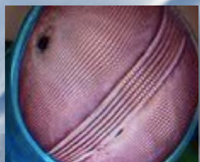
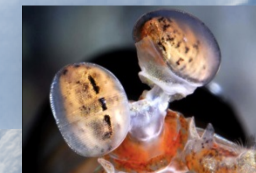
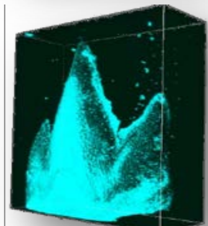


Bio-Inspired Materials

Lessons learned from Nature





Pablo D. Zavattieri

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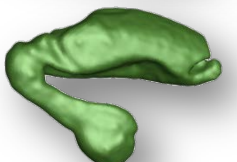
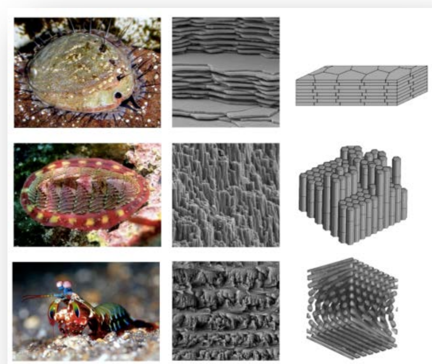
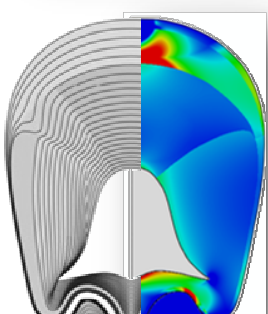
PURDUE UNIVERSITY







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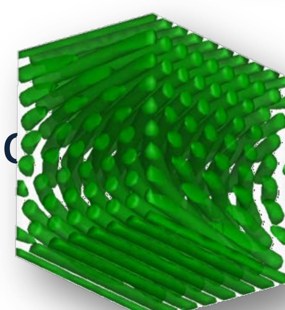
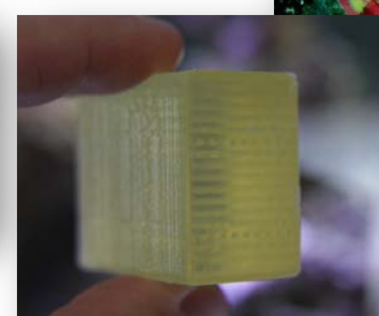
Outline

- Introduction
  - ✓ Biomimetics in Materials
- Motivation
- Examples
  - ✓ Abalones
  - ✓ Stomatopods
  - ✓ Chitons
- Current and Future Directi
- Conclusions





Computational Multi-Scale Materials Modeling Laboratory

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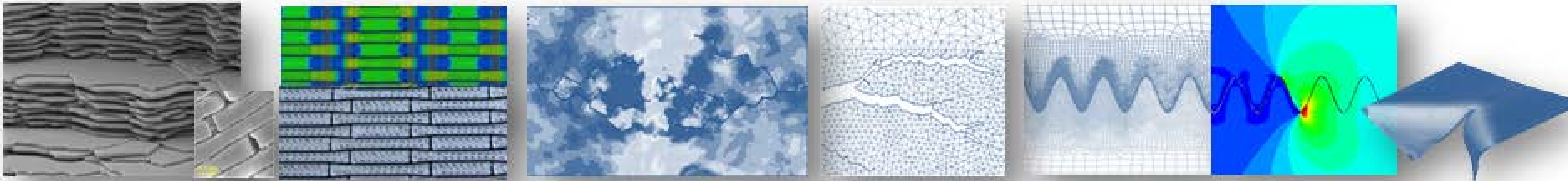

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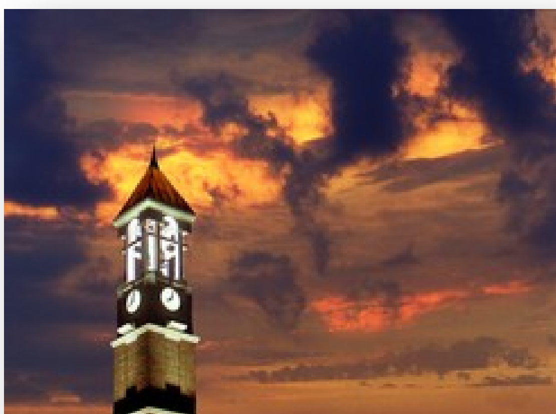

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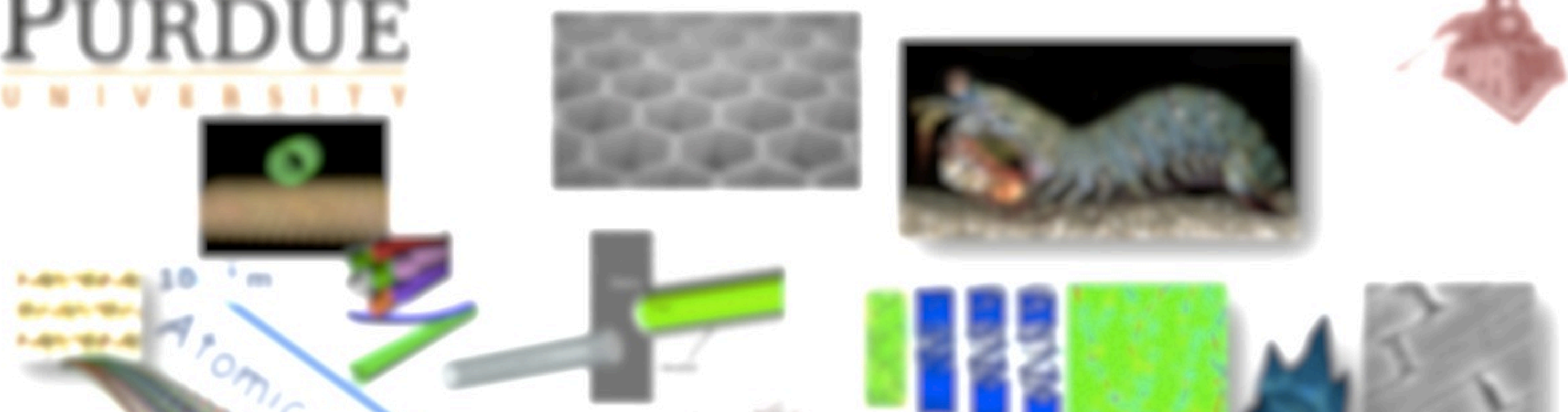


Research Areas of Interest:

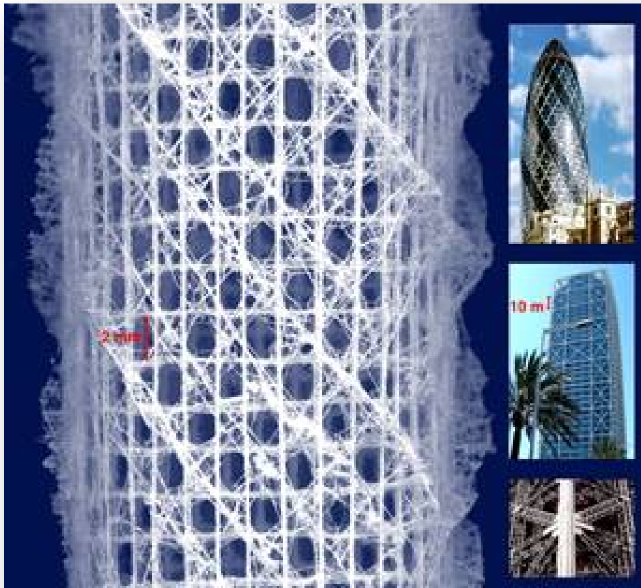
- ***Multi-scale modeling of materials (atoms-to-structures)***
- ***Green nano-materials (Cellulose NanoCrystals, CNC)***
- ***Biological and Biomimetic materials***
- ***Smart and multifunctional materials research.***

Multifunctional materials that can sense, adapt, self-heal, control energy flow, harvest energy, exchange energy with environment

From atoms to structures….

from nature to engineering

What does Nature has to do With Engineering?

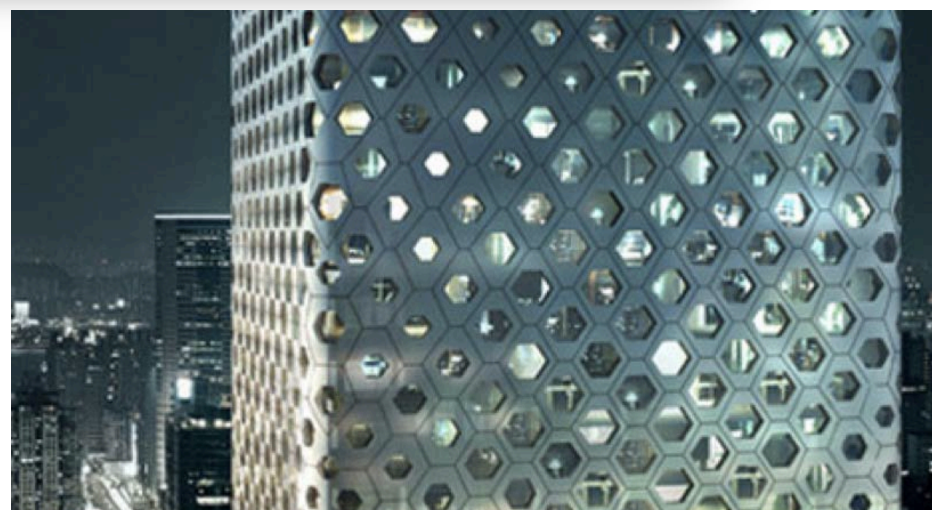


http://www.arkitecto.info

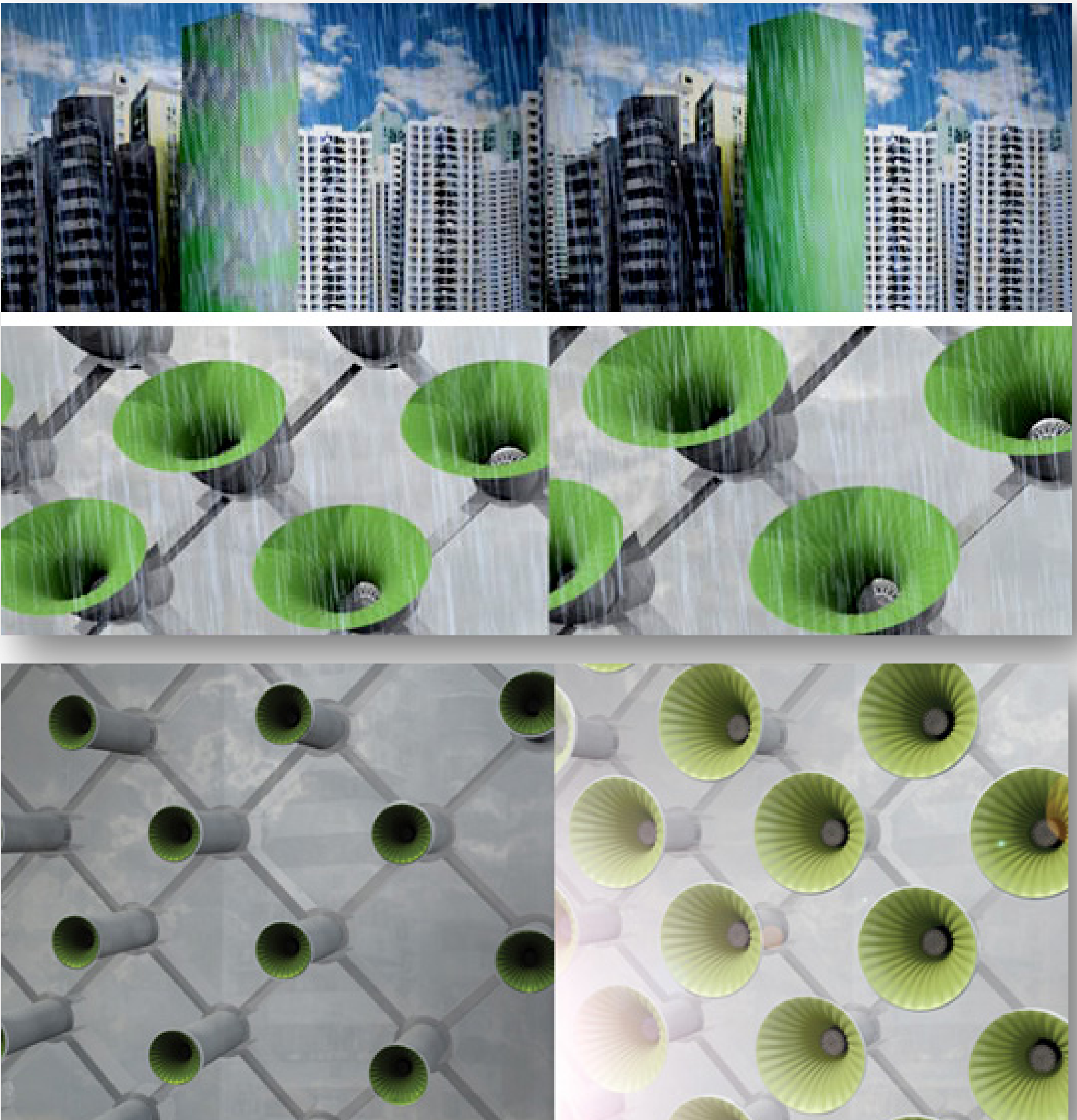
http://Inhabitat.com

The design of Venus' Flower Basket contains major construction strategies that are used in civil and mechanical engineering, but at the 1,000 times smaller scale. In this image, its structure is compared with the Swiss Tower in London, Hotel De Las Artes in Barcelona and a structural detail of the Eiffel Tower in Paris.

