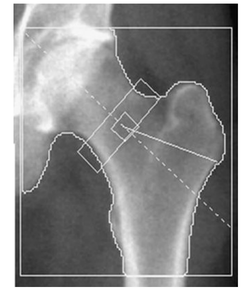
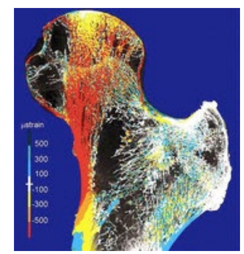
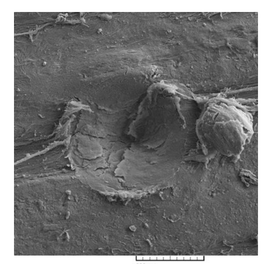
# Cone and Wedge Indentation of Cortical Bone

Kevin F. Hoffseth
Assistant Professor

Louisiana State University
Department of Biological and Agricultural Engineering
LSU A&M, LSU AgCenter
November 2, 2018

# Overview

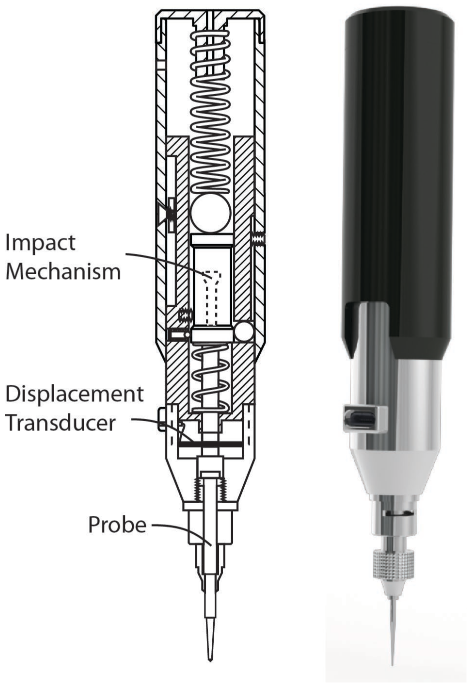
**Bone Quality**

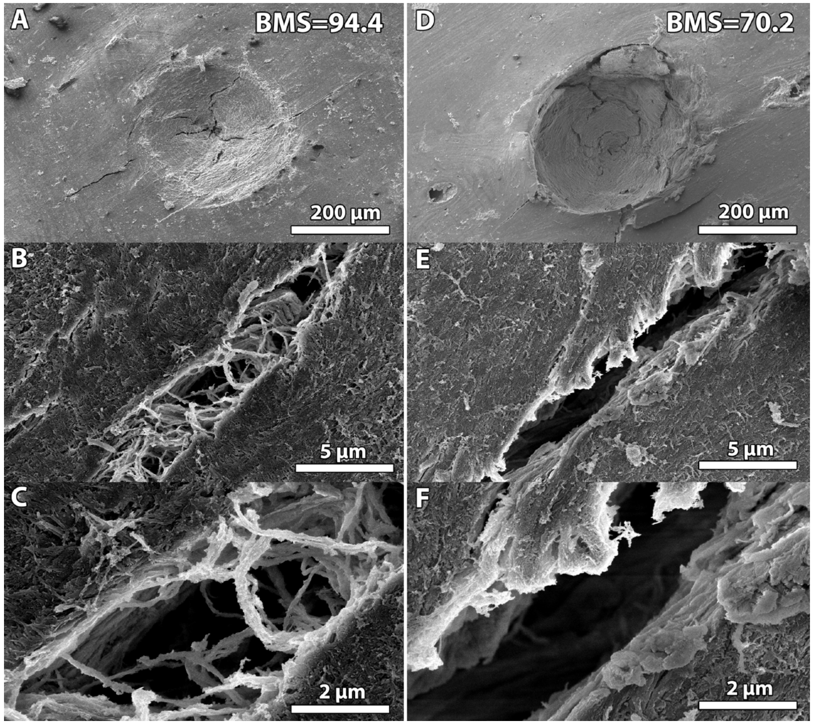
| Component | Clinical Measurement | |
|---|---|---|
| Bone mass: How much? |  | Bone Mineral Density (BMD) measured by DXA |
| Macro/micro architecture: How good? |  | Multiple parameters measured by QCT, HR-QCT, MRI |
| Tissue composition: How good? |  | BMSi measured by micro-indentation |

# A need for research

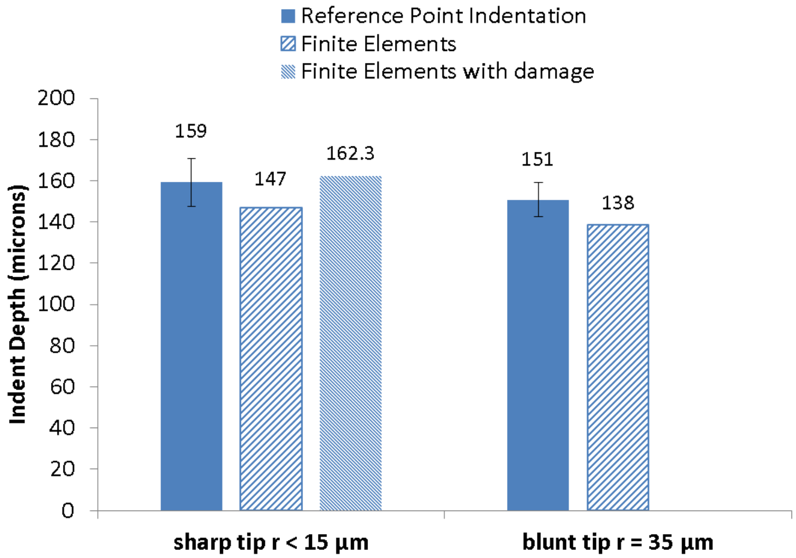
- Recent clinical trials show that a form of indentation (Reference Point Indentation) can distinguish between the bone of patients who have had osteoporotic fractures and patients who have not had osteoporotic fractures .

<u>In-vivo, where direct measurement of cracking is unavailable</u>

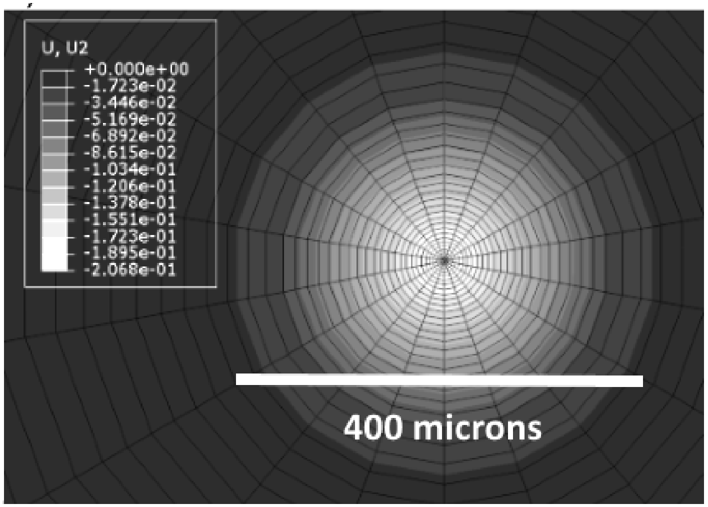


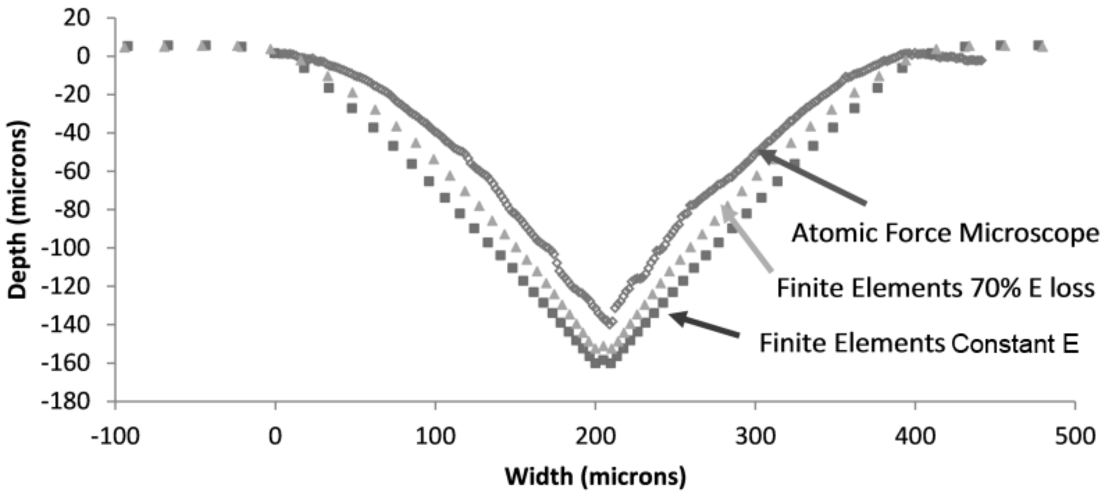
# Results



Reference Point Indentation
Finite Elements
Finite Elements with damage
Indent Depth (microns)
200
180
160
140
120
100
80
60
40
20
0
159
147
162.3
151
138
sharp tip r < 15 µm
blunt tip r = 35 µm

