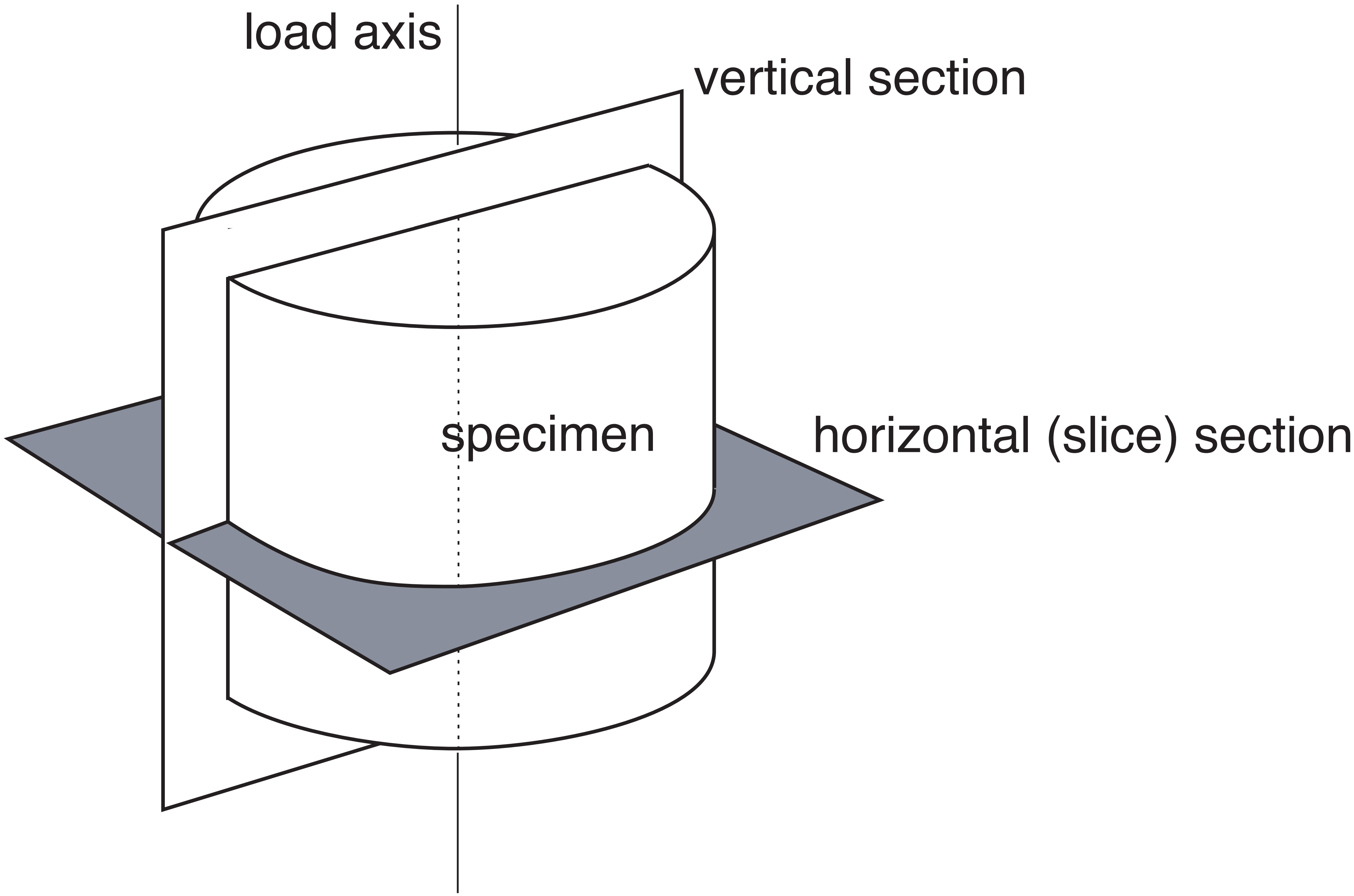
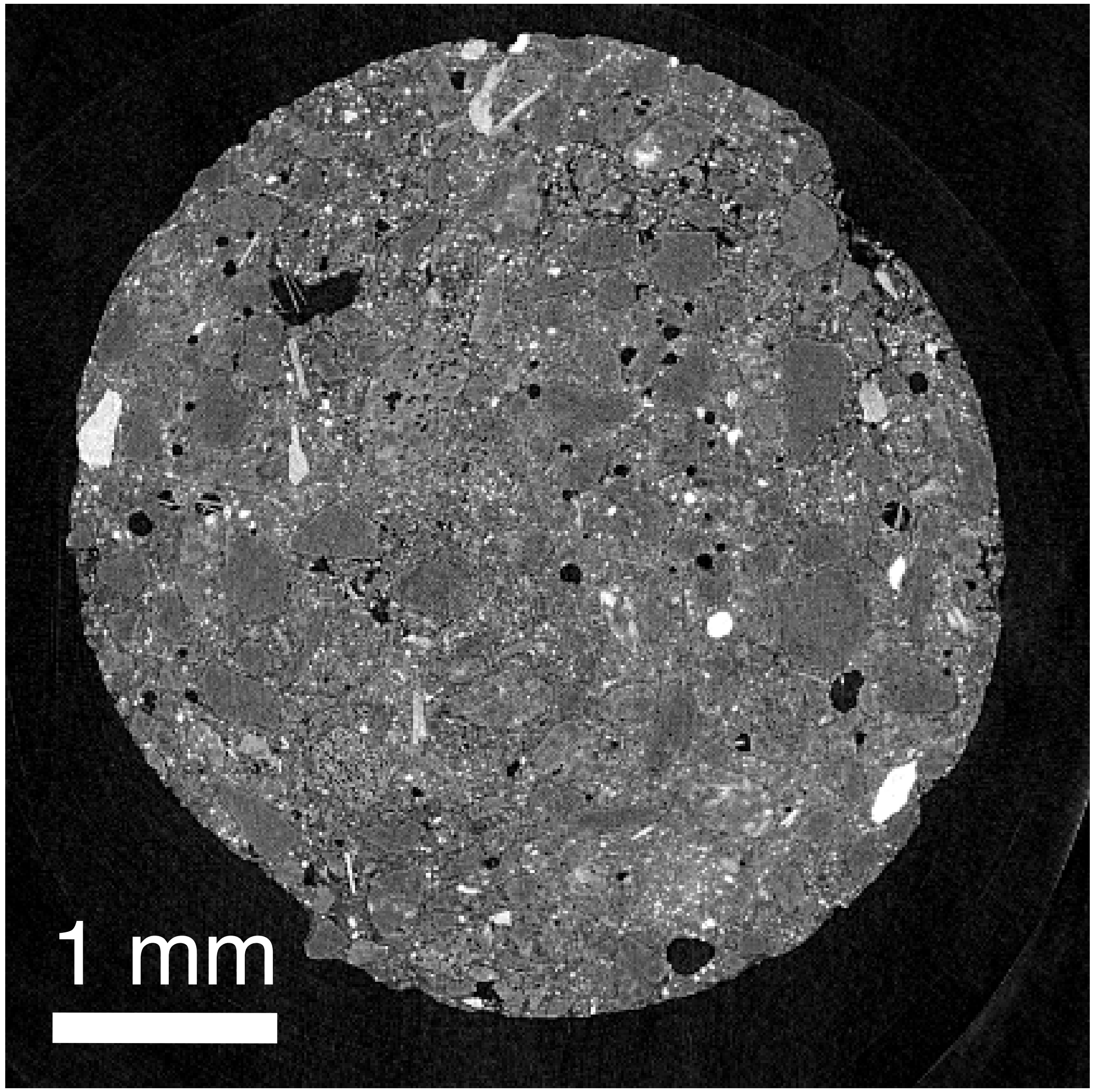
Axial Compression




load axis
vertical section
specimen
horizontal (slice) section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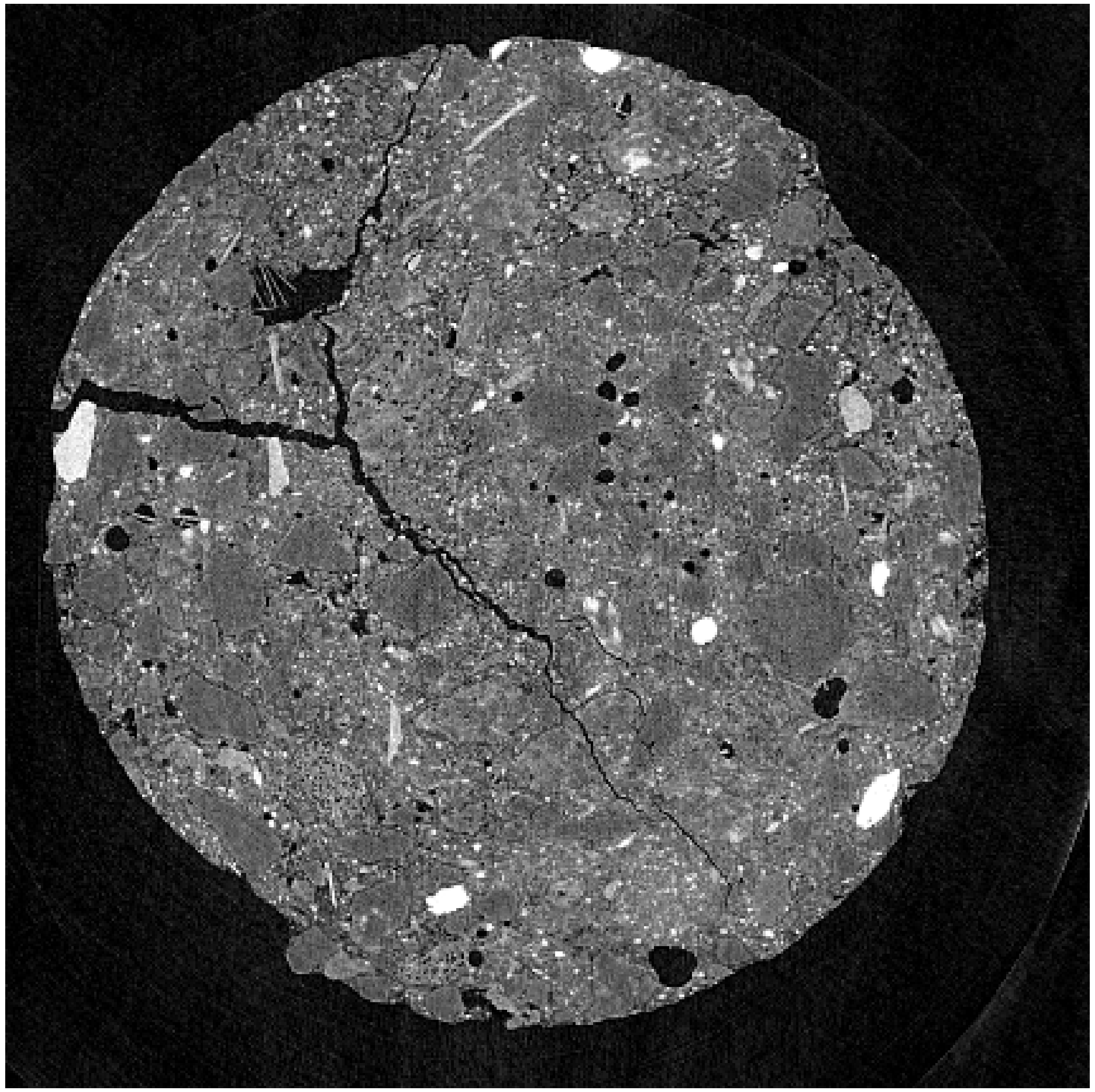