Joana Aizenberg, http://www.msnbc.msn.com



the building's hexagonal curtain is based upon climate modeling and serves to regulate the structure's temperature and daylight by varying the size of each cell's window.



Biomimetic Architecture

Habitat 2020 is a future forward example of biomimetic architecture that fuses high-tech ideas with basic cellular functions to create ‘living’ structures that operate like natural organisms. http://inhabitat.com

What does Nature has to do With Engineering?

Biomimetic Building Uses Termite Mound As Model

A building in Harare, Zimbabwe that has no air-conditioning, yet stays cool thanks to a termite-inspired ventilation system.

Source: http://www.biomimicryinstitute.org

What does Nature has to do With Engineering?

21 Century Oasis (Taiwan)

http://en.51arch.com/

The world’s first algae-powered building just opened in Hamburg!

What does Nature has to do With Engineering?

Shanghai 2010 Expo

Seed Cathedral

http://www.heatherwick.com/uk-pavilion/

What does Nature has to do With Engineering?

http://www.sciencedump.com/content/buildings-inspired-nature

Bioinspiration

Leaves → **Solar Cells**

Spider Silk → High-strength fibers

Abalone → Fracture Resistant Materials

Termite Towers → Heating and Air Conditioning

Bat → Multifrequency Radar

Dolphin Skin → Smart Materials

Squid/Octopus → **Camouflage** / MorPhiNg

Humming Birds → Fuel Economy

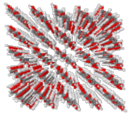
Silkworm → Single Molecule Detection

Stiffness

Strength

Ductility

Toughness



Mechanics of Biological materials

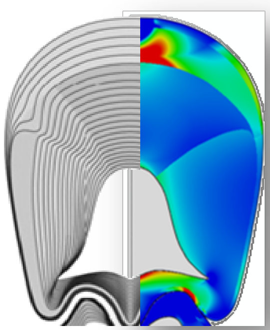
(biomineralized marine organisms)

Mechanics of Natural Materials

As building blocks

(e.g., cellulose from trees)

Development of Biomimetic materials



Engineering Materials

Computational Multi-Scale Materials Modeling Lab

Engineering Materials



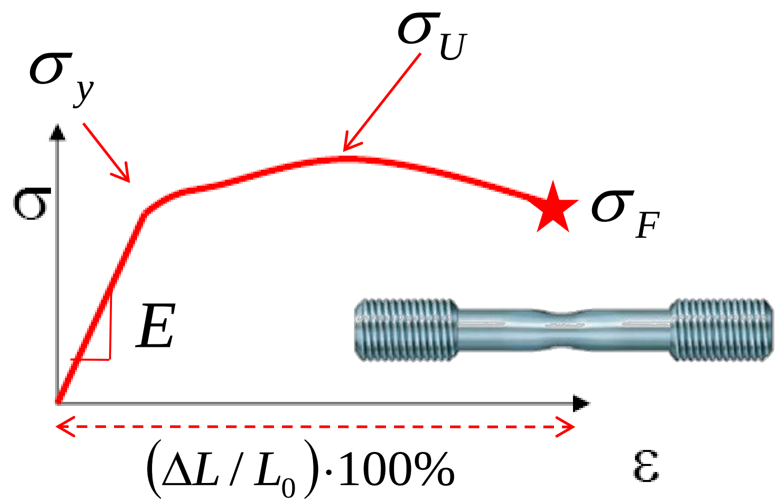

Why?



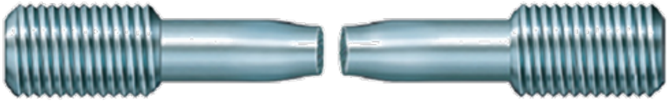




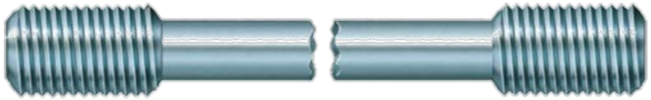
Common properties used in design



Necking



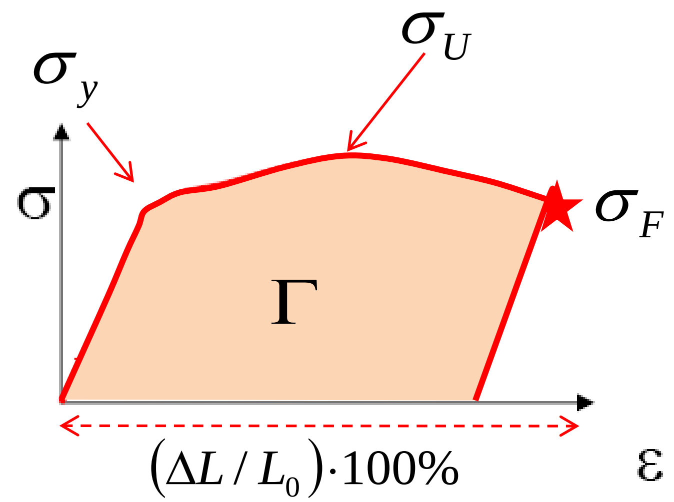
Failure of a ductile material



Tension failure of a brittle material

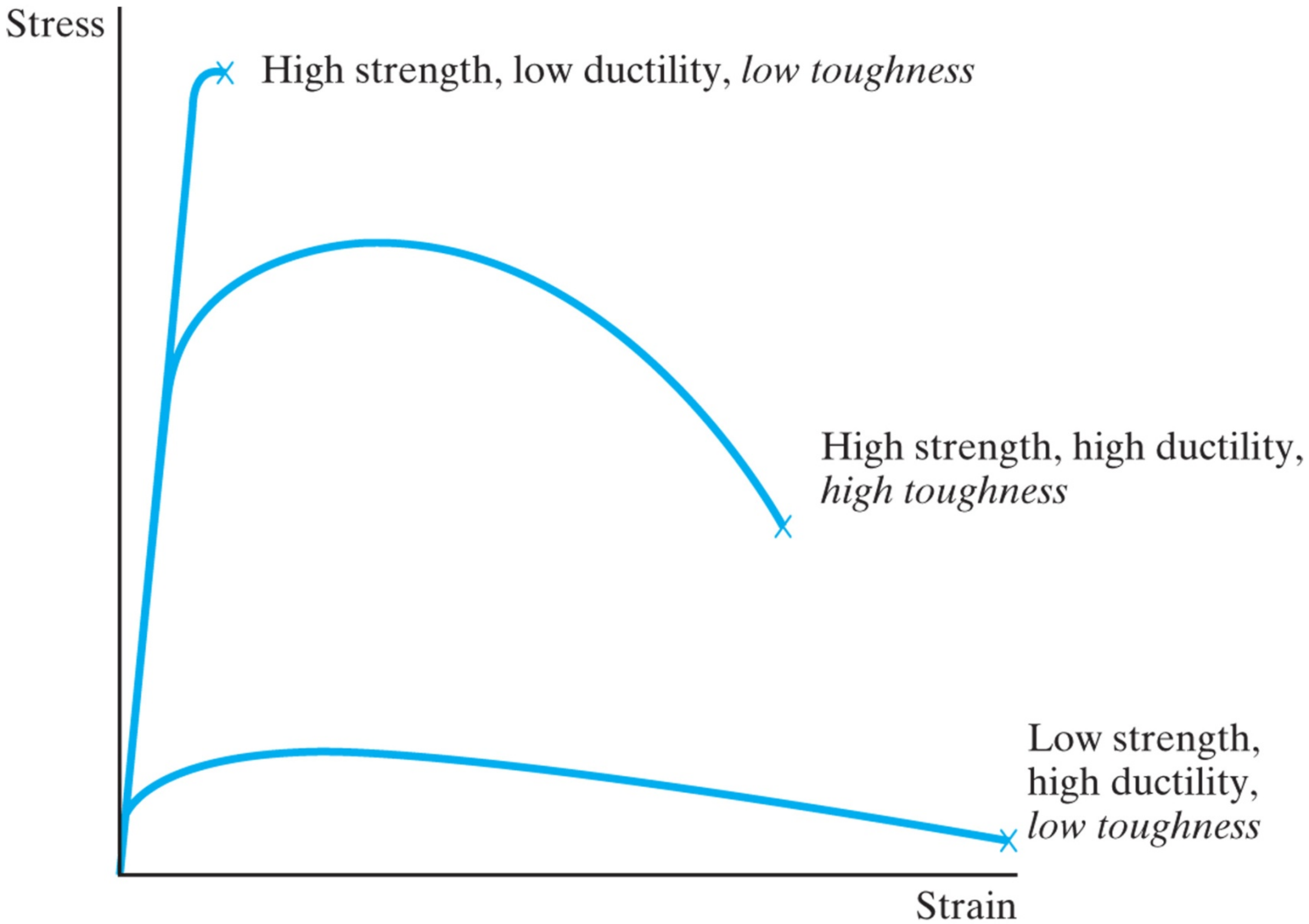
Common properties used in design

- <u>Strength:</u> $\boldsymbol{\sigma_Y}$, $\boldsymbol{\sigma_U}$ *(or* $\boldsymbol{\sigma_F}$*)*
- <u>"Stiffness":</u> ***E***
- <u>Ductility:</u> ***% elongation***