U, U2
+0.000e+00
-1.723e-02
-3.446e-02
-5.169e-02
-6.892e-02
-8.615e-02
-1.034e-01
-1.206e-01
-1.378e-01
-1.551e-01
-1.723e-01
-1.895e-01
-2.068e-01
400 microns

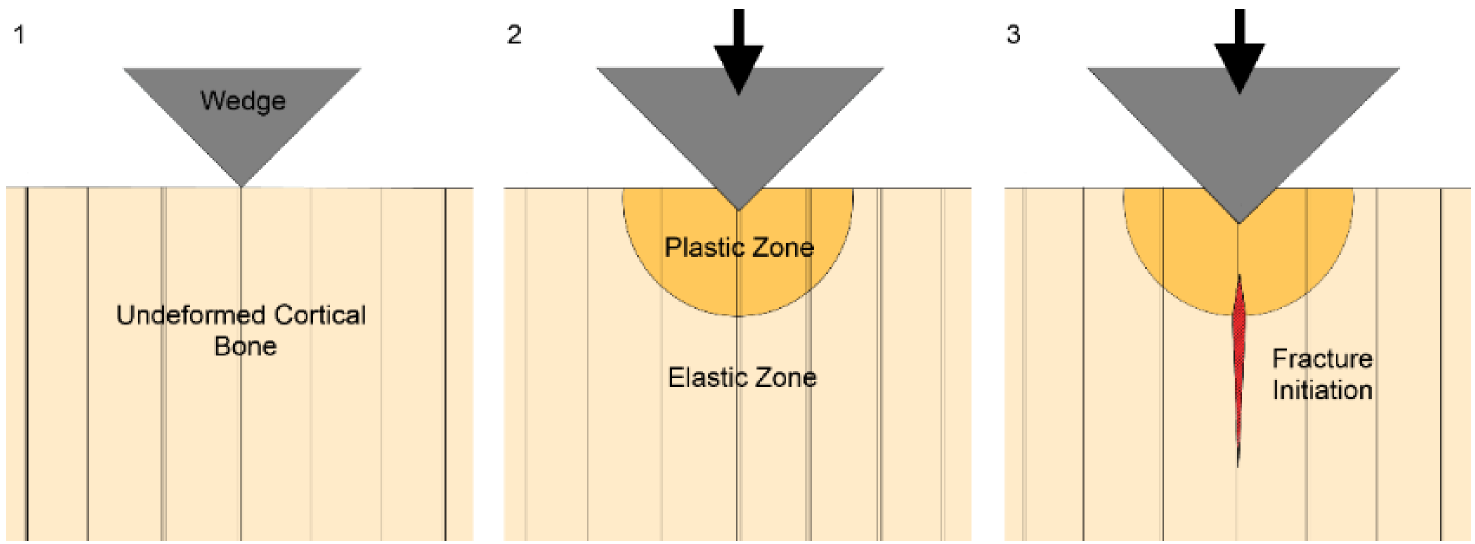



Depth (microns)
20
0
-20
-40
-60
-80
-100
-120
-140
-160
-180
-100
0
100
200
300
400
500
Width (microns)
Atomic Force Microscope
Finite Elements 70% E loss
Finite Elements Constant E

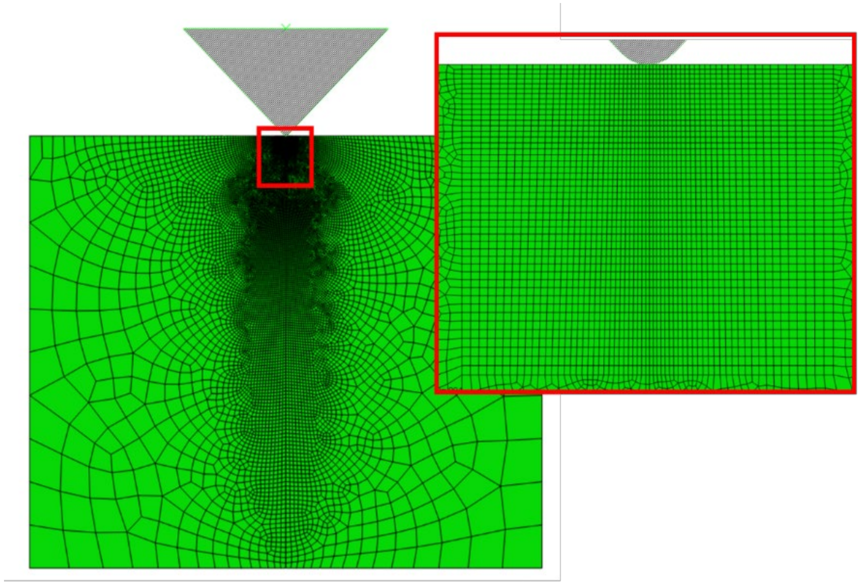
# Plane Strain Wedge I

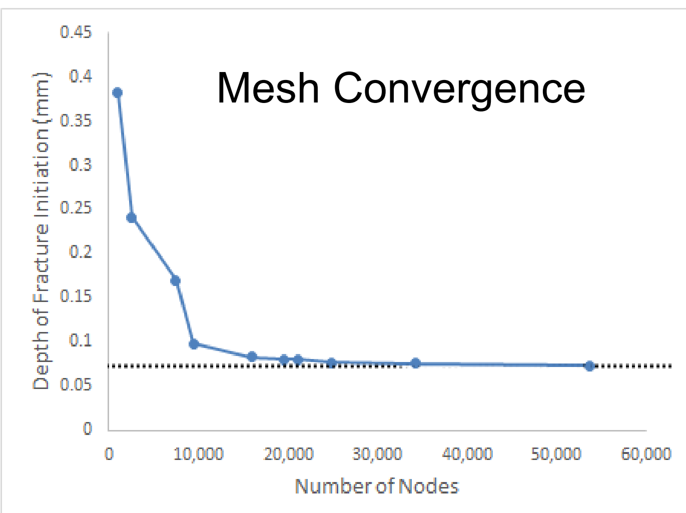
A new approach:

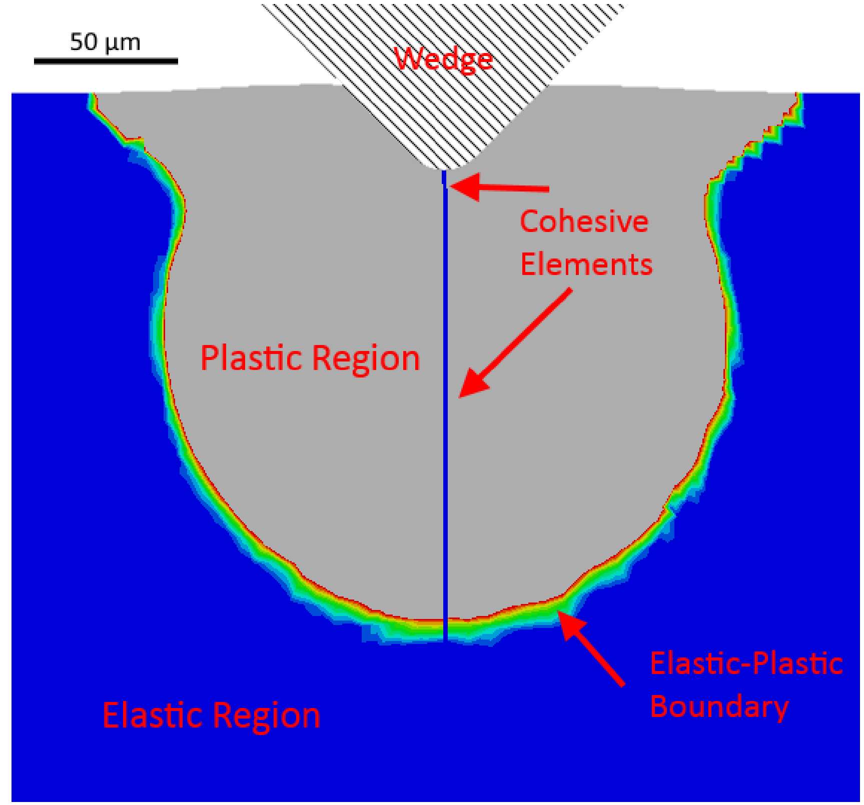
elastic-plastic indentation fracture



# Finite element model






Length of Cohesive Zone (*l*):

$$l_c = \frac{G_{IC} E}{\sigma_o^2}$$

Where $G_{IC}$ = Critical Strain Energy Release Rate,
E = Elastic Modulus, $\sigma_o$ = Peak stress of cohesive law

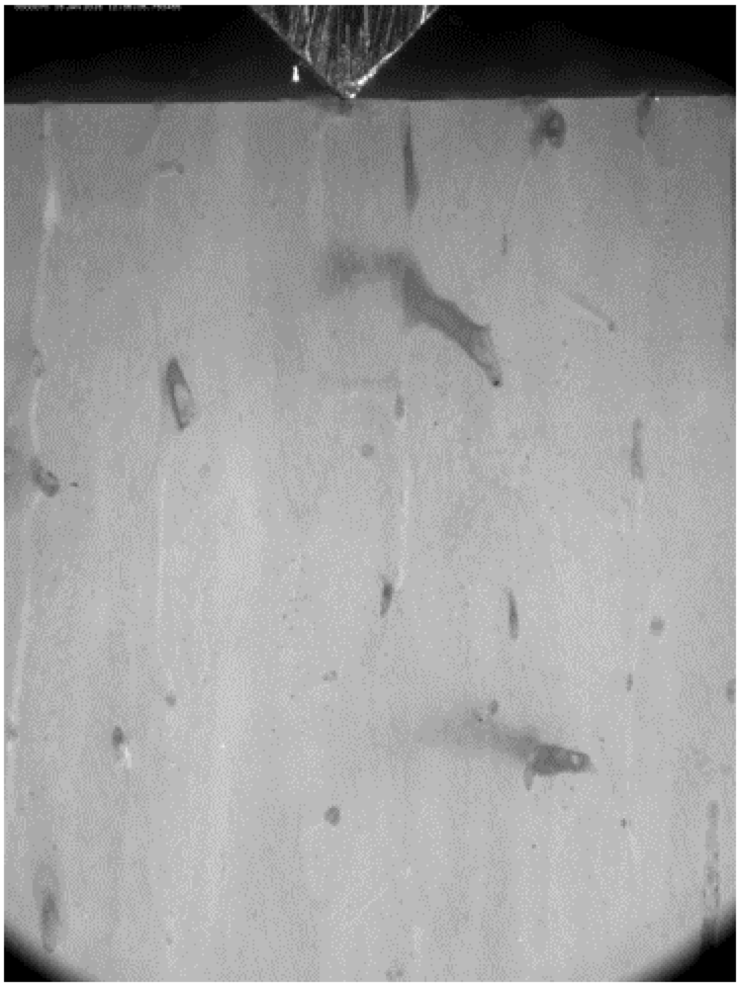
$$l_c = \sim 1\, mm$$

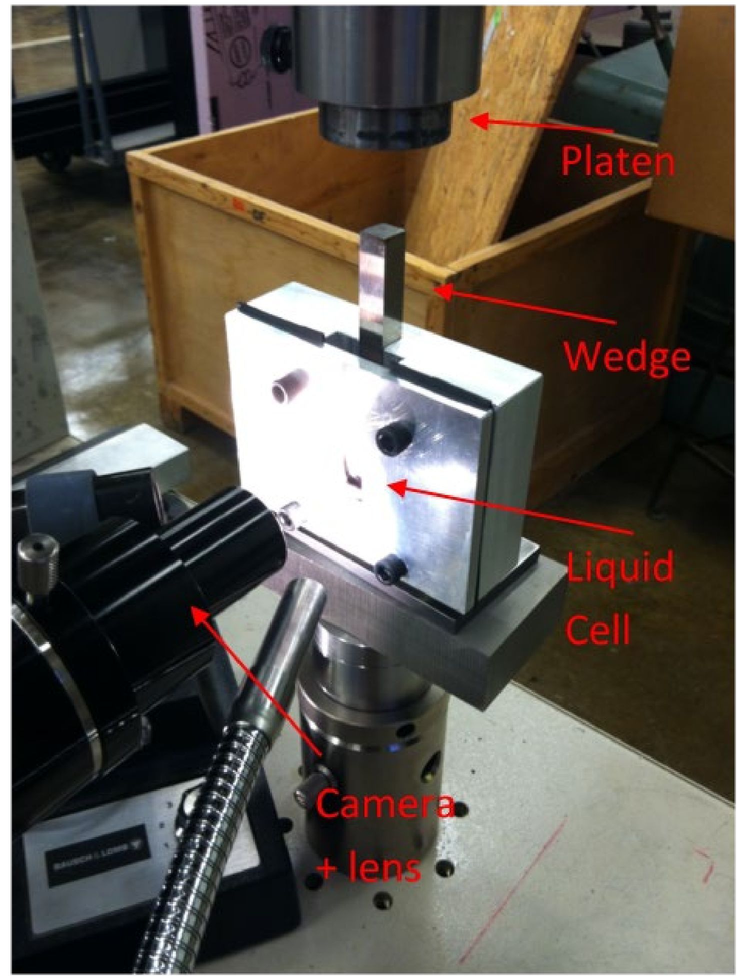
With $G_{IC}$ = 182 N/m,
E = 20 GPa, $\sigma_o$ = 60 MPa

Yang, Q. and B. Cox, 2005; Cox, B.N. and Q. Yang, 2007; Johanns, K.E. et al., 2013