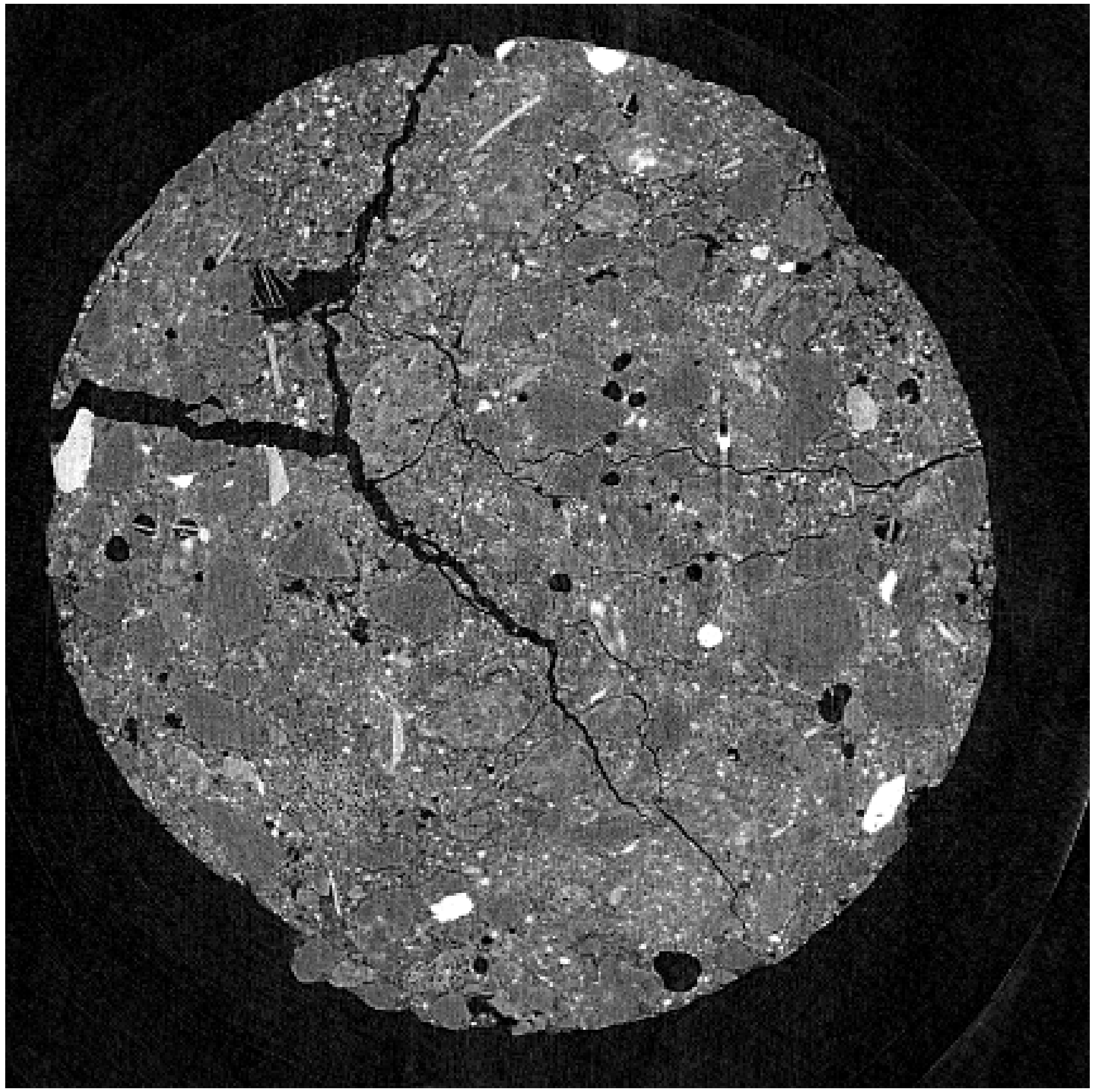

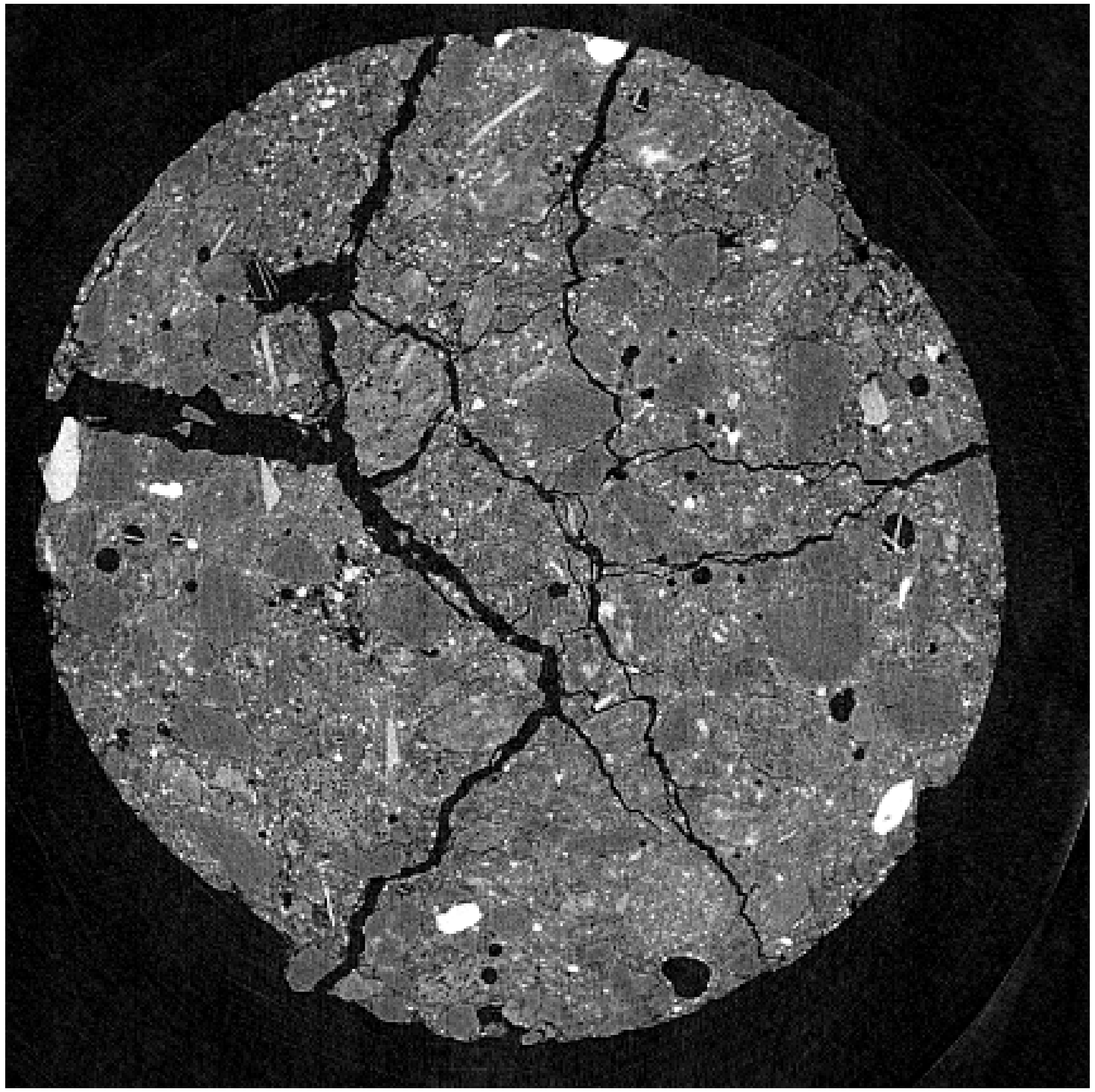

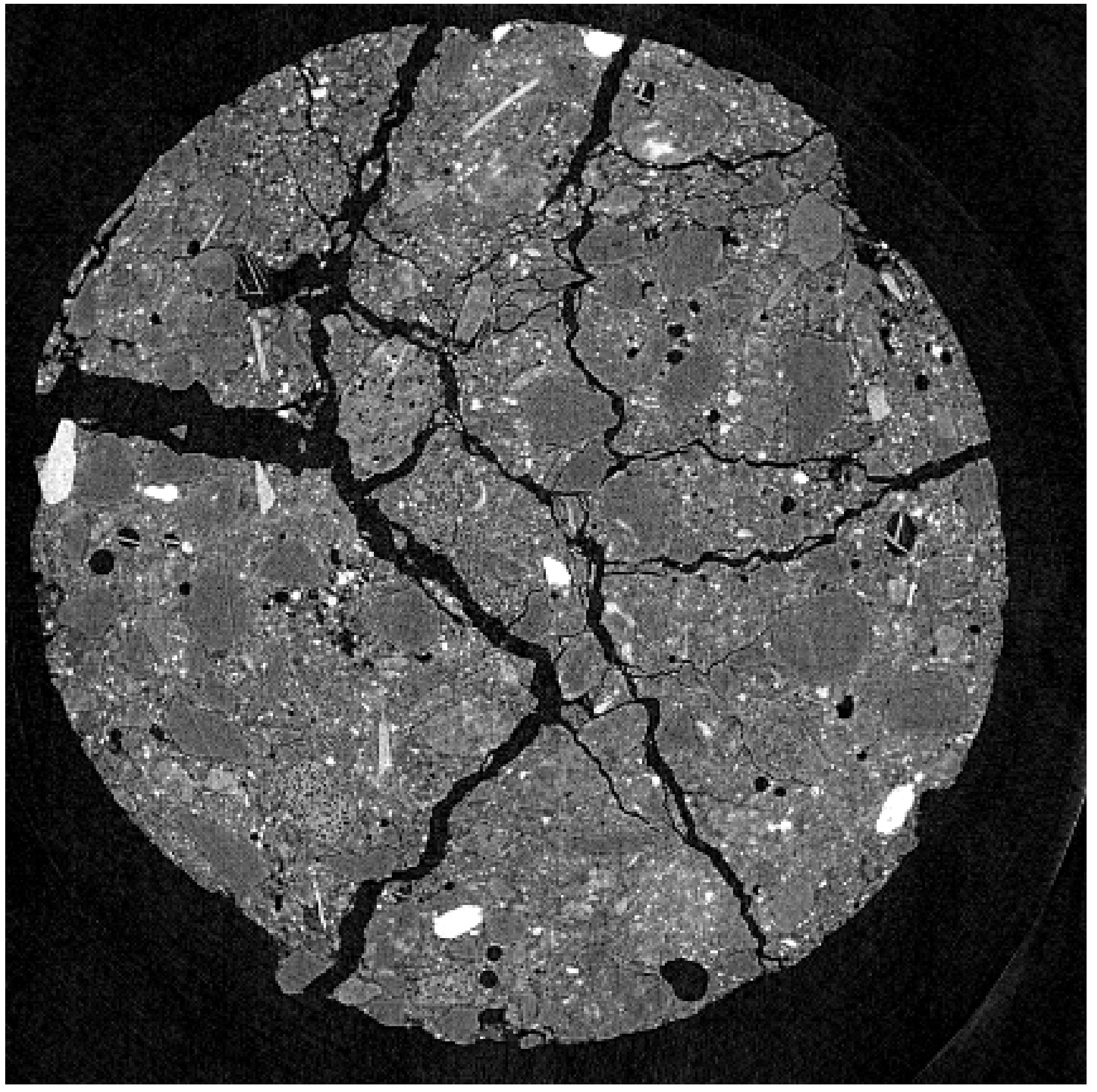

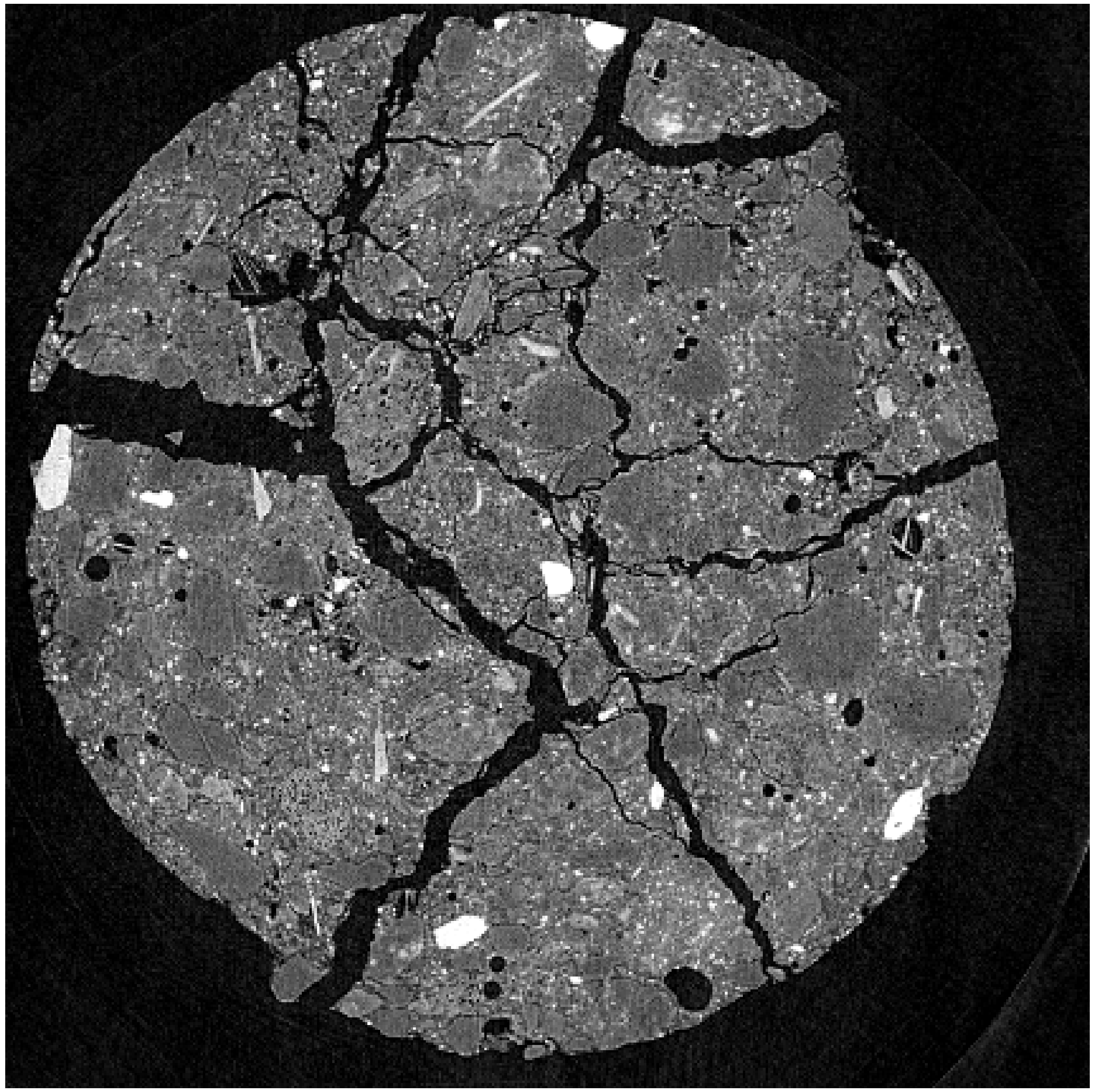

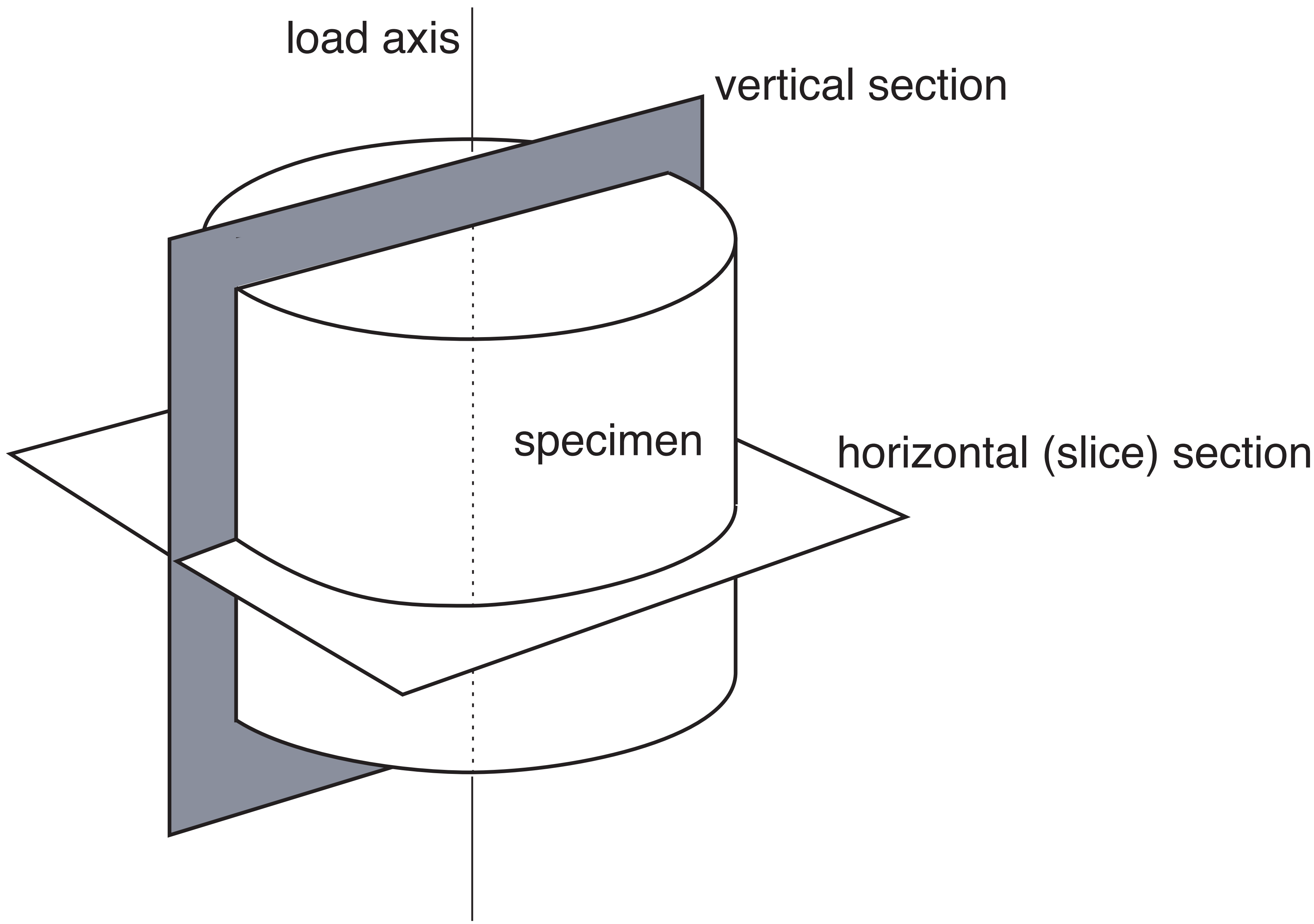
load axis
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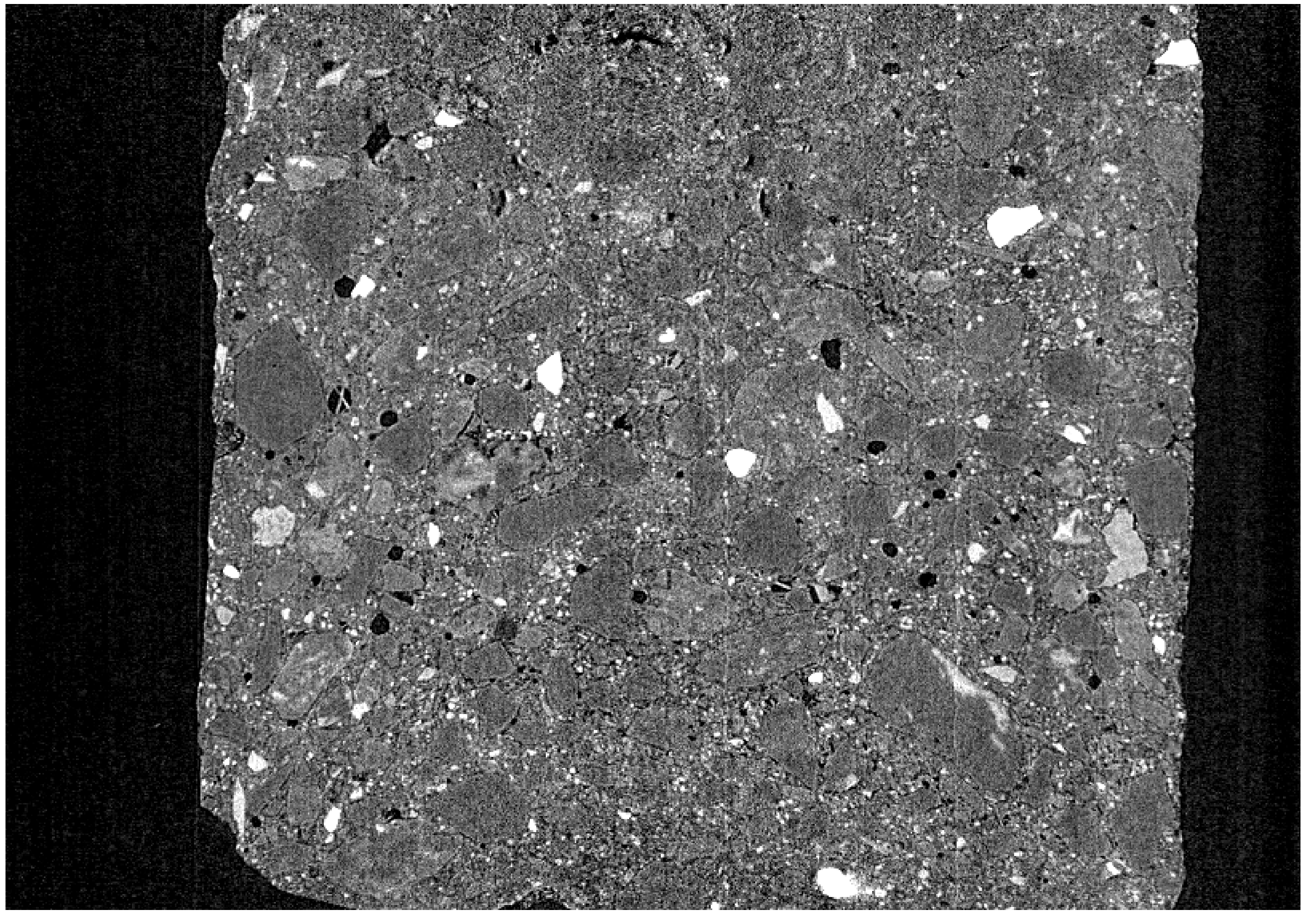
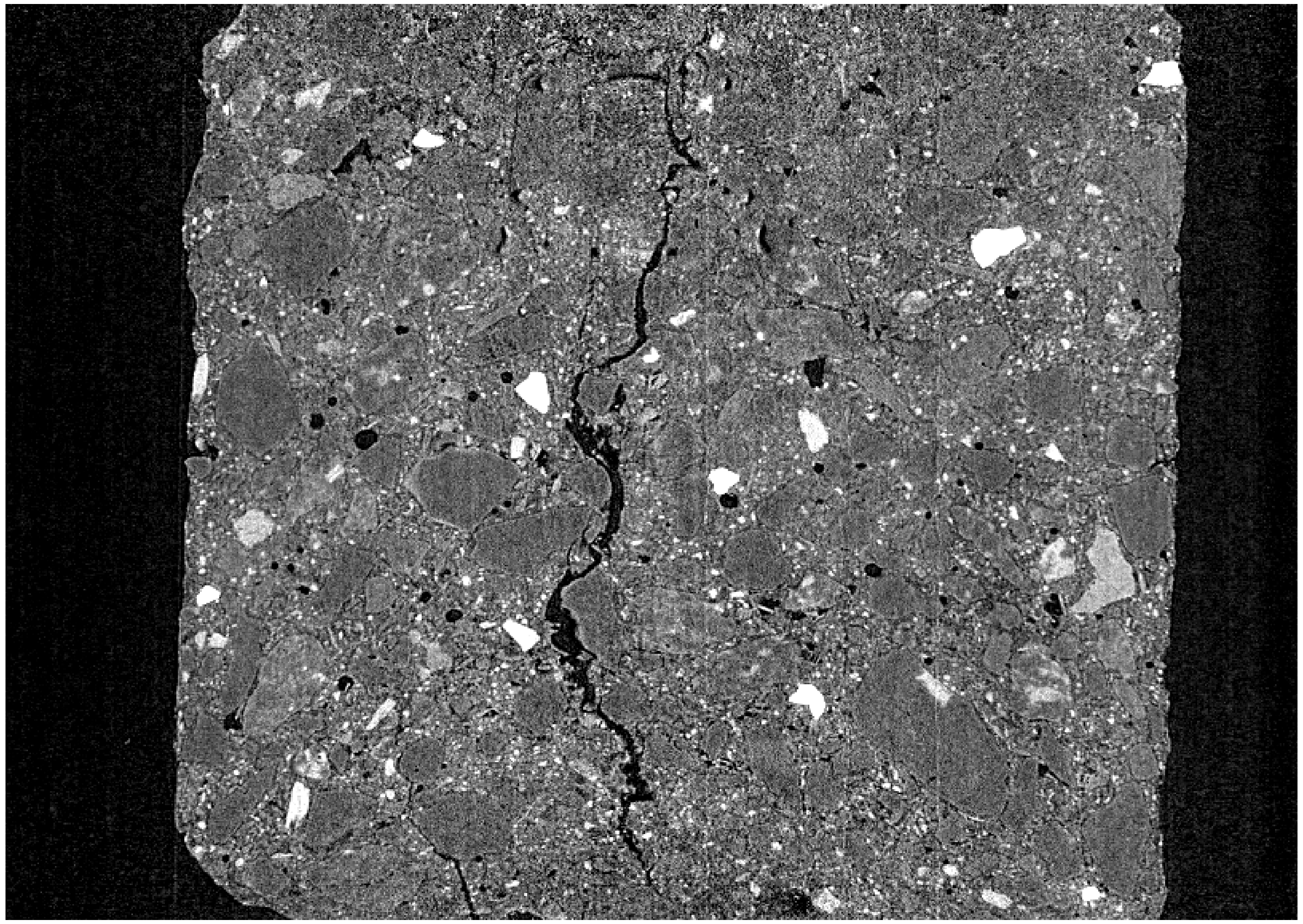
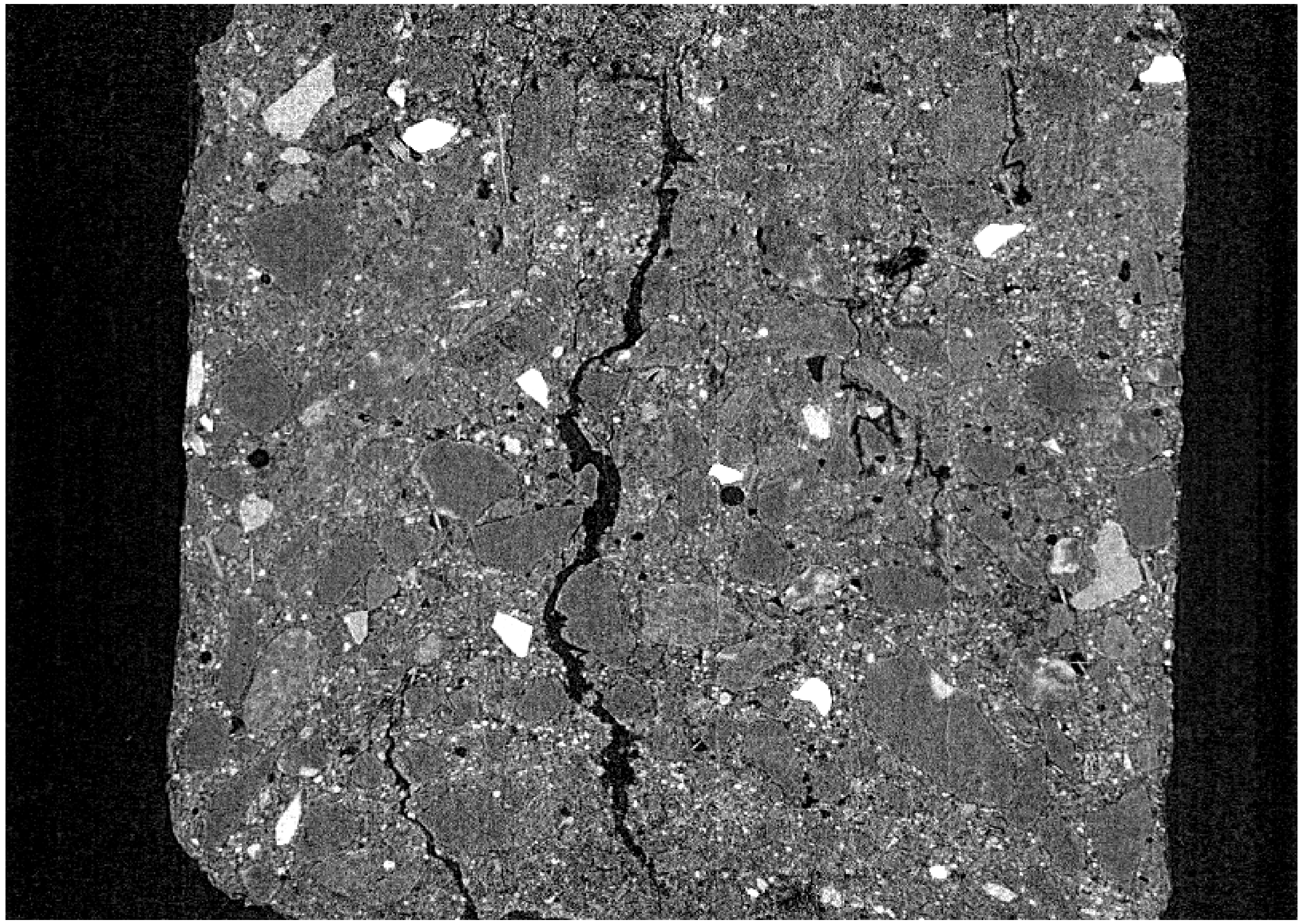
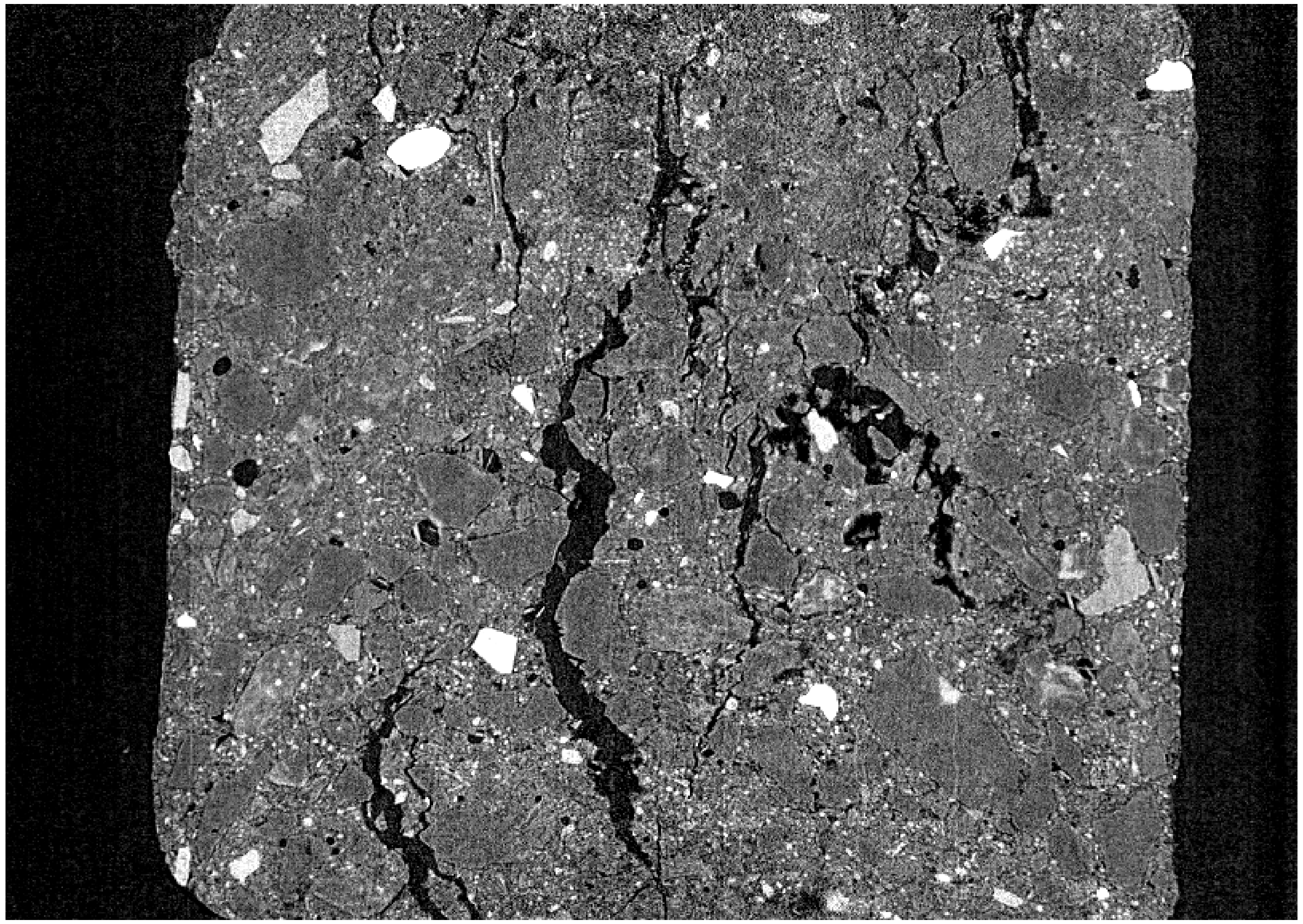
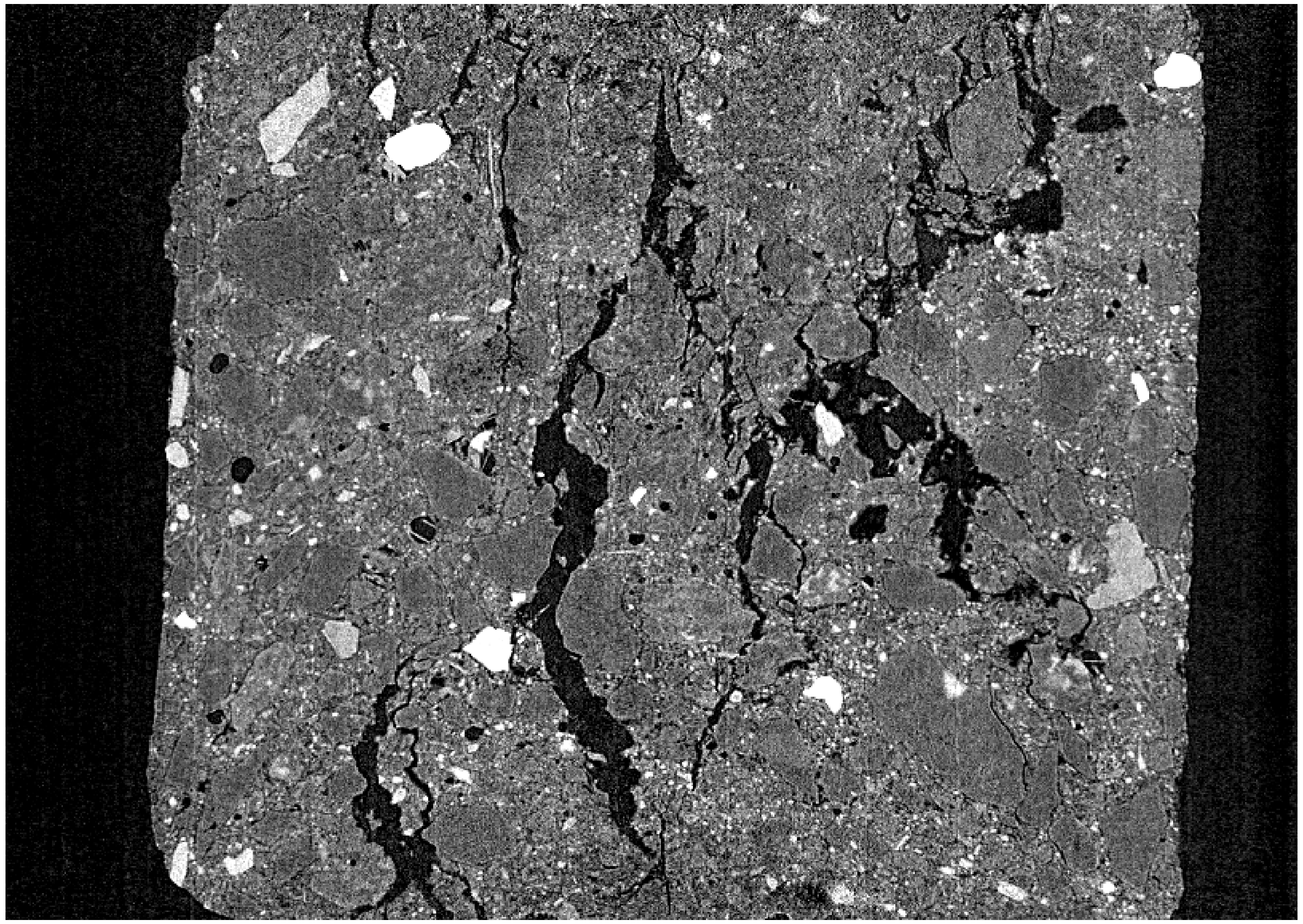




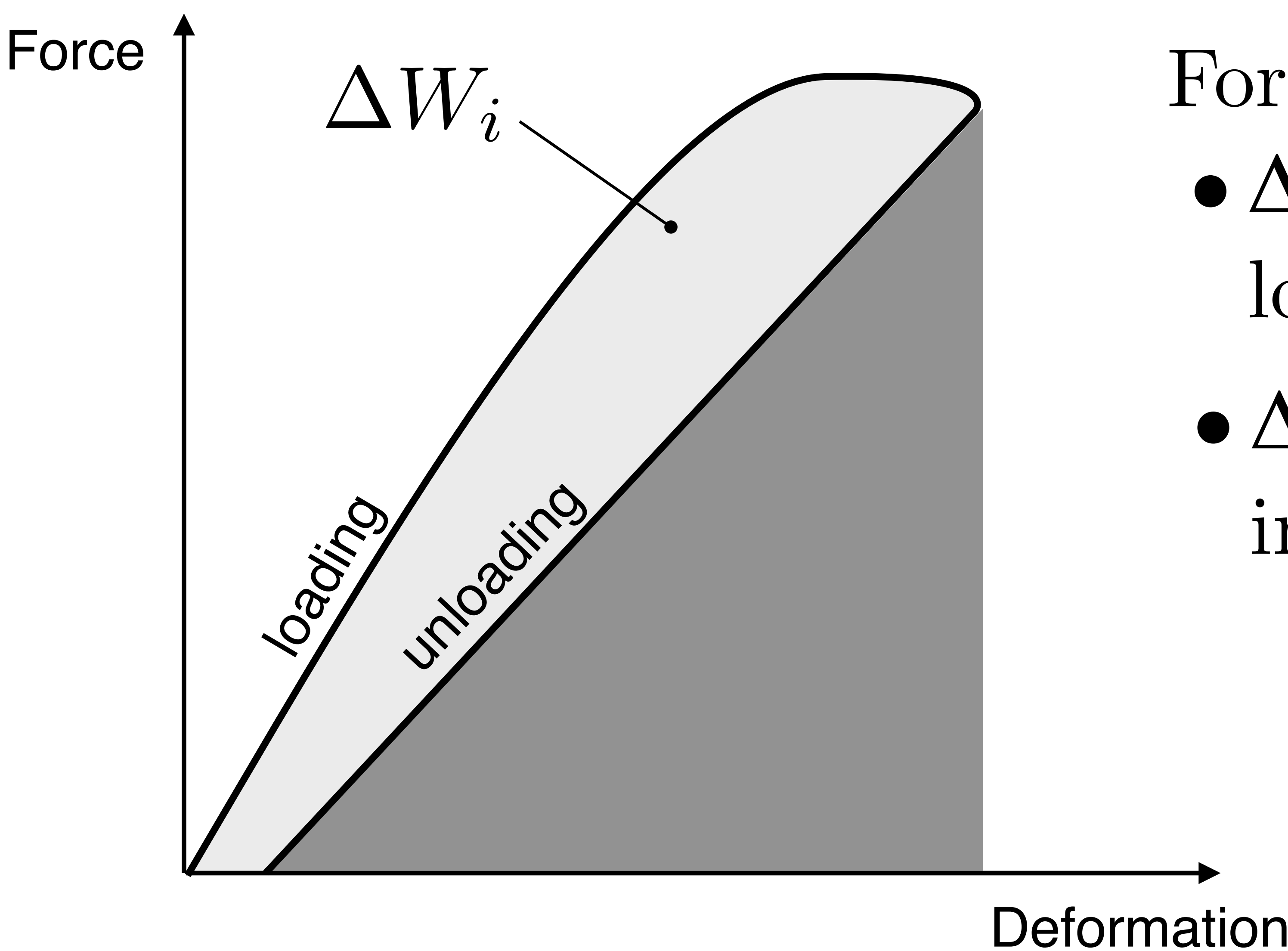






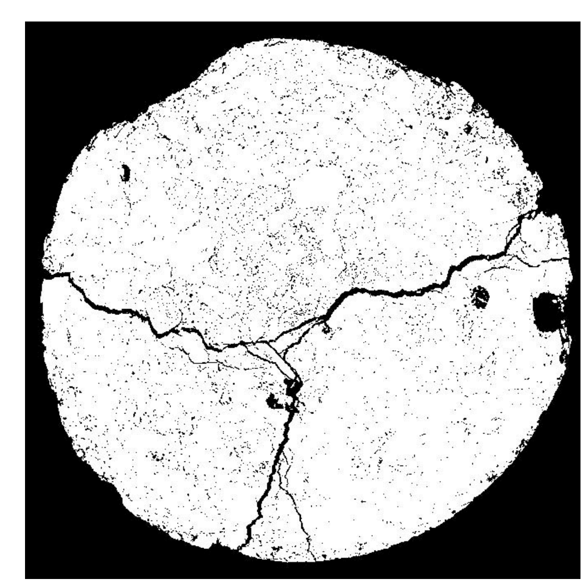
Specific Fracture Energy

First principles approach: $G_f = \frac{dW}{dA} \approx \frac{\Delta W}{\Delta A}$

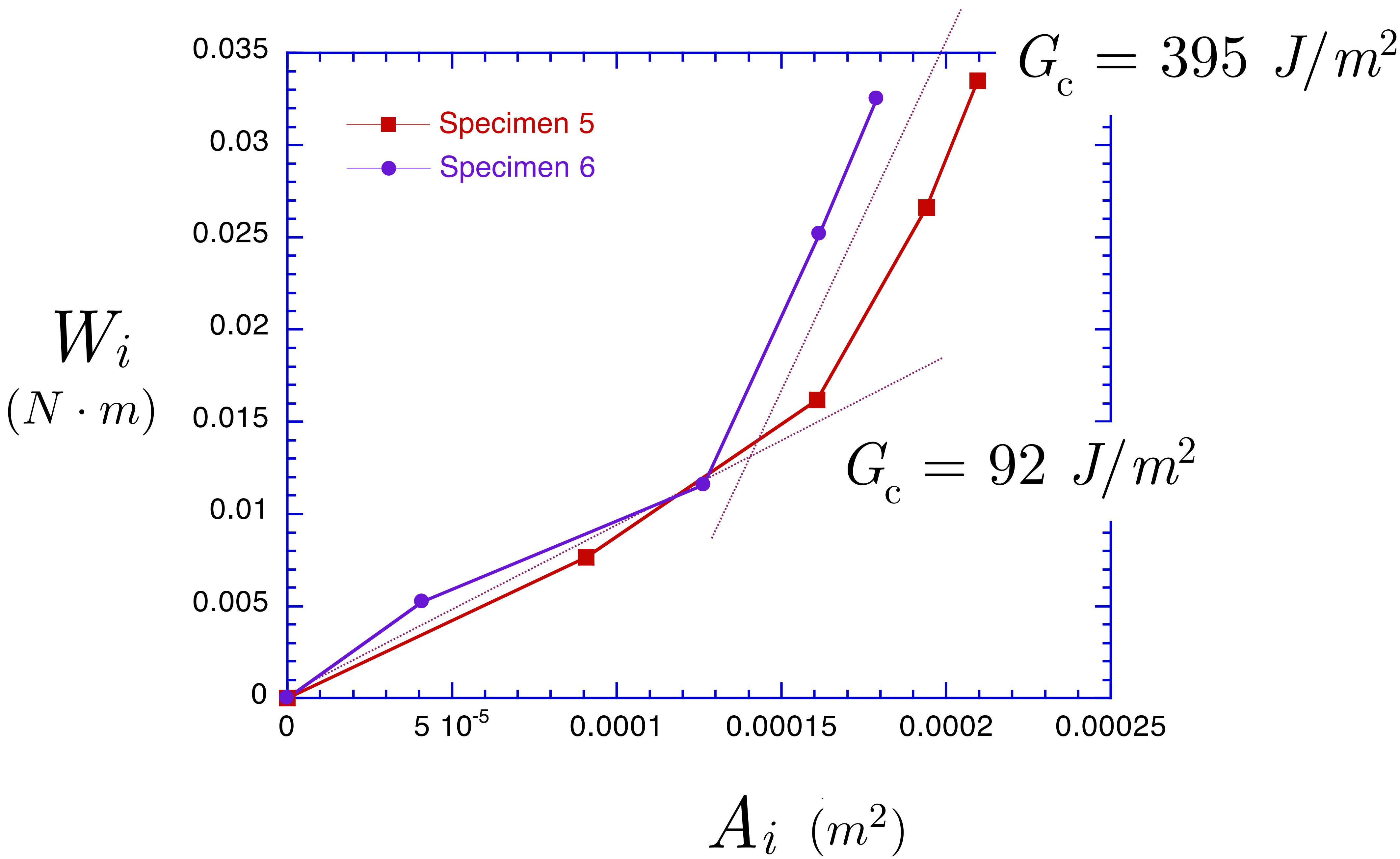


For load increment, i:

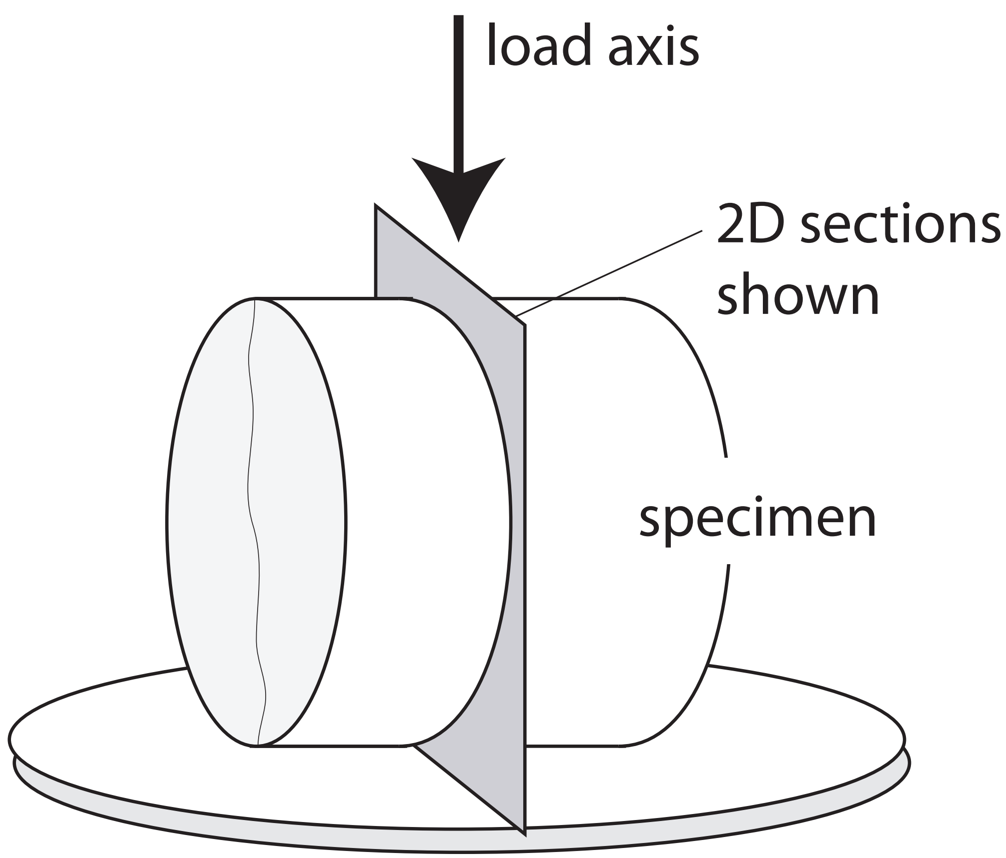
- ΔW_i determined from load-deformation plot
- ΔA_i measured from 3D images:

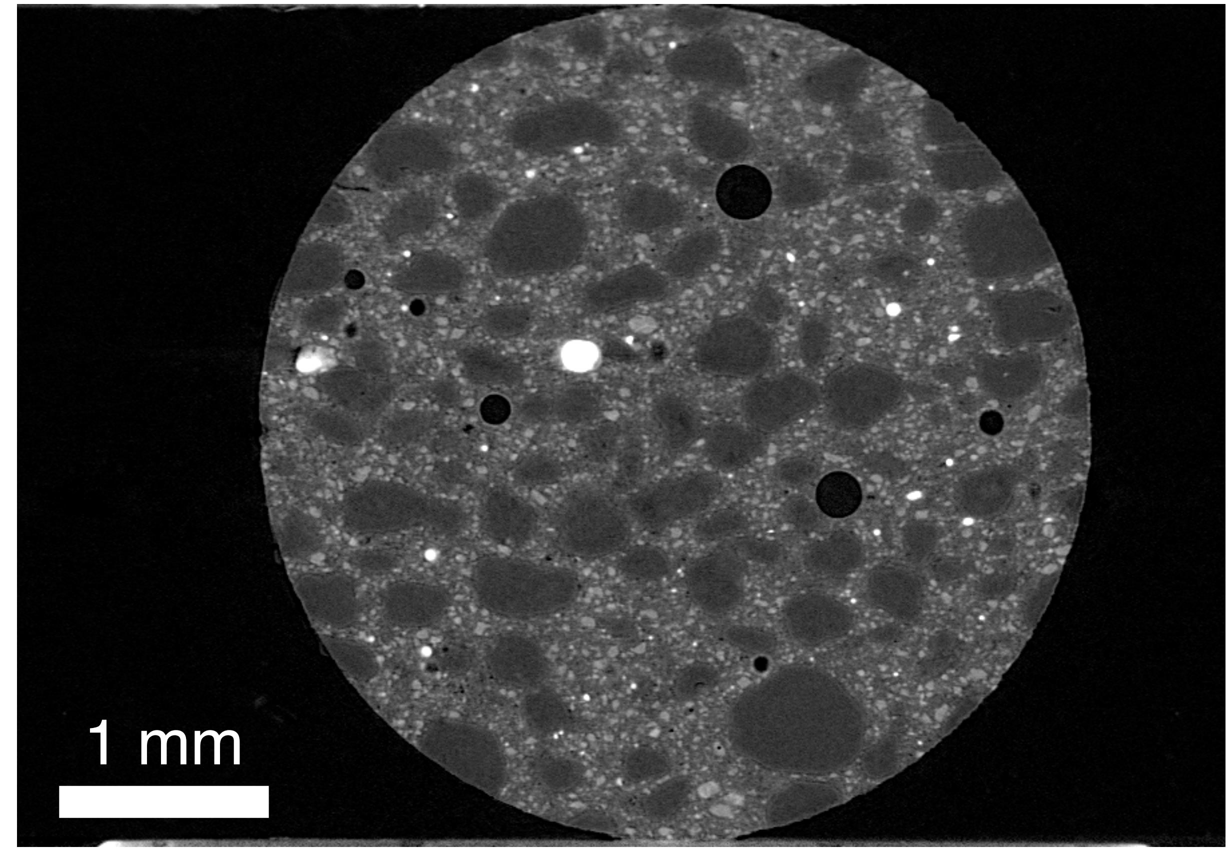


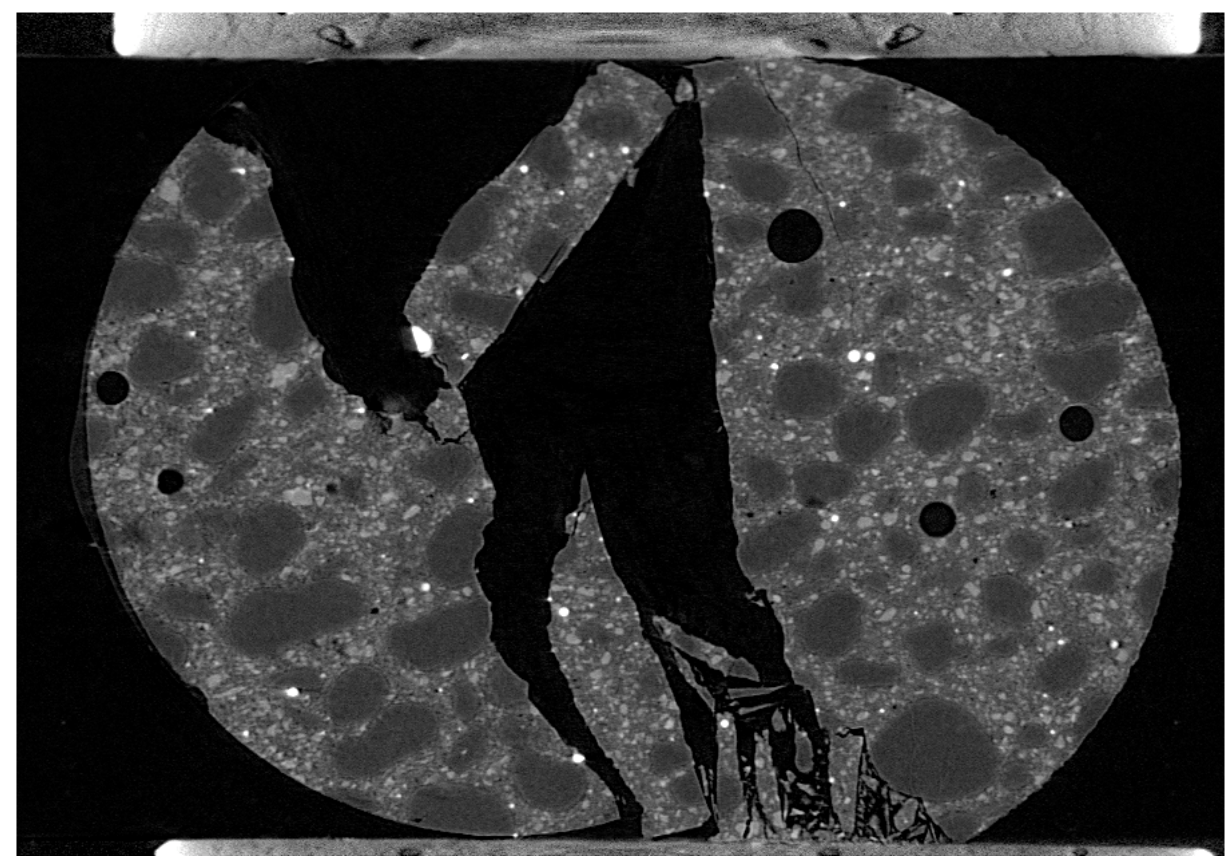
Fracture Measurements



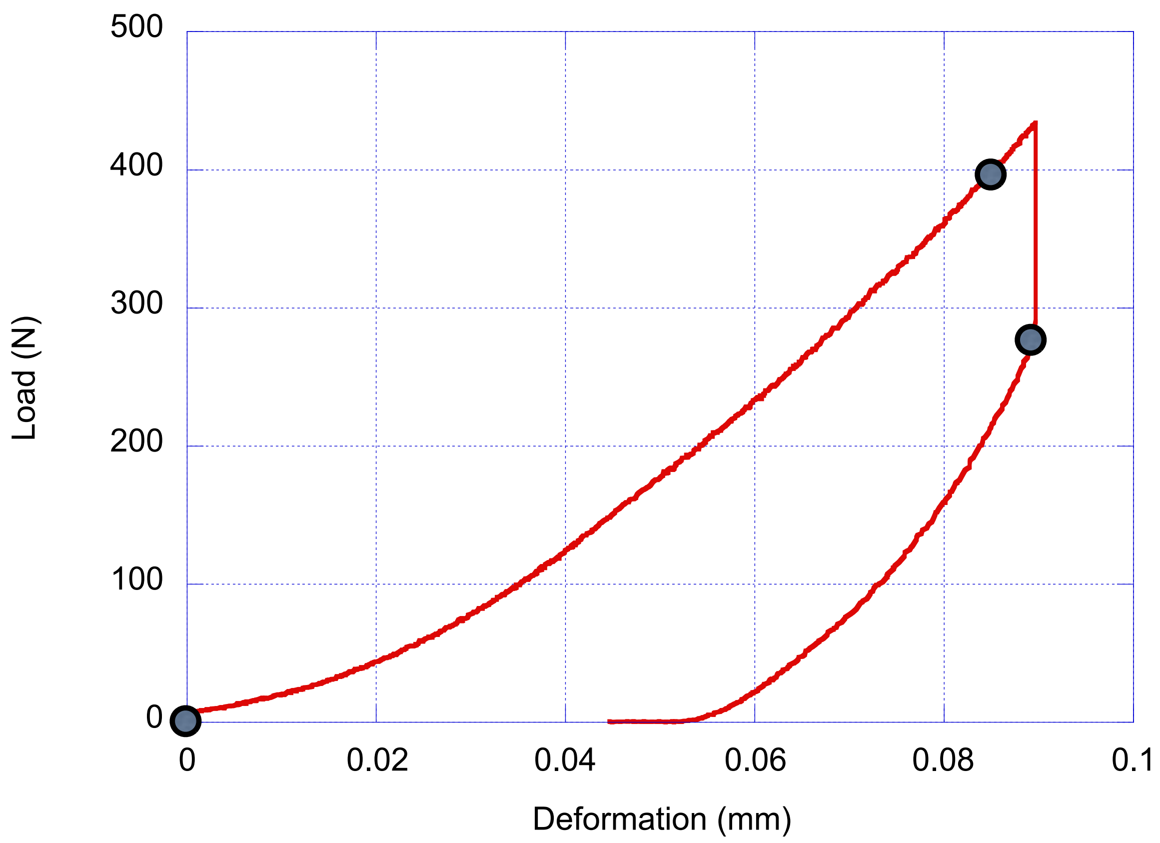
Split Cylinder Fracture

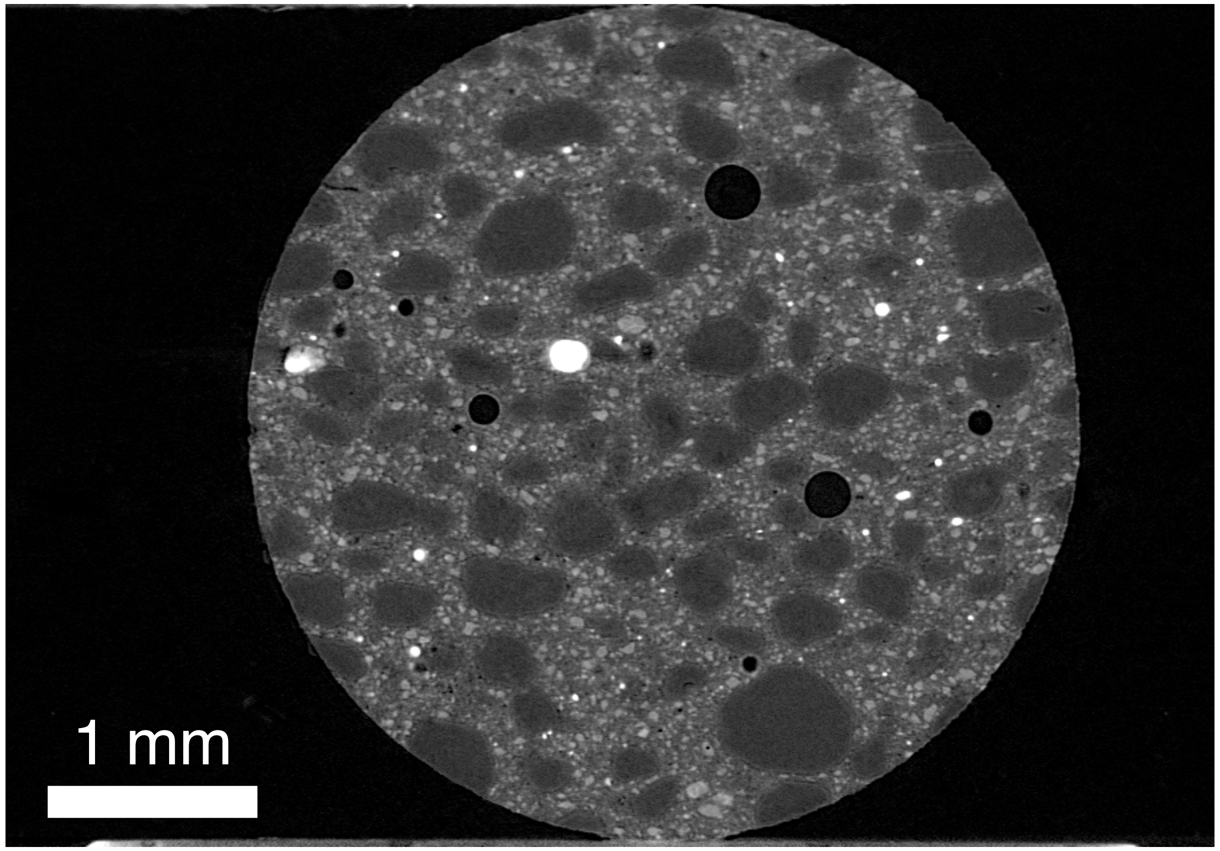


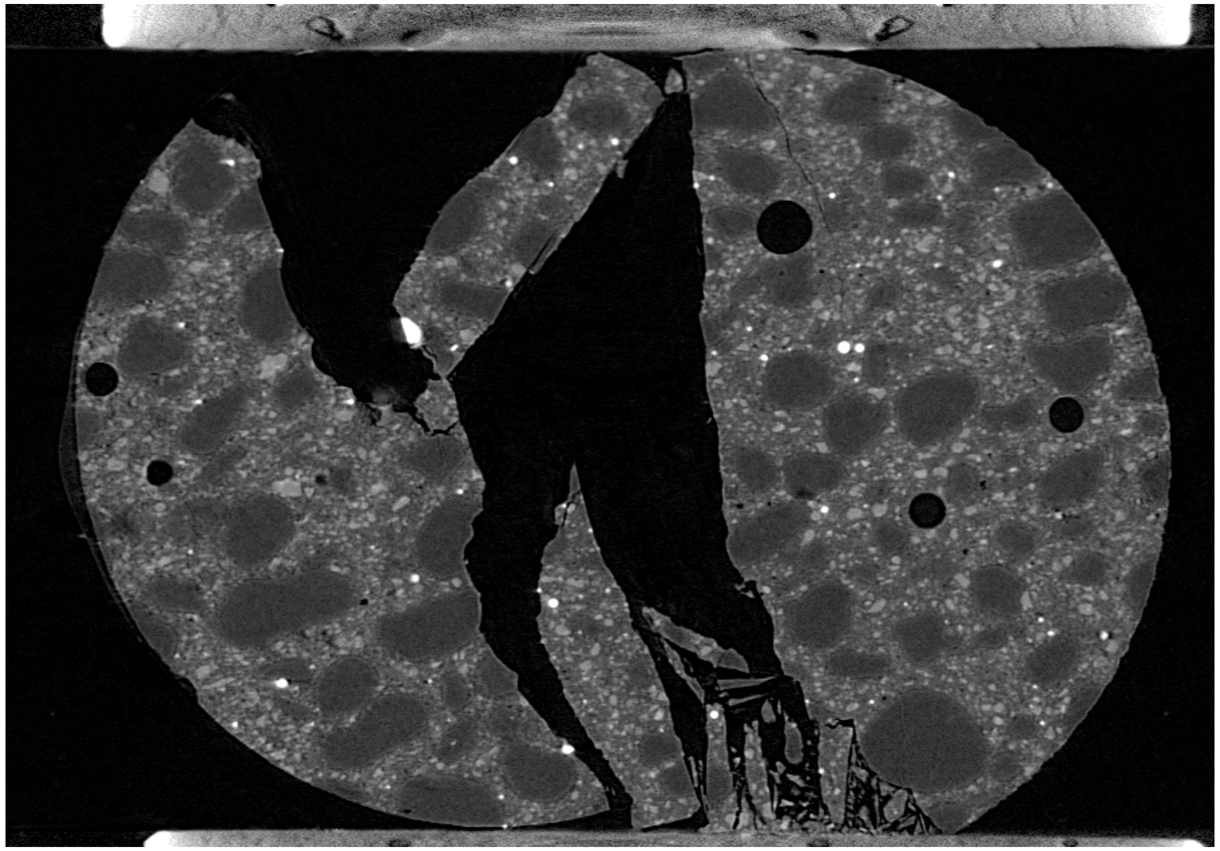




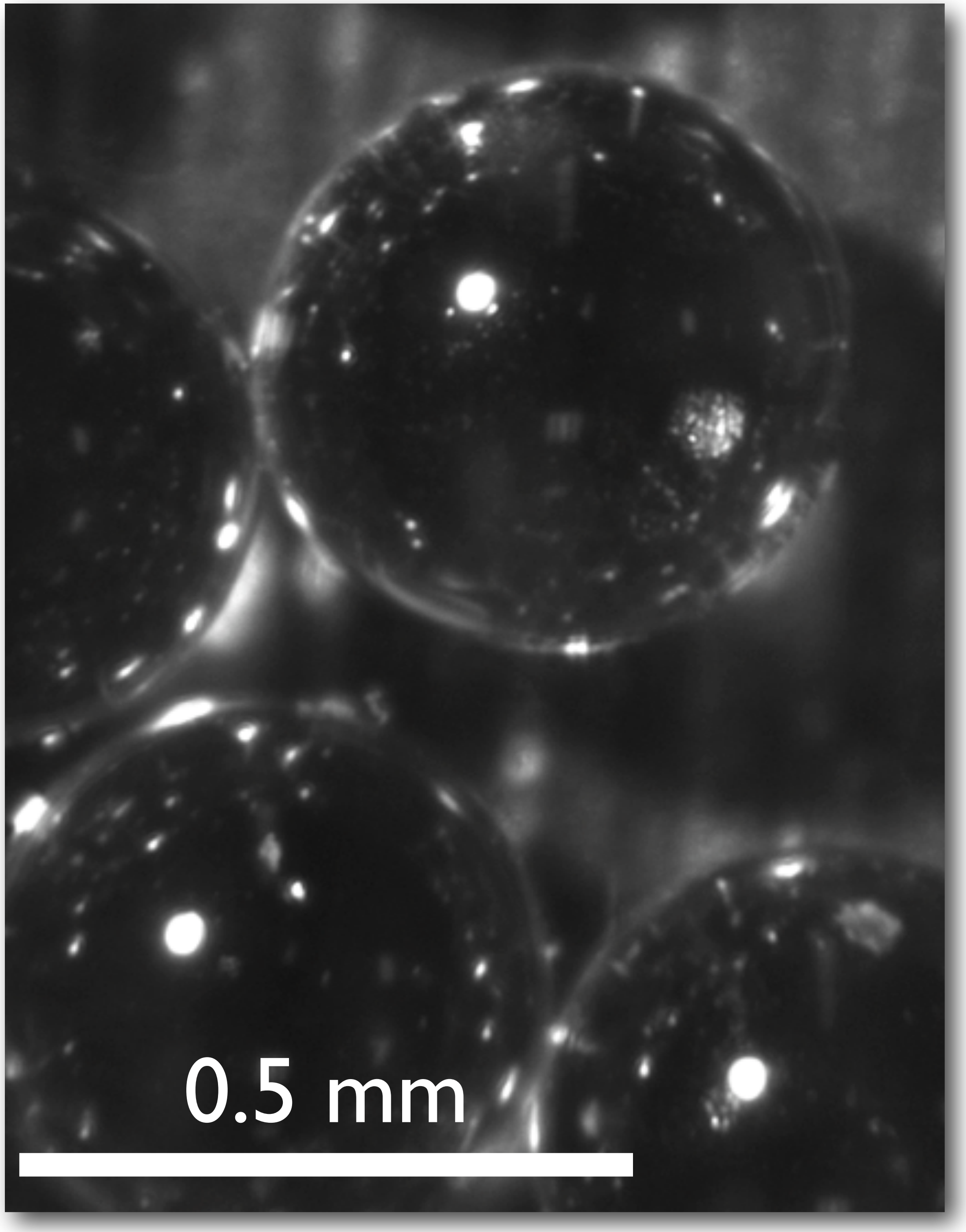
Split Cylinder Fracture

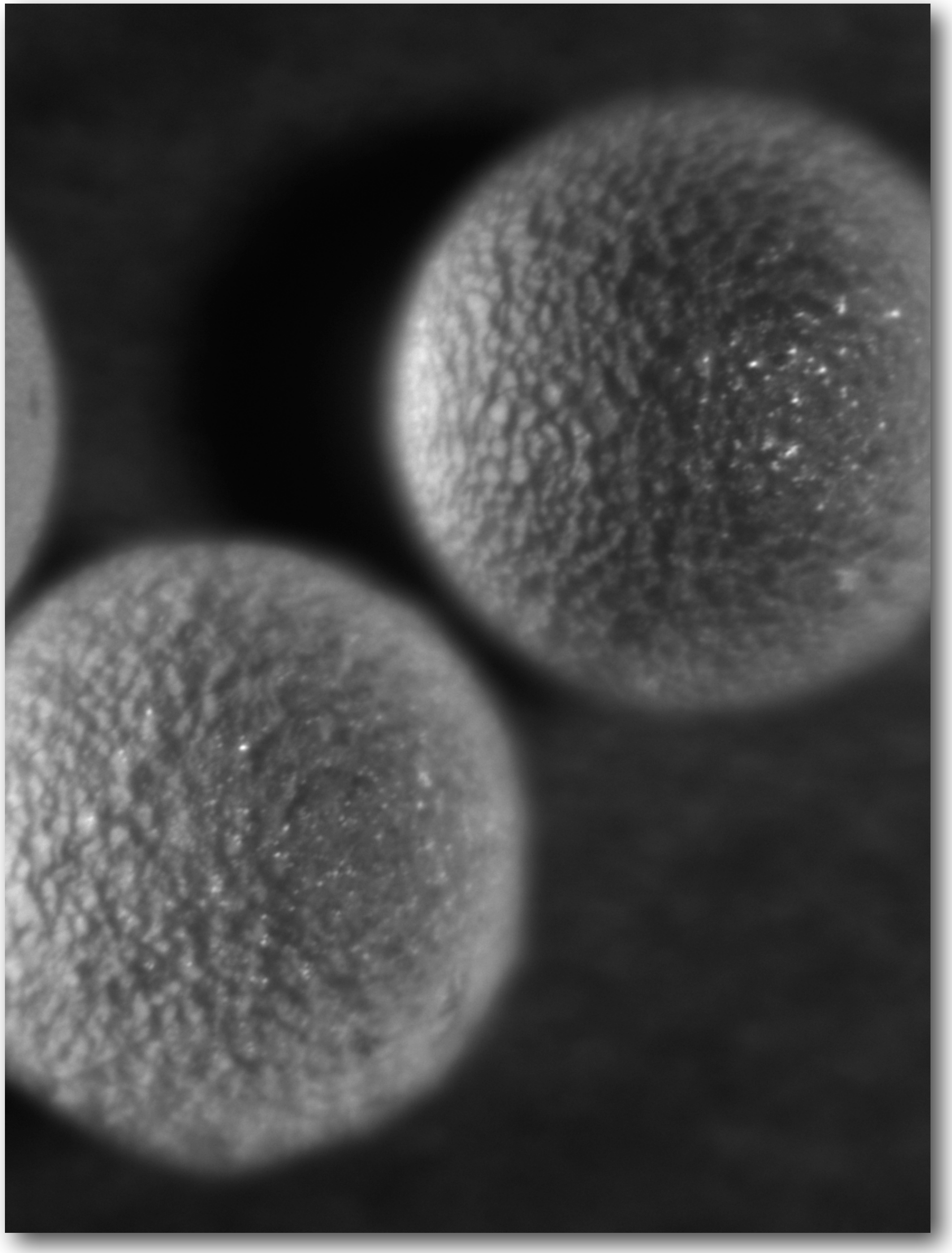


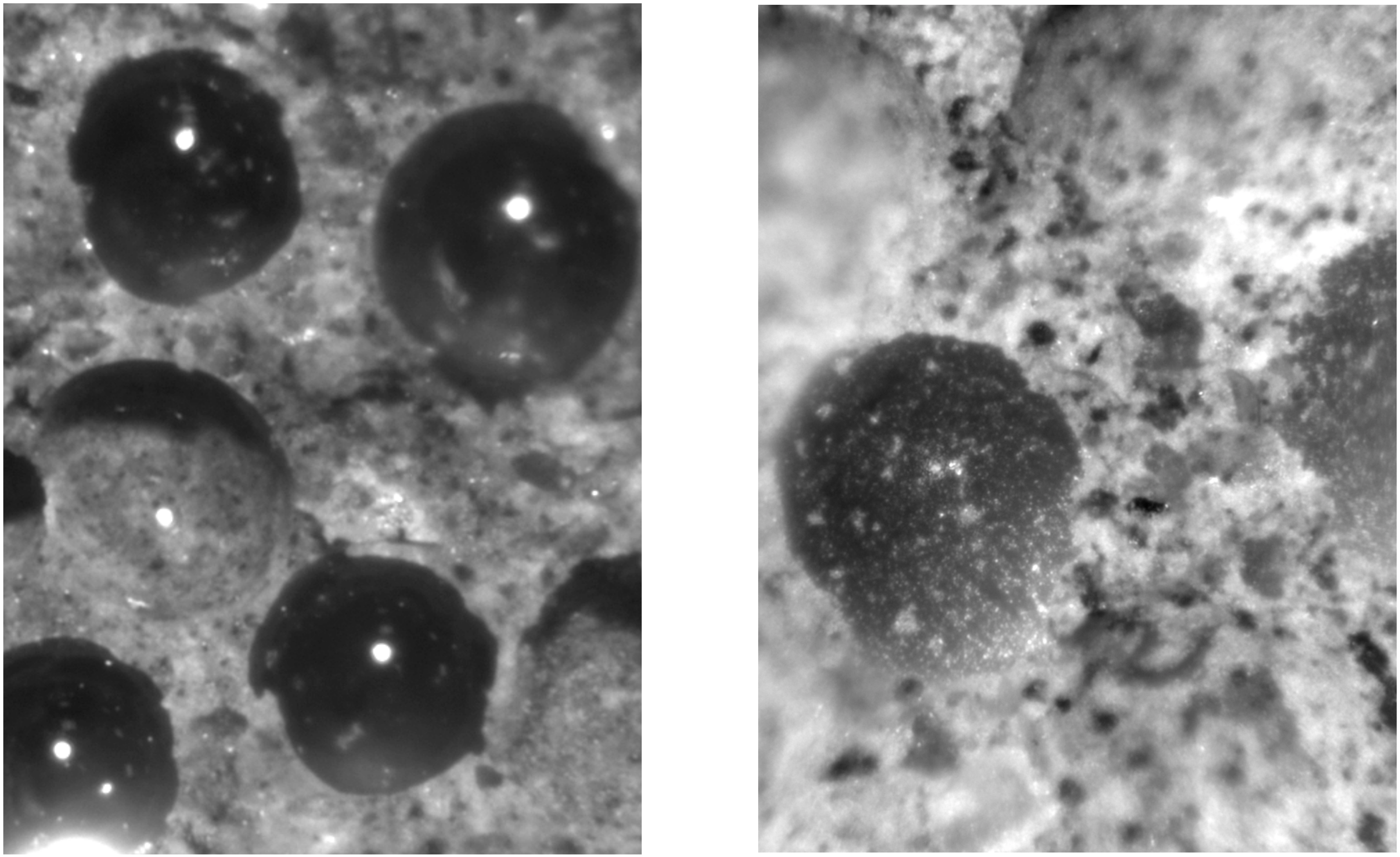




"Model" Aggregates

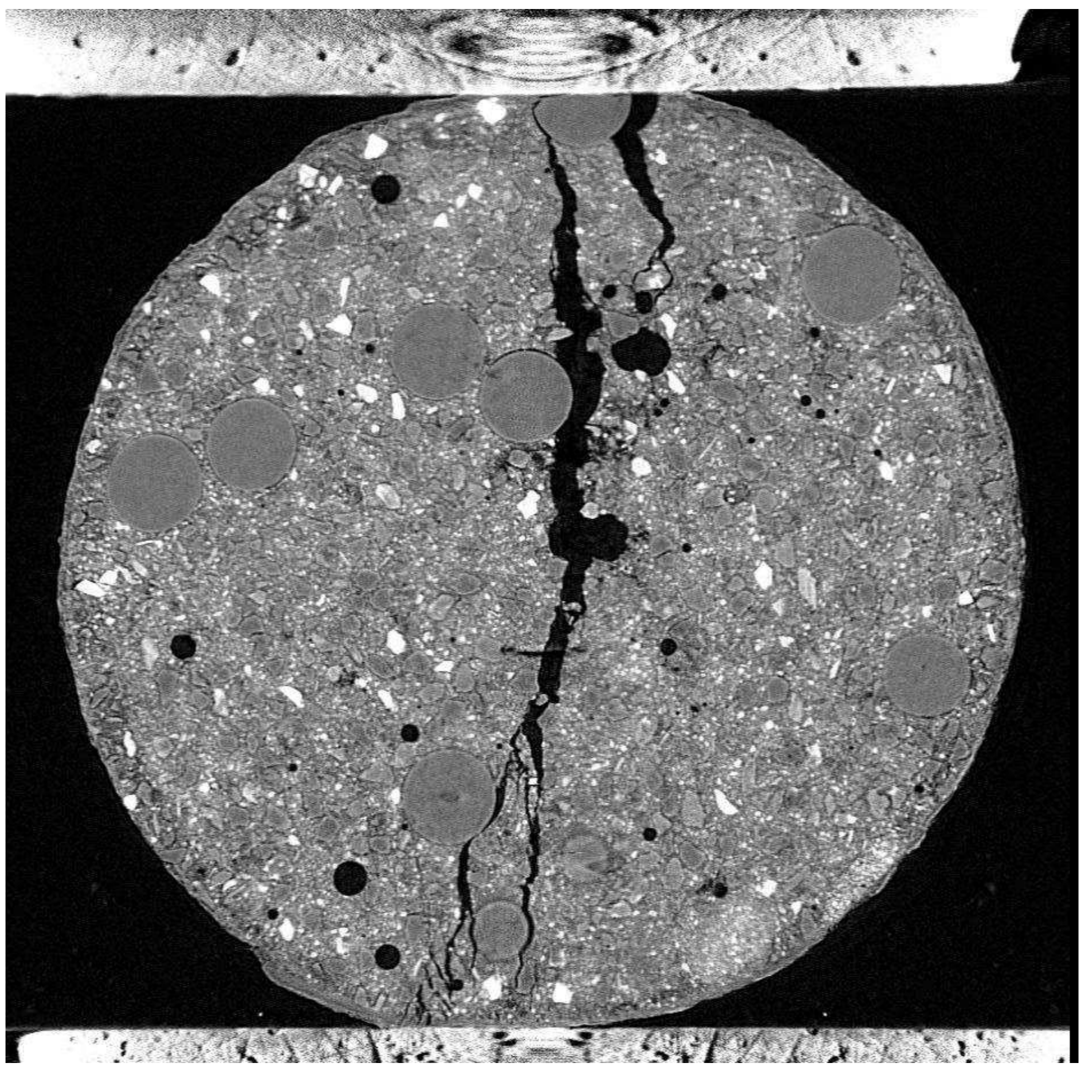






Specimens: 10% by volume (U & E)
50% by volume (U & E)

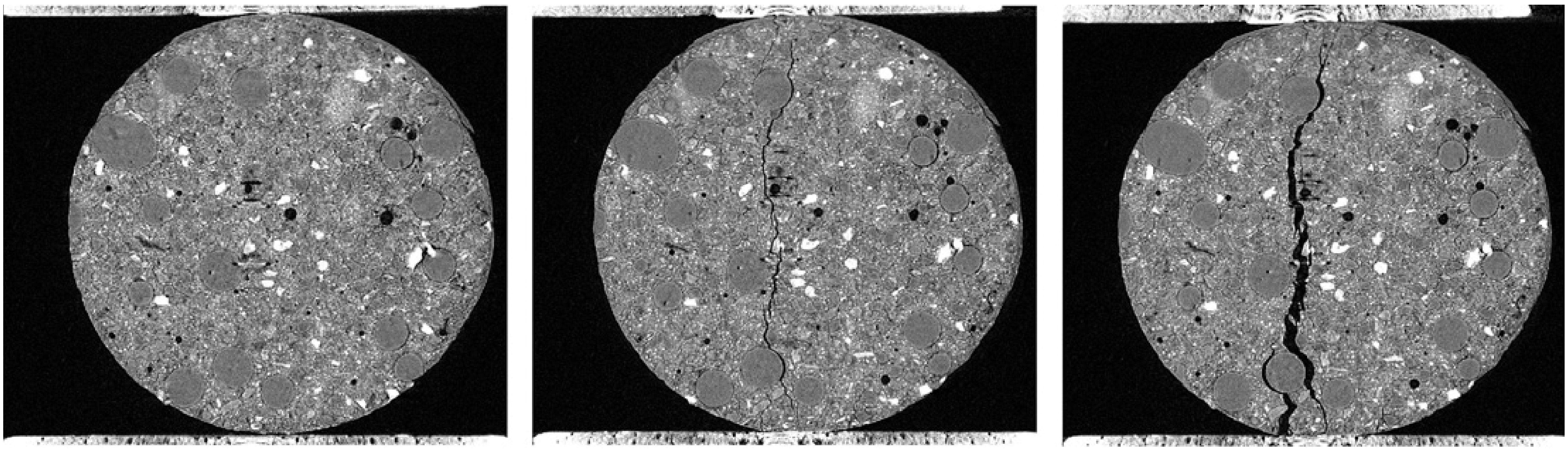
Example Slice Image



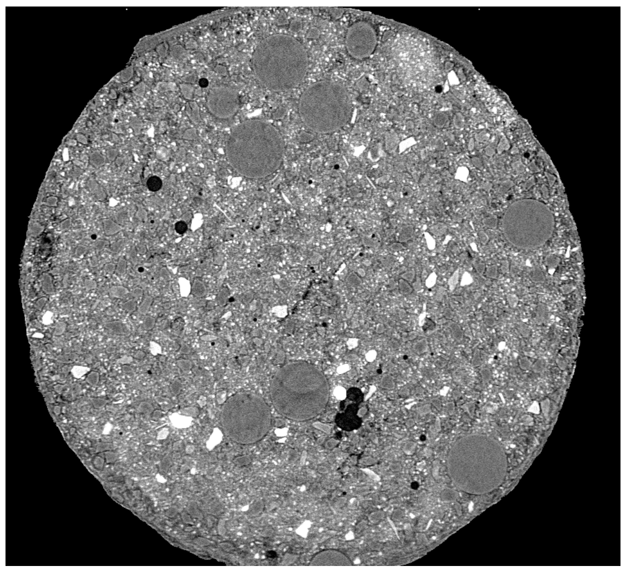
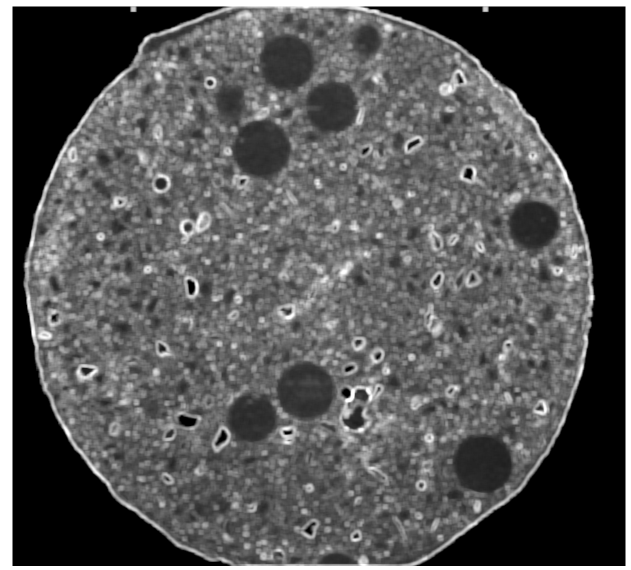
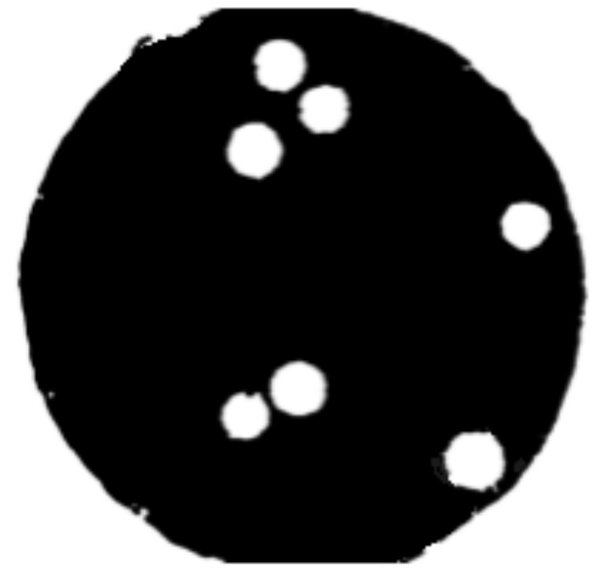
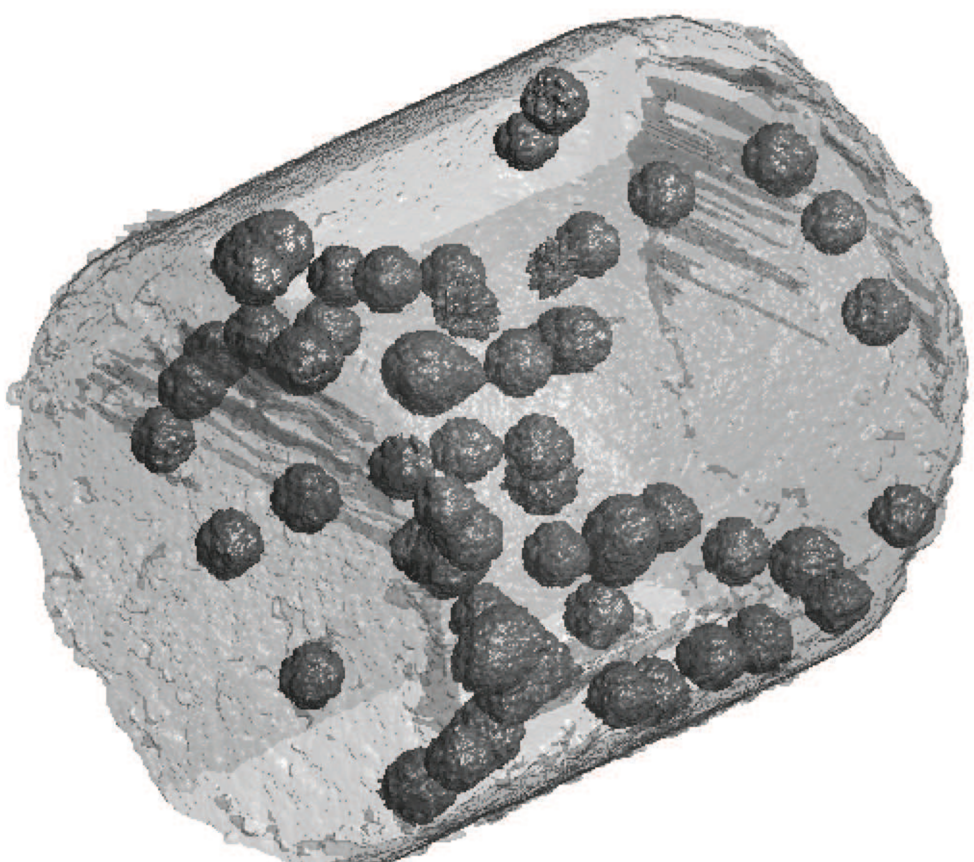
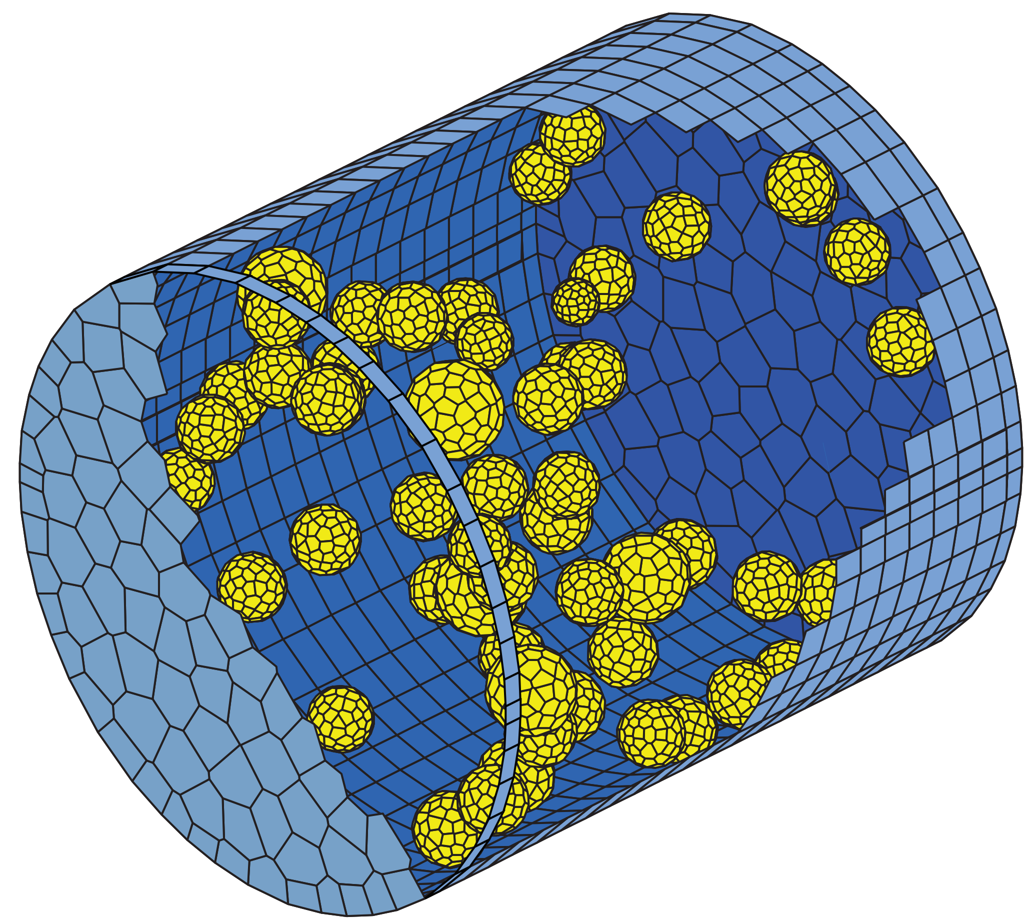
strong interface