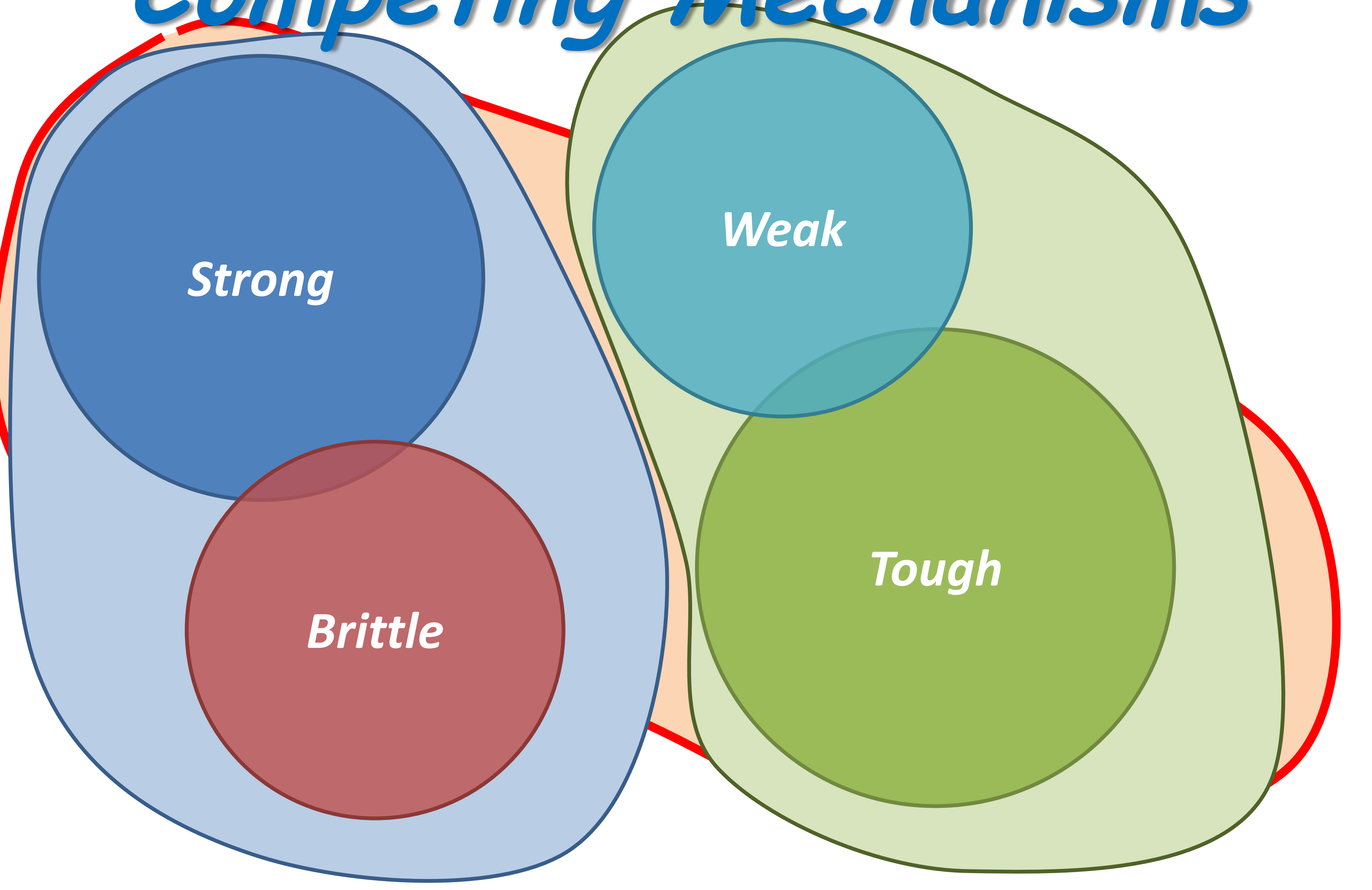


- *<u>Toughness:</u> area below the curve*

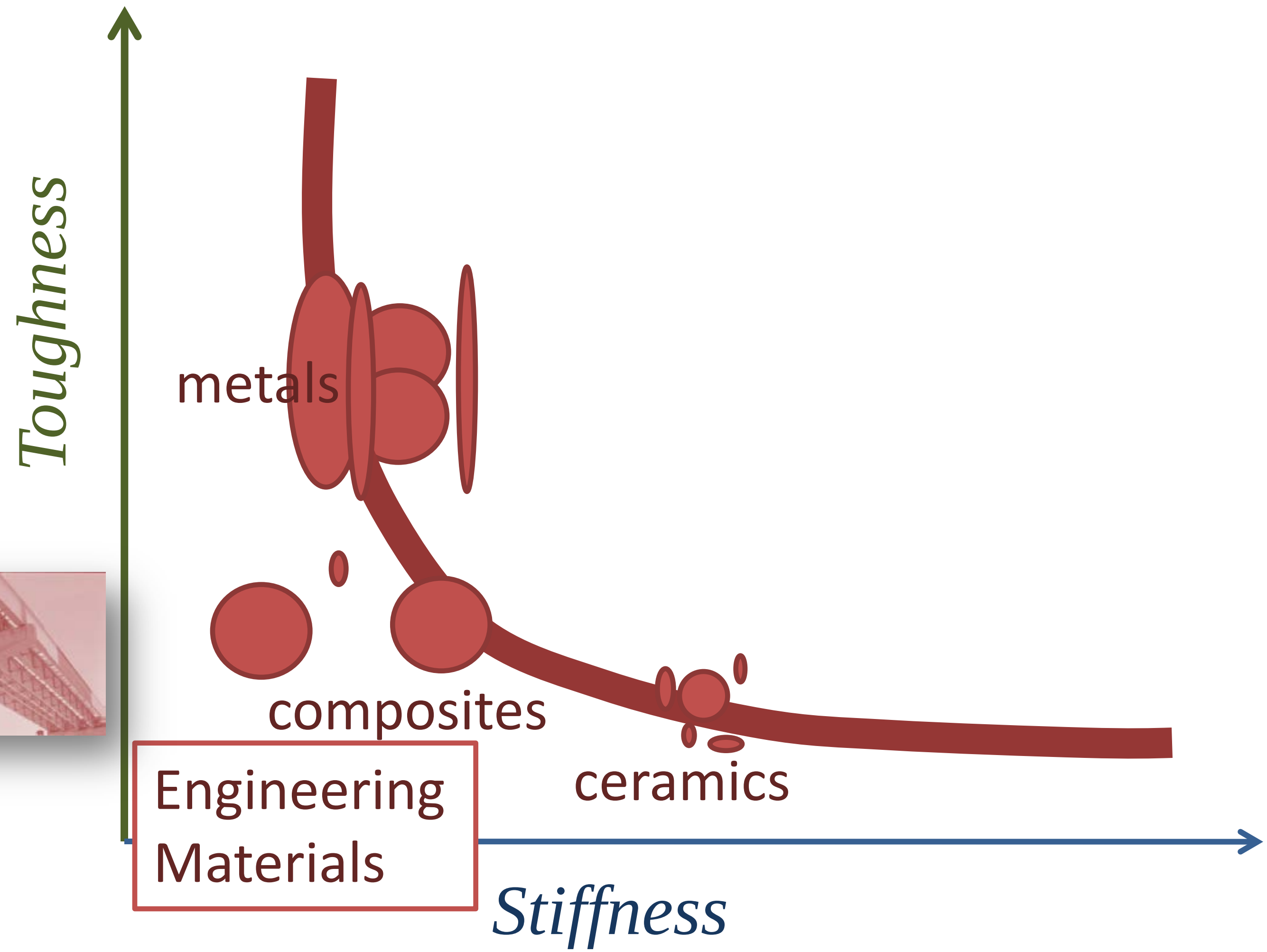
The toughness of an alloy depends on a combination of strength and ductility



Competing Mechanisms



Engineering Materials

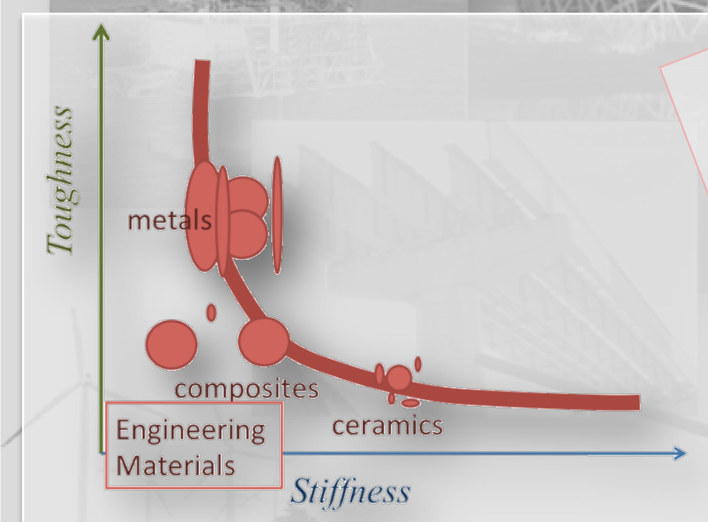


Adapted from Fratzl, et al. J. Mater Chem. 2004.

Engineering Materials

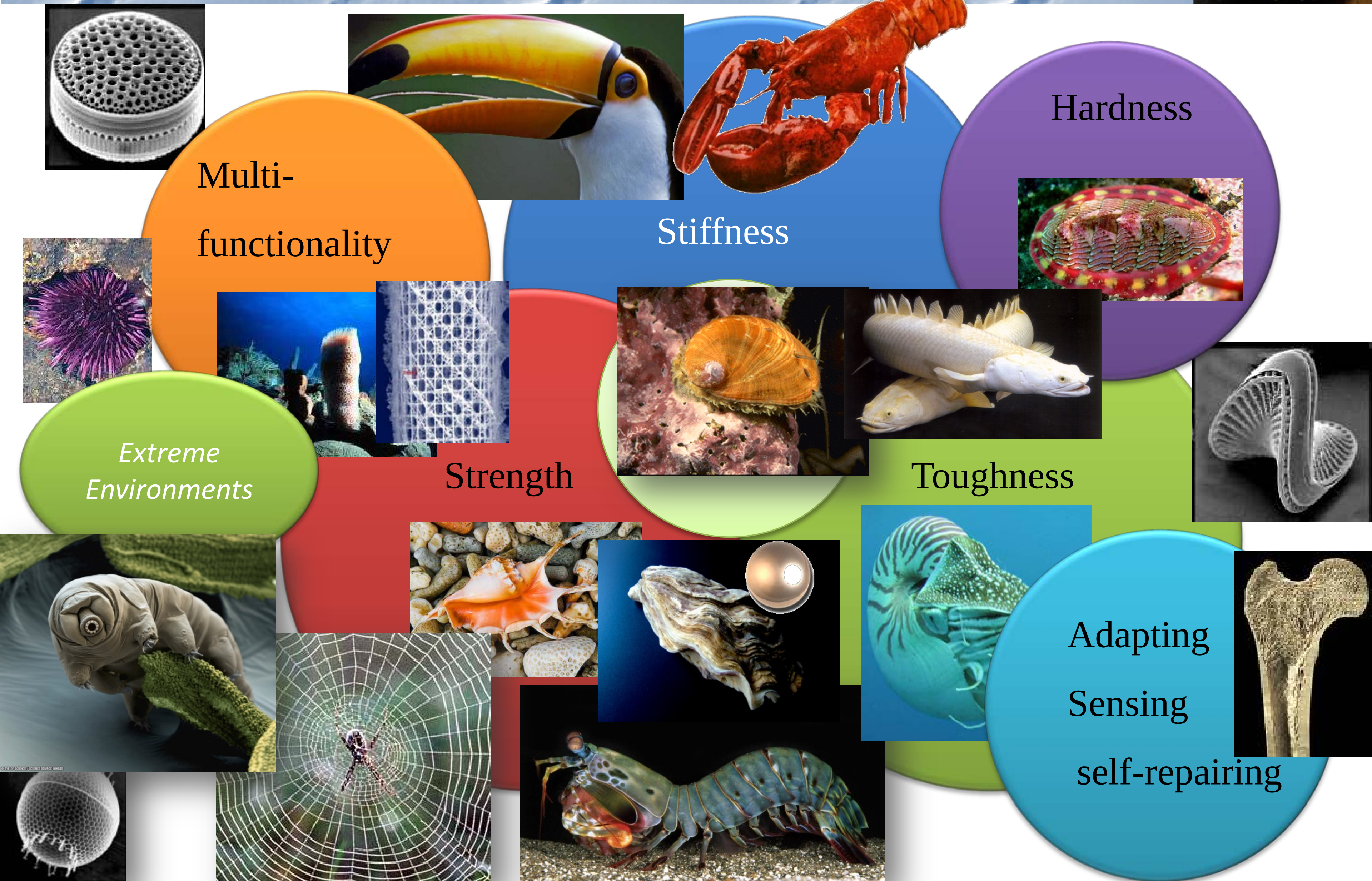
Brute Force

Heat and Beat (Energy)



Nature

Computational Multi-Scale
Materials Modeling Lab

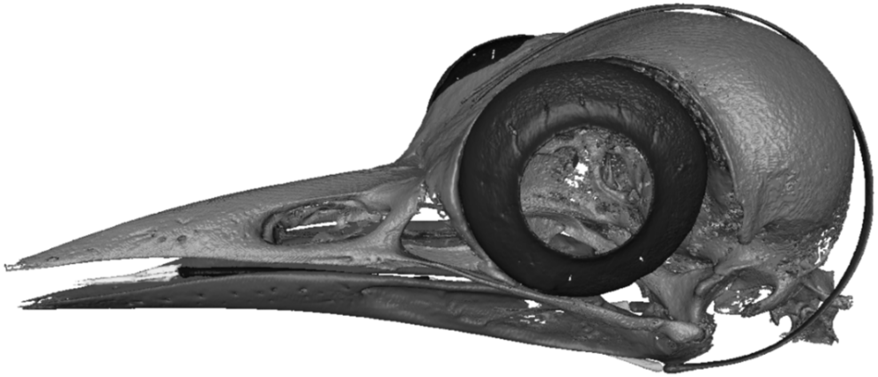


Nature offers multiple comparatives

Hammering conditions[3]

- Pecking rates: 20 Hz
- Head speeds: up to 7 m/s (15 mph)
- Deceleration: up to 1200 ***g***'s

(Concussion in human: 80 ***g***'s from the NFL)



Joanna McKittrick's group at

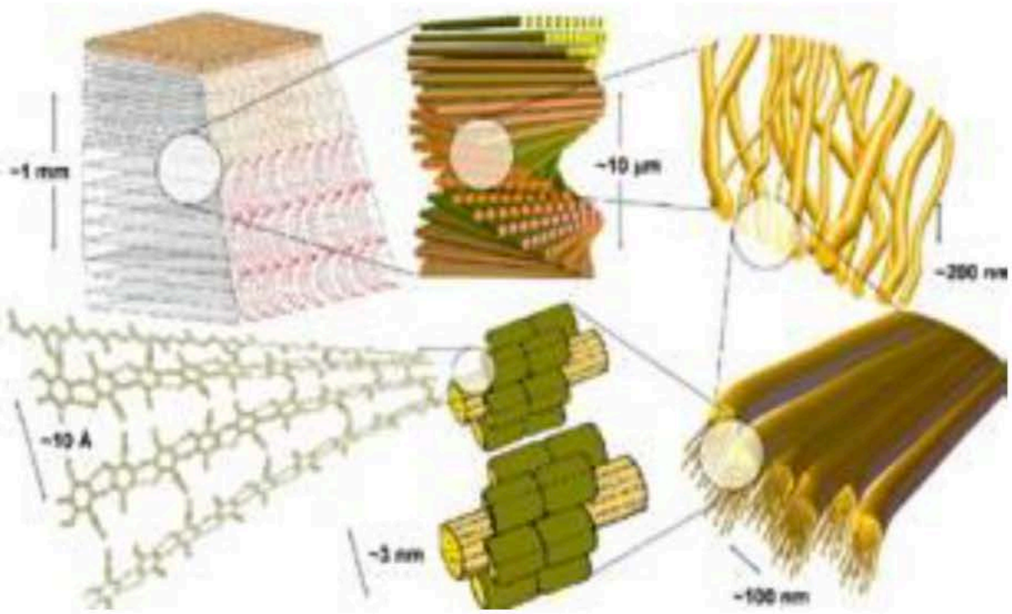
University of California San Diego

[1] Taken from "http://TomSlatin.com - Confused Woodpecker.flv"

[2] Taken from "https://youtu.be/akweH8KBcGM"

[3] May PA, Fuster J, Newman P, Hirschman A. "Woodpeckers and head injuery." The Lancet 1976;307:1347-8.