# Experimental Setup

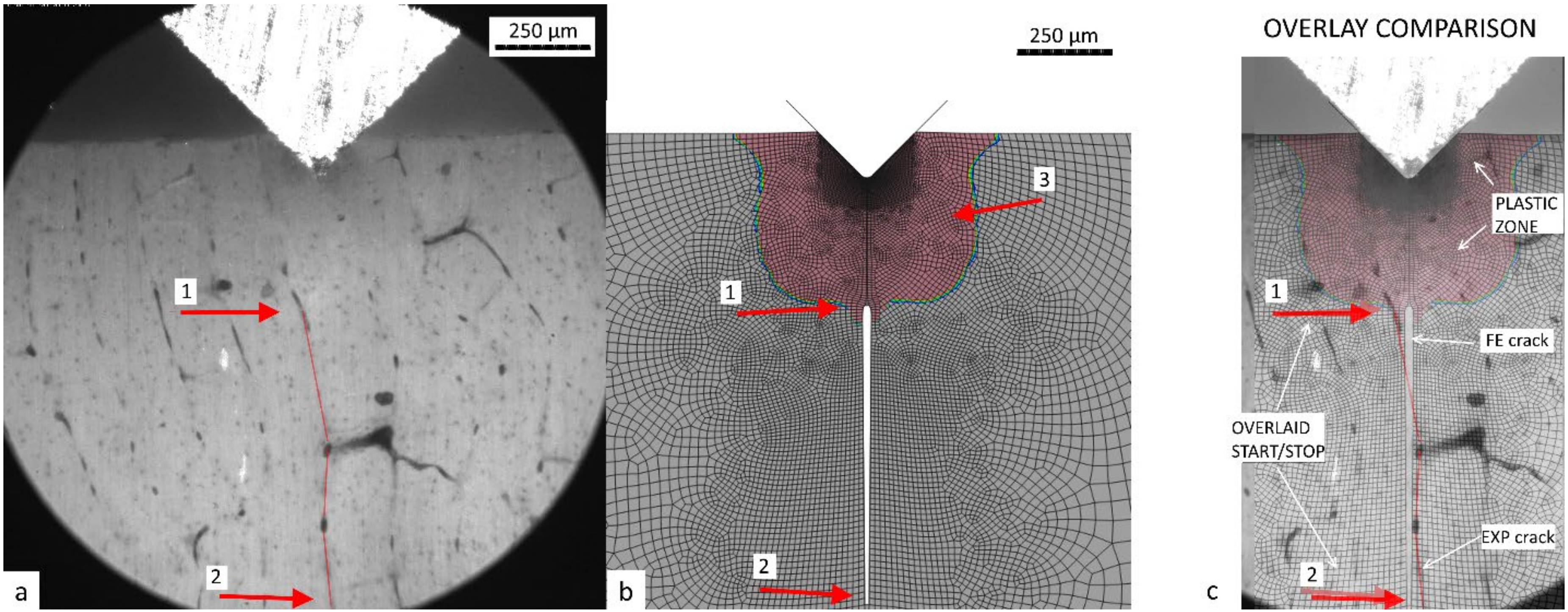
200 mc





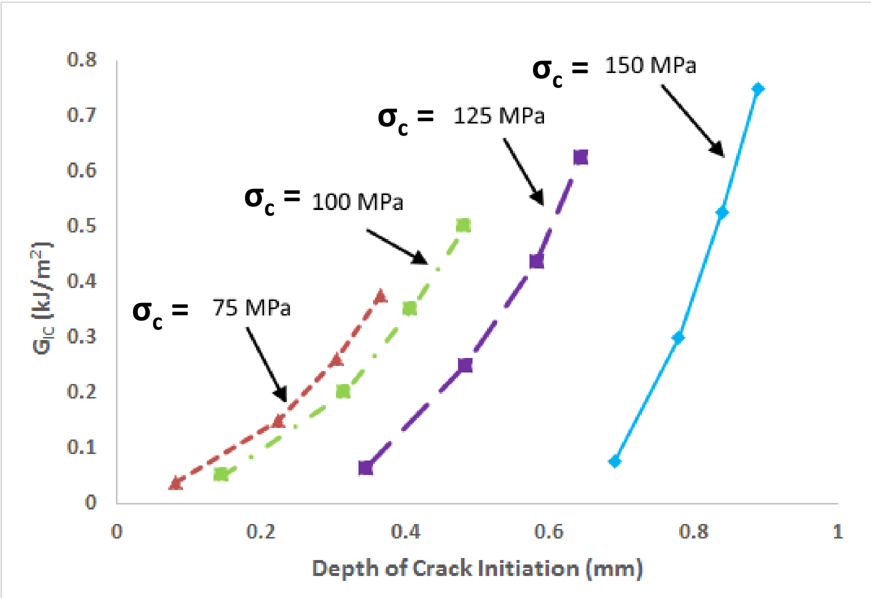
# Results

Experiment | Finite Elements | Overlay

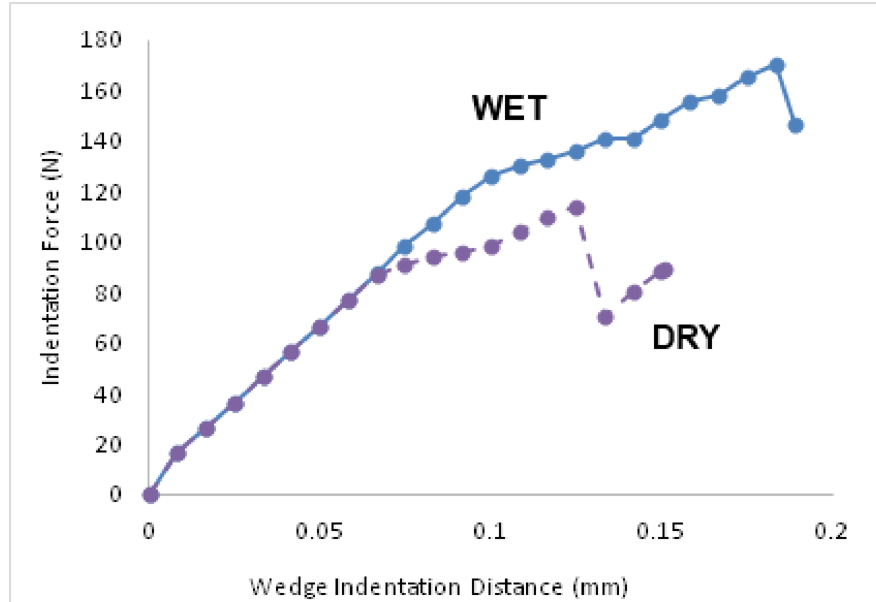



1. Crack initiation
2. Crack tip
3. Plastic zone

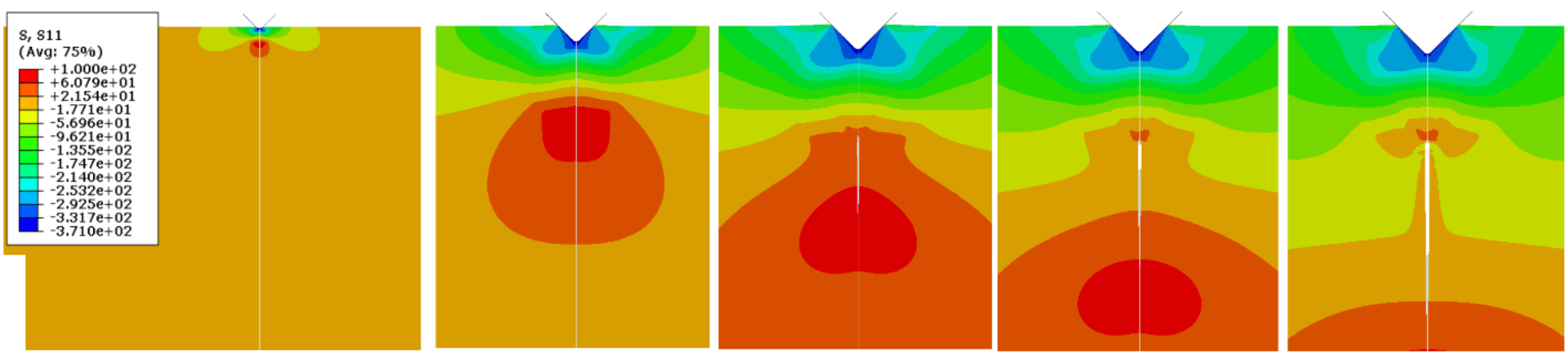
# Results




Finite element results showing effect of cohesive toughness $G_{Ic}$ vs. crack initiation depth, for a range of cohesive strength values

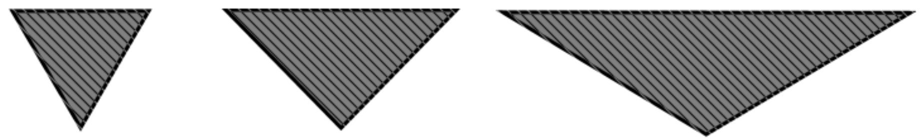



Finite element results for wedge force vs. wedge indentation distance, showing differing behavior for wet and dry cortical bone