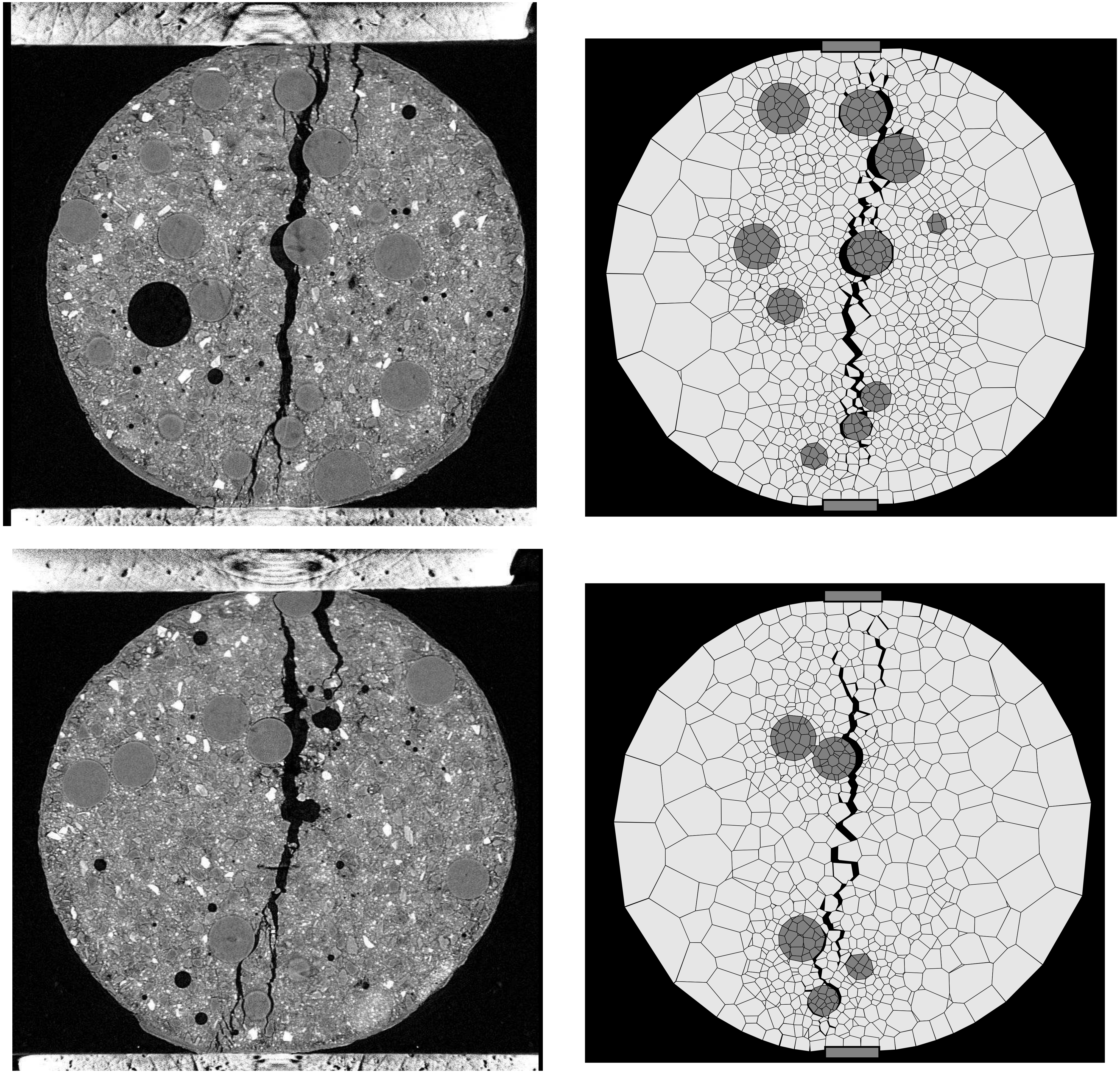
weak interface

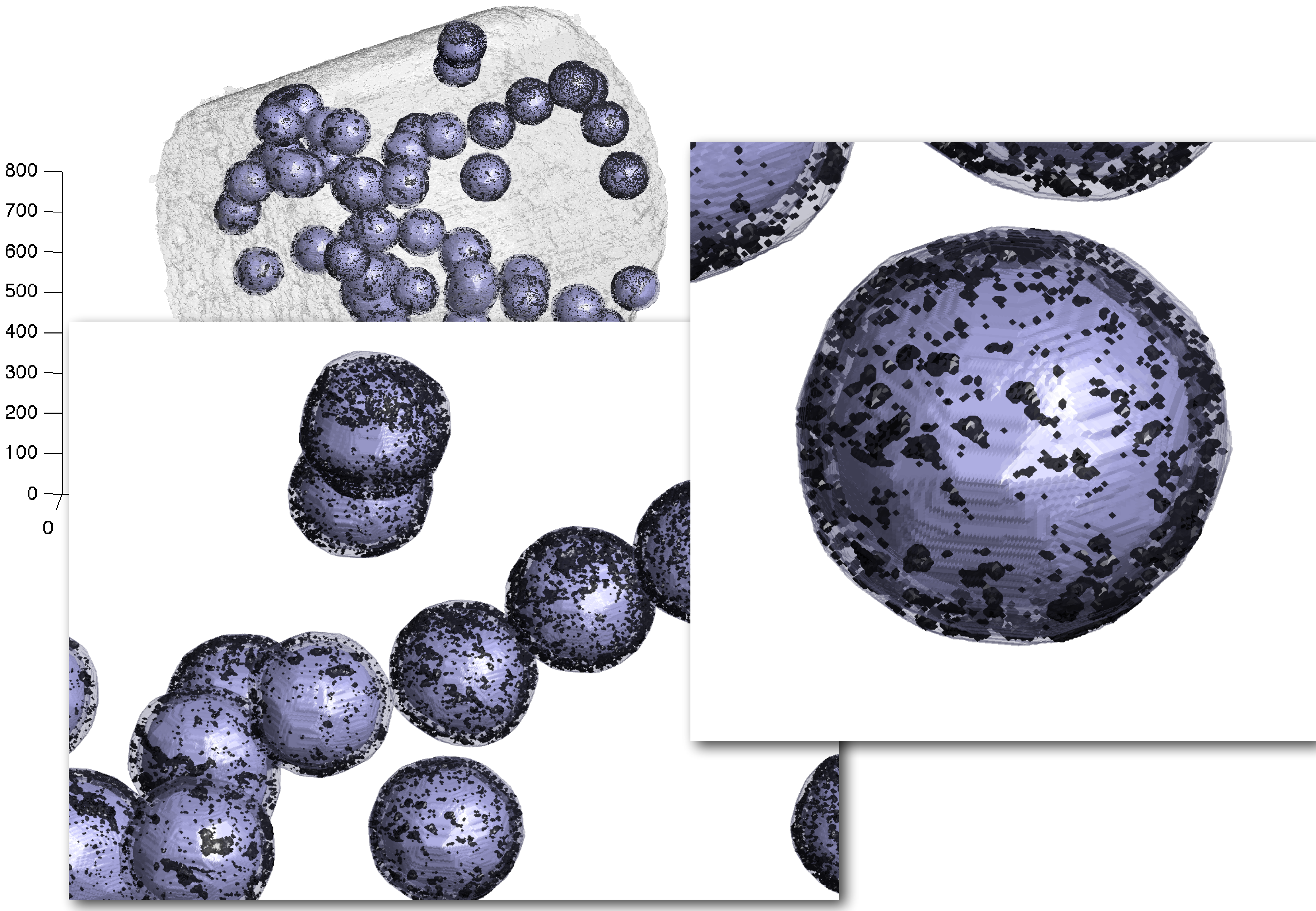
Fracture Sequence



Matched Specimens

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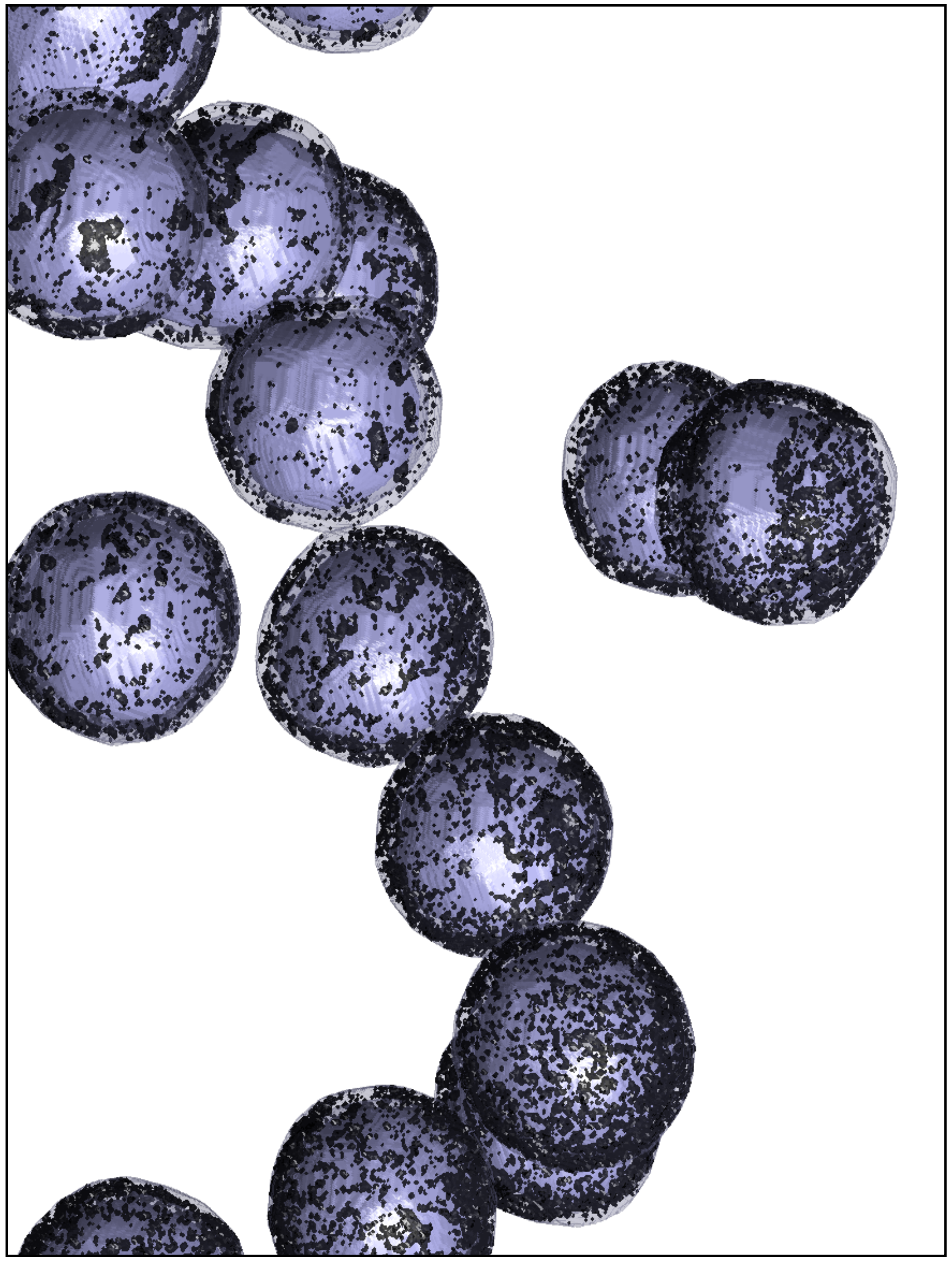
Where is the "Weak Link"?

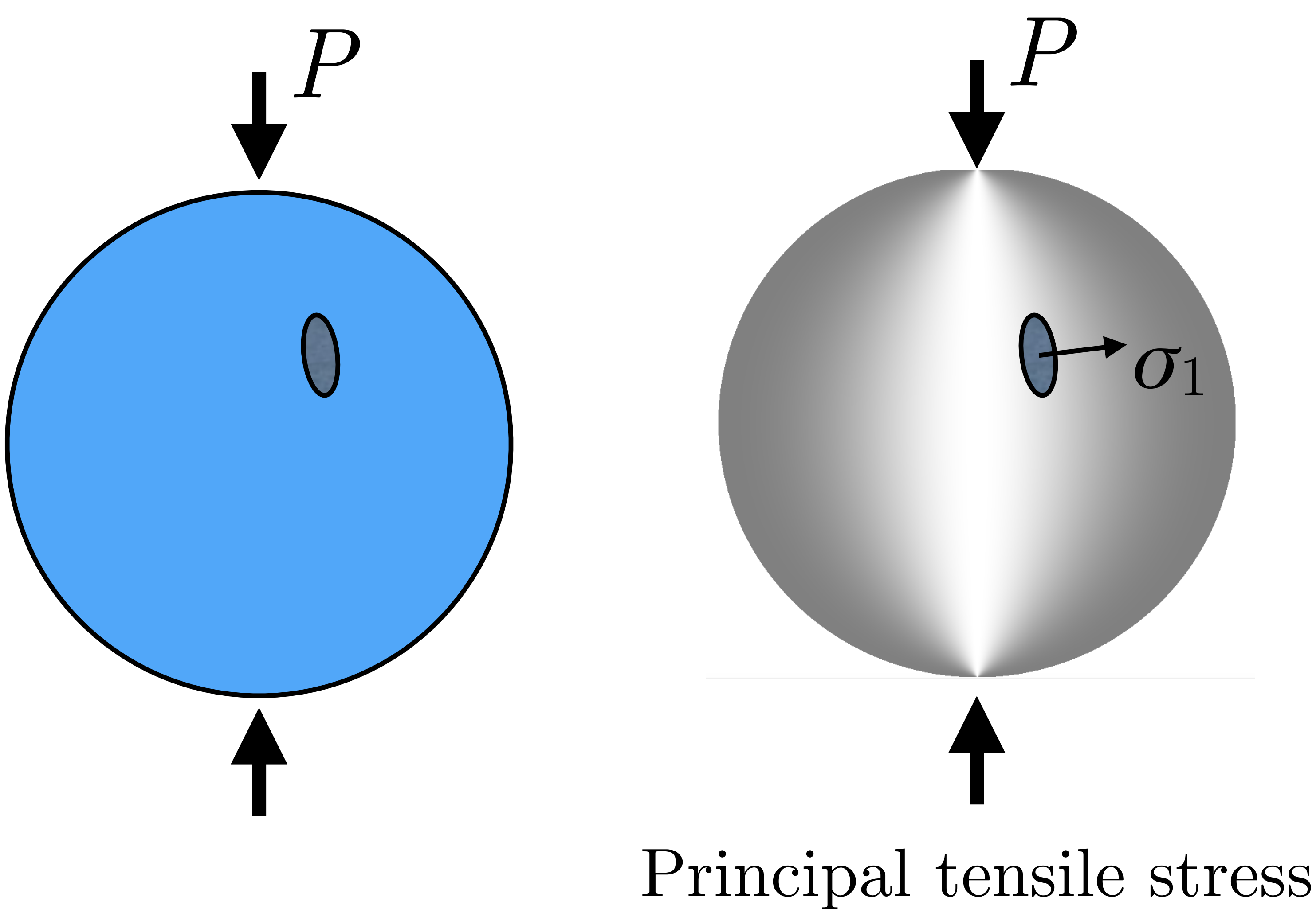
- Question: can we identify critical flaw in specimen?
  - Is it in cement paste?
  - Is it a segment of the ITZ?



Fracture Analysis

- Apply a quasi stress intensity approach.

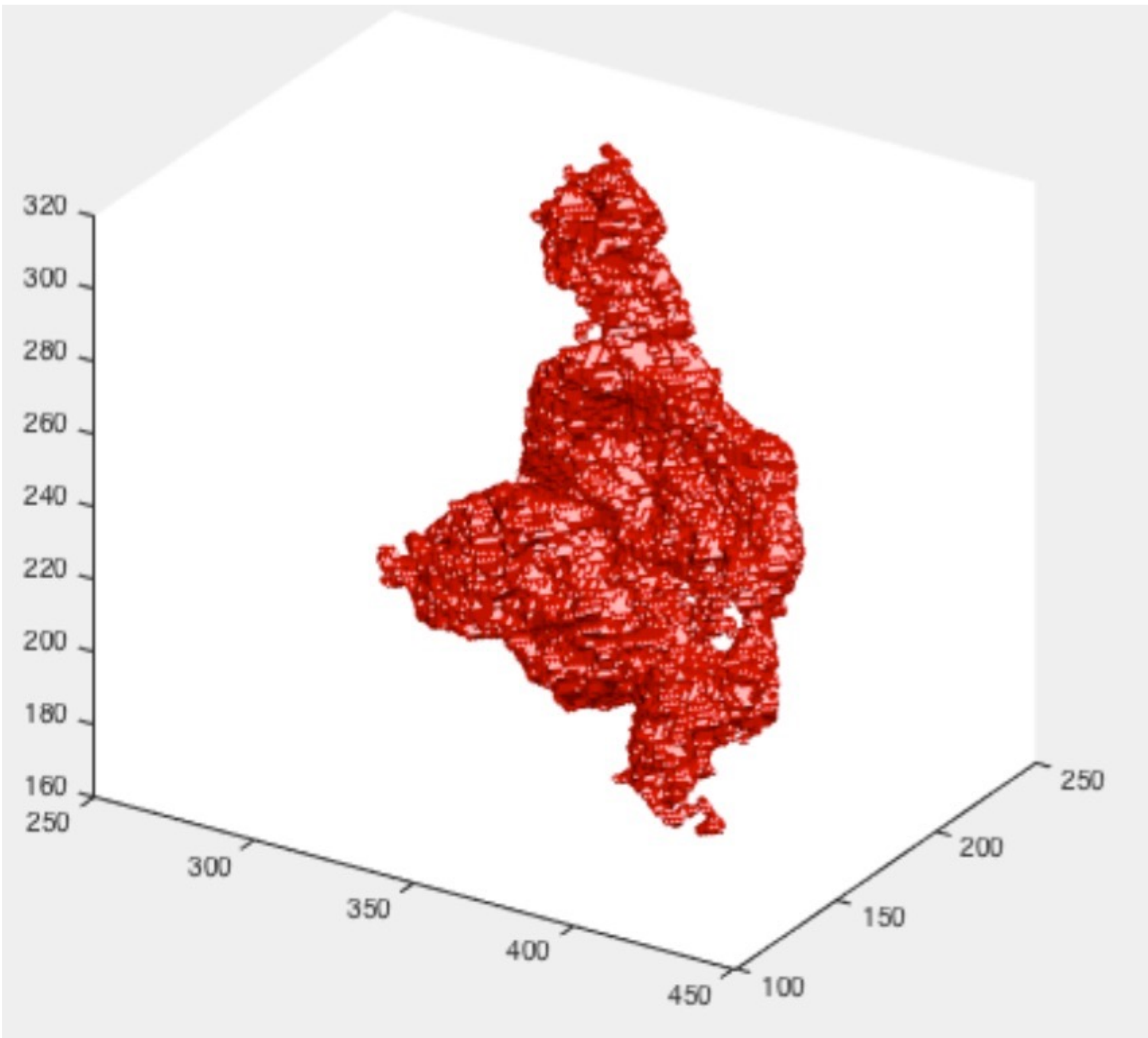
$$K = \beta \sigma \sqrt{a} \quad \Rightarrow \quad K_q = P \alpha \sqrt[4]{A}$$



$\alpha =$ magnitude of principal tensile stress due to unit load

$A =$ projected area oriented normal to principal direction

Critical flaw is assumed to produce highest K



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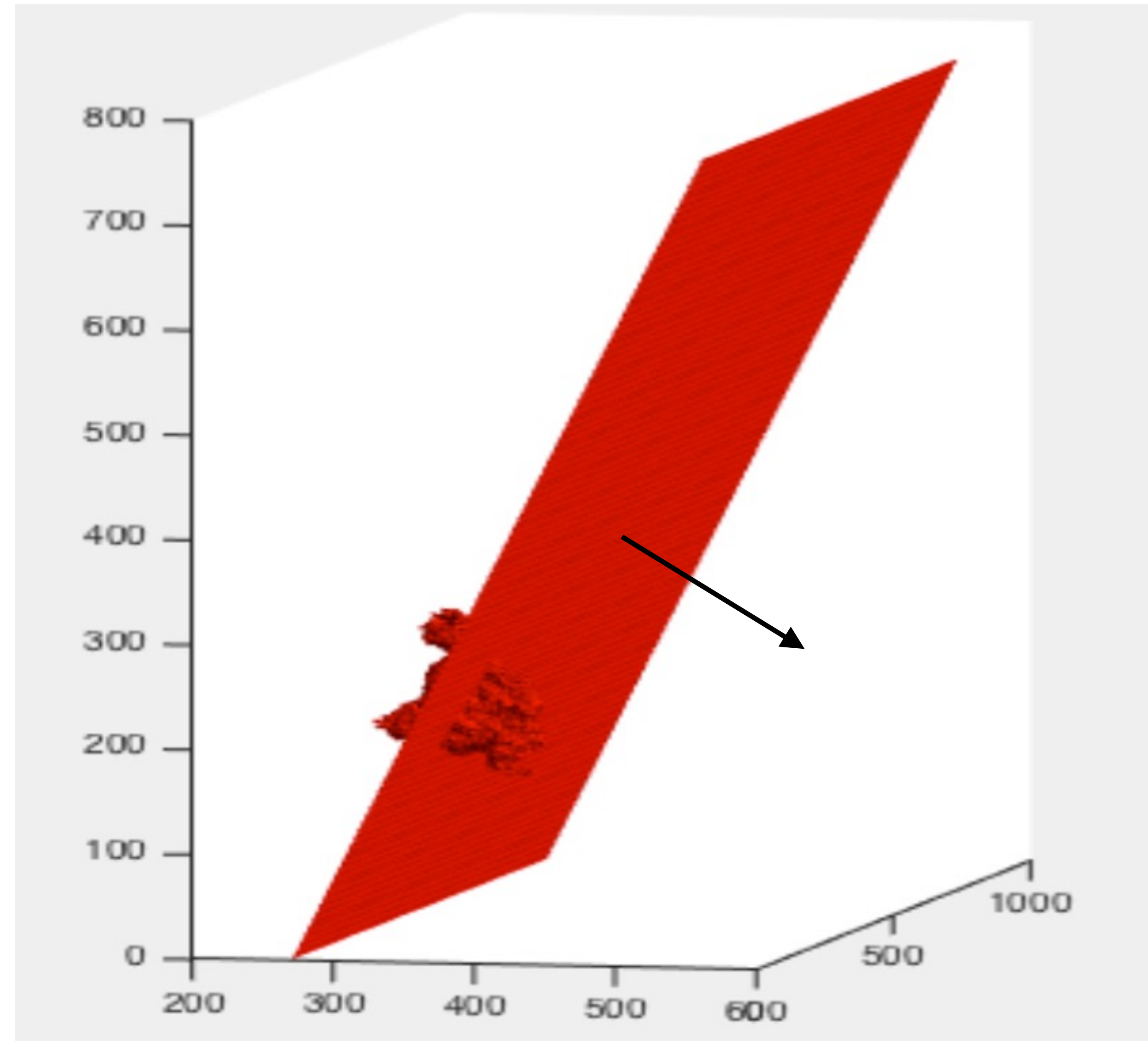

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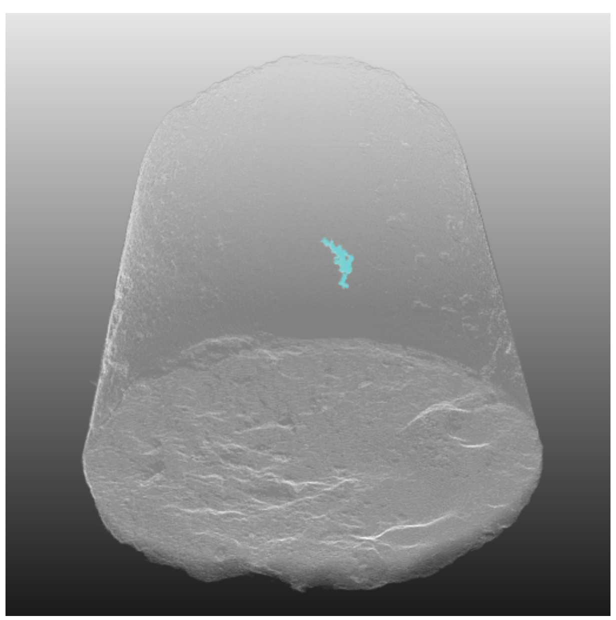
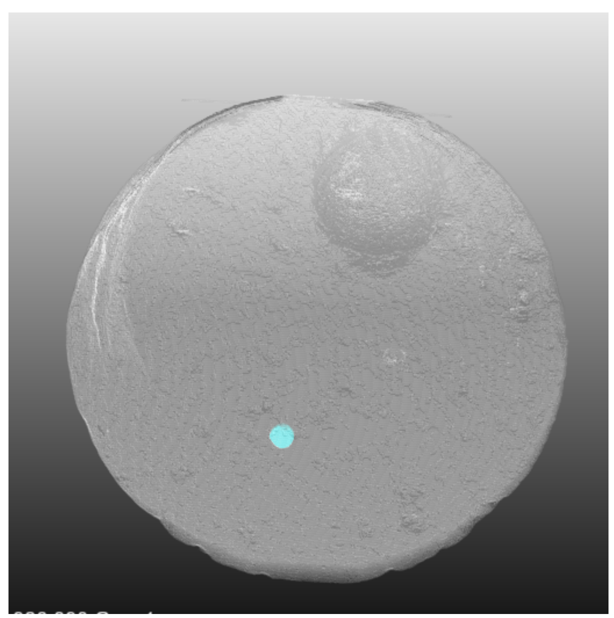
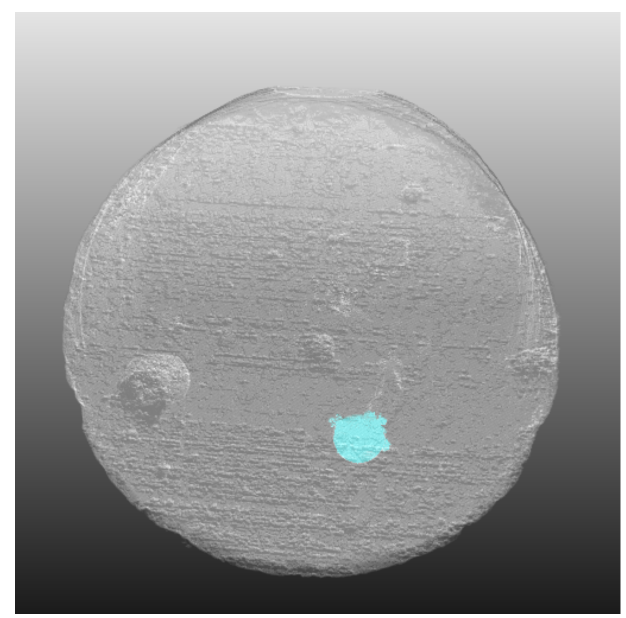
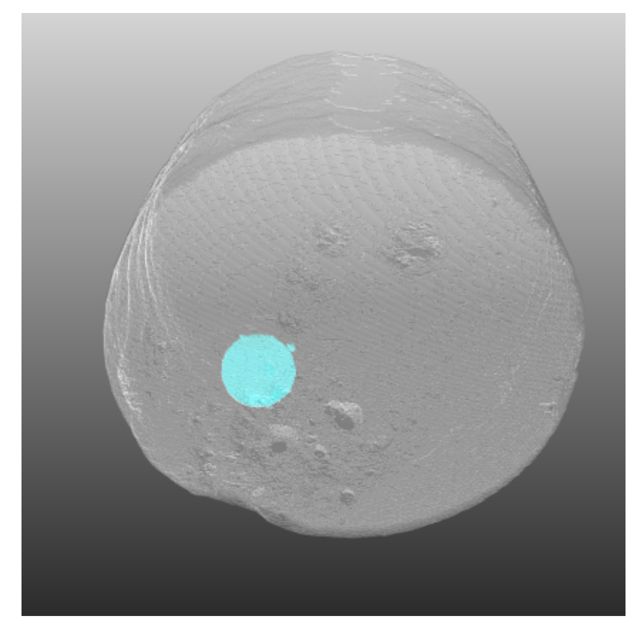
1000

Results: Paste Specimens

$$K_{qc} = P_{ult}\alpha\sqrt[4]{A}$$

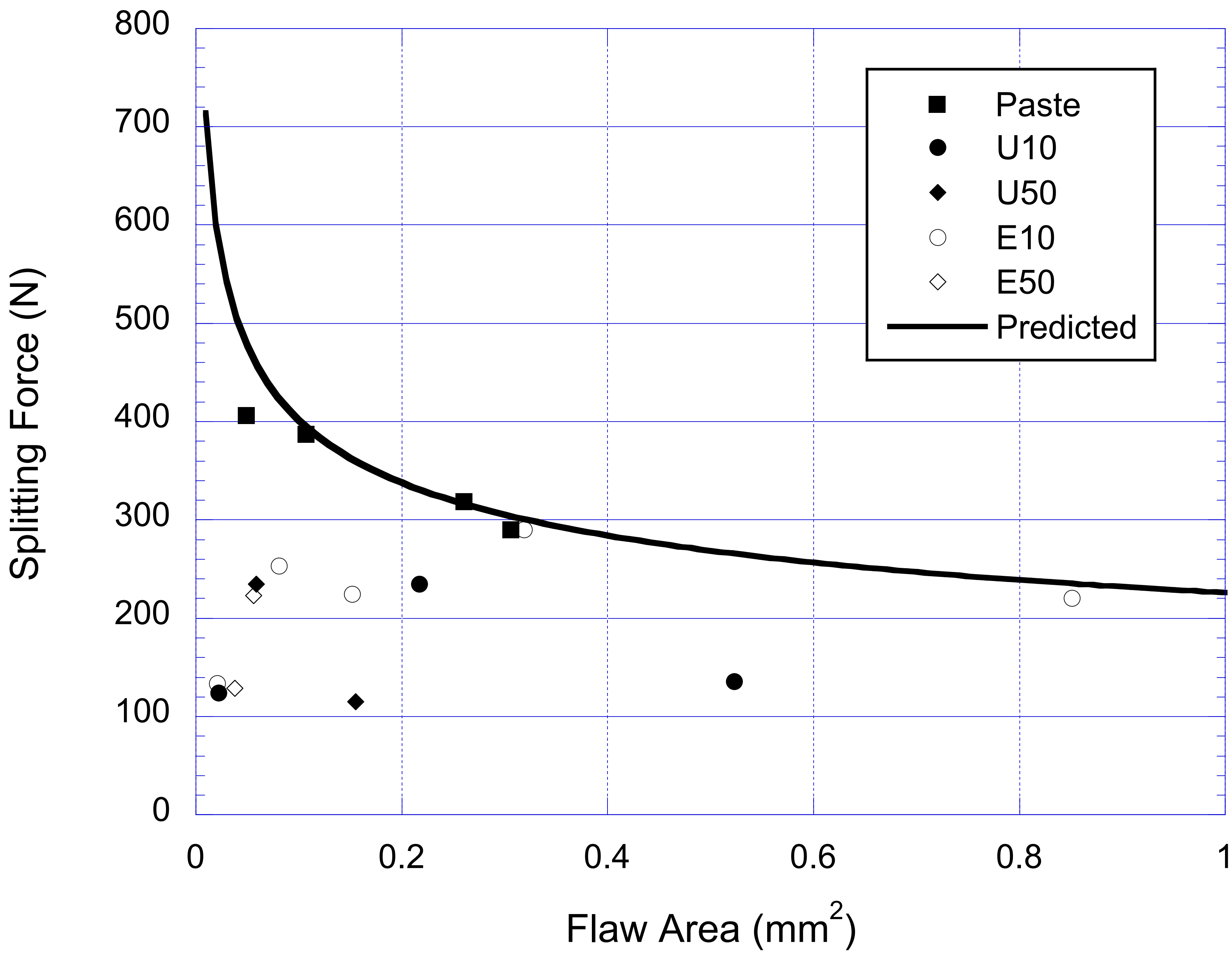
P_{ult} (N)	α (mm^{-2})	A (mm^{2})	$\boldsymbol{K_{qc}}$ **(MPa mm$^{.5}$)**
525	0.024	0.049	**5.9**
480	0.025	0.107	**6.9**
430	0.023	0.260	**7.1**
450	0.020	0.396	**6.7**

Results: All Specimens

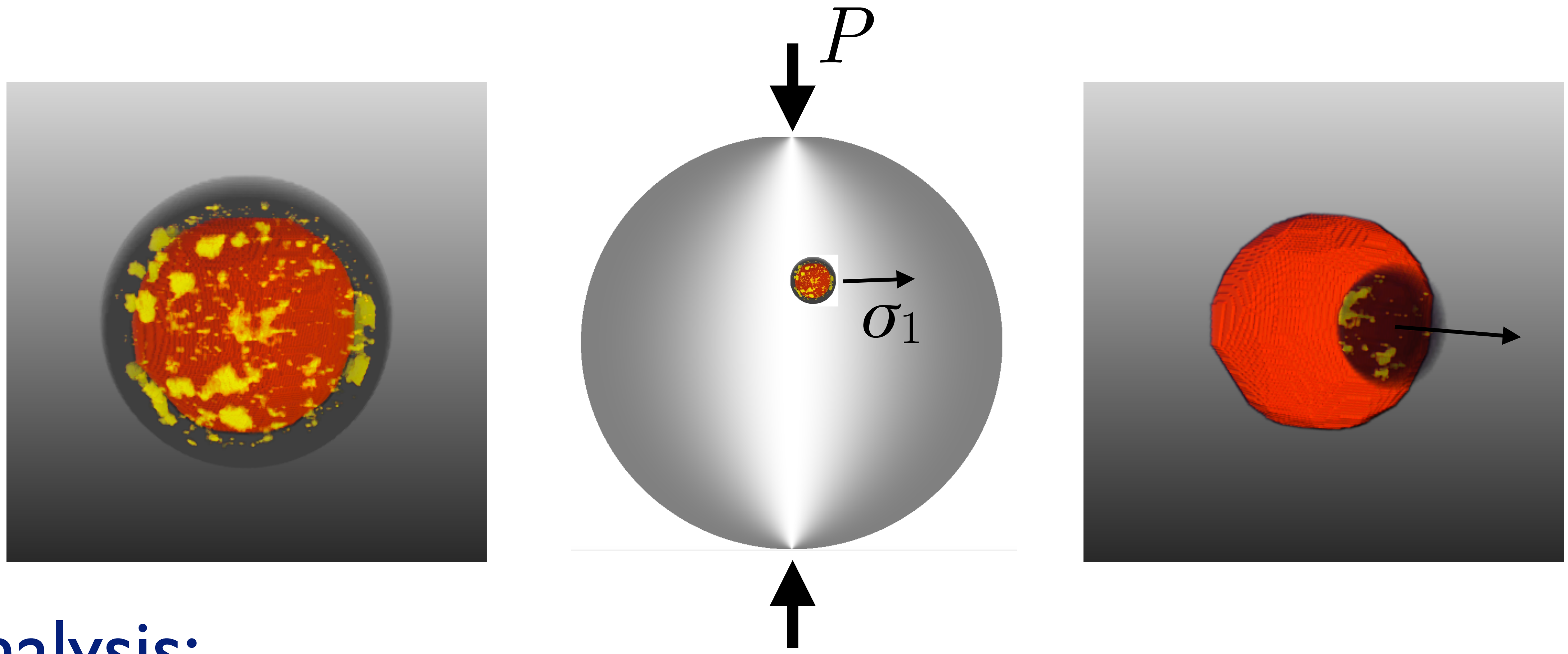
Specimen	P_u (N)	α	A (mm^2)	K_q (MPa$\cdot\sqrt{mm}$)
U10-1	175	0.022	0.022	1.5
U10-2	420	0.010	0.532	3.6
U10-3	485	0.015	0.217	5.0
U50-1	275	0.013	0.155	2.2
U50-2	415	0.026	0.059	1.6
E10-1	415	0.010	0.021	1.6
E10-2	410	0.017	0.152	4.4
E10-3	375	0.024	0.319	6.8
E10-4	280	0.028	0.081	4.2
E10-5	220	0.031	0.851	6.6
E50-1	400	0.010	0.038	1.8
E50-2	385	0.018	0.056	3.4