Bouligand



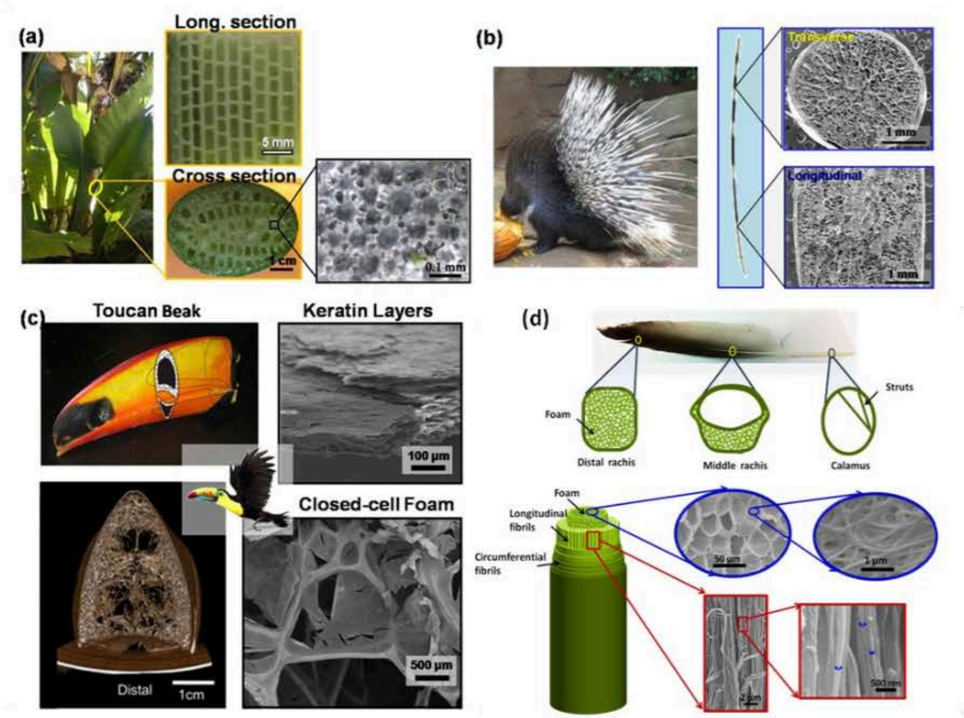
Example: Hierarchical arrangement of the crustacean cuticle, from the molecular to macroscopic level

Form: A twisted plywood structure, with each layer rotated by a fixed angle from the adjacent layer, eventually completing a rotation of 180°.

Function: provides in-plane isotropic strength, prevents microcrack coalescence and dissipates energy during impact loadings.

Species: observed in **insects, crustaceans, plants, and fish.**

Cellular



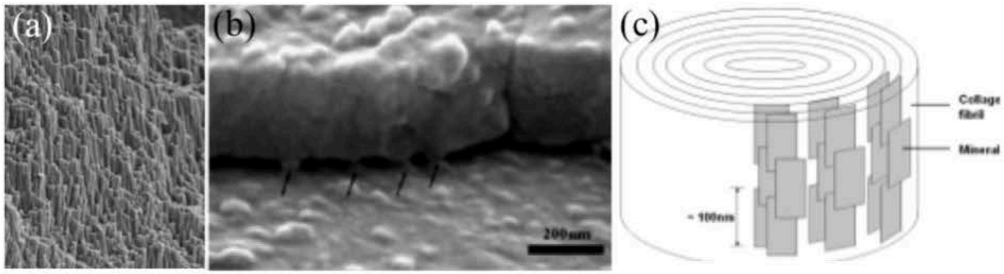
Examples of low-density and stiff Cellular materials: (a) Giant bird-of-paradise plant stem. (b) Porcupine quill. (c) Toucan beak (d) Feather rachis: superficial layers of fibers, wound circumferentially round the rachis.

Form: 3D opened or closed cells as typically observed in foams.

Function: exhibit high flexural and torsional stiffness. Optimal bending and buckling resistance without excessive mass. Nature crates a thin solid shell and fills the core with light-weight foam and internal reinforcing struts or disks.

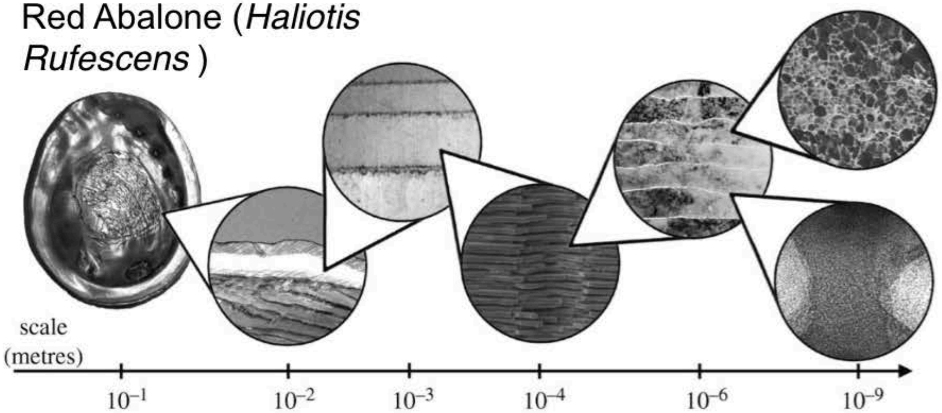
Species: observed in antler, some skeletal bones, bamboo, wing bones in birds, plants, porcupine quills, bird beaks and feathers .

Lamellar



Lamellar structures: (a) mineral rods in chiton (~200nm); (b) mineral bridges in abalone nacre (~20-50 nm); (c) mineral platelets in bone (~10 nm thickness).

Red Abalone (*Haliotis Rufescens*)



Form: 3D organization in brick and mortar with well defined overlaps.

Function: achieve high stiffness and toughness by diffusive damage that results in very high energy absorption. Material components exhibit very distinct properties.

Species: observed in in arthropods (e.g., crab and lobster exoskeleton), sea sponges (e.g., *Euplectella aspergillium*), mollusks (e.g., chiton's teeth, gastropods and bivalves), fish scales, and vertebrates (bone and antler).

Biological Building Blocks

Structural Proteins

Collagens

Glycoprotein and proteoglycans

Keratins

Elastomeric proteins

Elastin

Resilin

Abductin

Polysaccharides

Cellulose

Lignin

Hemicelluloses

Suberin

Chitin

Minerals

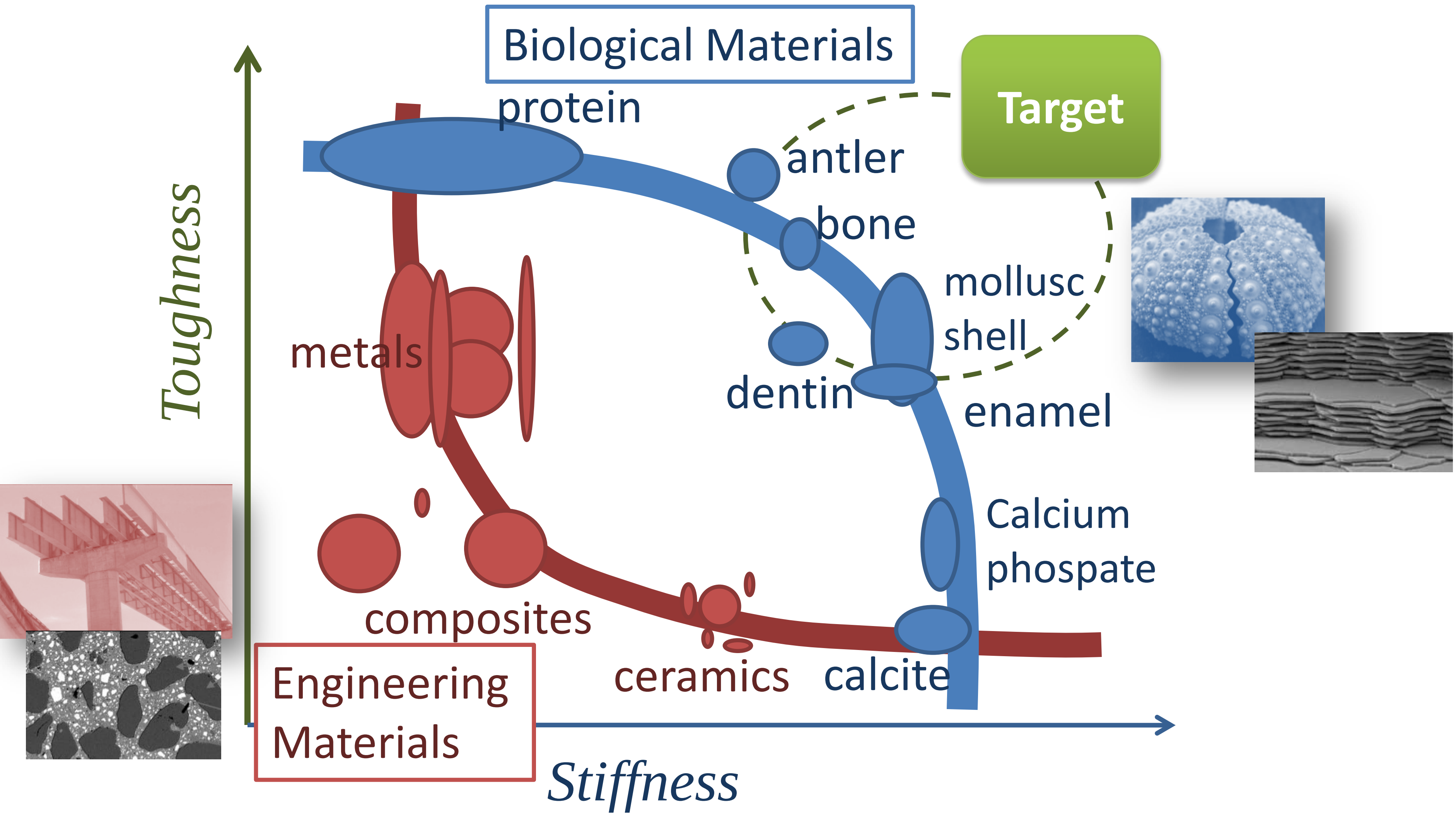
Calcite

Aragonite

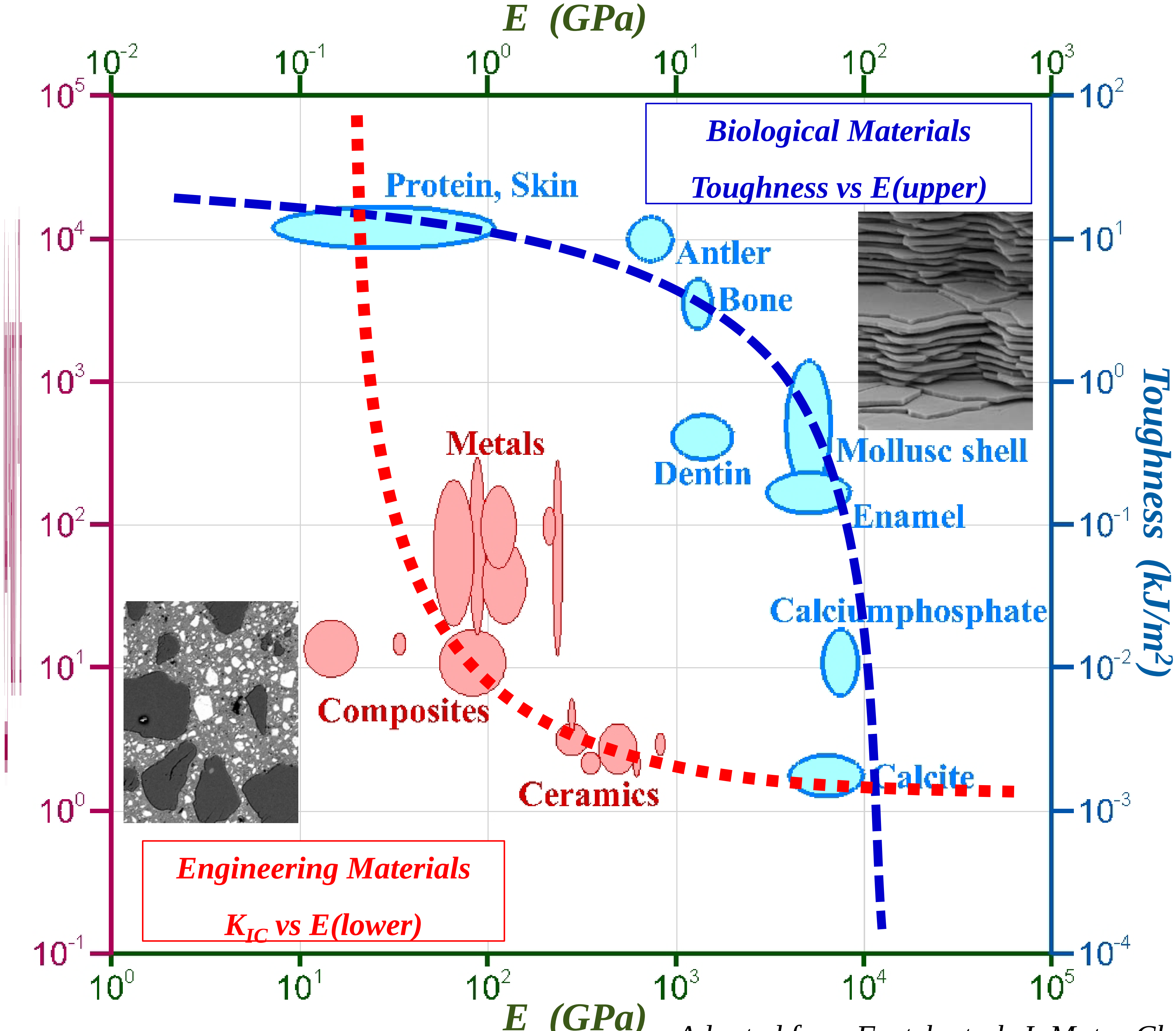
Hydroaxyapatite

Bio-silica

Engineering vs. Biological Materials



Adapted from Fratzl, et al. J. Mater Chem. 2004.