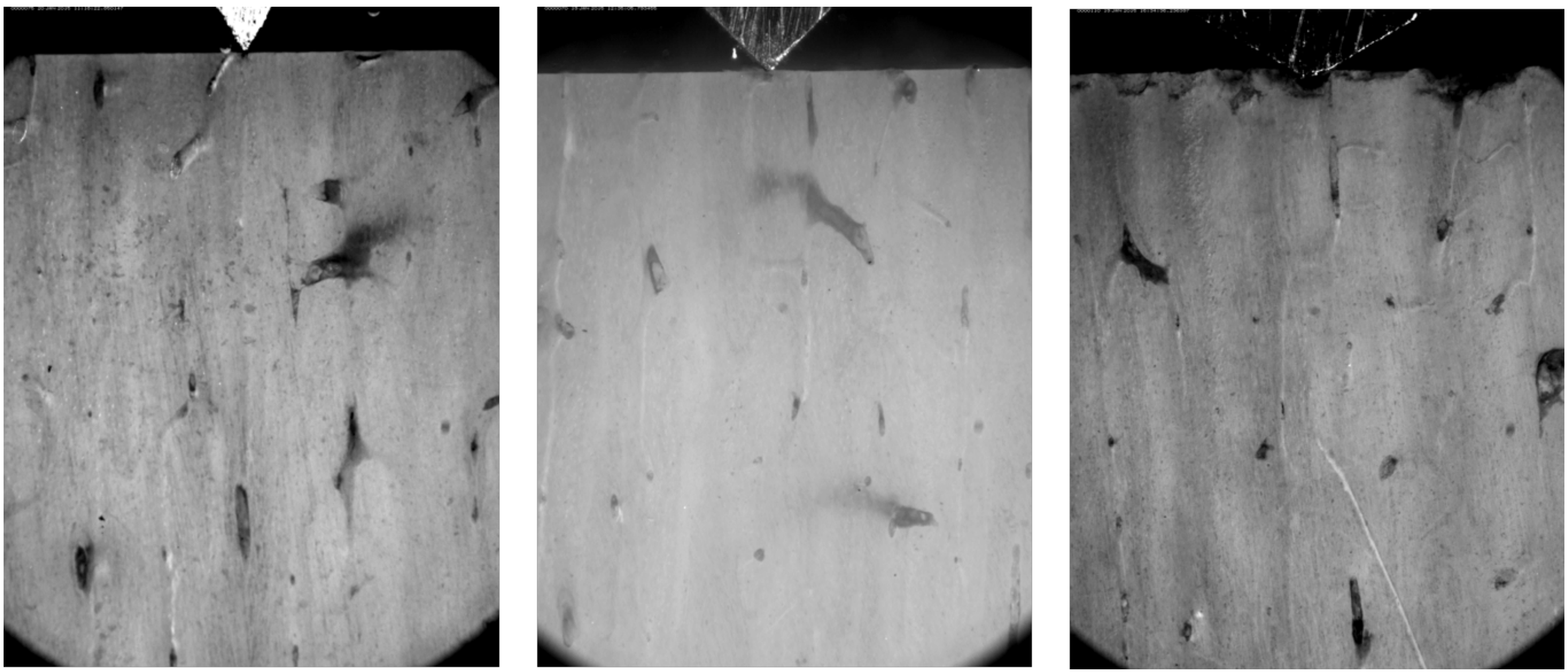


# Plane Strain Wedge II

Change in deformation with wedge apical angle



60°    90°    120°



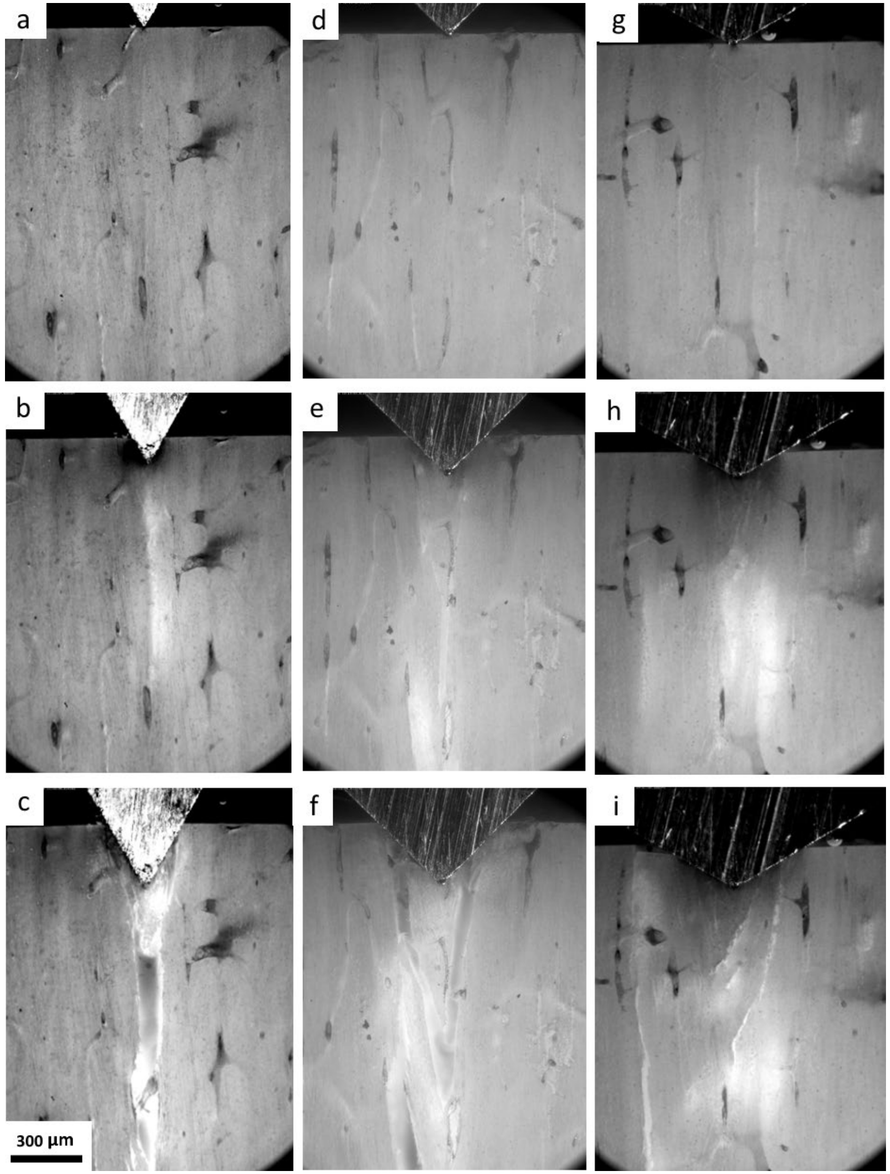
Cleavage - Cutting - Radial Compression

# Results

Test start

Crack initiation

Prior to catastrophic failure

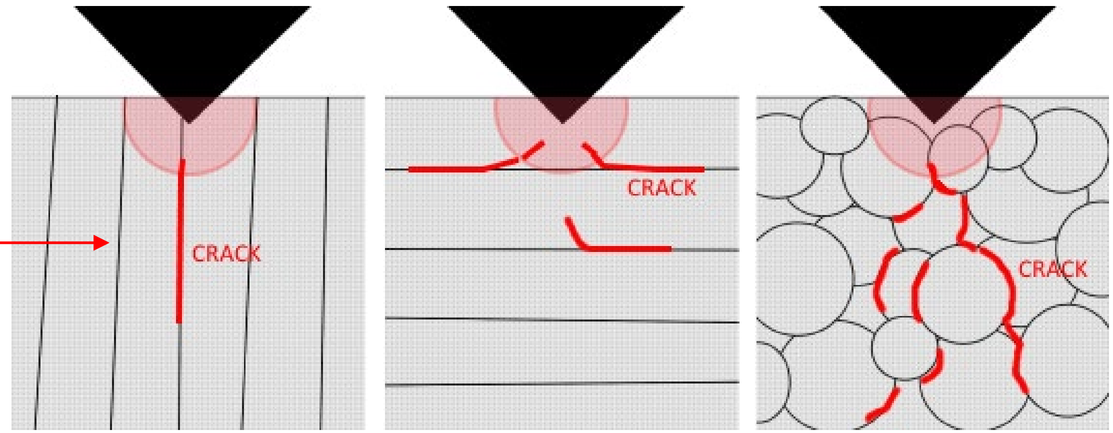



Progression of loading in the vertically oriented osteonal direction, for:

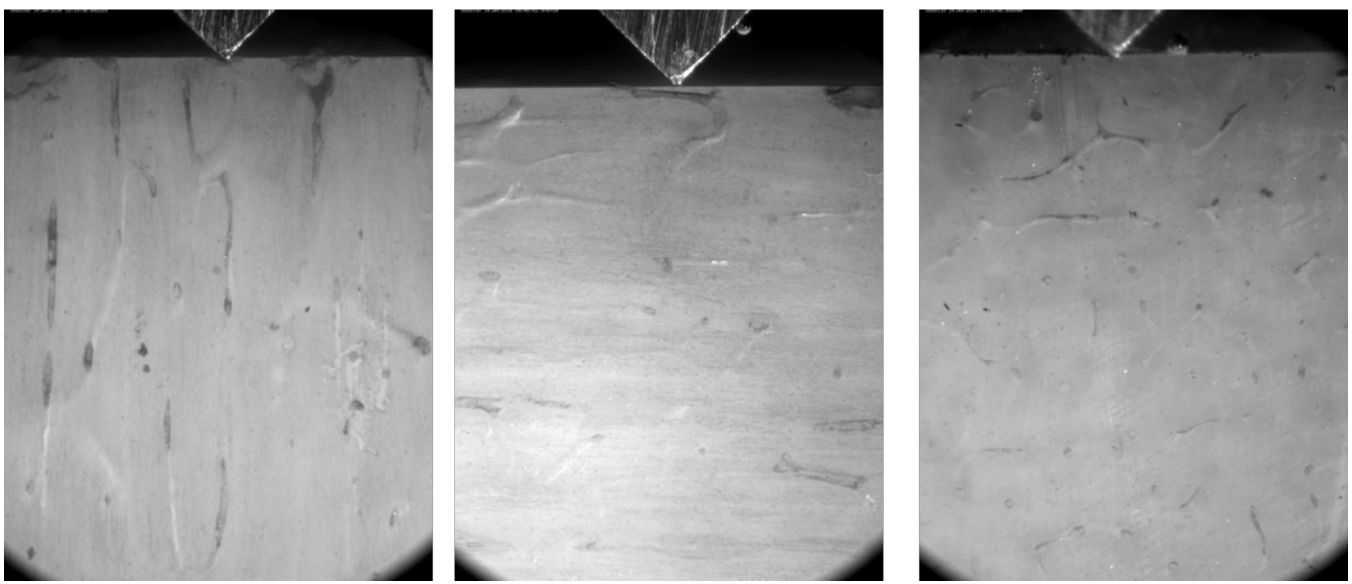
60 degree wedge (a-c)
90 degree wedge (d-f)
120 degree wedge (g-i)

# Microstructural Influence

Cement lines




Expected Crack Paths



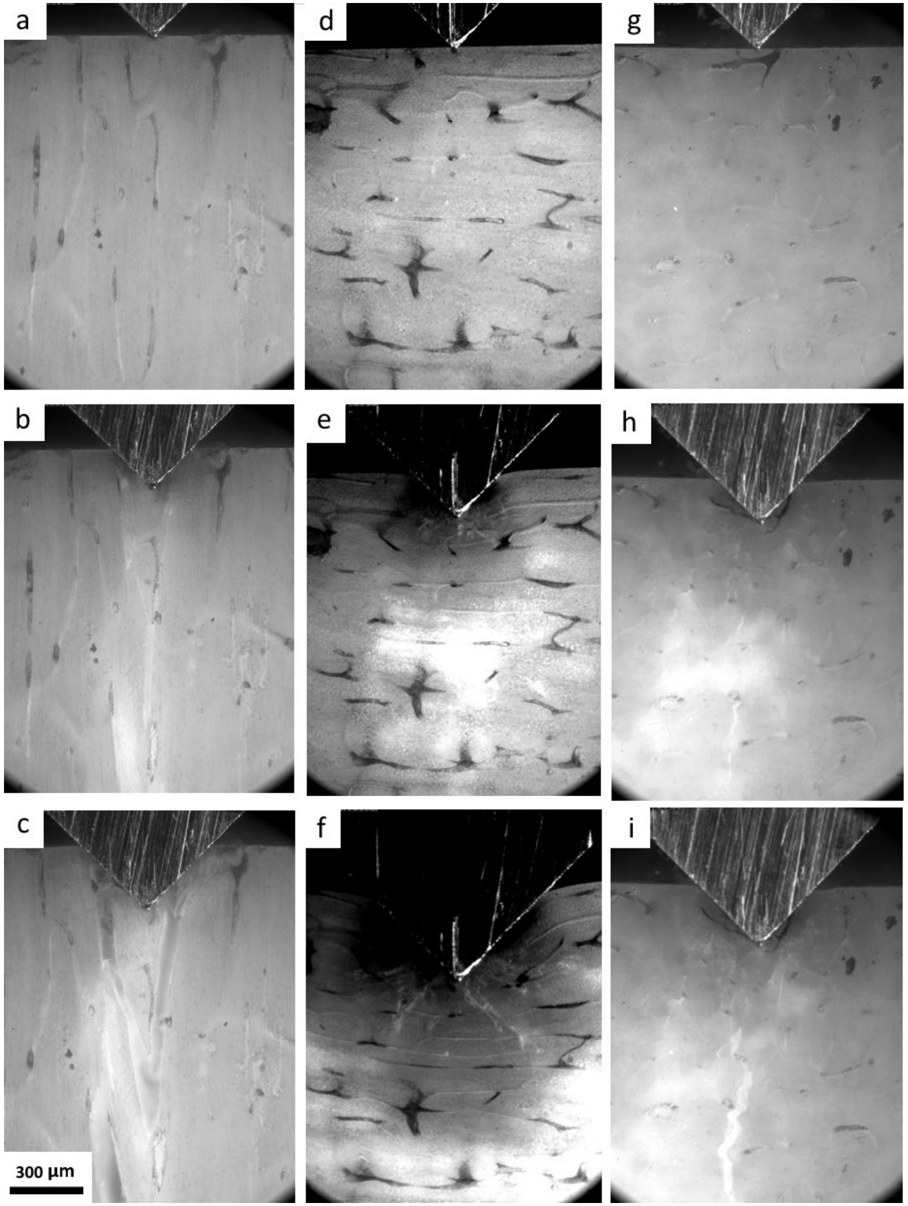
Osteonal boundaries, or cement lines, act as weaker interfaces and natural toughening mechanisms