Results: All Specimens



$$P_{ult} = \frac{K_{qc}}{\alpha \sqrt[4]{A}}$$

ITZ as Weak Link



Analysis:

$$f_t = f_0\,(1 - p_i)$$ tensile strength of porous interface

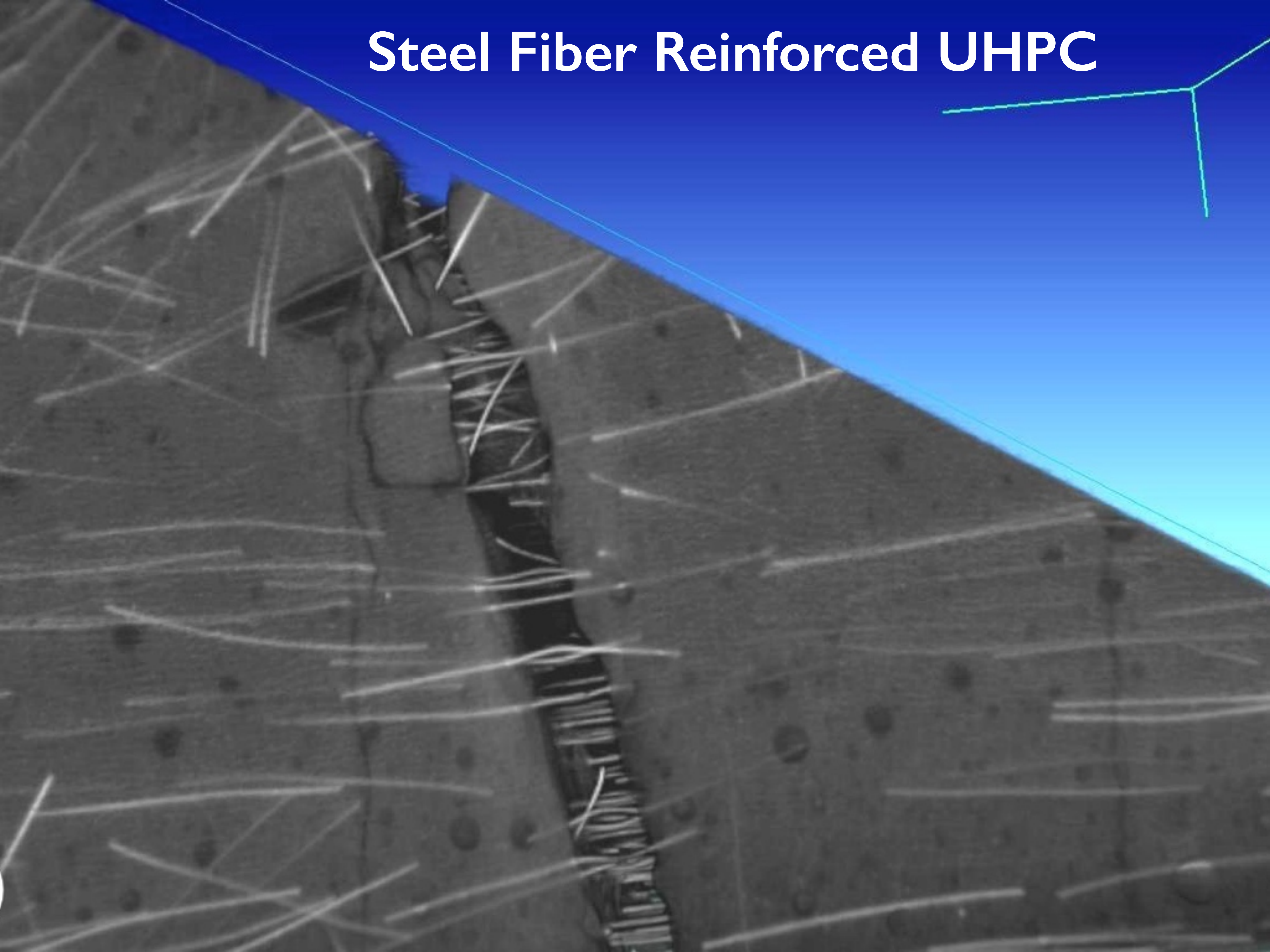
$$\alpha_i P_u = f_0\,(1 - p_i)$$ tensile stress at each interface

$$f_0 = \frac{\alpha_i P_u}{(1 - p_i)}$$ baseline interfacial strength

Results: ITZ as Weak Link

Specimen	P_u (N)	f_o (MPa)	mean, $\bar{p}$	std. dev., s_p	max, p_{max}	K_q (MPa$\cdot\sqrt{\text{mm}}$)
U10-1	175	4.8	0.029	0.011	0.057	1.5
U10-2	420	8.6	0.037	0.012	0.062	3.6
U10-3	485	6.4	0.063	0.033	0.137	5.0
U50-1	275	7.5	0.038	0.028	0.140	2.2
U50-2	415	7.7	0.049	0.019	0.083	1.6
E10-1	415	11.2	0.036	0.019	0.080	1.6
E10-2	410	8.8	0.025	0.013	0.056	4.4
E10-3	375	6.2	0.047	0.014	0.085	6.8
E10-4	280	10.1	0.032	0.016	0.064	4.2
E10-5	220	6.3	0.030	0.017	0.082	6.6
E50-1	400	10.8	0.038	0.017	0.104	1.8
E50-2	385	10.6	0.041	0.015	0.092	3.4

Steel Fiber Reinforced UHPC



Research Objective

- Measure internal energy dissipation in fiber reinforced UHPC beams subjected to quasi-static and impact loads through the analysis of x-ray CT images.
- *Is there a shift in internal energy dissipation mechanisms?*

Materials

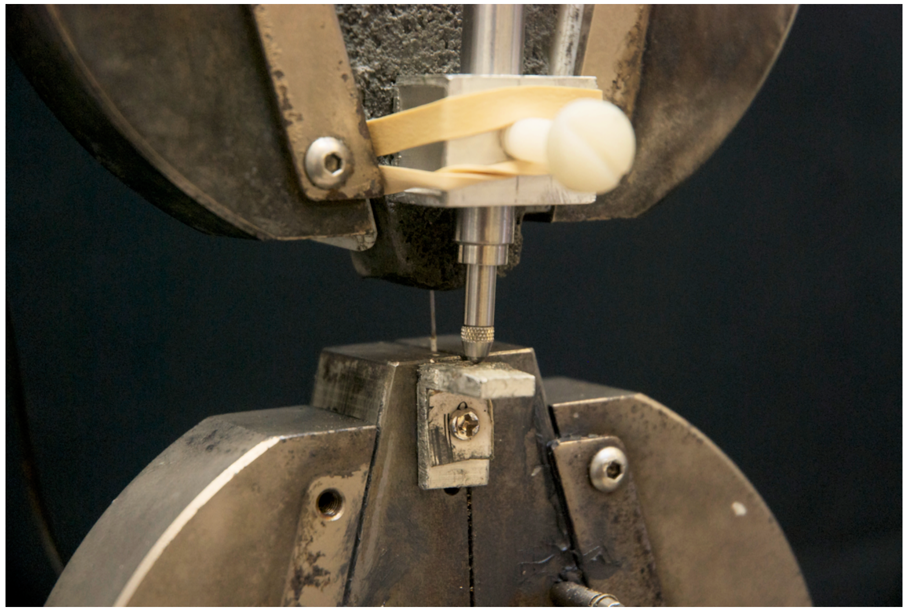
- UHPC Matrix: 180 MPa compressive strength
- 2 fiber types
  - 30 mm hooked steel
  - 12 mm brass coated straight
- 3.5% nominal volume fraction

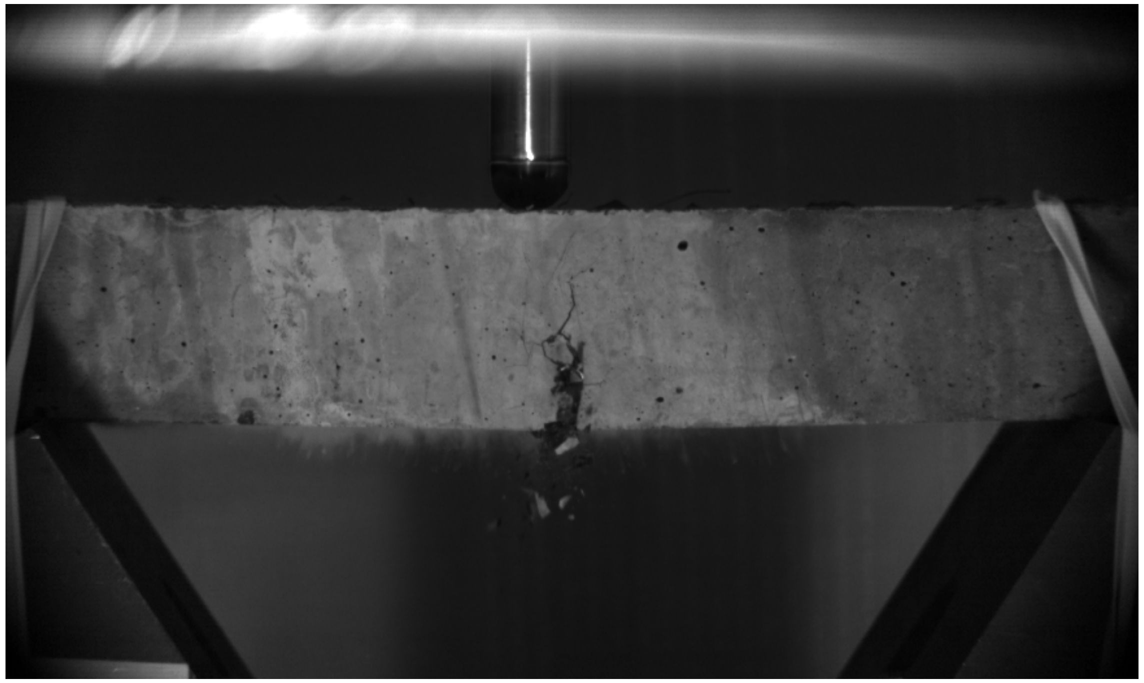
Materials

- Specimens:
  - 28 x 5 x 5 cm prismatic beams
  - tension specimens for fiber pullout

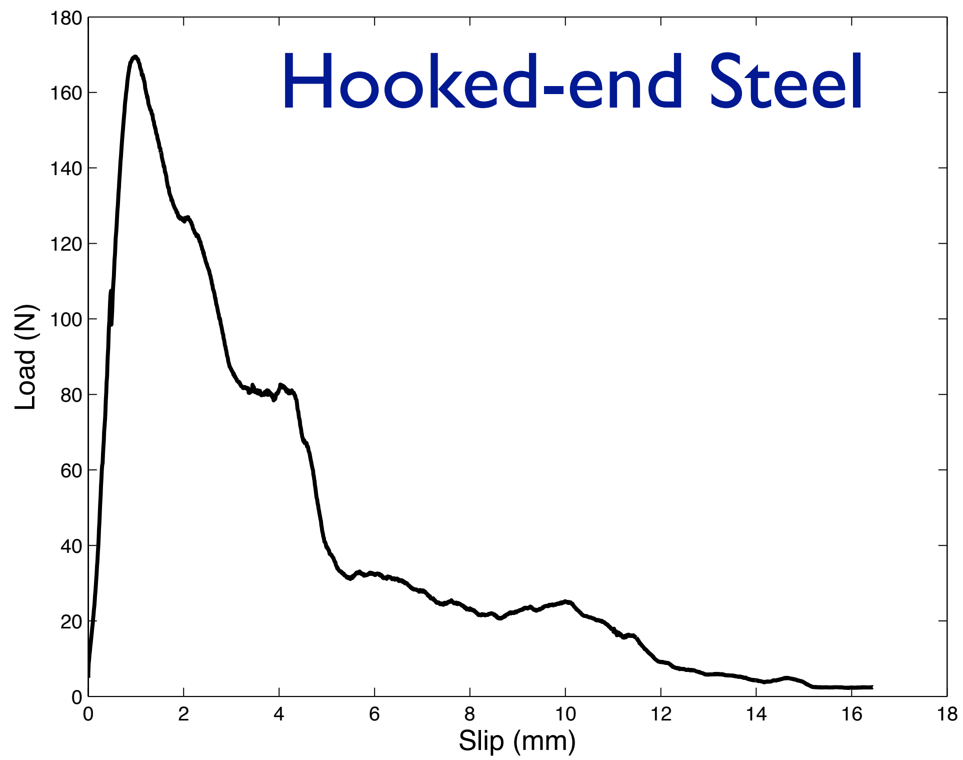
Laboratory Testing

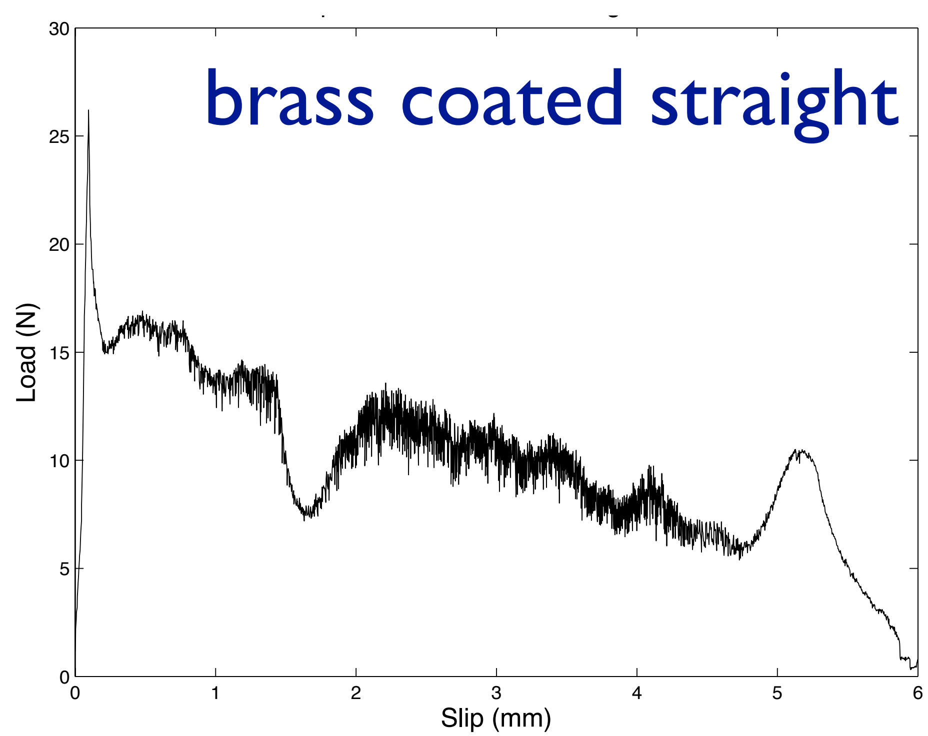
- Fiber pullout
- Quasi-static bending
- Drop weight impact

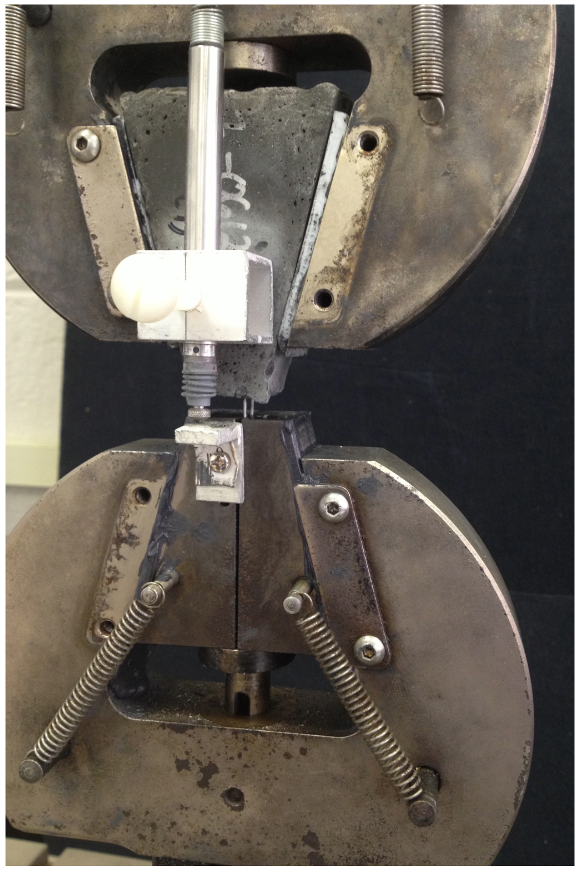




Fiber Pull-Out

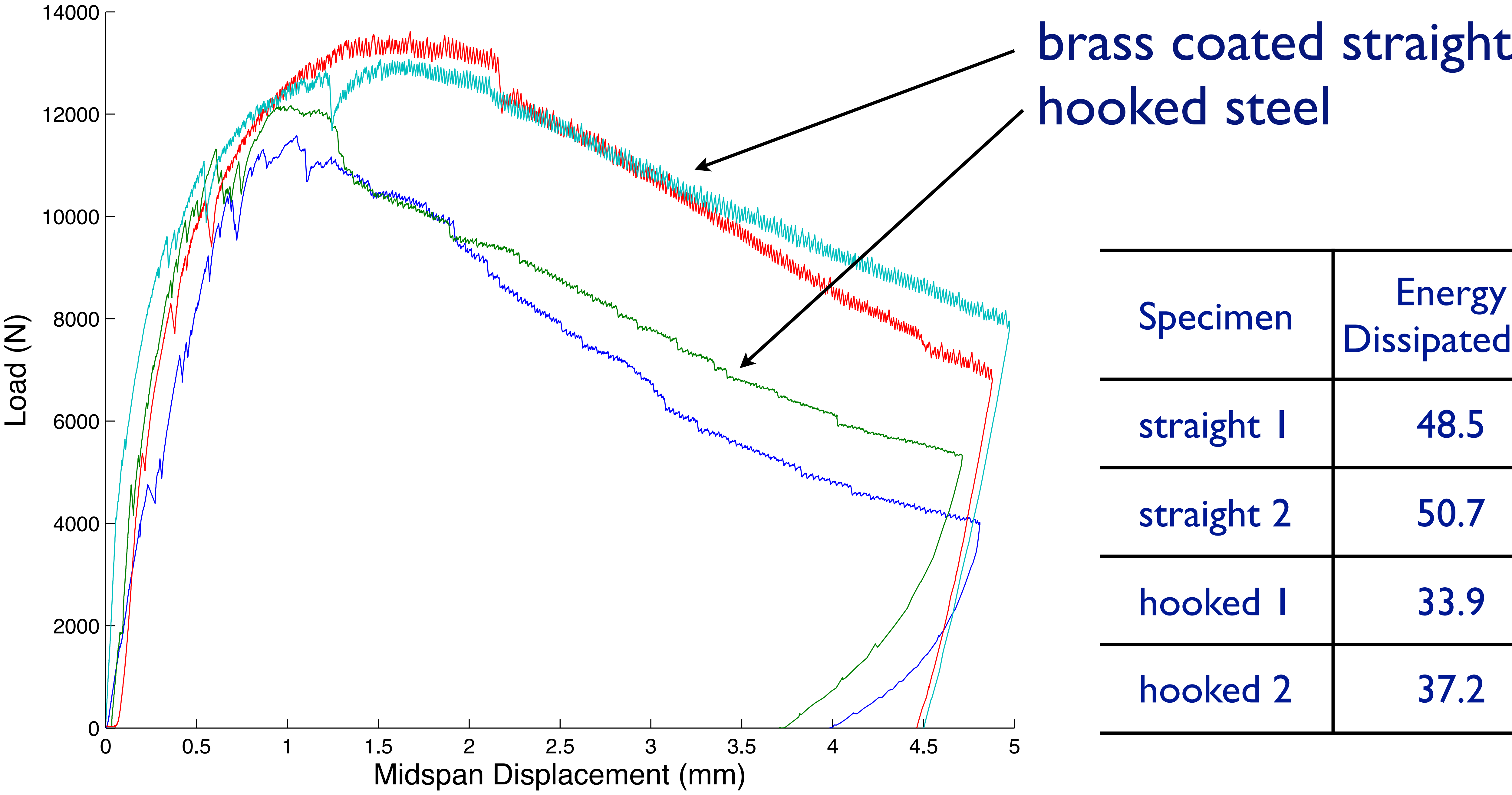






Tests: quasi-static

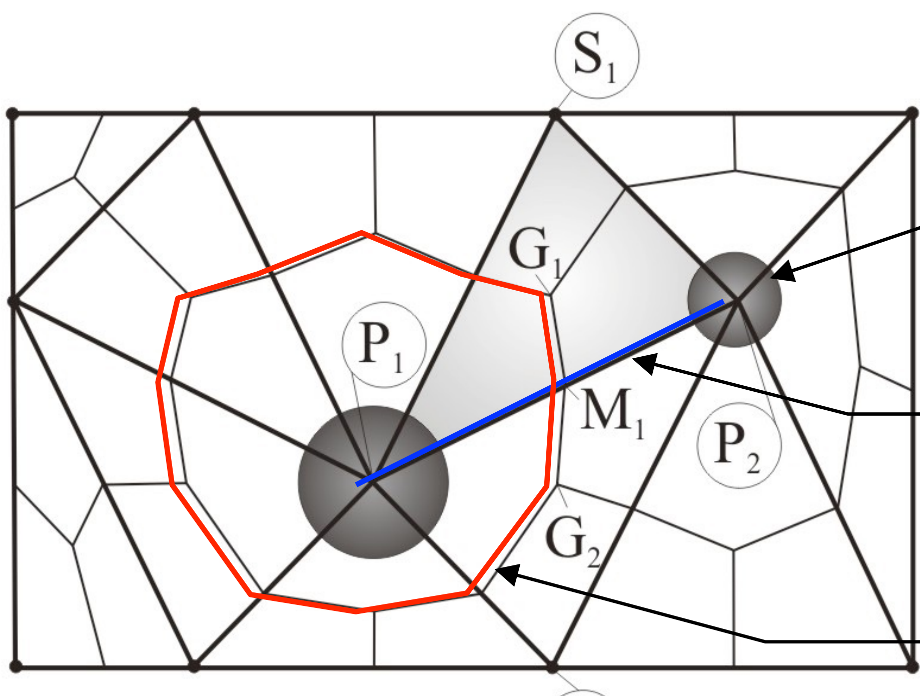
Quasi-Static Tests



Specimen	Energy Dissipated (J)
straight 1	48.5
straight 2	50.7
hooked 1	33.9
hooked 2	37.2

The Lattice Discrete Particle Model

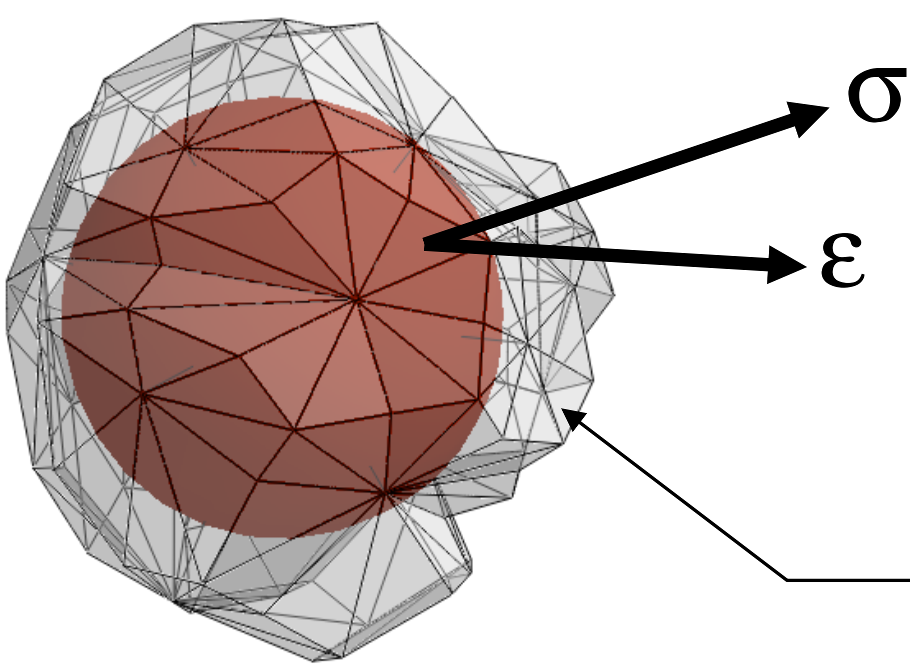
- The discrete LDPM meso-scale (10^{-2}m – 10^{-3}m) model represent concrete as a two-phase material with:
  1. Mortar (Fine aggregates)
  2. Particles (Coarse aggregates)



2D representation of spherical idealization of coarse aggregate

Delaunay tetrahedralization defines the lattice connection of the particle centers

Dual tessellation of the domain defines a set of discrete polyhedral cells

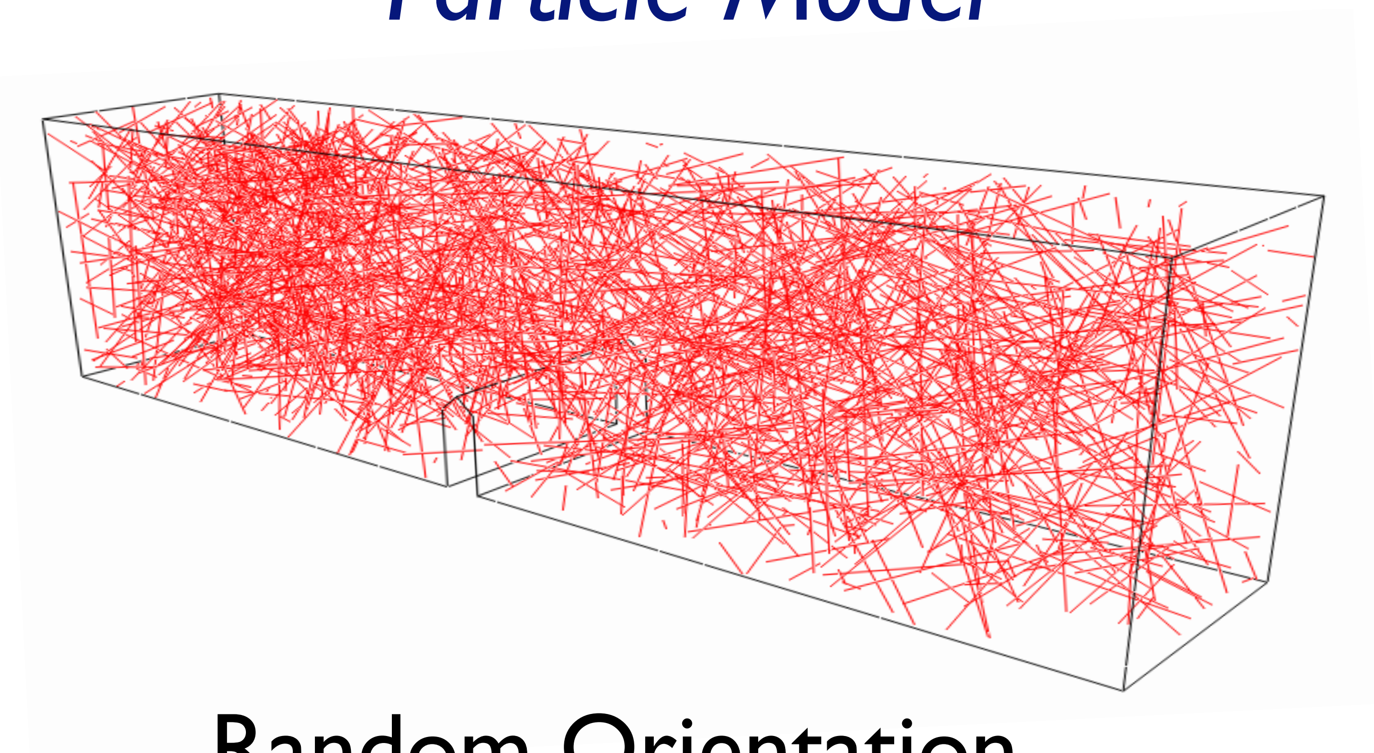


3D representation of spherical idealization of coarse aggregate

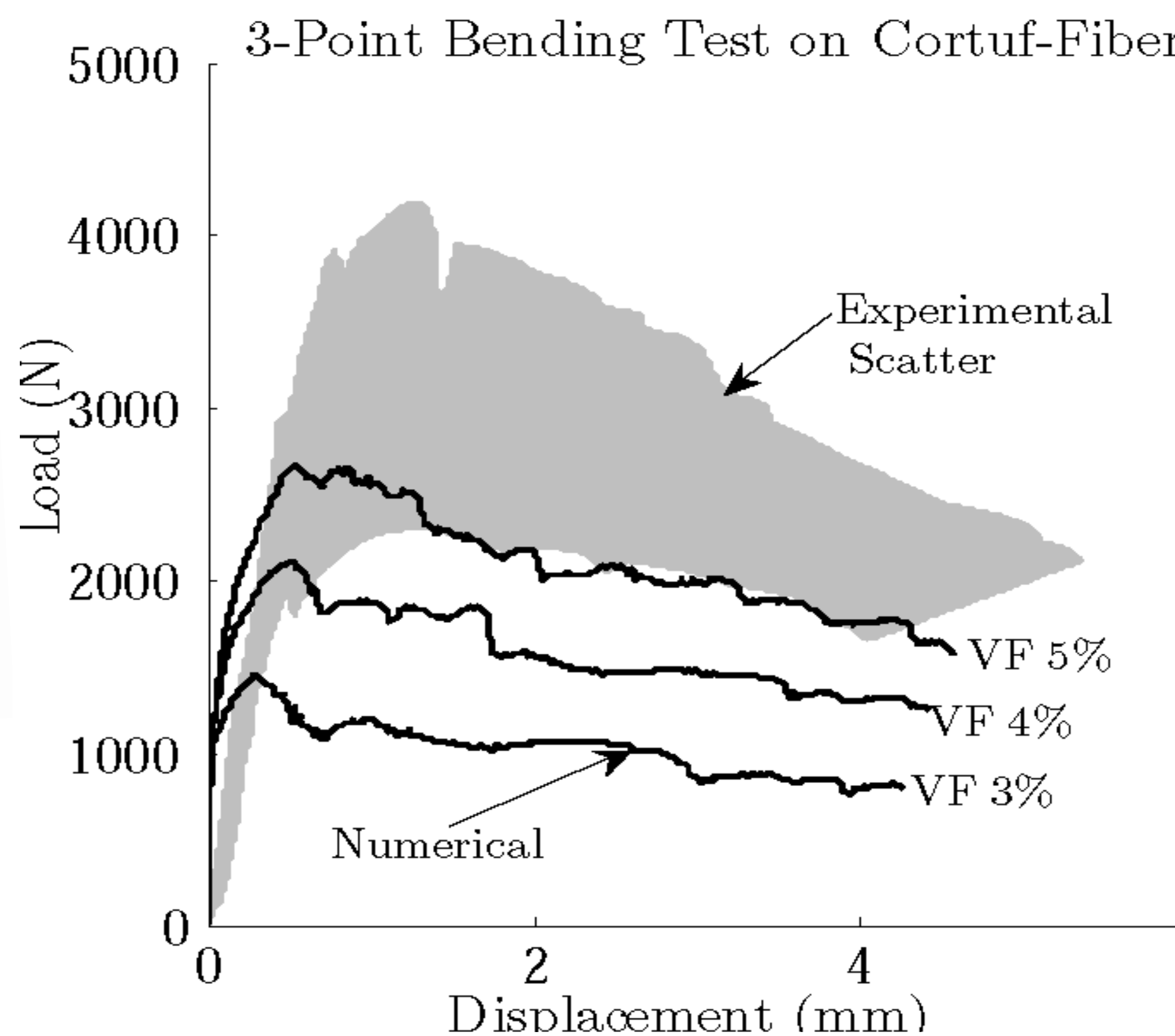
The external triangular faces where adjacent cells interact are the facets