Adapted from Fratzl, et al. J. Mater Chem. 2004.

Biological Materials

Biological ceramics and ceramic composites

Sponge spicules

Shells

Shrimp hammer (stomatopod)

Marine worm teeth (chiton)

Bone

Teeth

Biological polymers and polymer composites

Ligaments (bone connection)

Silk (spider silk)

Arthropod exoskeletons

Keratin-based materials (hairs, nails, hooves, and horns)

Biological elastomers

Skin

Muscle

Blood Vessels

Mussel Byssus

Cells

Biological cellular materials

Wood

Beak Interior

Feather

Functional biological materials

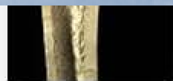
Gecko feet

Structural colors (photonic crystal arrays and thin film interference)

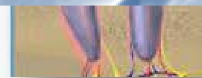
Chameleon

Living organisms and minerals

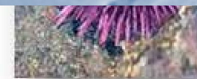
Computational Multi-Scale
Materials Modeling Lab



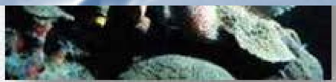
Bone: 50 % hydroxyapatite
(nanocrystals)



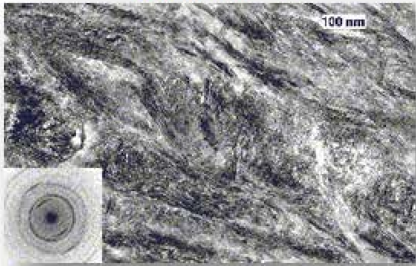
Tooth Enamel (outer layer):
90 % hydroxyapatite

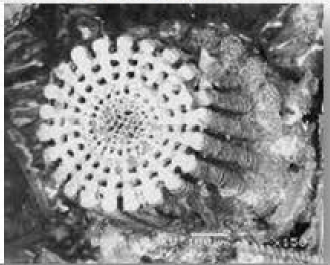


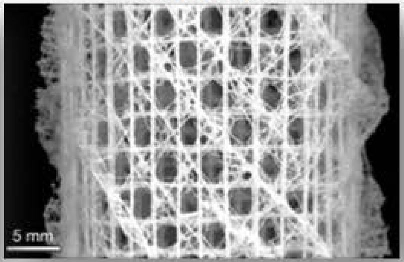
Sea Urchin spines:
99 % calcite



Glass Sponge skeleton:
95 % Silica



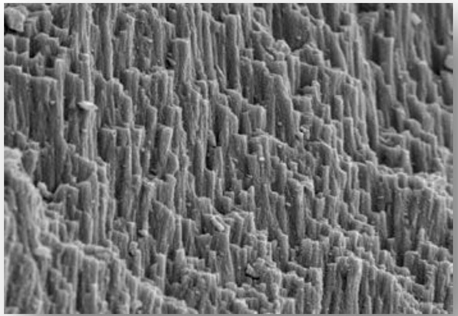


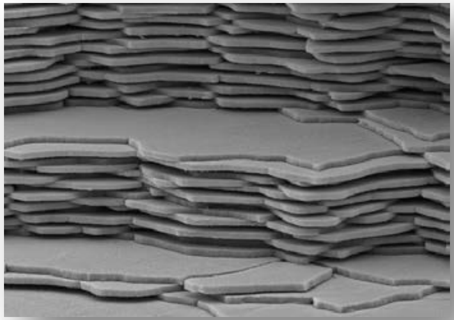


Stomatopod’s dactyl club: HAP, $CaCO_3$

Chiton’s teeth: 95 % Fe_3O_4
(magnetite)

Mollusk Nacre: $CaCO_3$ (Aragonite)





Living organisms and minerals

Minerals (Structural purposes) + **Soft Organic Materials** = Composite Materials

Hierarchical Structures
over several length scales

surprising **mechanical performance**

Multifunctional, self-sensing, self-repairing, self-adapting

Stomatopod's dactyl club: HAP, $CaCO_3$

Chiton's teeth: 95 % Fe_3O_4 (magnetite)

Mollusk Nacre: $CaCO_3$ (Aragonite)

Nature builds strong and tough materials using modest building blocks

PURDUE ENGINEERING

Living organisms and minerals

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Stomatopod's dactyl club: HAP, $CaCO_3$

Biomimetics is the study of the structure and function of biological systems as models for the design and engineering of materials and machines.

Living organisms and minerals

Minerals (Structural purposes) + **Soft Organic Materials** = Composite Materials

Hierarchical Structures
over several length scales

surprising **mechanical performance**

Multifunctional, self-sensing, self-repairing, self-adapting

Stomatopod's dactyl club: HAP, $CaCO_3$

Biomimetics: Necessary steps

Understand the Structure-Function … onship of the natural material.

1. Structure: architect… …s, distribution. Fundament… …f the constituent mat…

2. … conditions, constraints, environment,

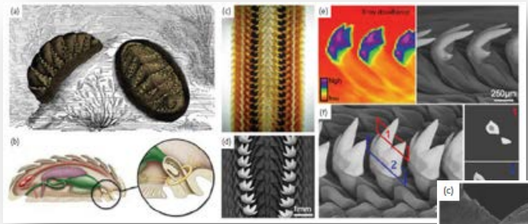
…hat makes a material interesting? Can we extrapolate these lessons learned to engineering materials?

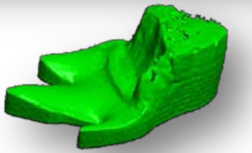
Mechanisms that only activate during the damage process

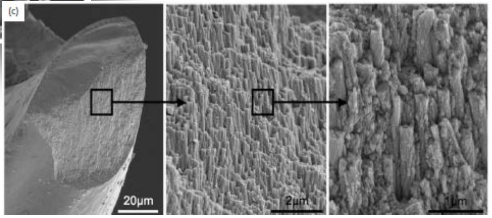
Biomimetics tools

Characterization:

- *Energy Dispersive Spectroscopy*
- *Electron and Optical microscopy*
- *Synchrotron X-ray diffraction (XRD)*



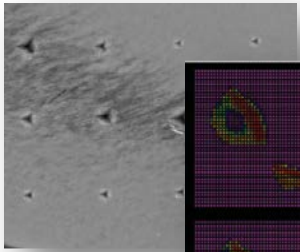


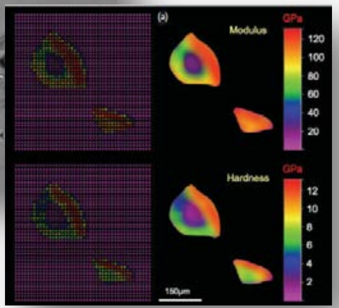


[1] Weaver et al., Materials Today, 2010

Experiments:

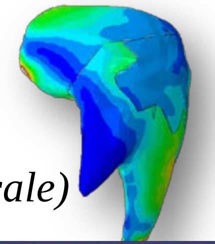
- *nano- and micro-mechanical tests (e.g., nanoindentation, in-situ microscope tests)*

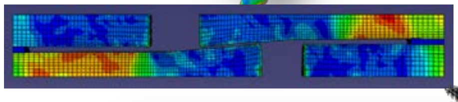




Modeling:

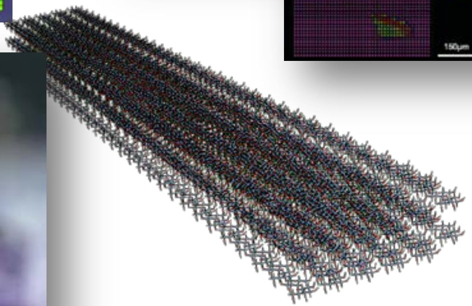
- *Analytical and numerical models (Multiscale)*

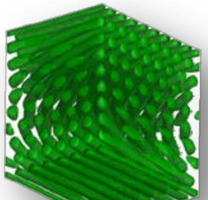




Biomimetics:

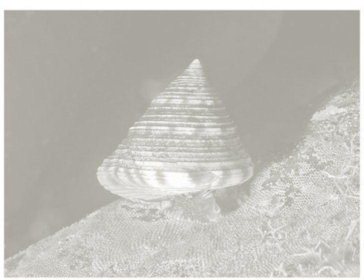
- *Lessons learned, Design guidelines*
- *Prototyping*
- *Synthesis*