# Results

Test start

Crack initiation

Prior to catastrophic failure

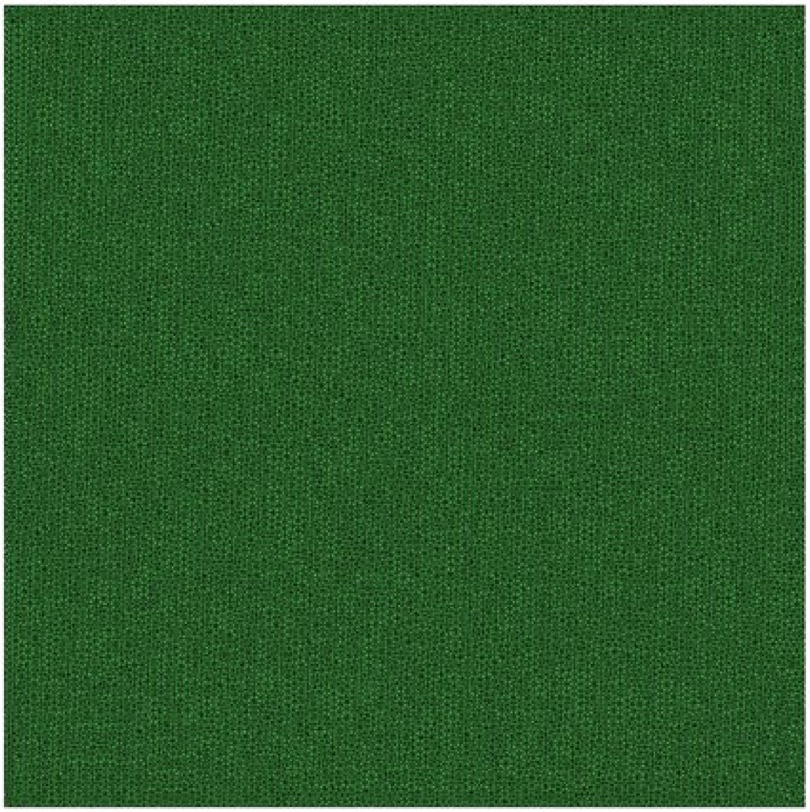


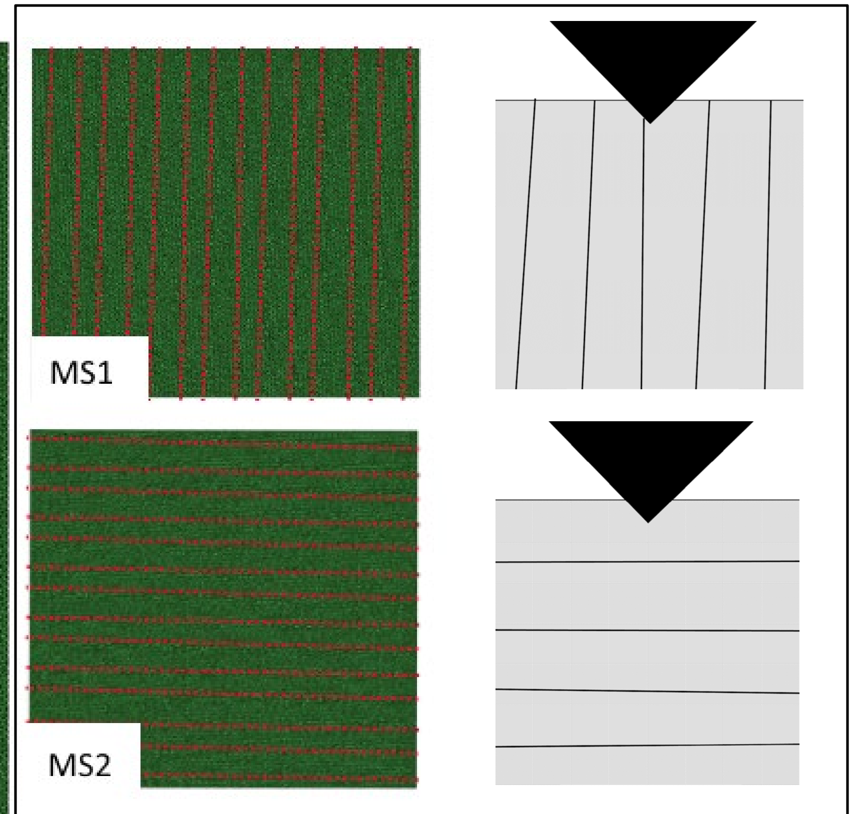

Progression of loading with 90° wedge for:

Vertical orientation (a-c)
Horizontal (d-f)
Osteonal (g-i)

# Finite Element Modeling

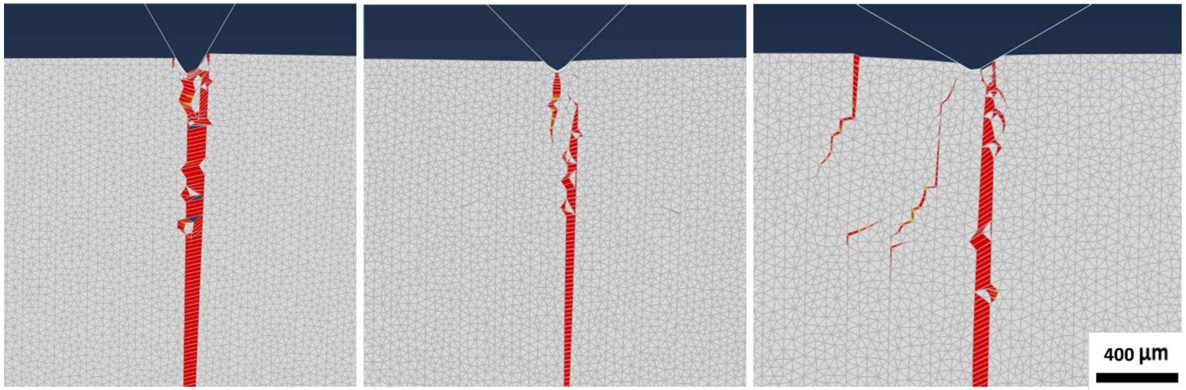
Finite element mesh with distributed cohesive elements



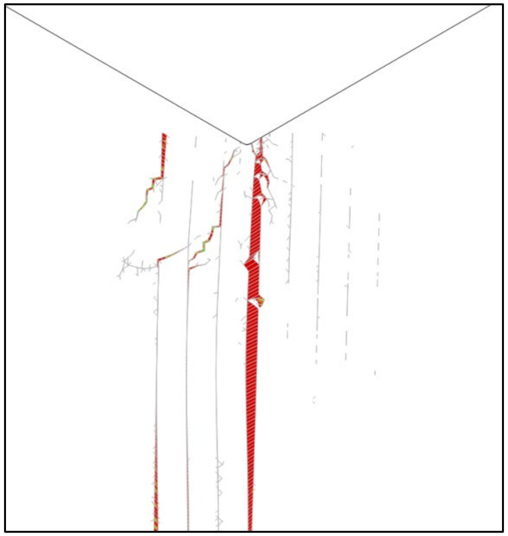



Microstructure simulation though cohesive element organization

# Finite Element Results

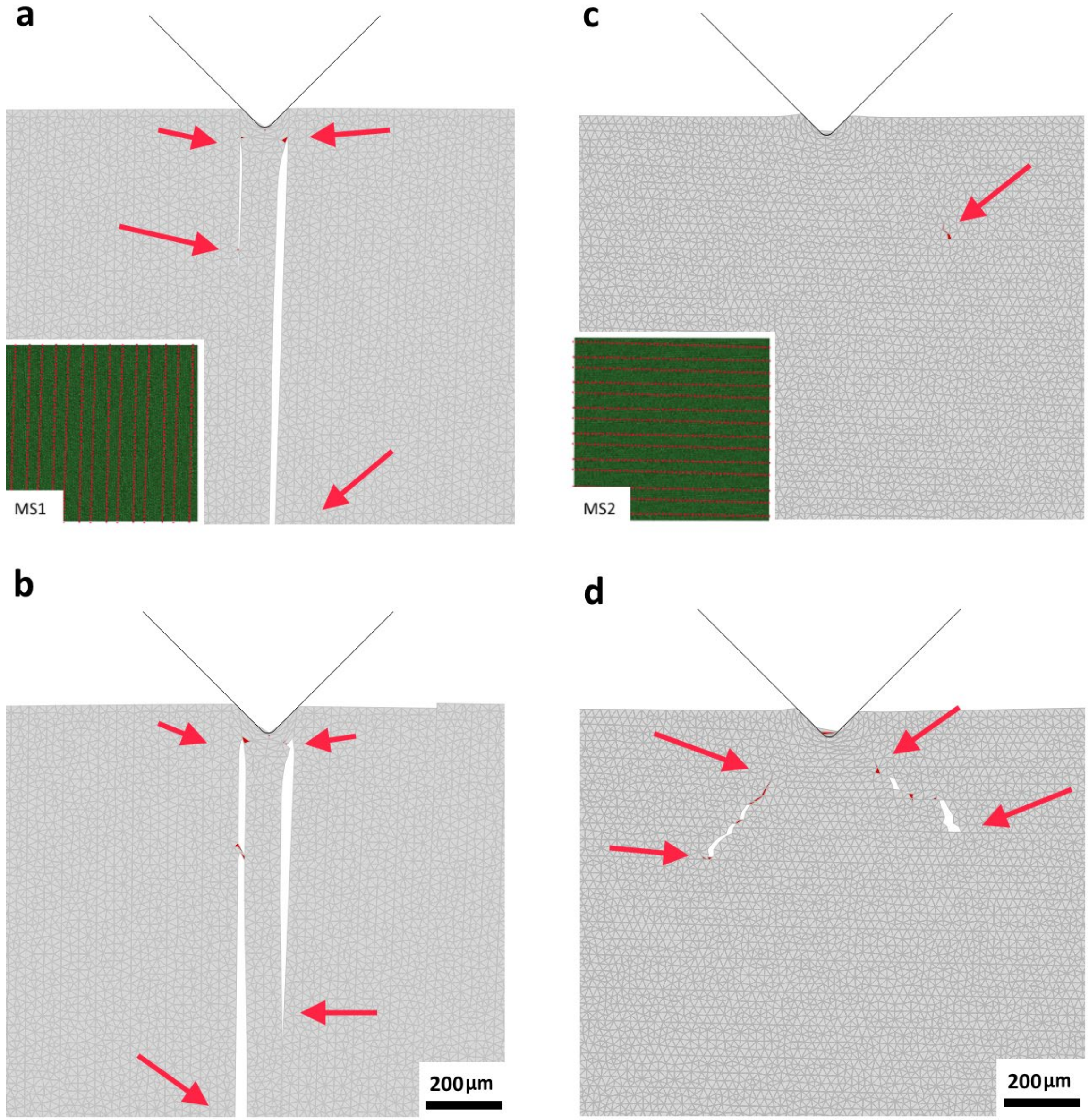



Comparison of Fracture behavior for different wedge angles (60° - 90° – 120°) with for vertical orientation.