Numerical Simulations

- Fiber Reinforcements - *Simulation with Particle Model*



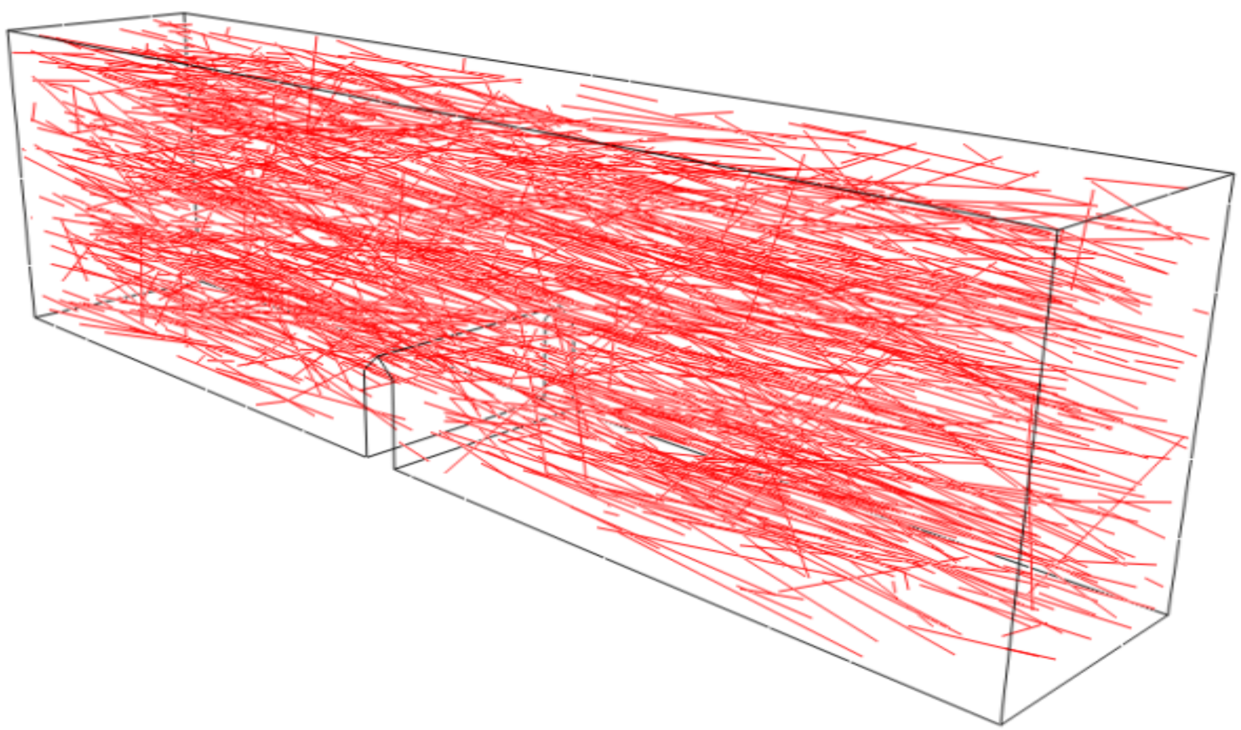
Random Orientation



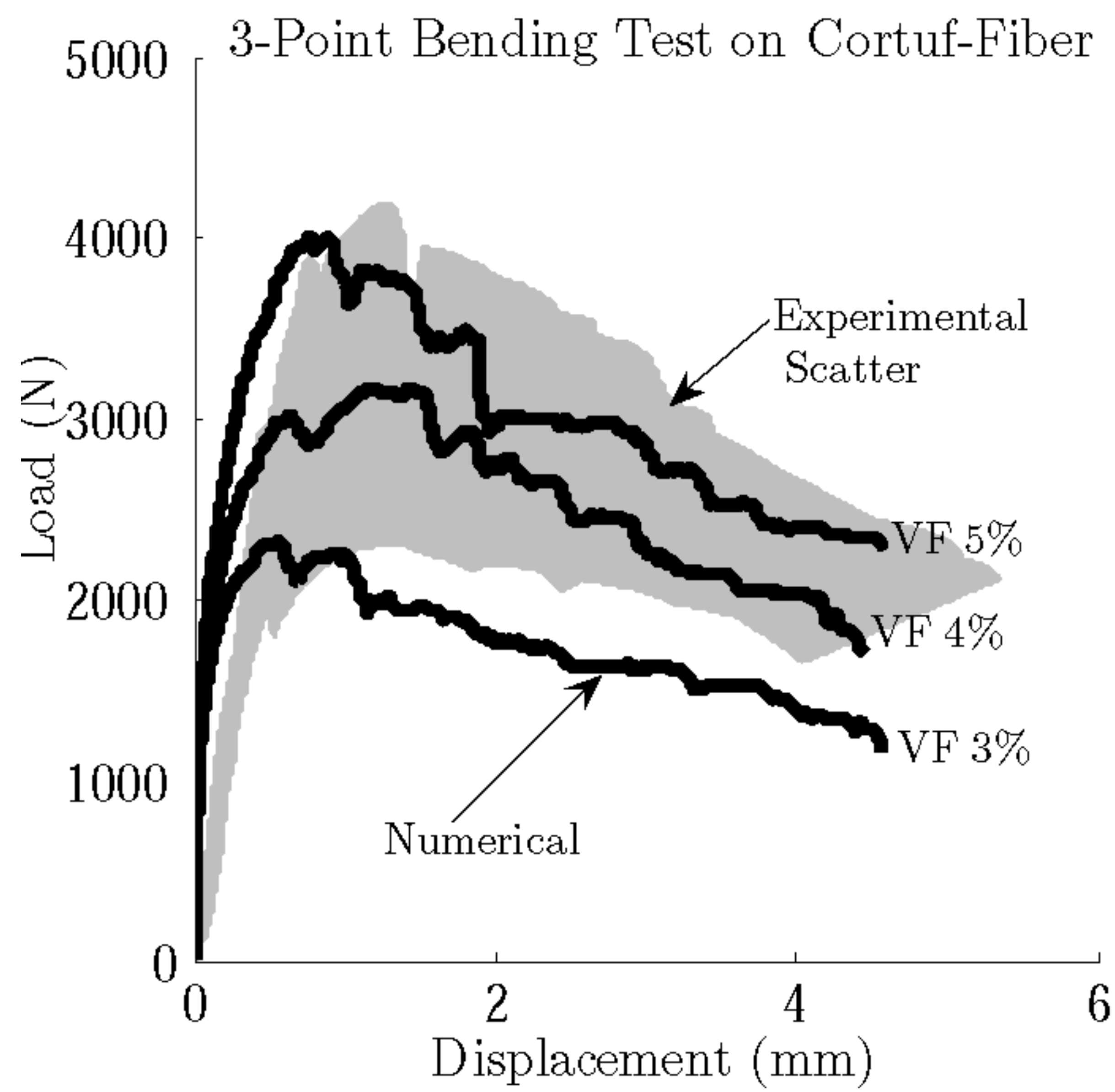
Simulations by G. Cusatis, Northwestern University

Numerical Simulations

- Fiber Reinforcements

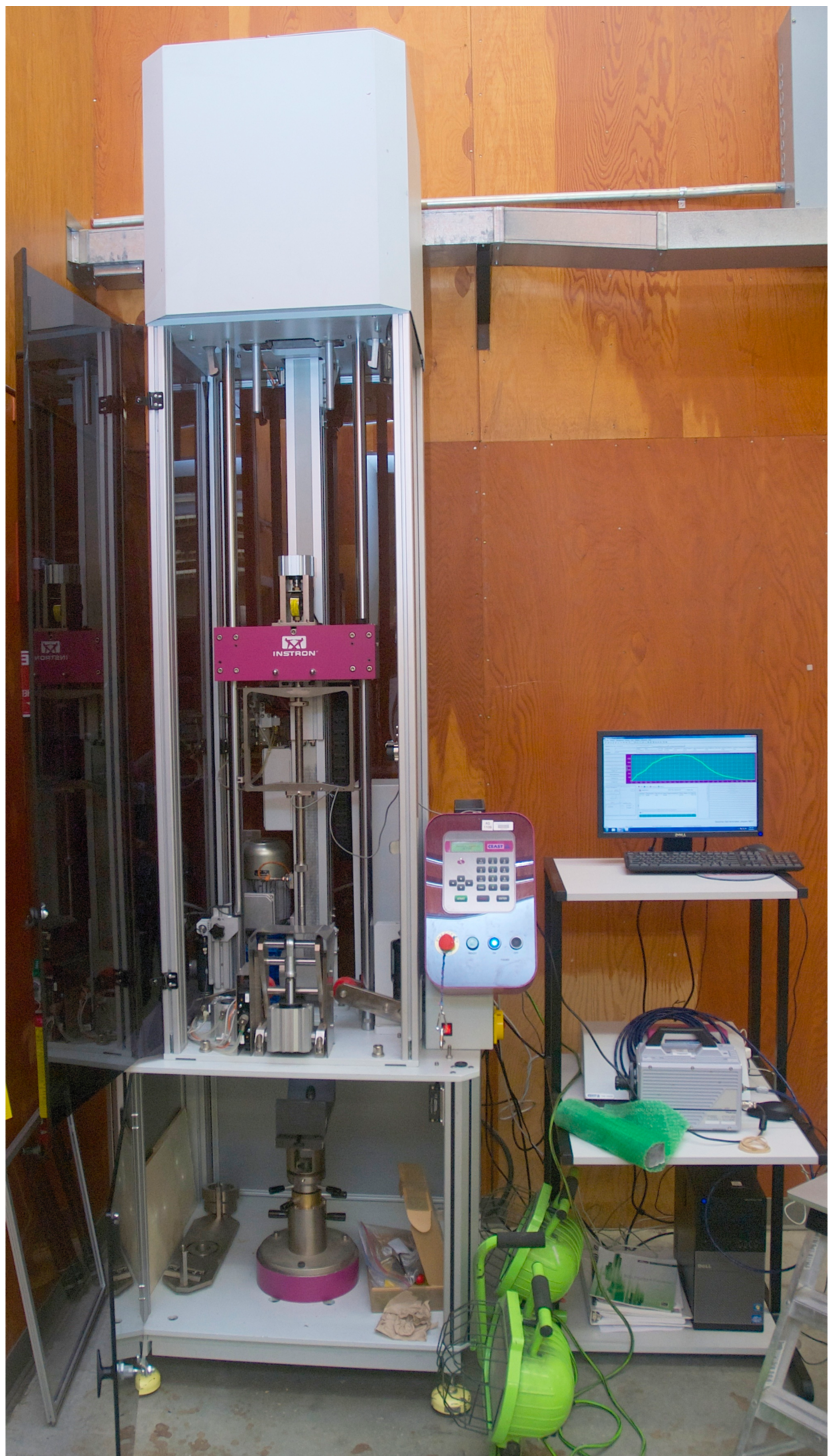


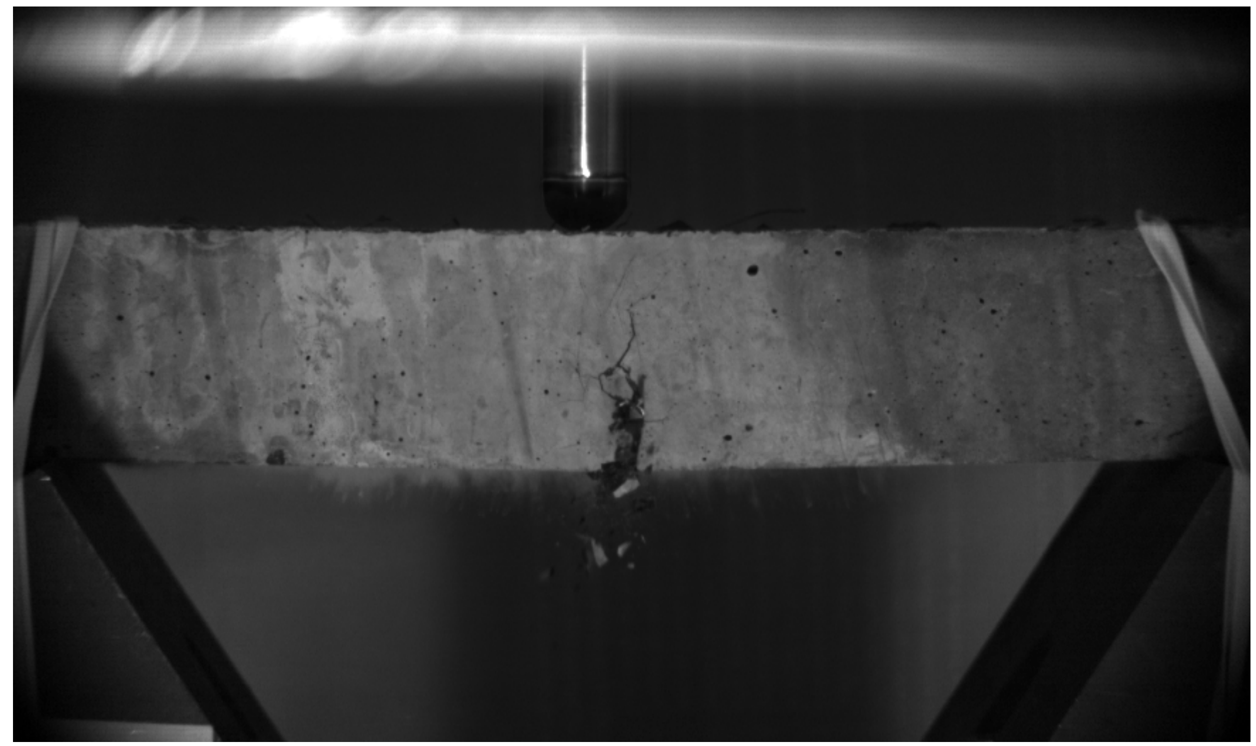
Aligned based on measurements



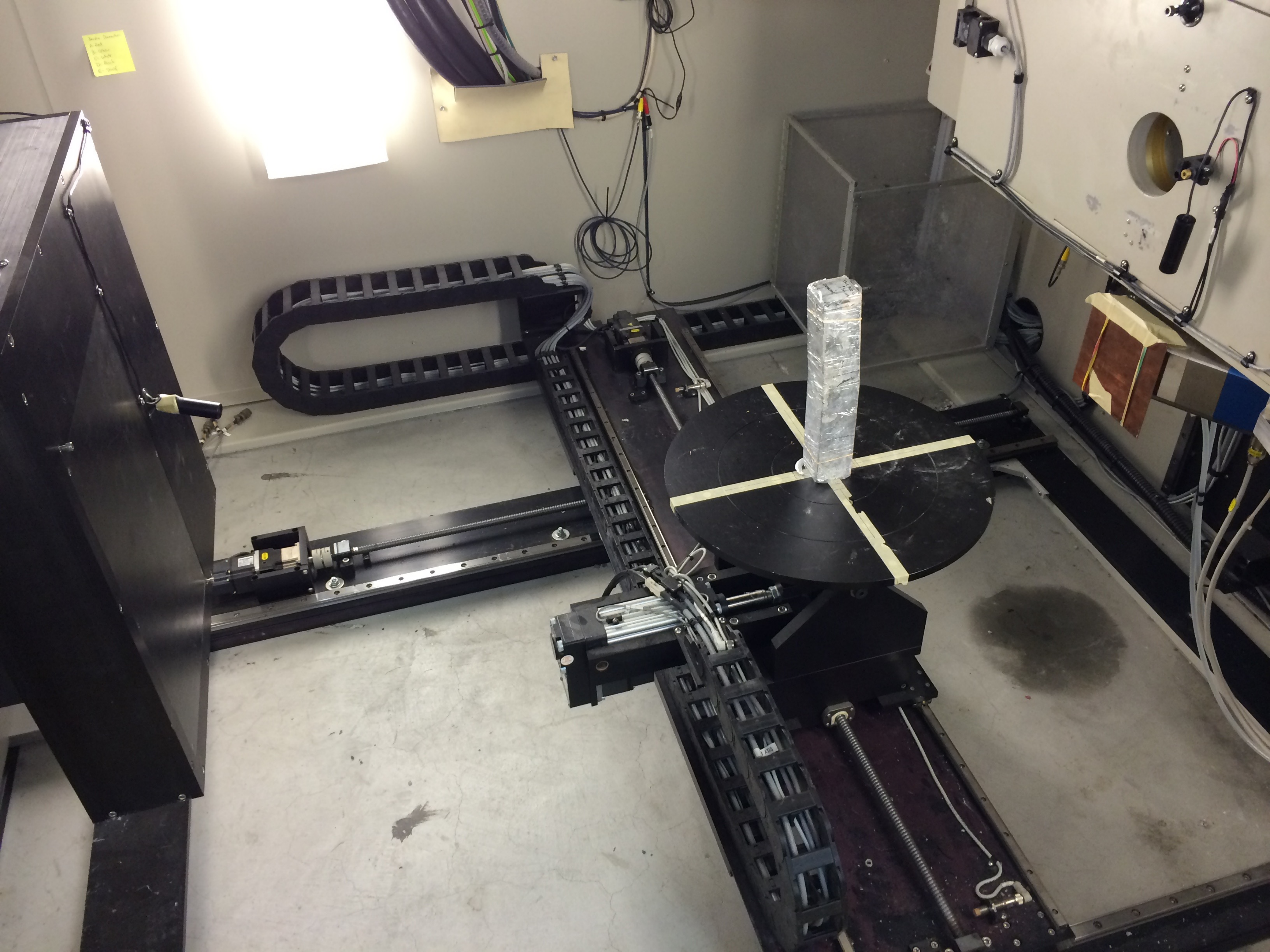
Simulations by G. Cusatis, Northwestern University

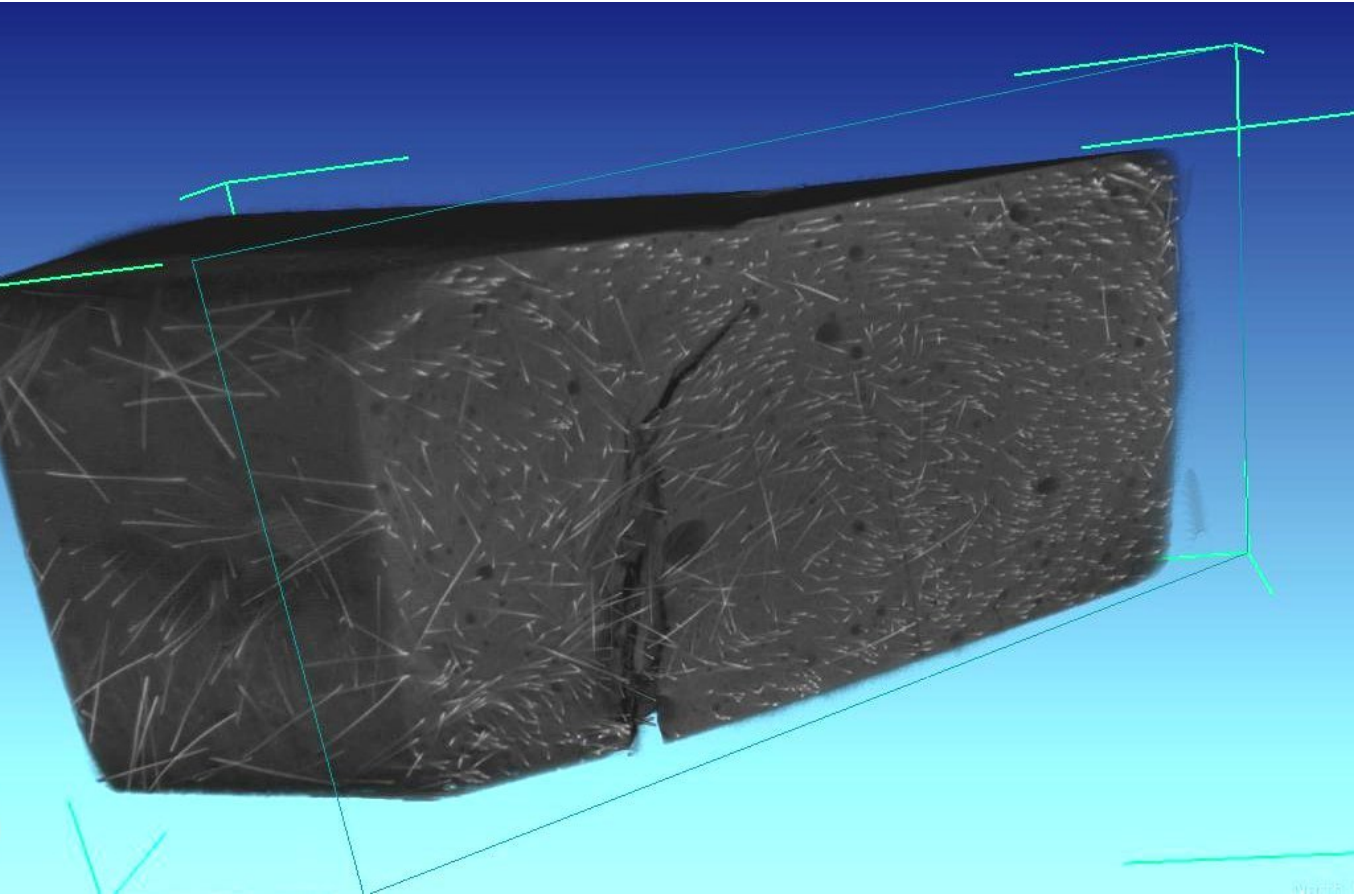
Tests: drop weight impact

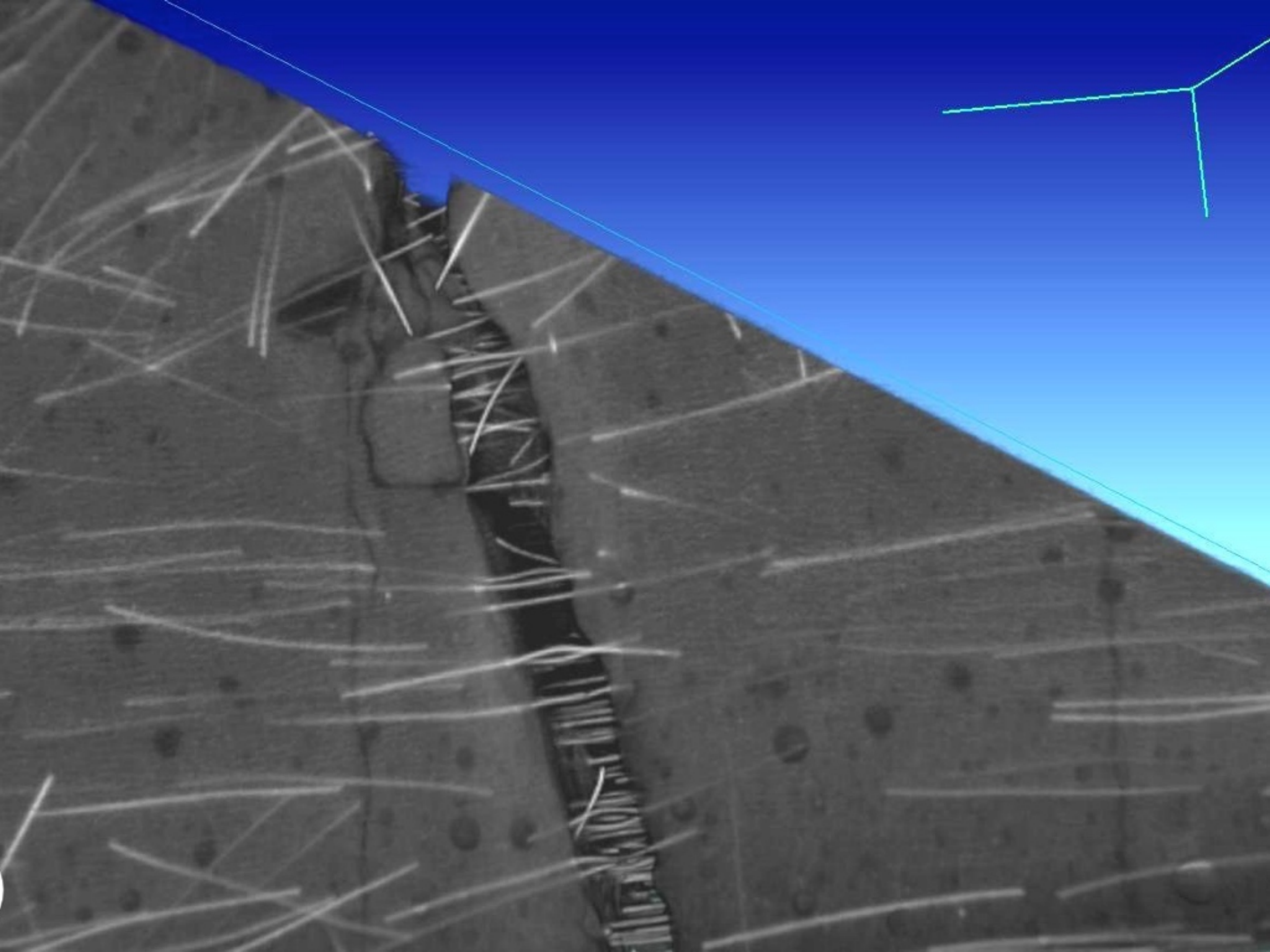




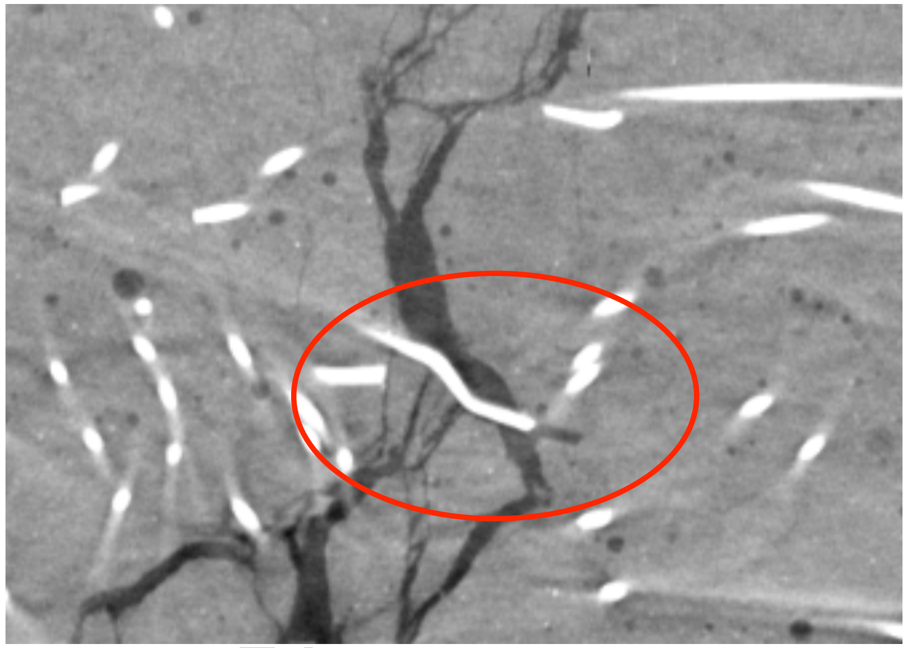
Specimen	Impact Energy (J)
brass 3	50
brass 4	50
hooked 3	35
hooked 4	35





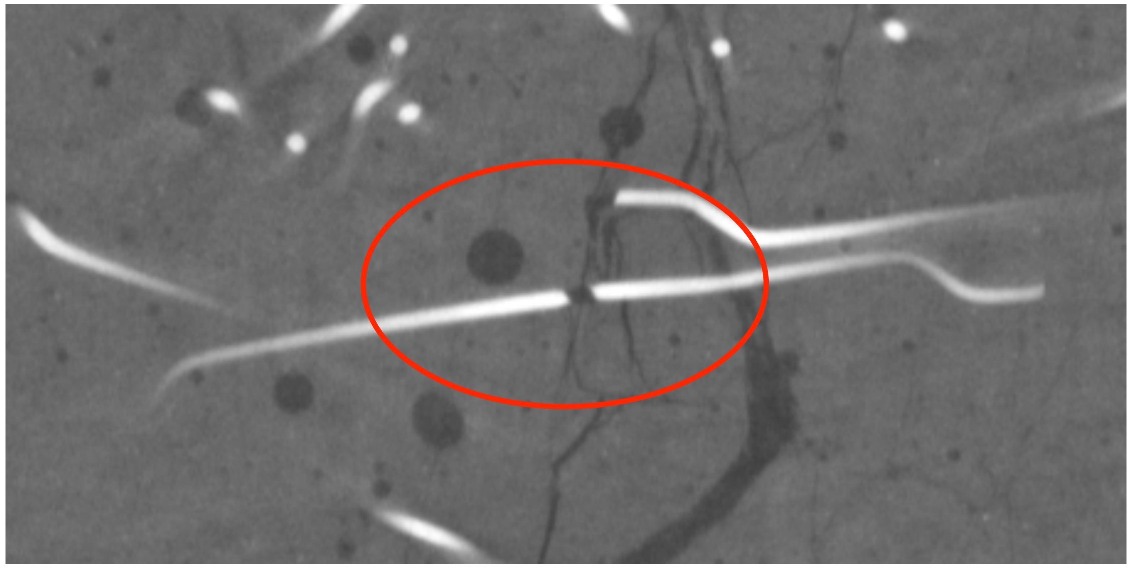


Qualitative Observations



Fiber pull-out

Plastic deformation

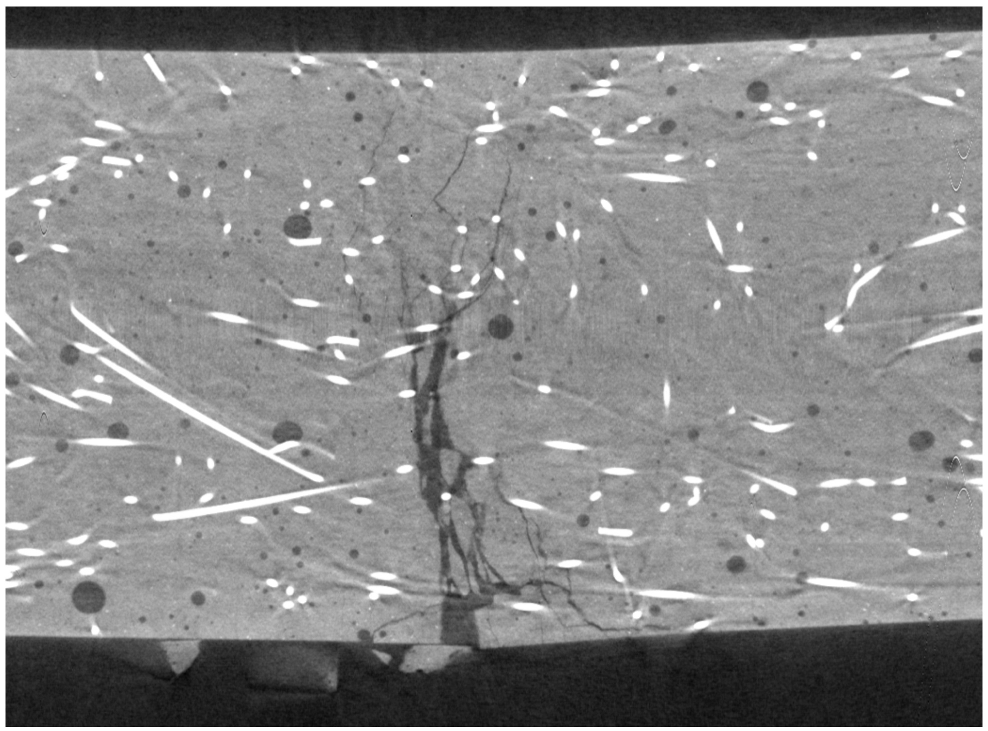


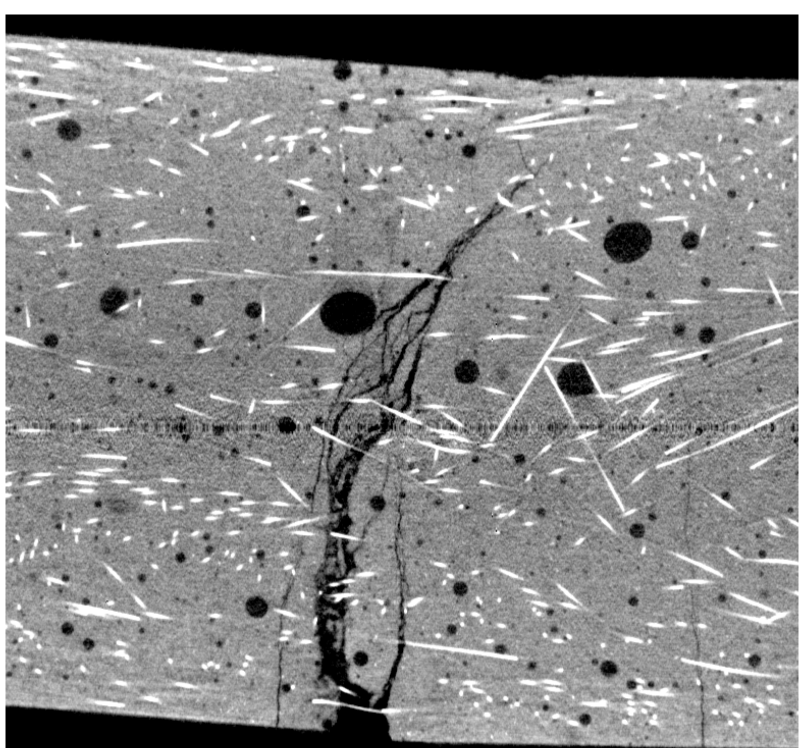
Rupture

Crack networks

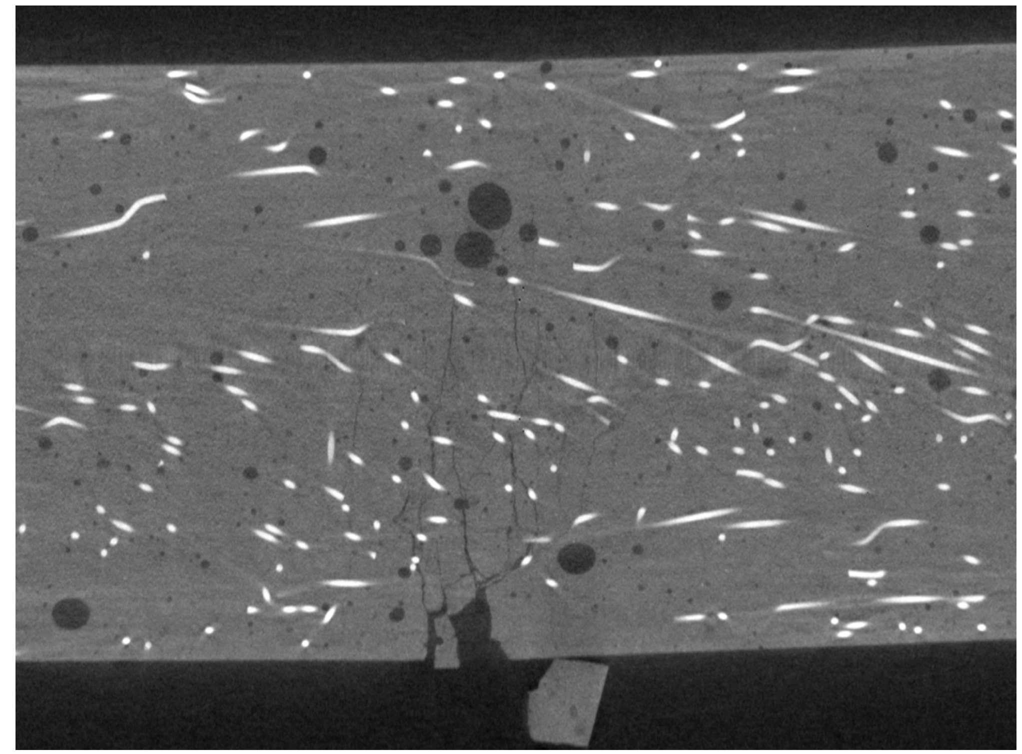
Qualitative Observations

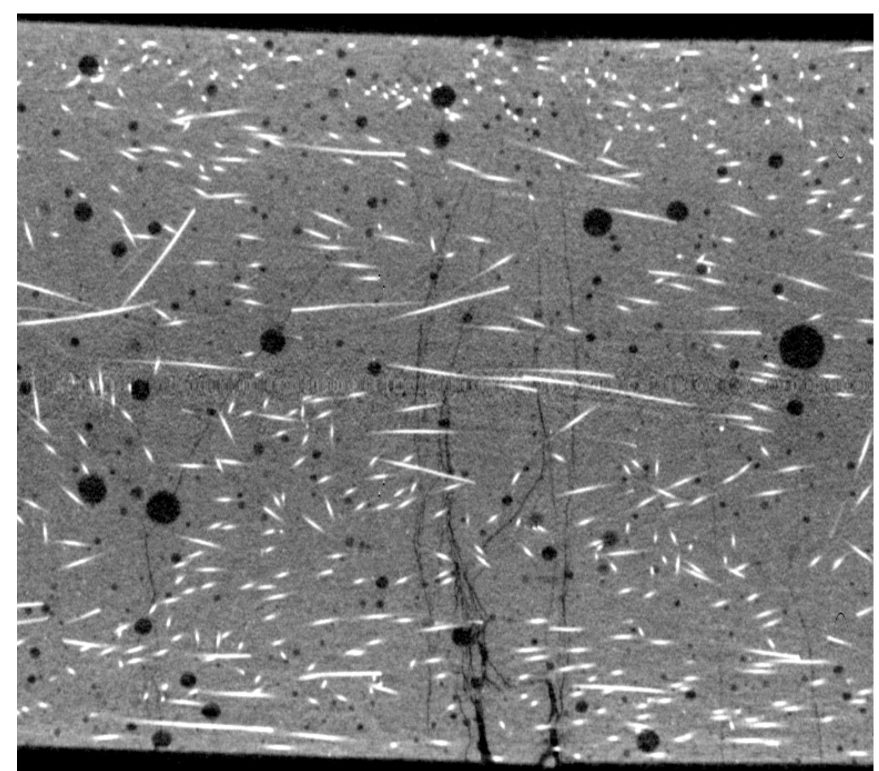
Quasistatic





Impact





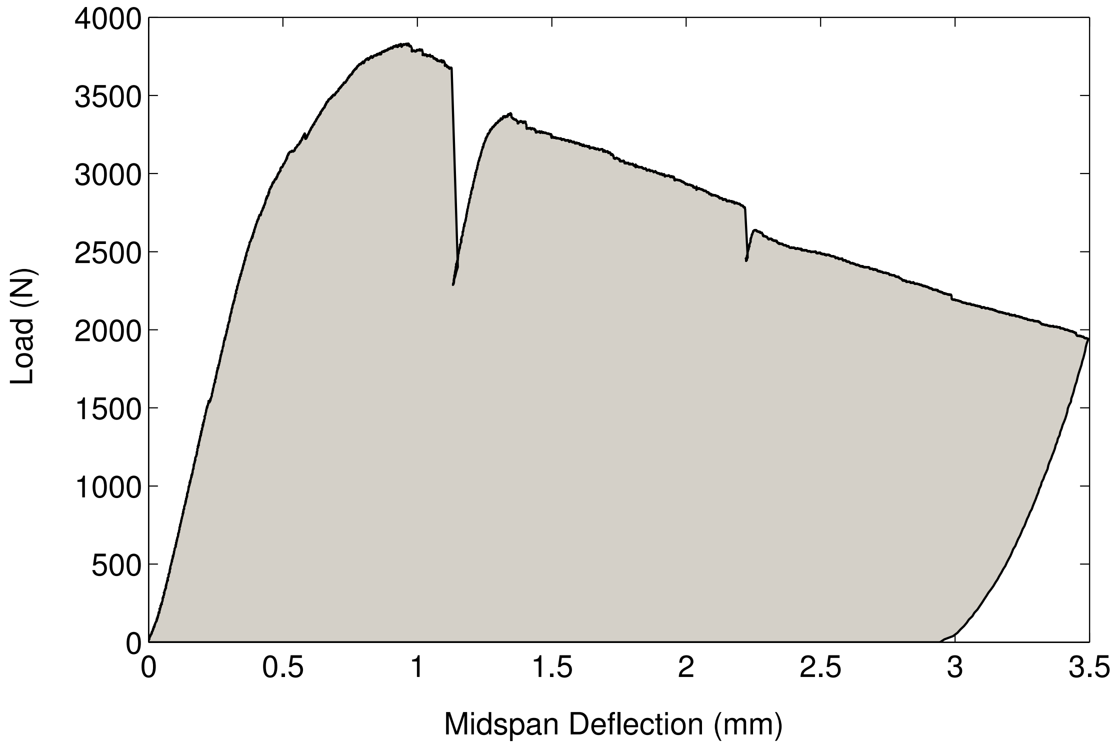
Quantitative Analysis

- Spatial distribution of fibers
- Fiber alignment distribution
- Crack surfaces
- Fiber pullout & bridging
- Fiber bending & rupture