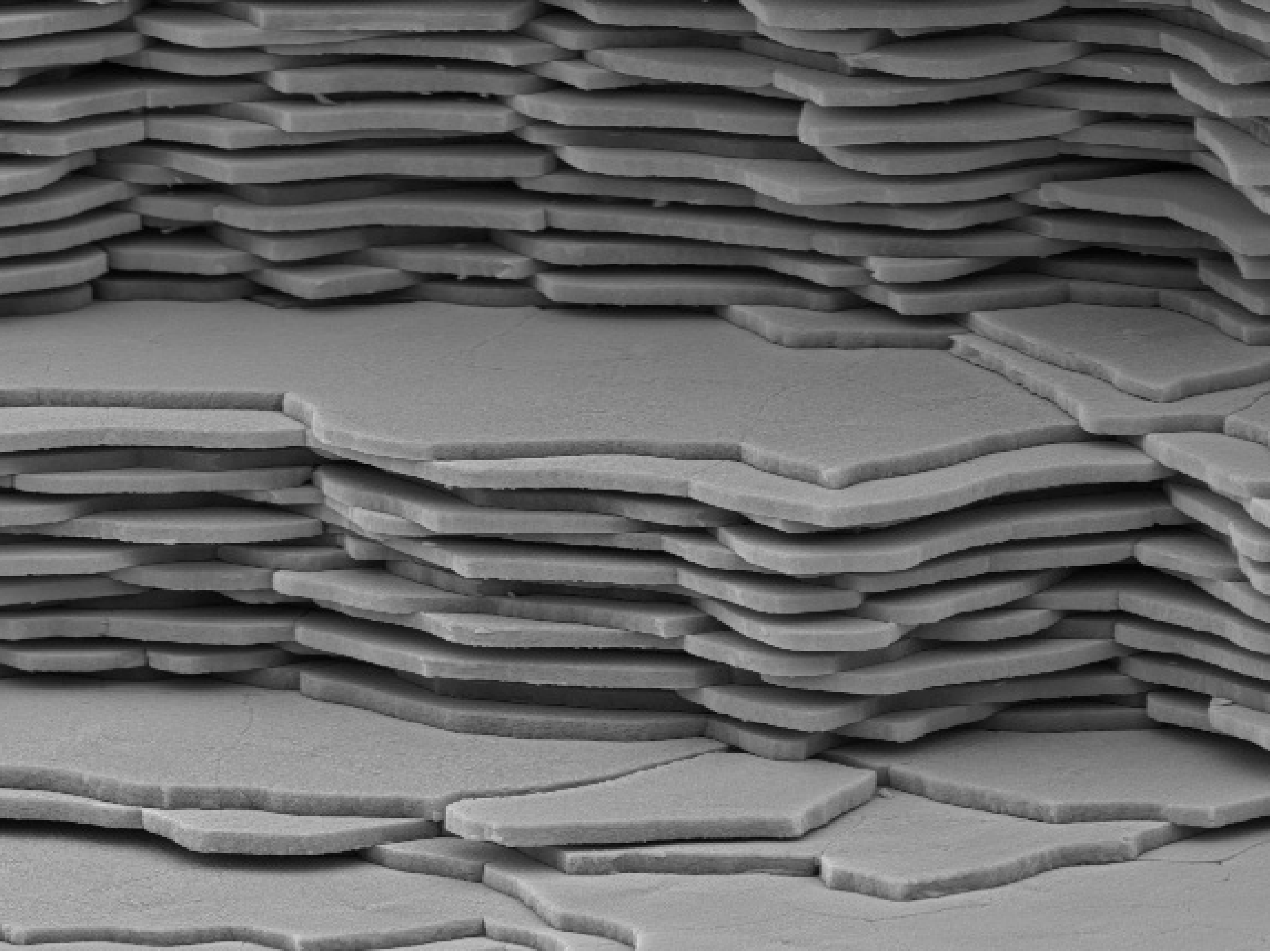




Nacre

Red Abalone,
Haliotis rufescens

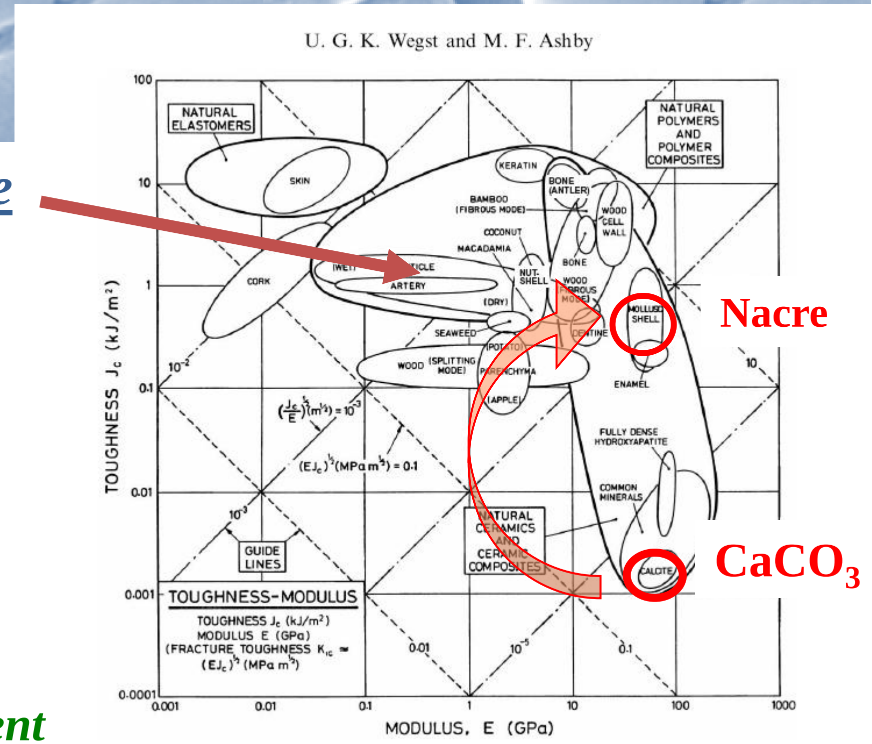




Nacre

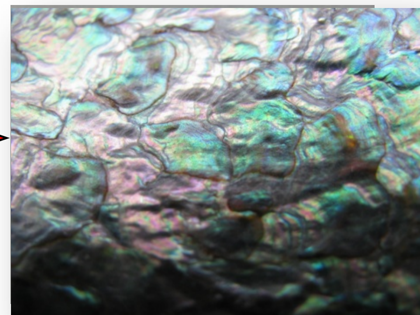
PURDUE ENGINEERING

• *Nacre is 1000 times tougher than aragonite*

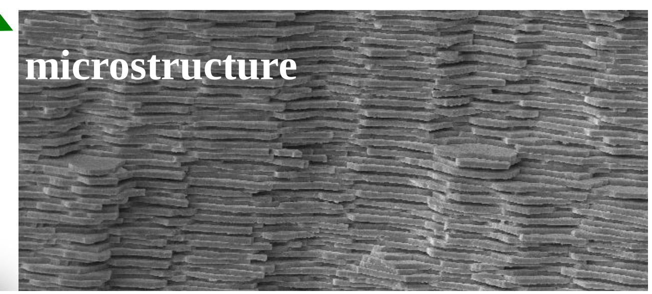


Geological Aragonite: A brittle ceramic

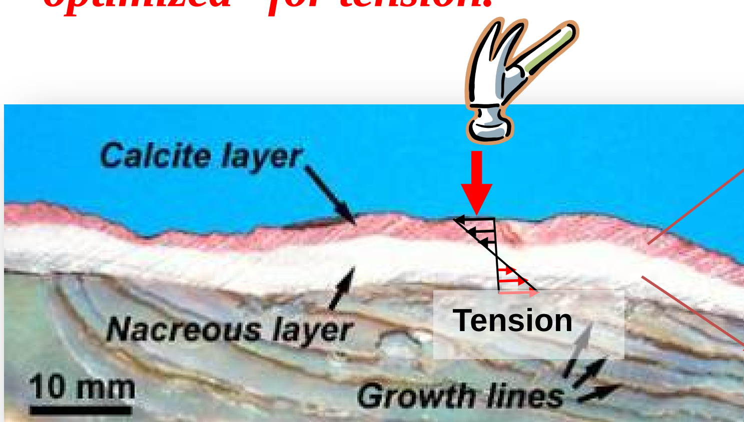
Nacre: A tough and ductile bio-composite

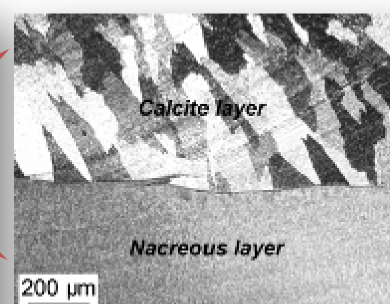


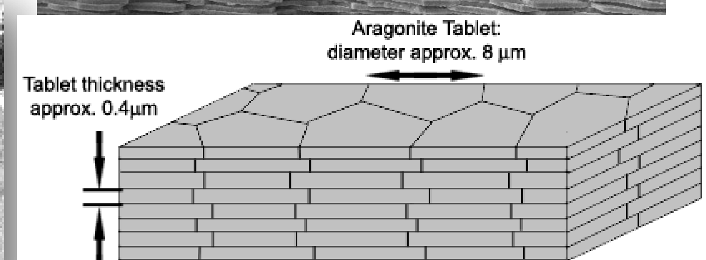
•Nacre achieves this remarkable improvement through a very well designed microstructure



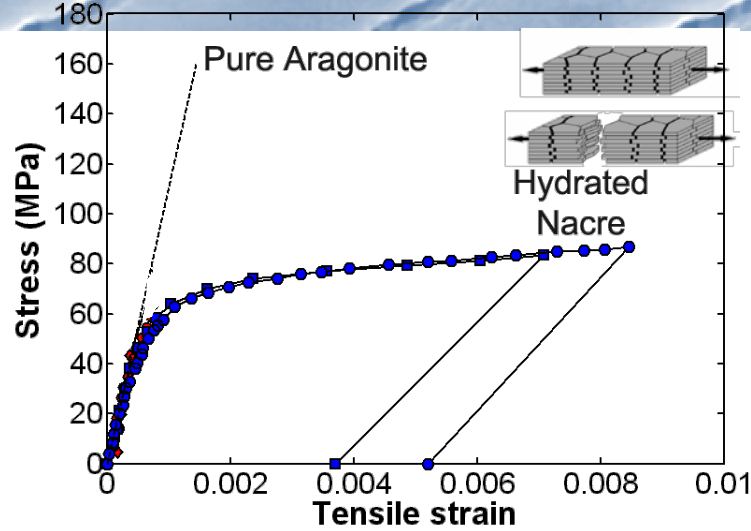
• Simplest case. We believe that nacre was "optimized" for tension.



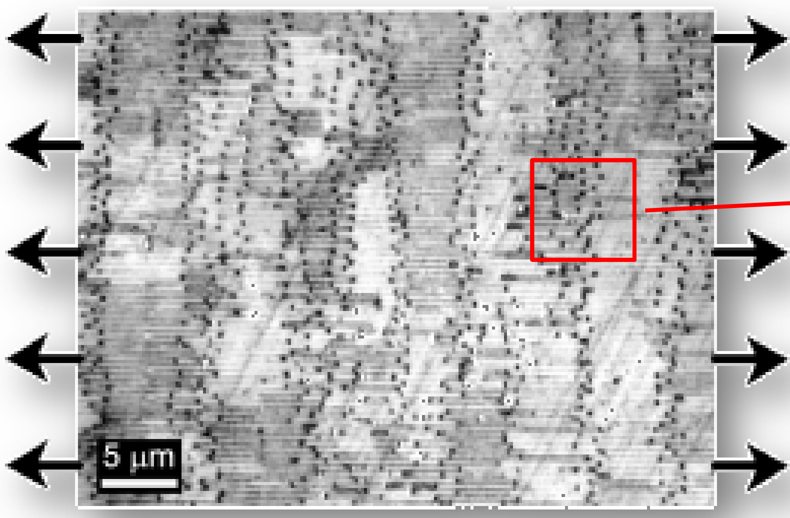


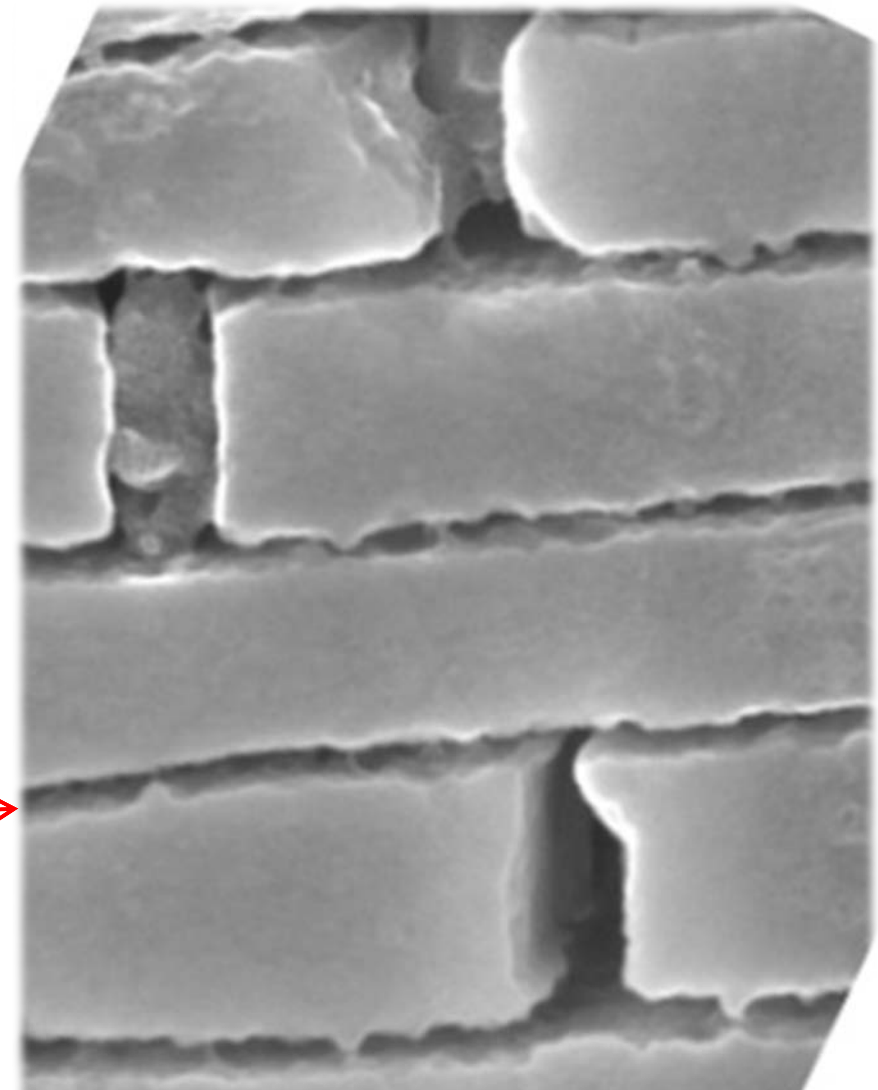


Distributed damage



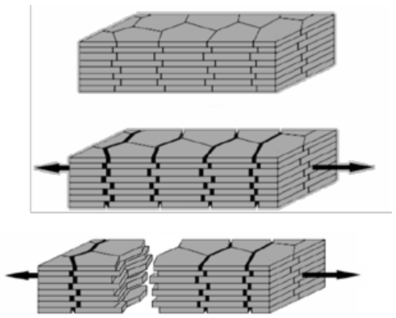
Barthelat, Tang, Zavattieri, Li, Espinosa, JMPS, 2007

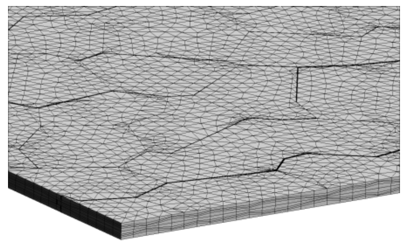


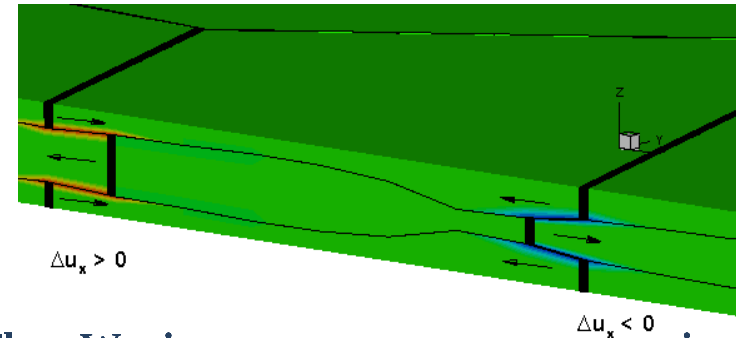


Deformation: Tablet sliding is the key mechanisms in the toughness of nacre.