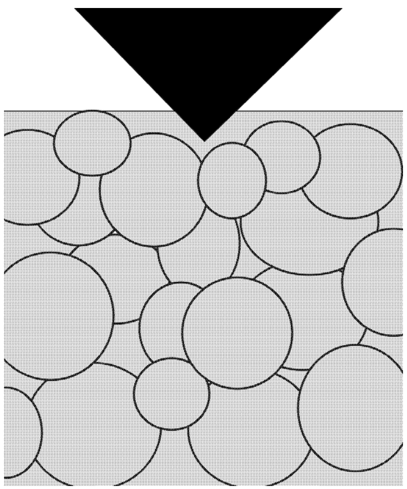
Only cracked elements visible for 120° wedge

# Finite Element Results

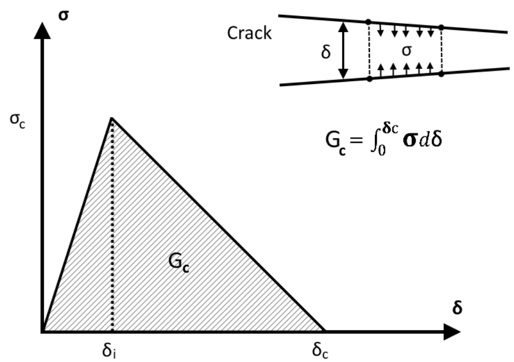


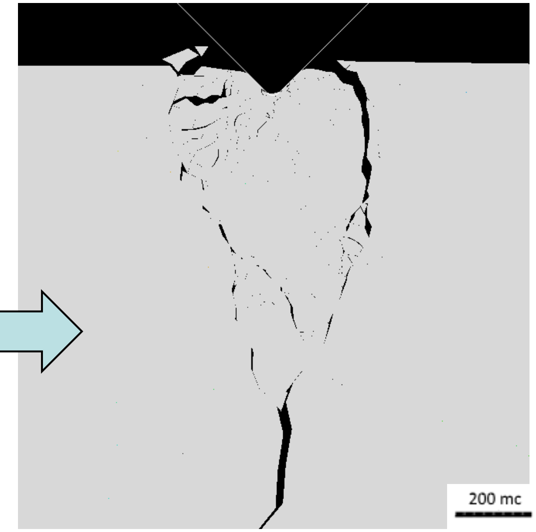

Vertically oriented cement lines versus horizontally oriented cement lines.

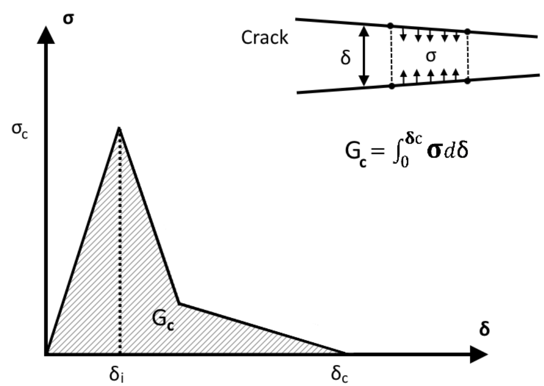
# Microstructural Influence

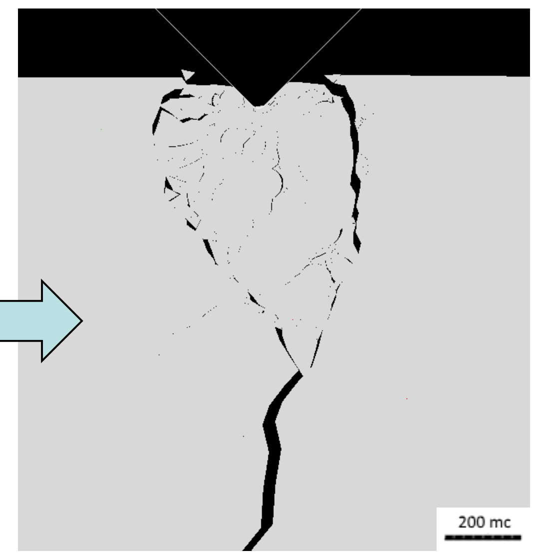


Varying cement line properties



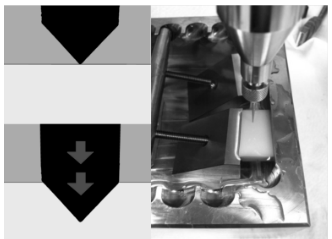



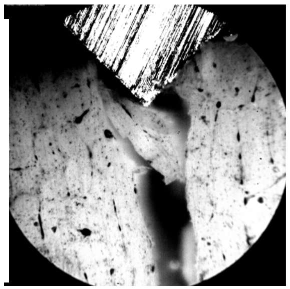



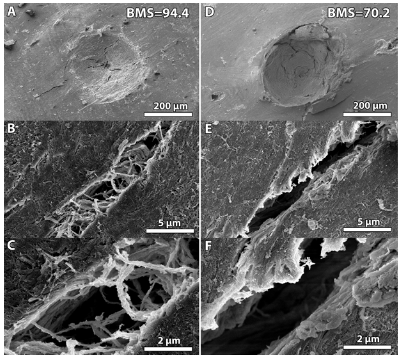




Reference Yang, Q.D., et al. 2006

## Interdisciplinary Approach



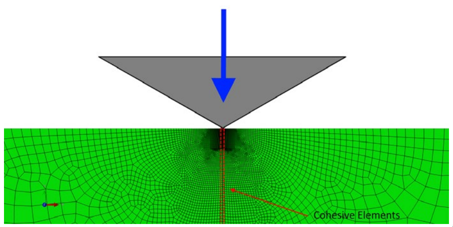


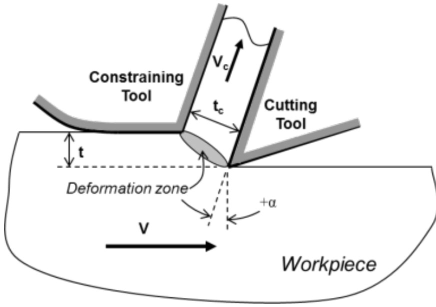


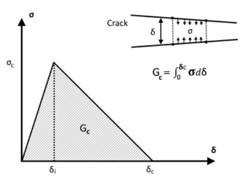

Biological/Biomedical Materials

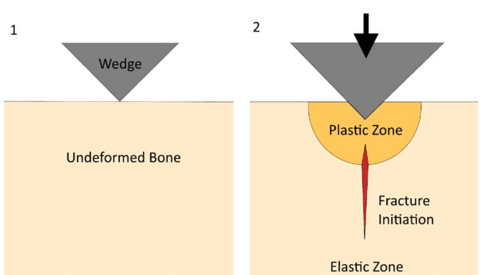
Computational Biomechanics

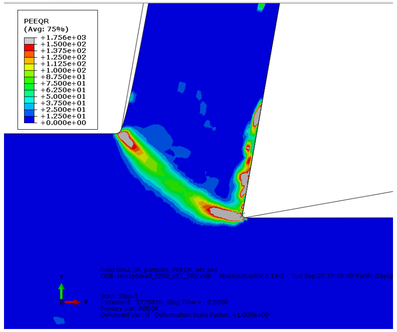
Advanced Manufacturing



# Acknowledgements

- Collaborators
  - Dr. Henry T. Yang
    - UCSB, Mechanical Engineering
  - Dr. Srinivasan Chandrasekar
    - Purdue University, Industrial and Materials Engineering
  - Dr. Paul Hansma
    - UCSB, Physics
  - Dr. Connor Randall
  - Dr. Timothy Lescun
    - Purdue University, College of Veterinary Medicine

- Funding and Support
  - LSU AgCenter
  - LSU College of Engineering