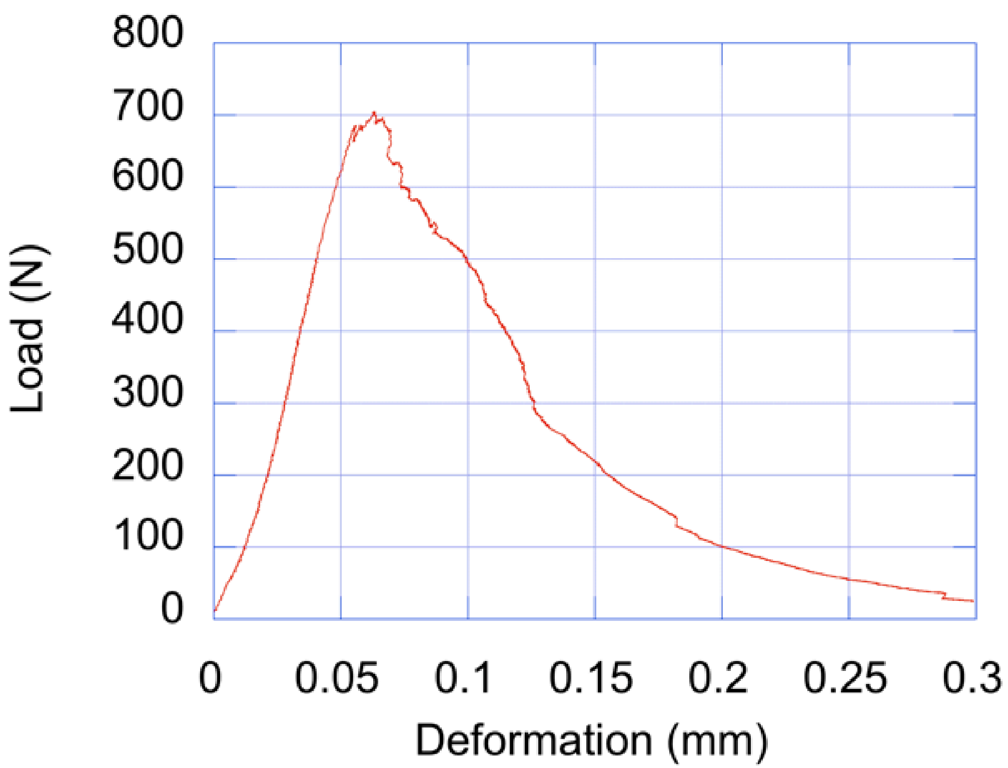
Internal Energy Dissipation

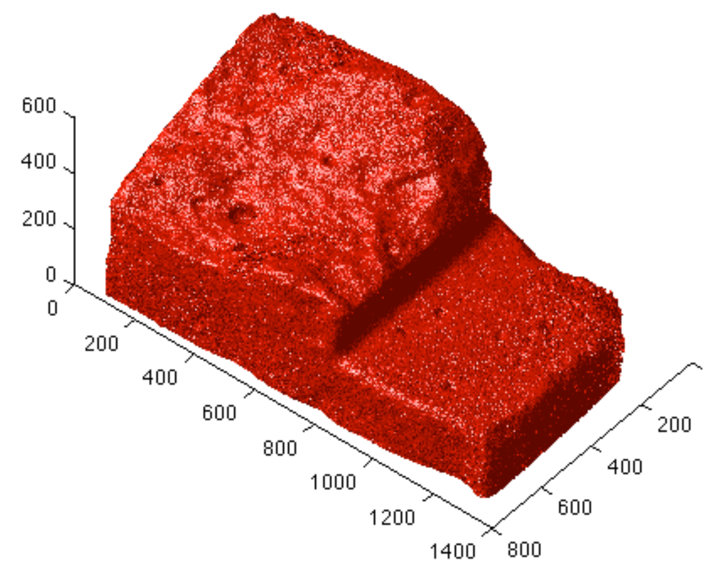
- Consider following mechanisms:
  - matrix fracture, W_f
  - fiber pull-out, W_p
  - fiber bending, W_b
  - fiber rupture, W_r

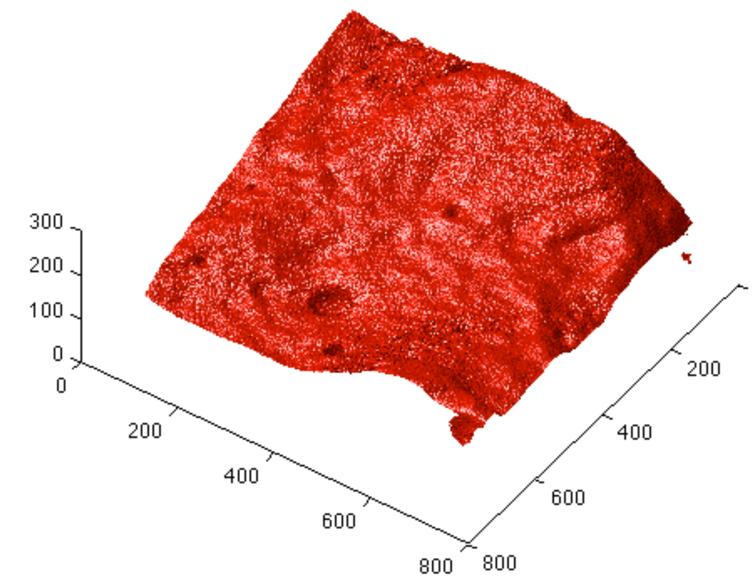
$$= U_{ext} ??$$

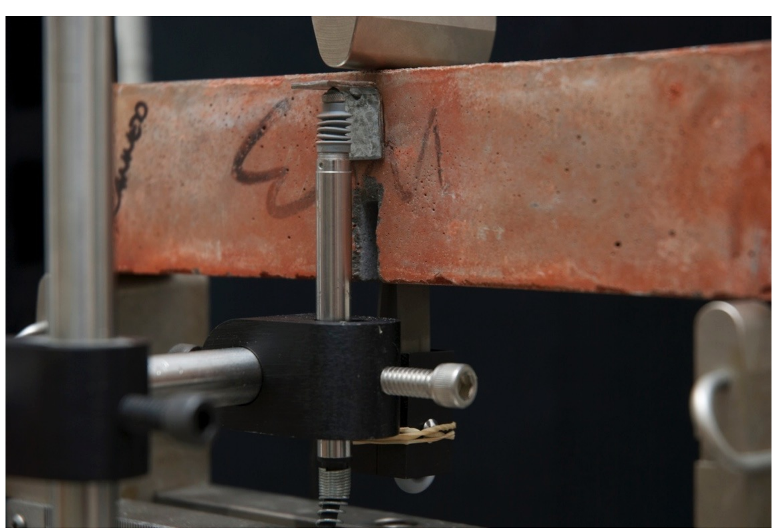


Specific Fracture Energy





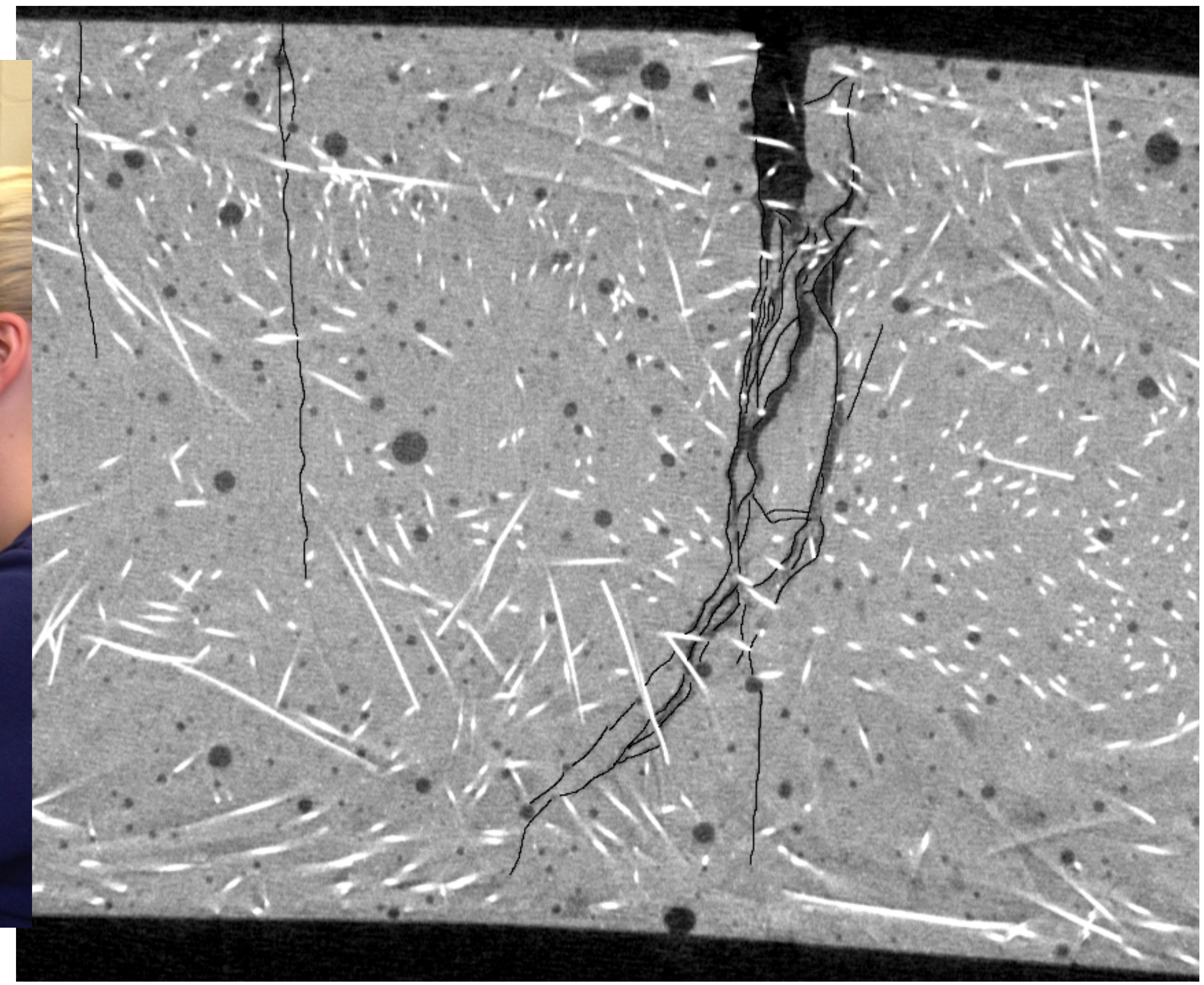




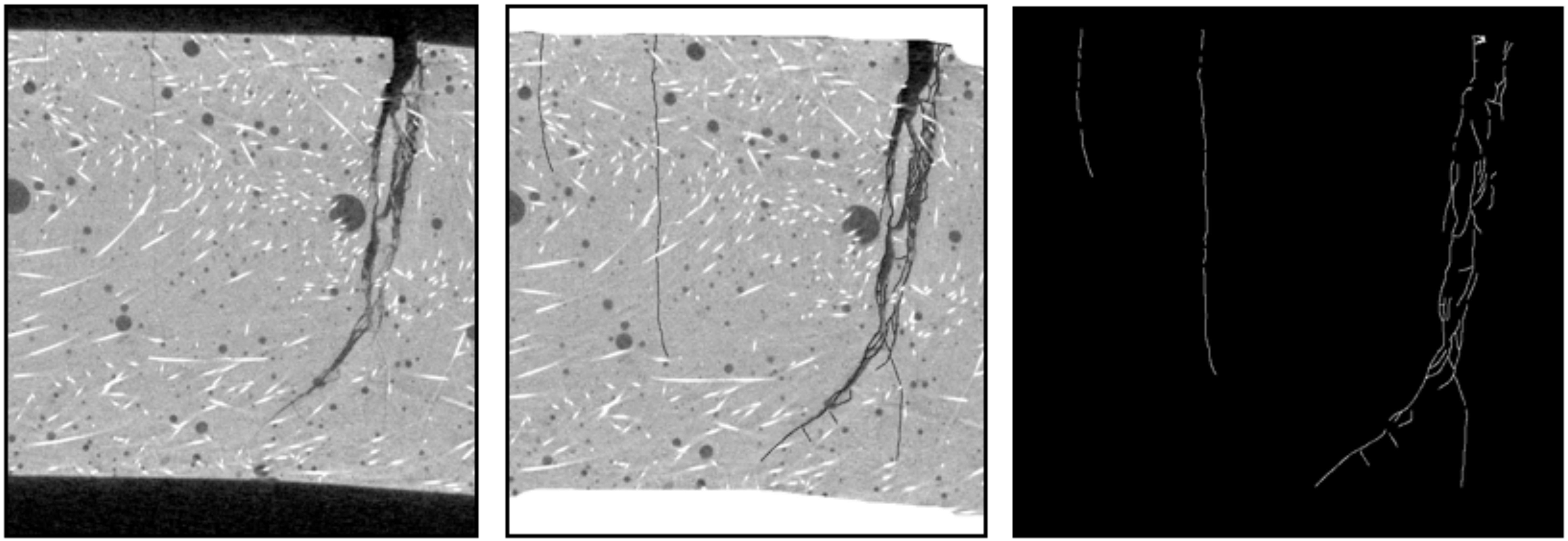
$$G_f = \frac{U_{ext}}{\Delta A}$$

120 J/m² for UHPC matrix

Crack Surface Area



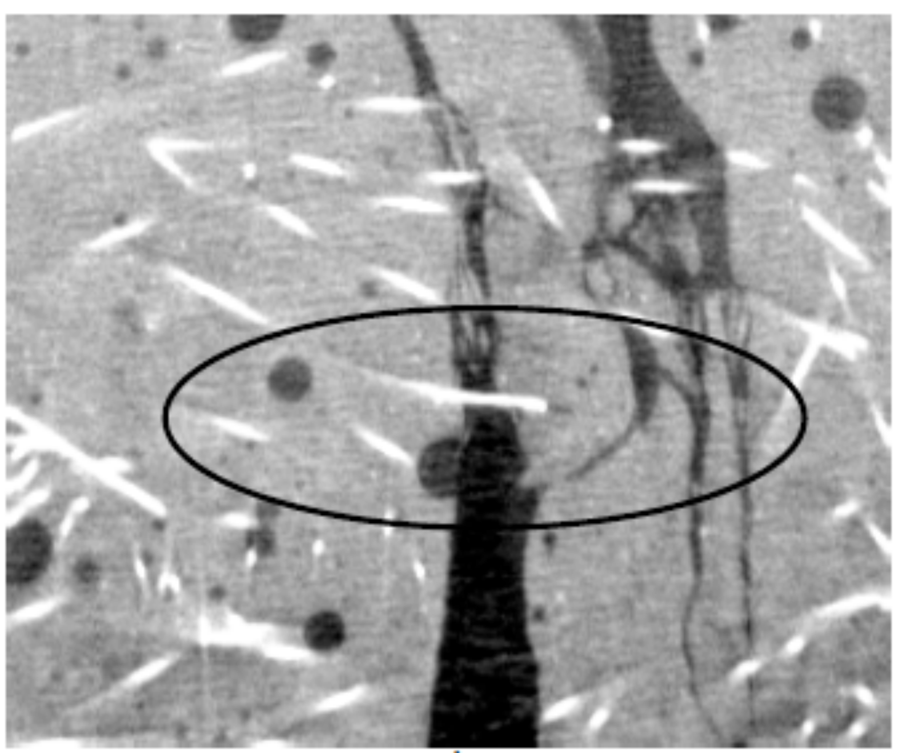
Dissipation by Matrix Fracture

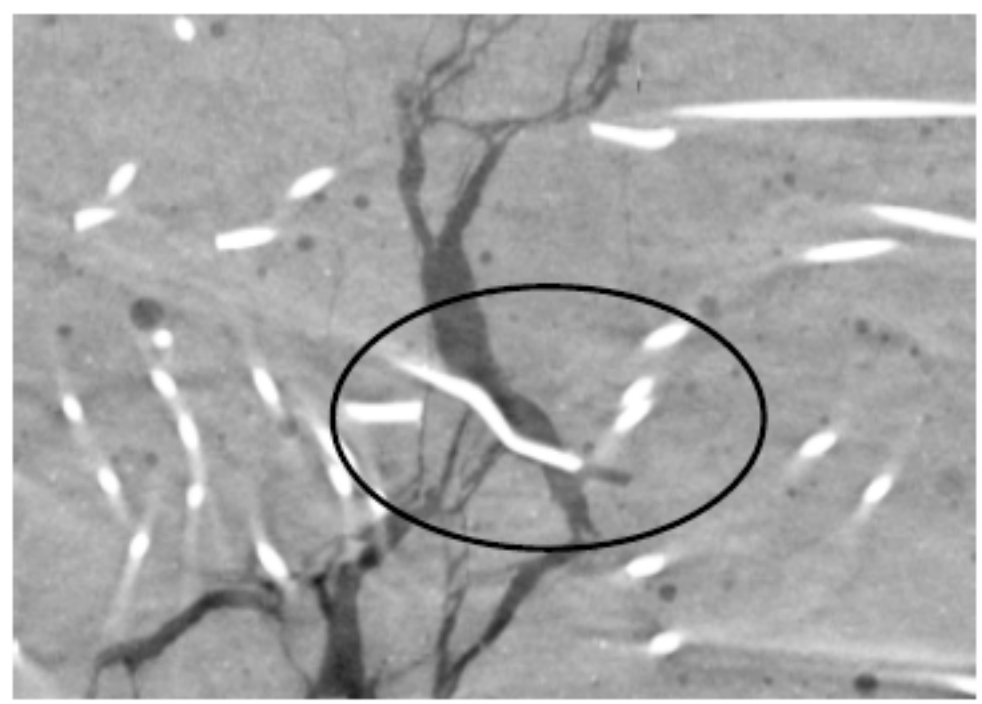


$$W_f = G_f \cdot \Delta A$$

Fiber Pull-Out

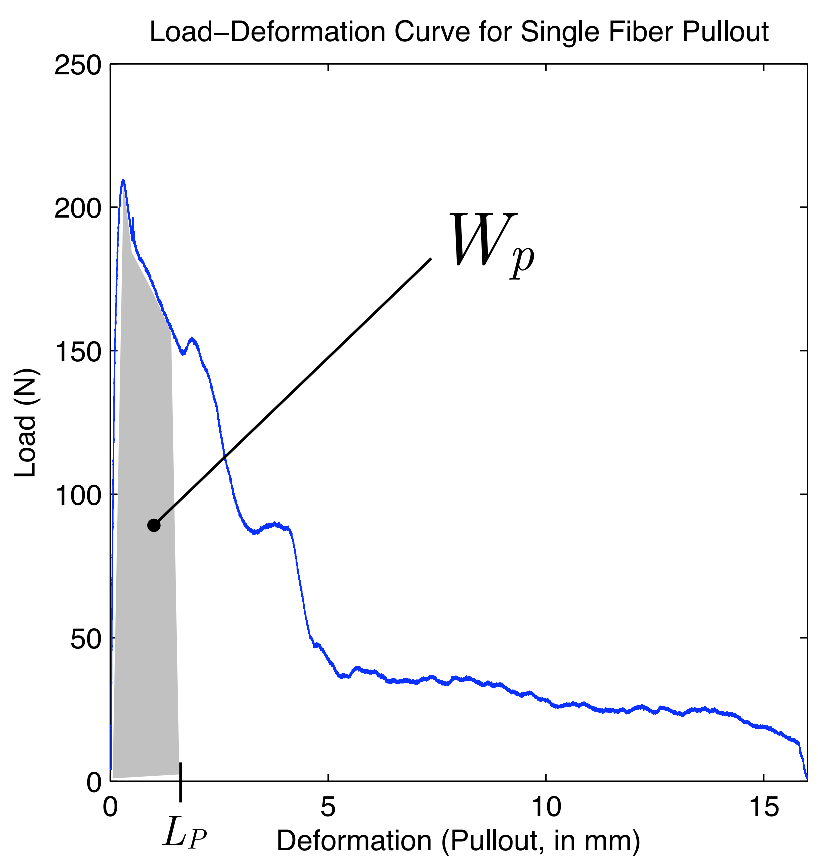
- Visually identified & manually measured
- Includes straightened hooks and fibers bridging large cracks

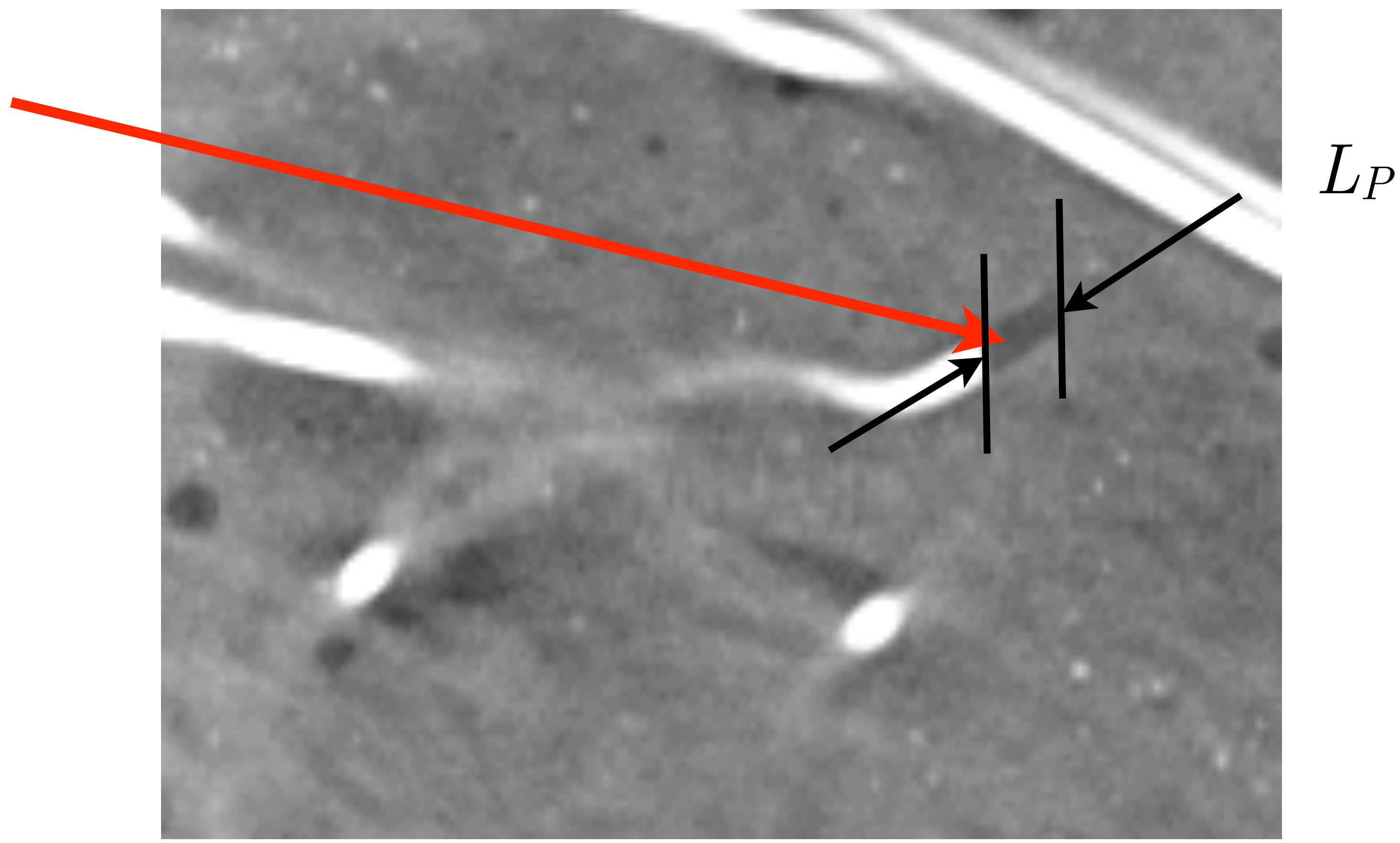




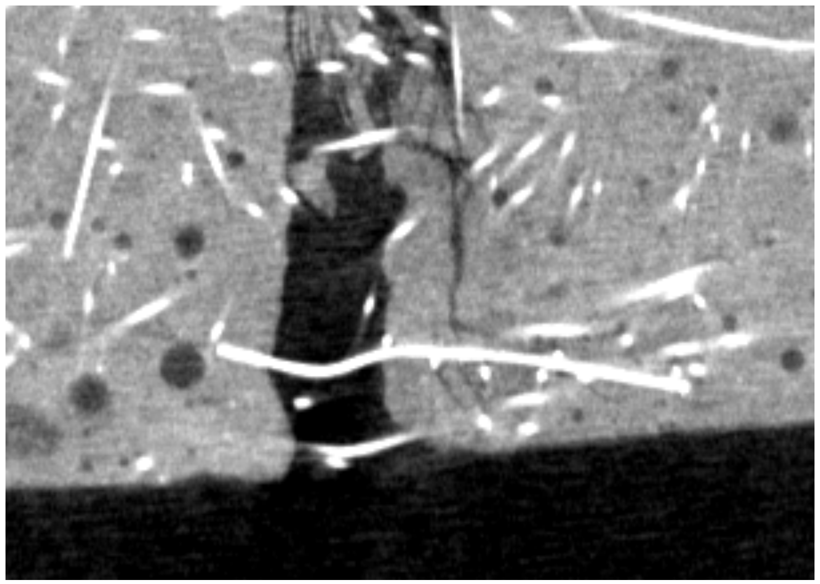
Fiber Pull-Out

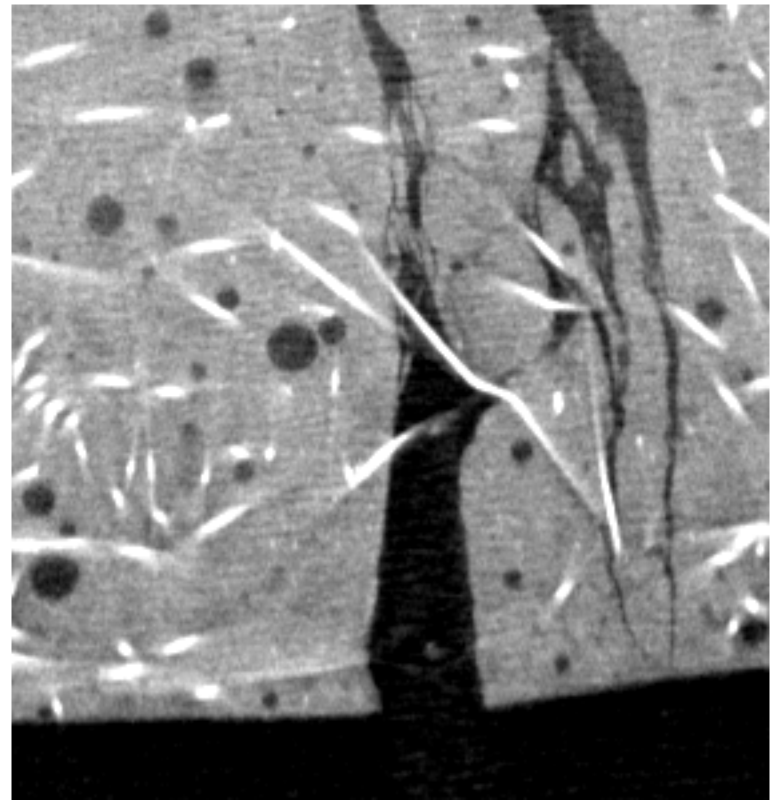
- Distance of pull-out measured manually
- Work of pull-out calculated from pull-out test data