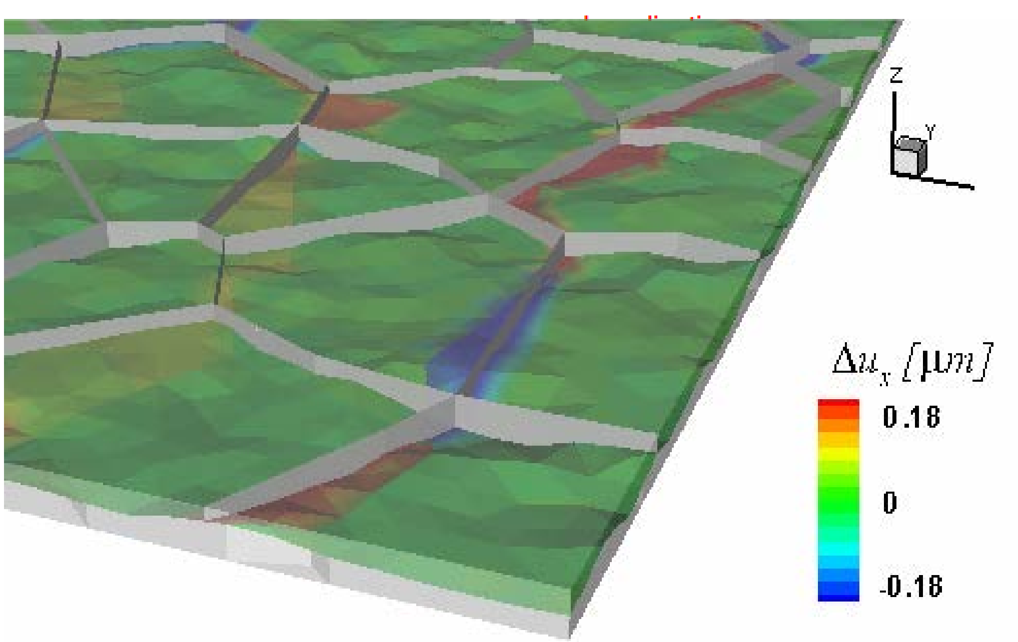
Results

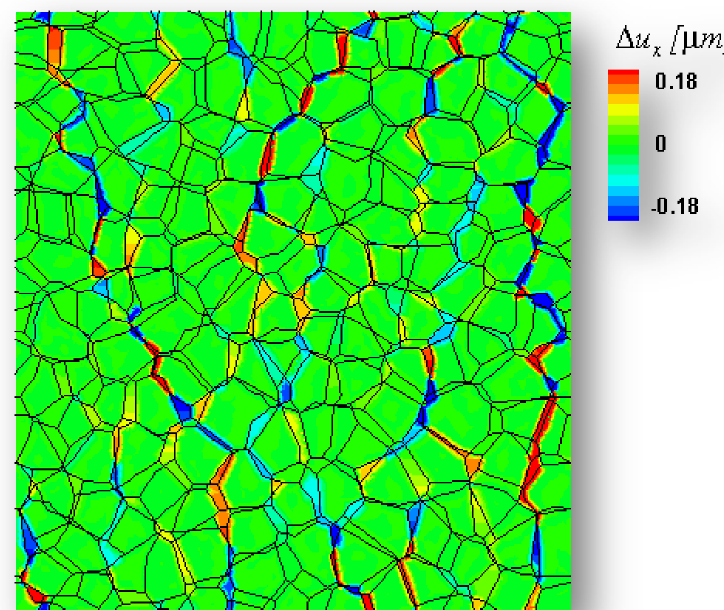






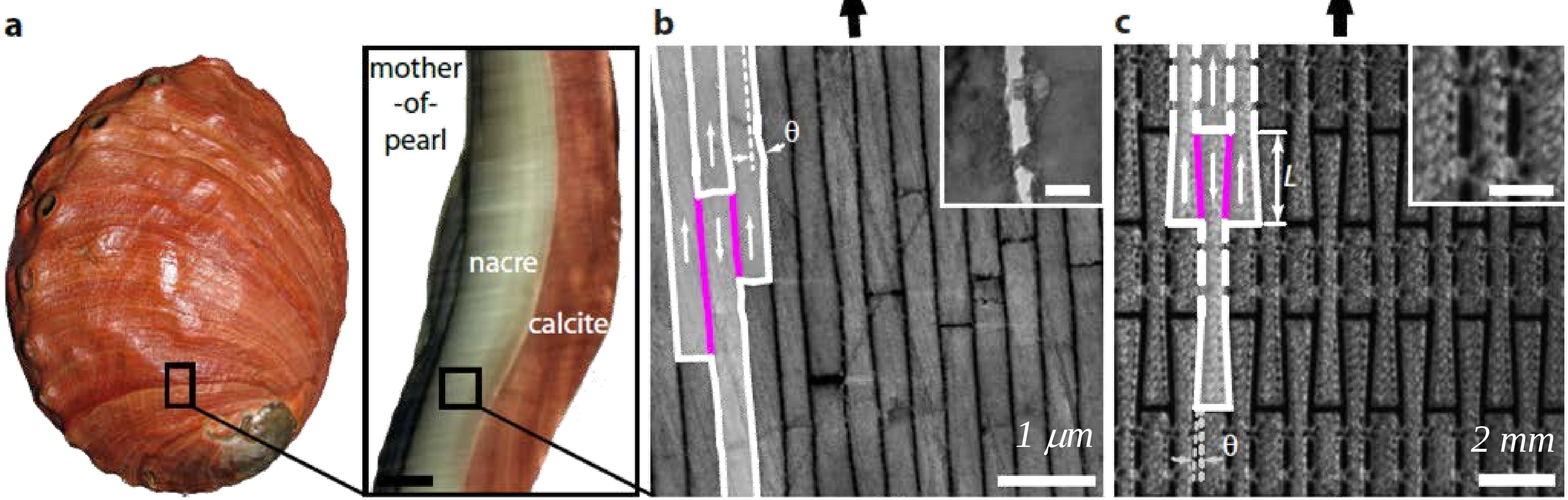
The Waviness generates progressive locking during the sliding of tablets.





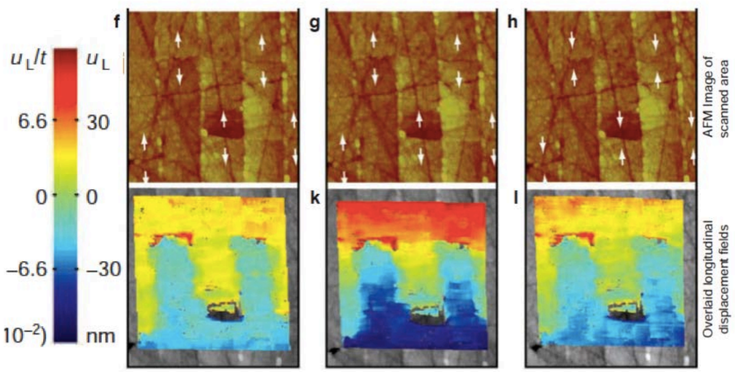
The waviness is implemented from real profilometry data

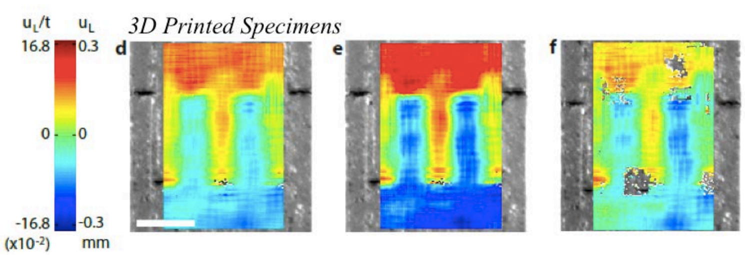
Artificial Nacre



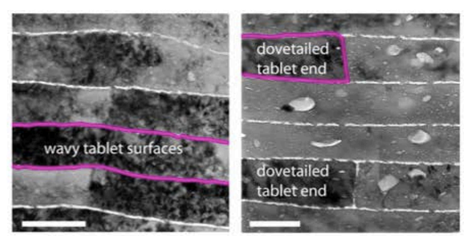
Nacre

Artificial

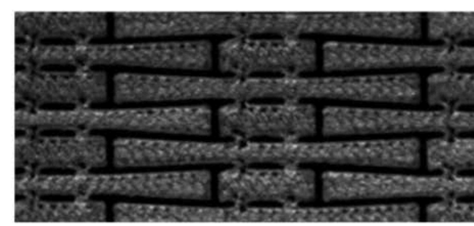




Natural Nacre



Artificial Composite



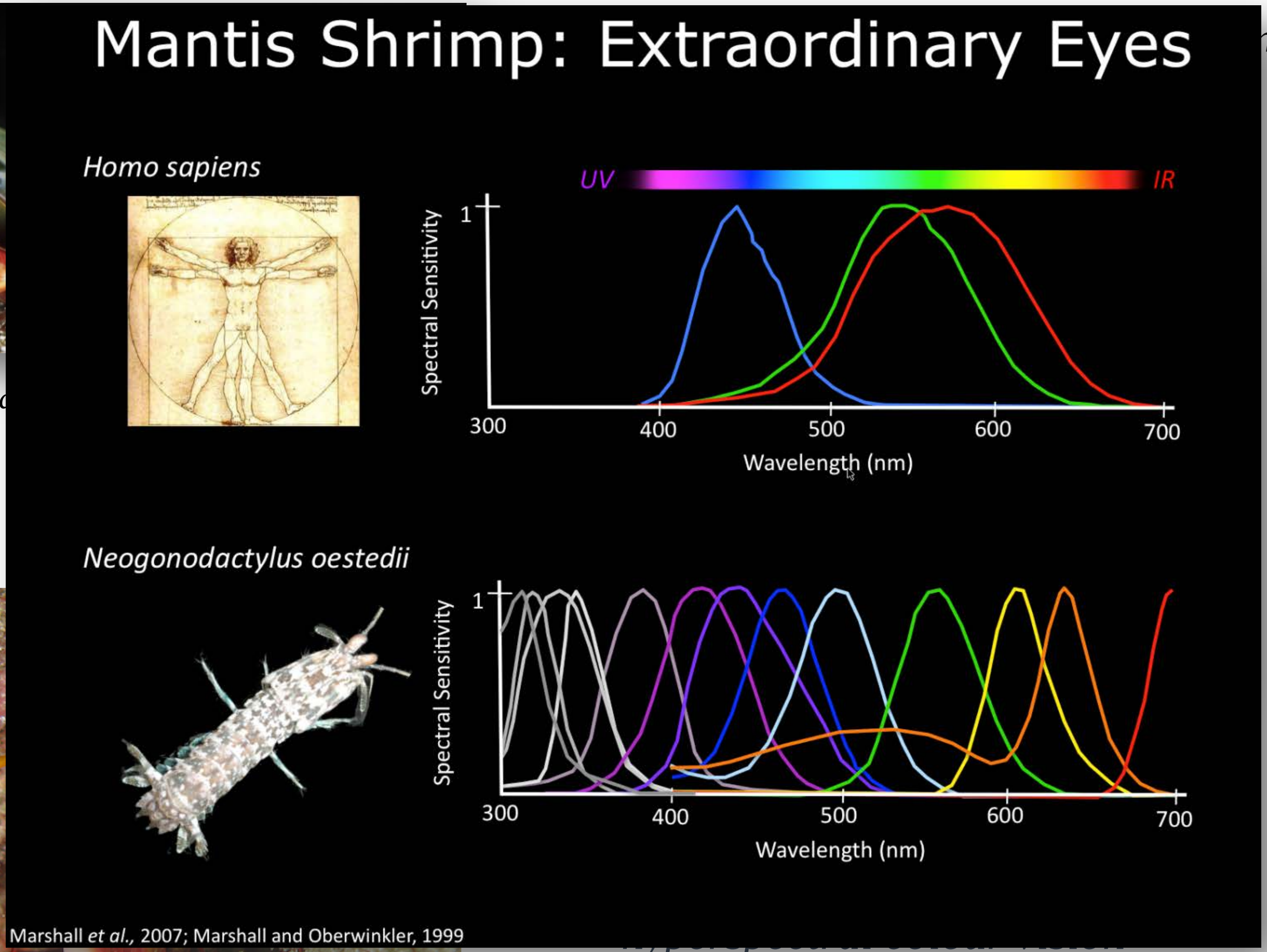
Espinosa., Juster, Latourte, Gregoire, Loh, Zavattieri, ***Nature Communications****, 2011*

Case Study: Impact-Tolerant Biological materials

Stomatopod: Mantis Shrimp

NATIONAL GEOGRAPHIC

Image: Roy Ca



nd not a shrimp)

courtesy of Silke Baron

- trinocular vision and depth perception in each eye

It is bright.