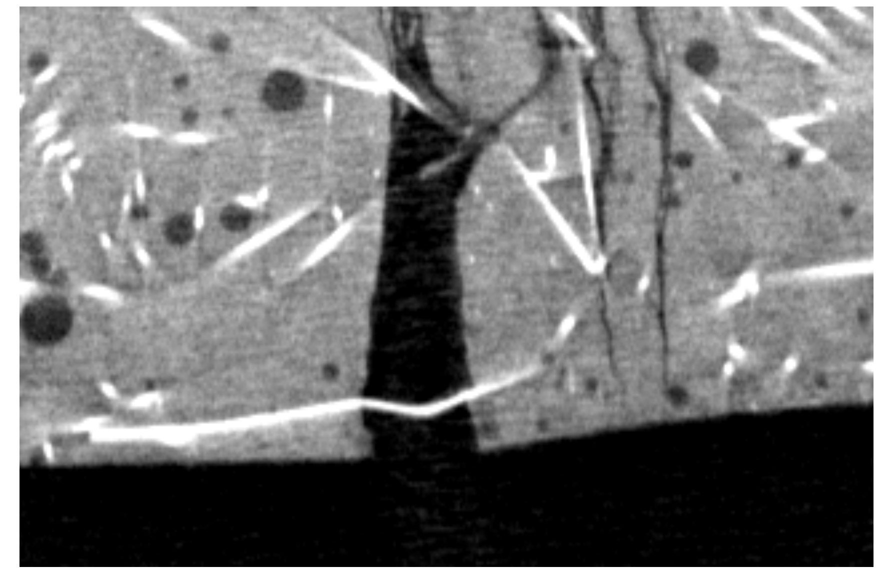


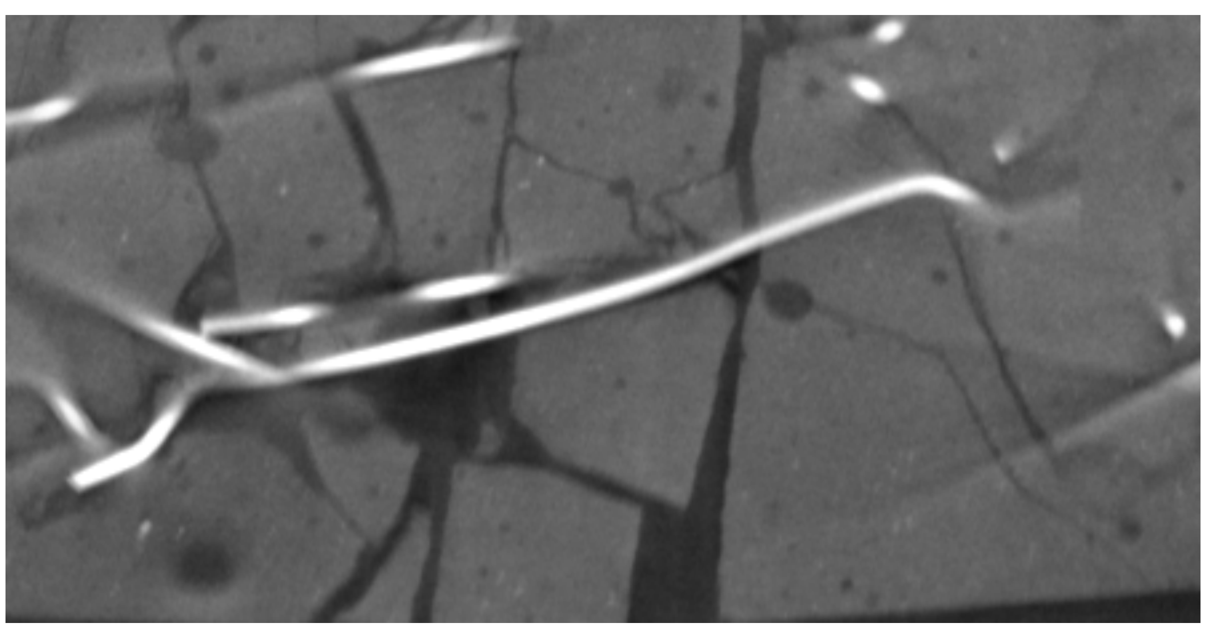


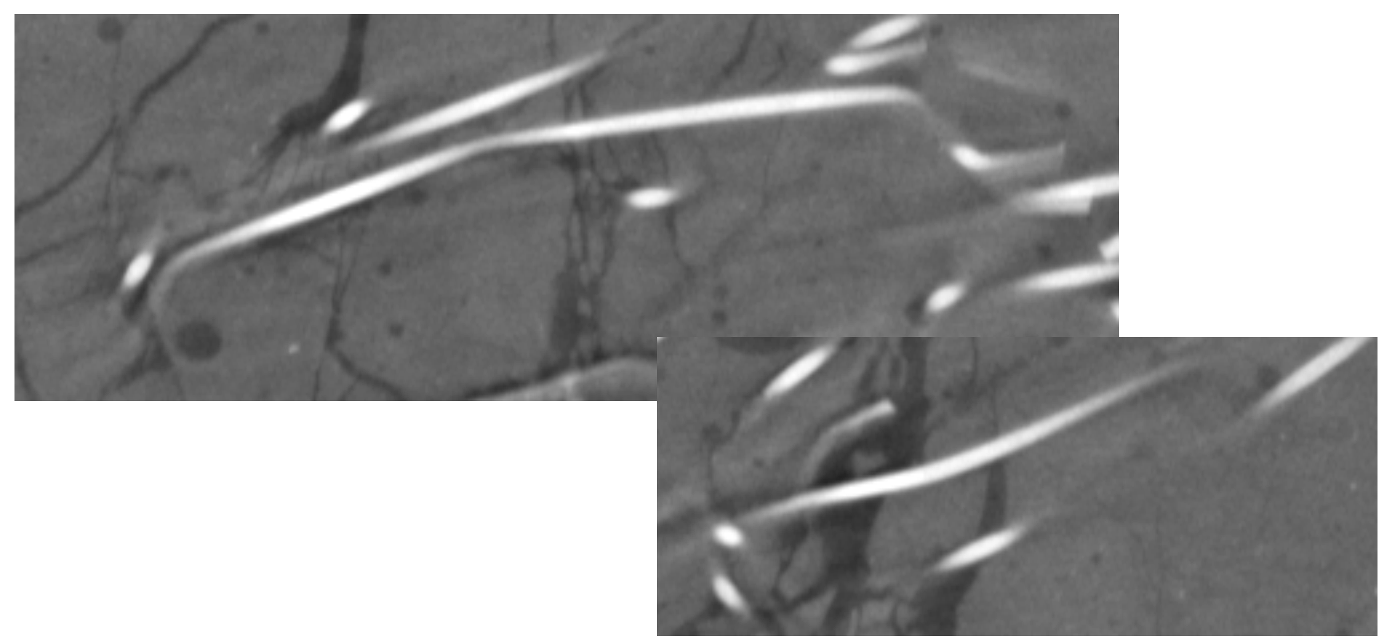
Plastic Deformation of Fibers



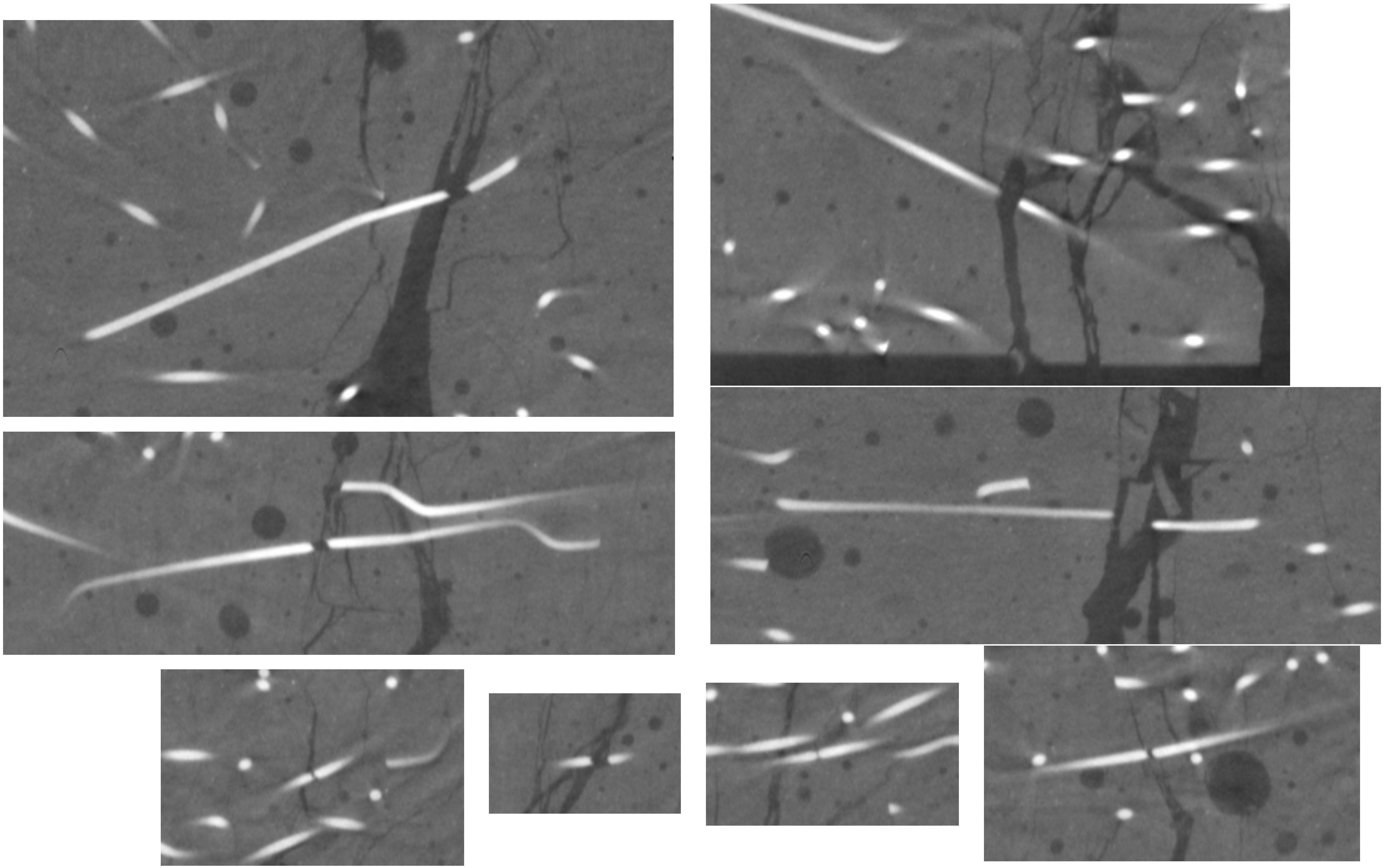








Fiber Rupture



Energy Dissipation Summary

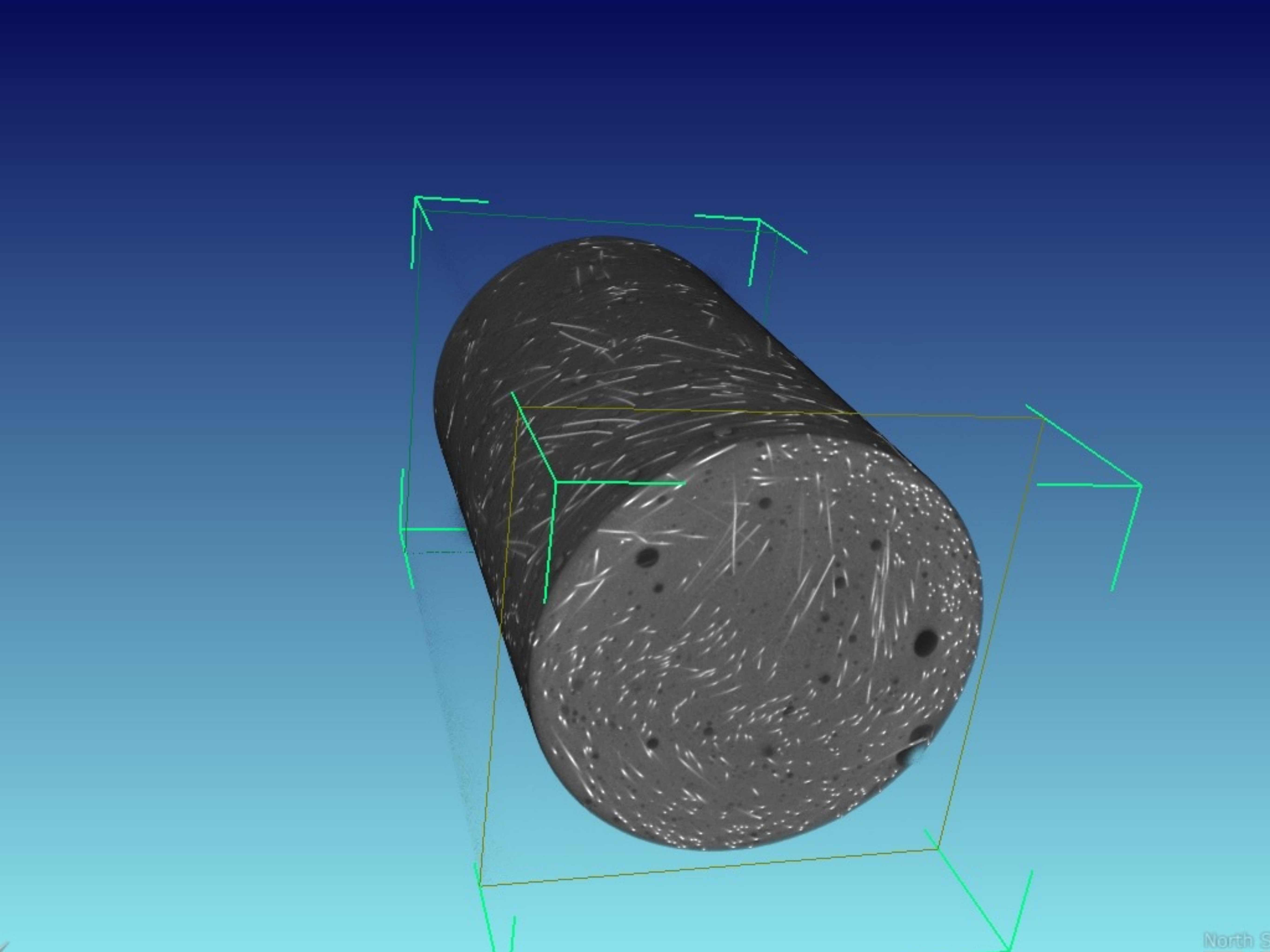
Specimen	Matrix Cracking (mJ)	Rupture (mJ)	Plastic Hinge (mJ)	Pull-Out (mJ)	Total Internal (J)	External (J)
hooked 1	2480	470	22	28100	31	34
hooked 3	3170	1580	37	24100	29	35
hooked 4	2260	400	24	25000	28	35
straight 1	1980	0	58	15600	18	50
straight 3	2460	0	6	9200	12	50
straight 4	4330	0	46	10200	15	50

Energy Dissipation Summary

Specimen	Matrix Cracking (%)	Rupture (%)	Plastic Hinge (%)	Pull-Out (%)	% of External
hooked 1	8.0	1.5	0.1	90.4	91
hooked 3	11.0	5.5	0.1	83.4	94
hooked 4	8.1	1.4	0.1	90.3	89
straight 1	11.0	0.0	0.3	88.4	36
straight 3	21.1	0.0	0.1	78.9	24
straight 4	29.7	0.0	0.3	70.0	30

Comments

- Energy accounting:
  - Good accounting for hooked fibers
  - Poor for smaller straight fibers.
- Research question unresolved:
  - No apparent dissipation shift for hooked fibers
  - Observe additional matrix cracking at expense of fiber pullout for straight fibers.
- Could benefit from more robust image analysis techniques.



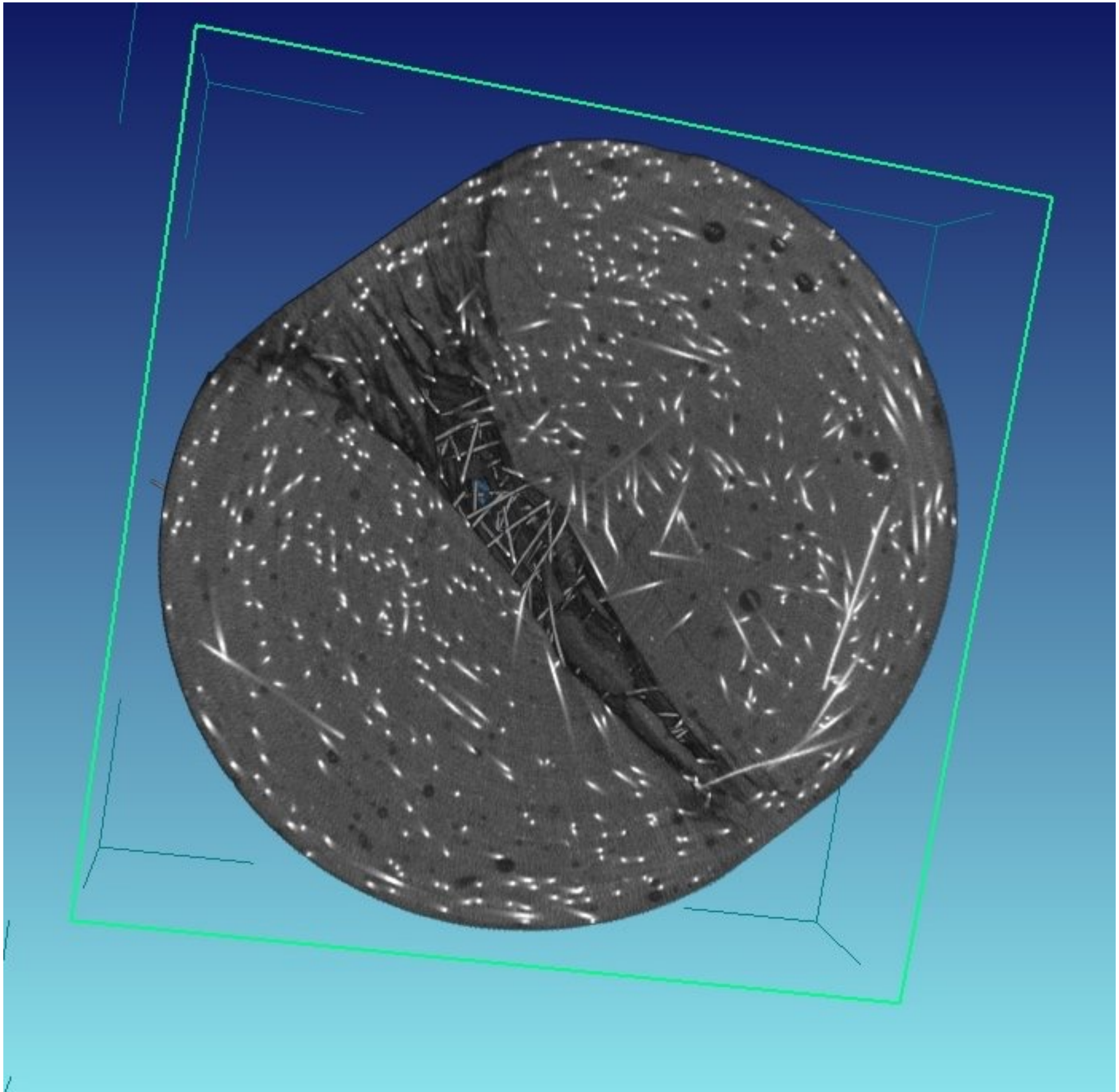
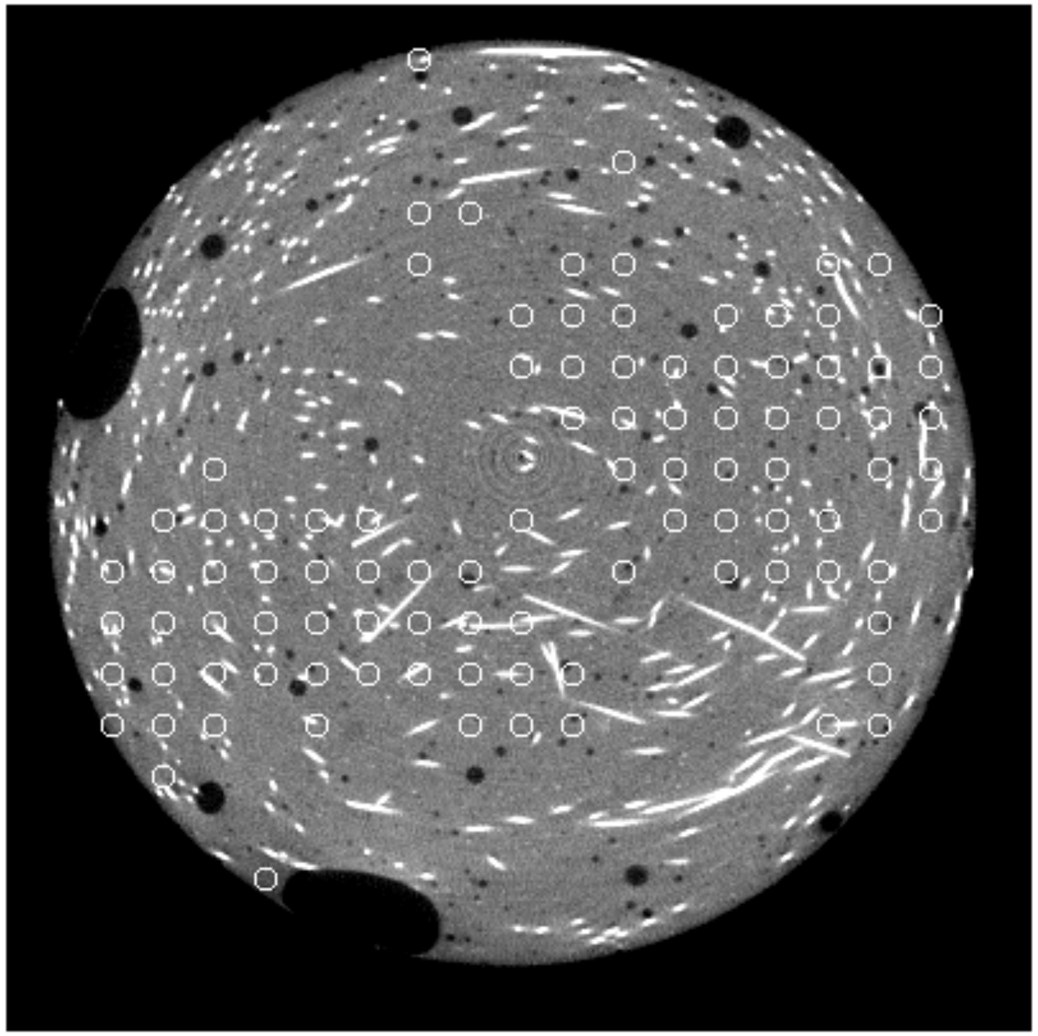


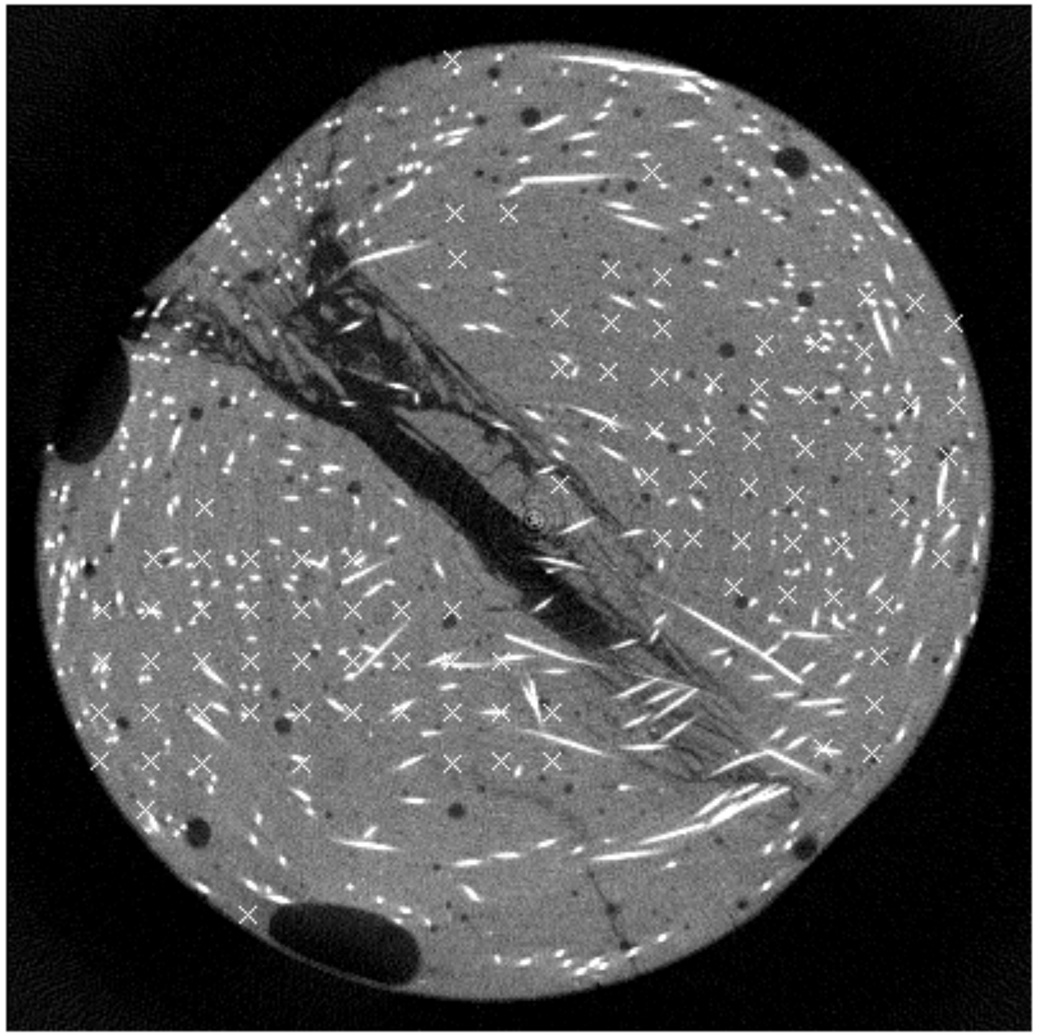
Image Analysis: Fiber Pullout

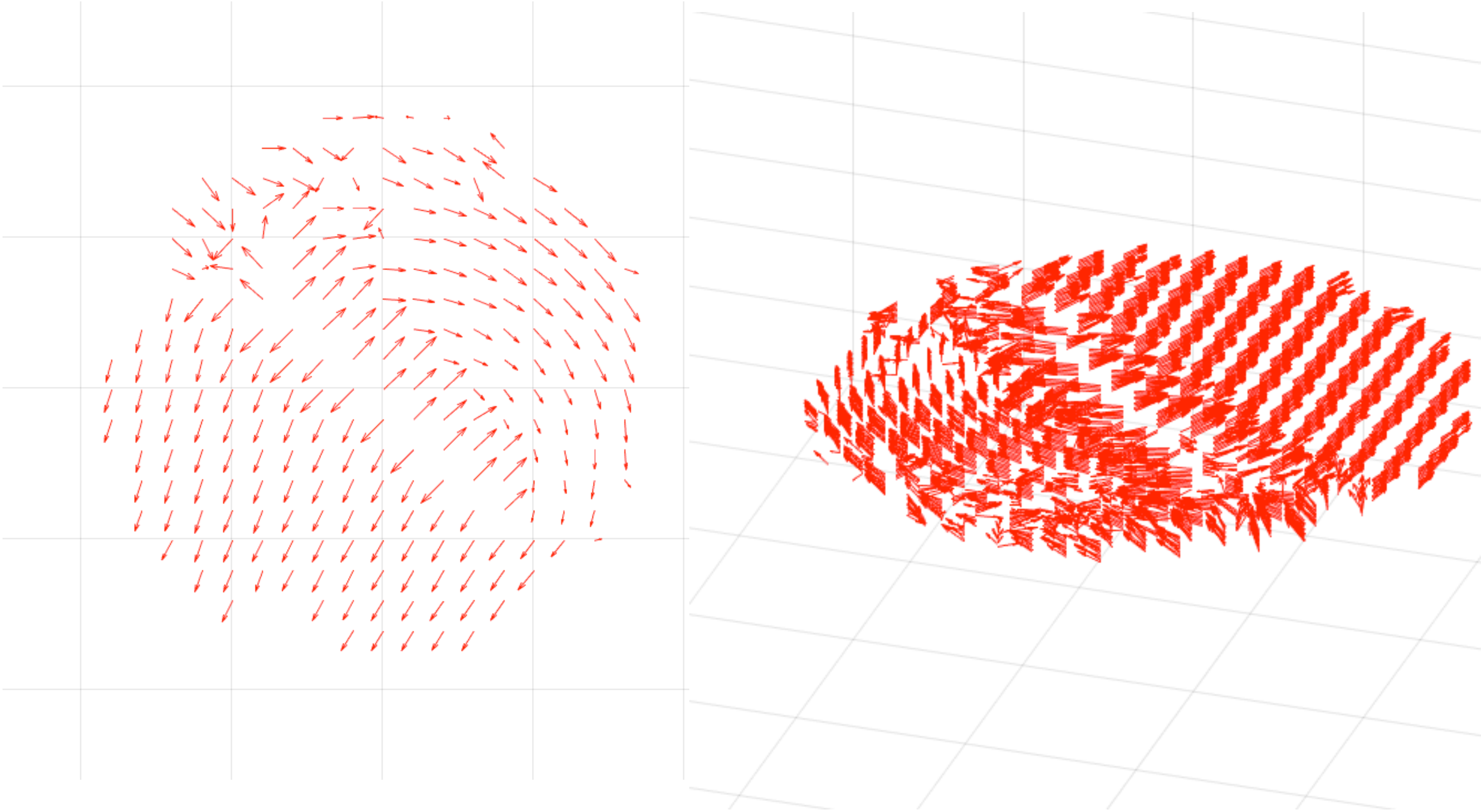
- Use motion to measure pullout distance

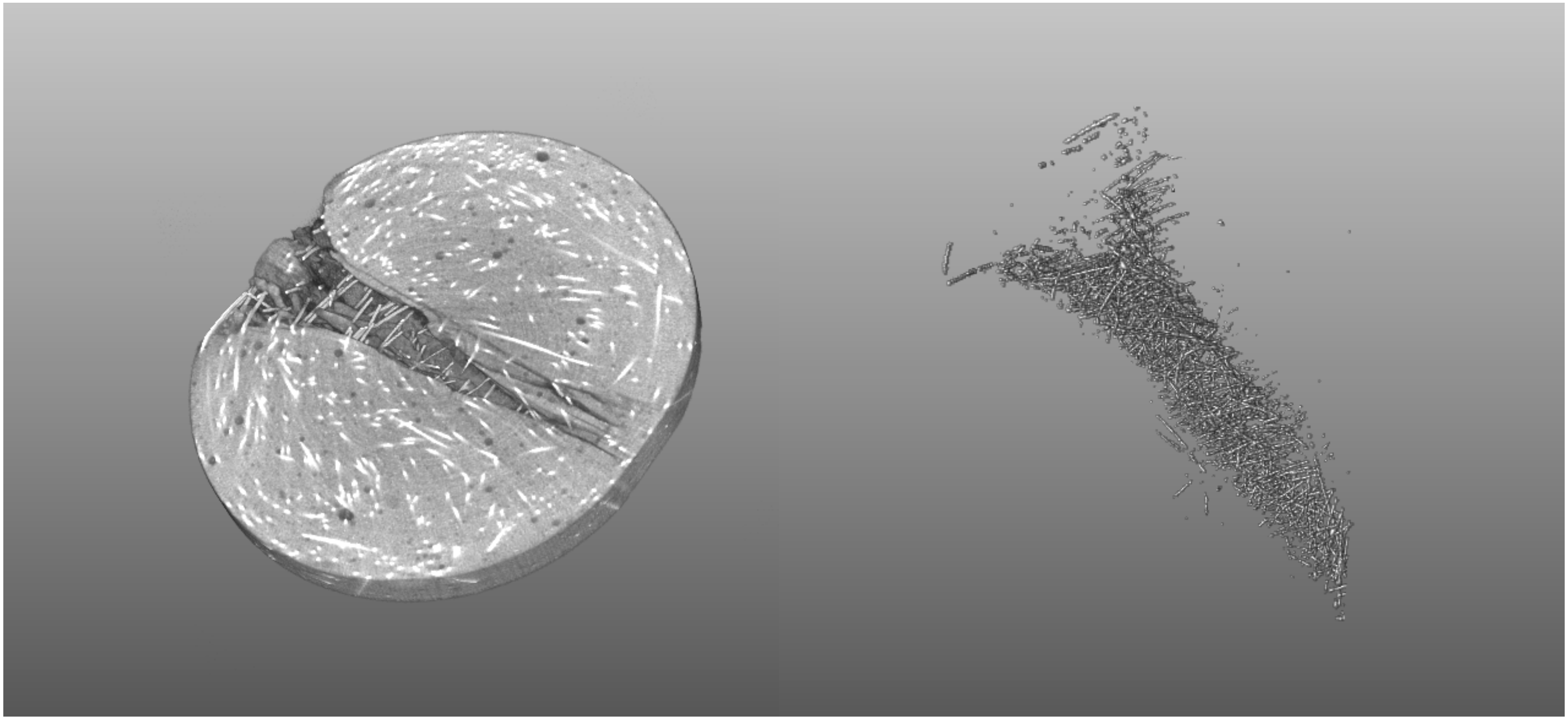
Slice number 600 (before crack).



Slice number 601.

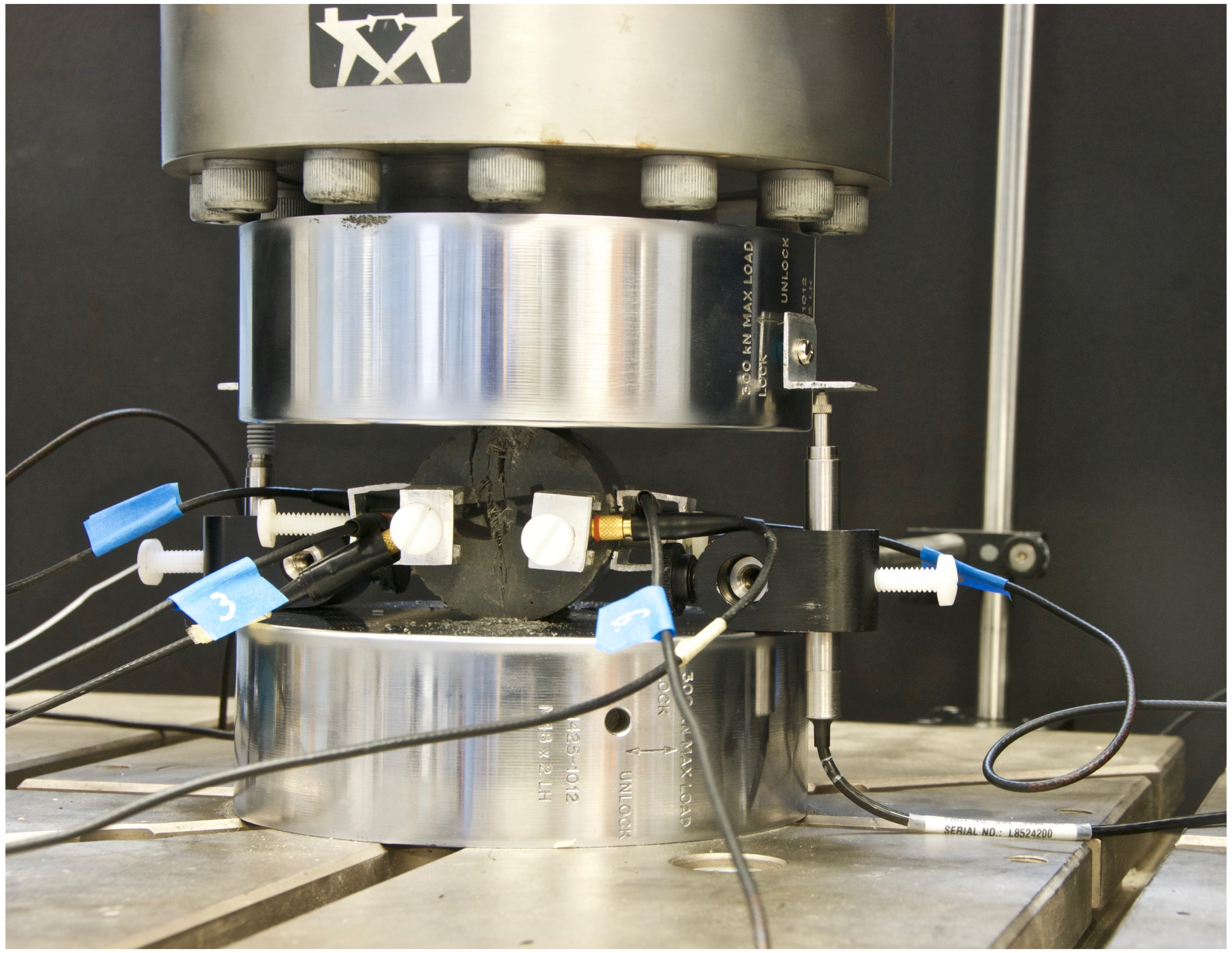






In Progress

- Robust crack measurement in noisy images
- Friction



Summary & Conclusions

- X-ray CT analysis allows us to look at old problems in new ways for new insights.
  - characterize fracture process zone in terms of specific energy dissipation distribution.
  - quantify "weak links" in material
- Much work still required for full potential of technique
- Look to alternate techniques for complementary information.

Acknowledgements

- Edwin Nagy, Sean deWolski, Kevin Trainor, Lauren Flanders, and Dmitry Loshkov - UMaine
- John Bolander & Daiske Asahina - UC Davis
- Gianluca Cusatis & Jovanca Smith - Northwestern Univ.

U.S. National Science Foundation
U.S. Army Corps of Engineers