And it is beautiful.

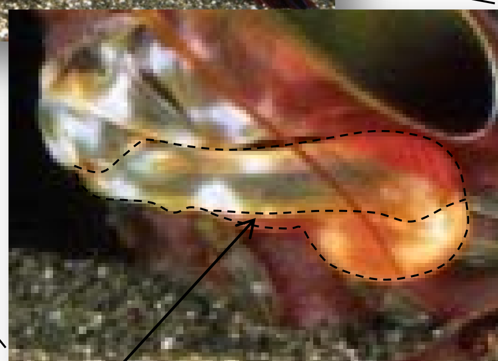
http://theoatmeal.com/comics/mantis_shrimp


BBC

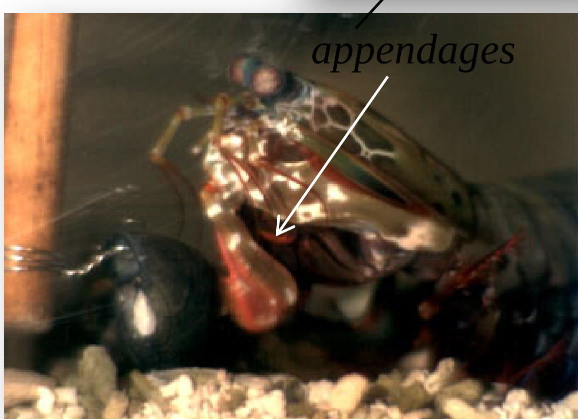
Stomatopod Dactyl Club

PURDUE ENGINEERING
Computational Multi-Scale Materials Modeling Lab

In Collaboration with Dr. David Kisailus, and James Weaver University of California , Riverside

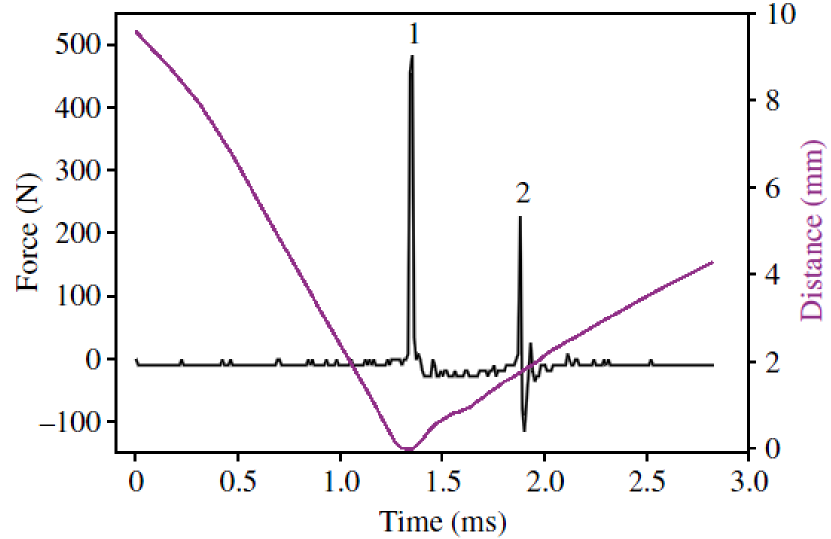


raptorial claws



Sheila Patek, University of Massachusetts

Study of the structure-function relationships in this impact tolerant material

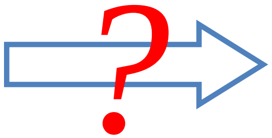


S. N. Patek, R. L. Caldwell, J. Exp. Biol. ***208****, 3655-64 (2005).*

-acceleration of 10,400 g (102,000 m/s^2)
[.22 calibre bullet]

- speeds of 23 m/s

What can certain ***crustaceans*** *teach us about the fabrication of impact-resistant* ***materials****?*

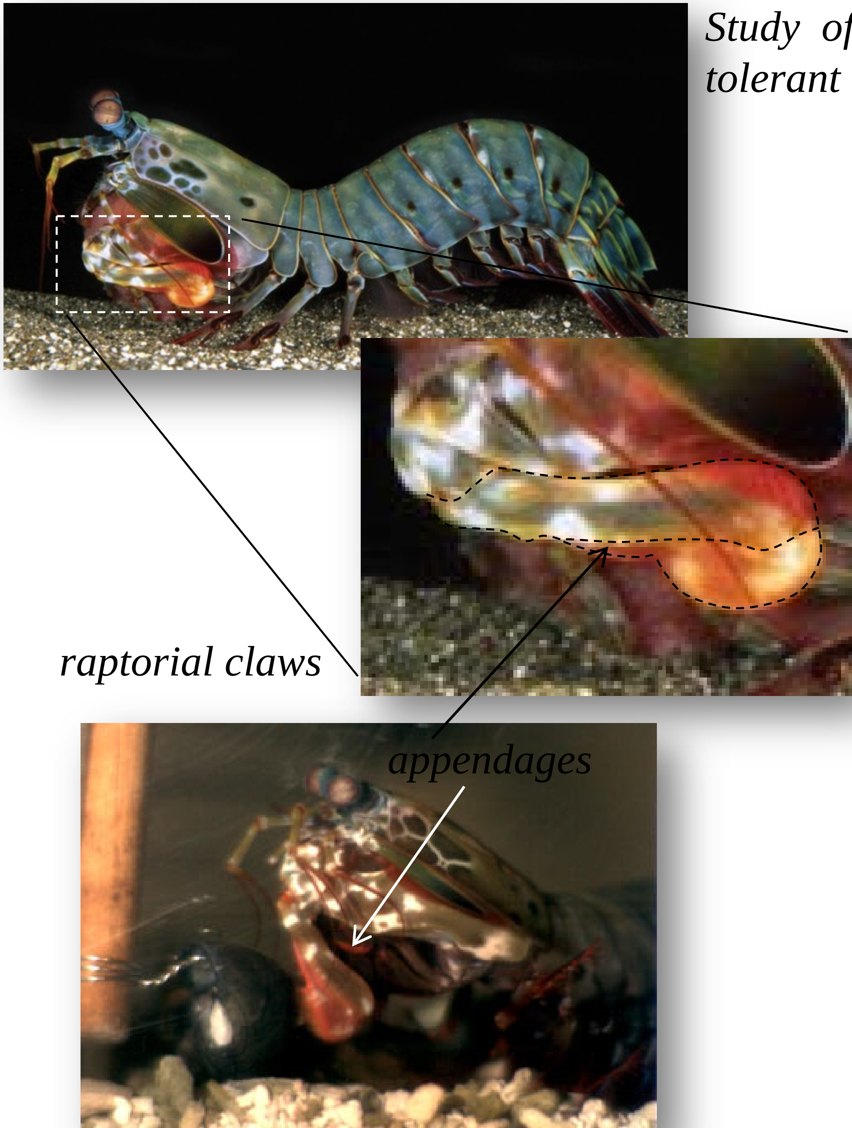


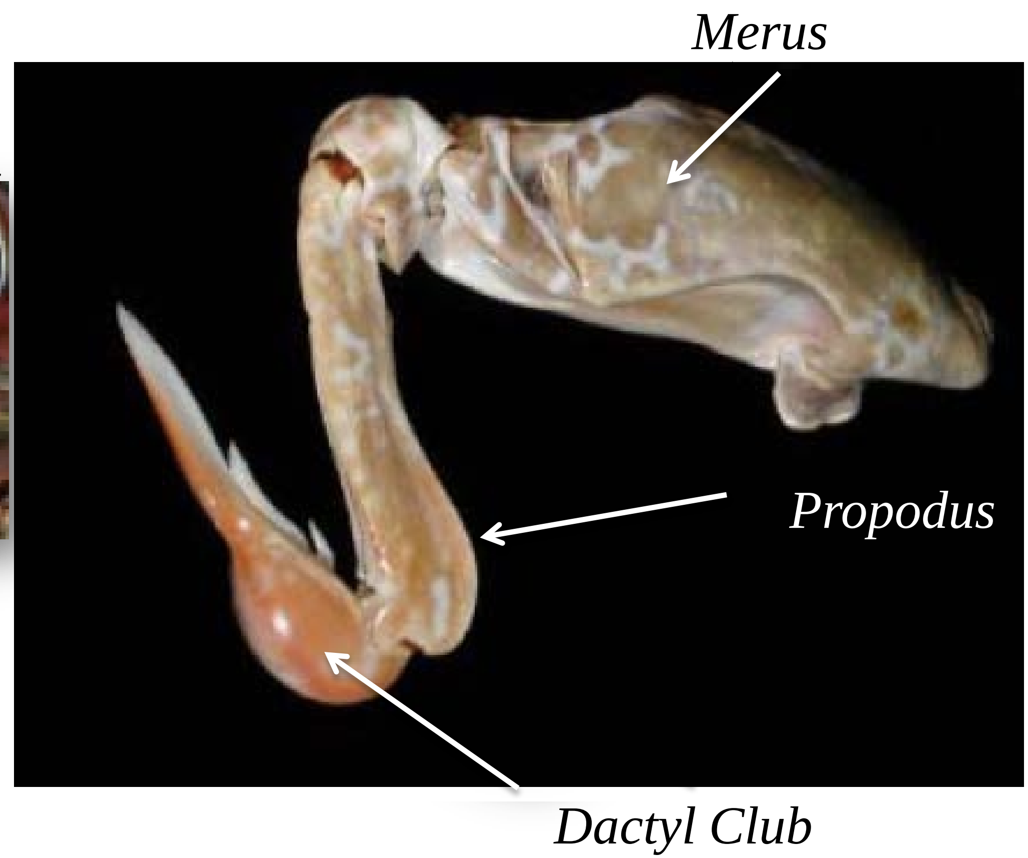
Stomatopod Dactyl Club

In Collaboration with Dr. David Kisailus, University of California , Riverside

Computational Multi-Scale Materials Modeling Lab

Study of the structure-function relationships in this impact tolerant material



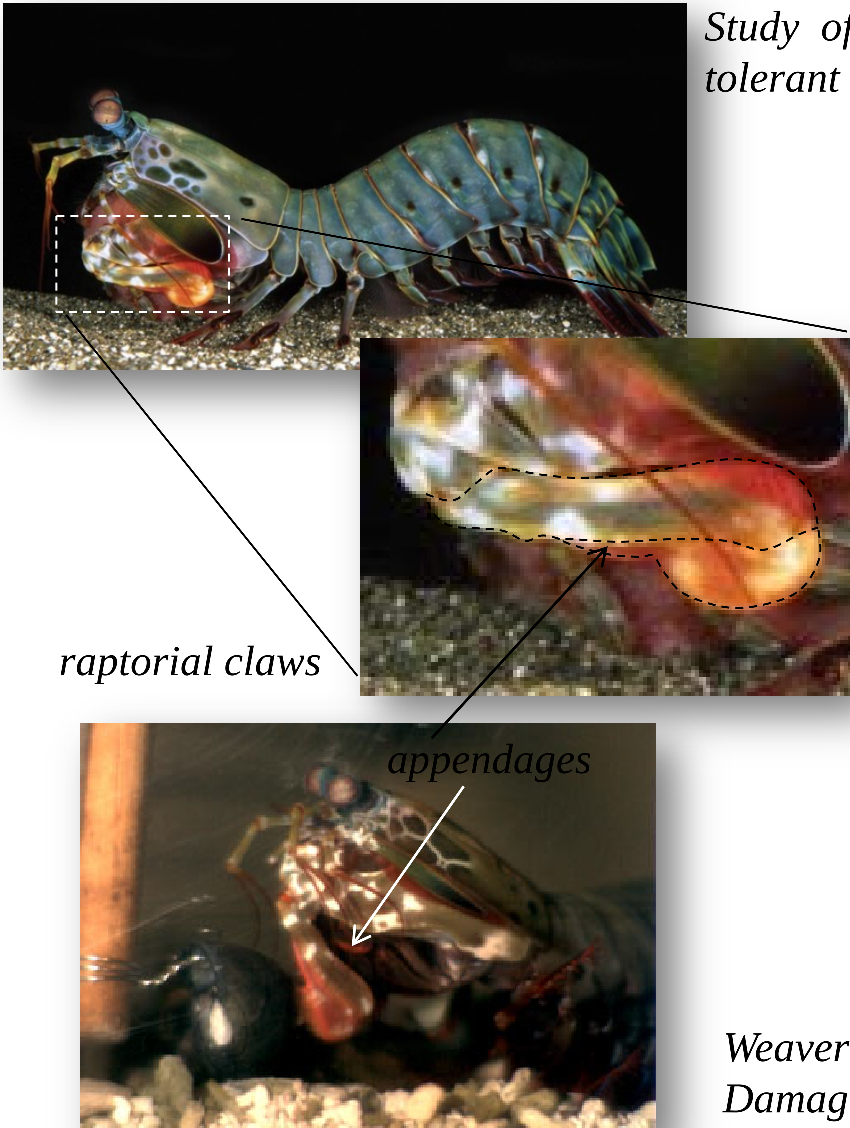


Sheila Patek, University of Massachusetts

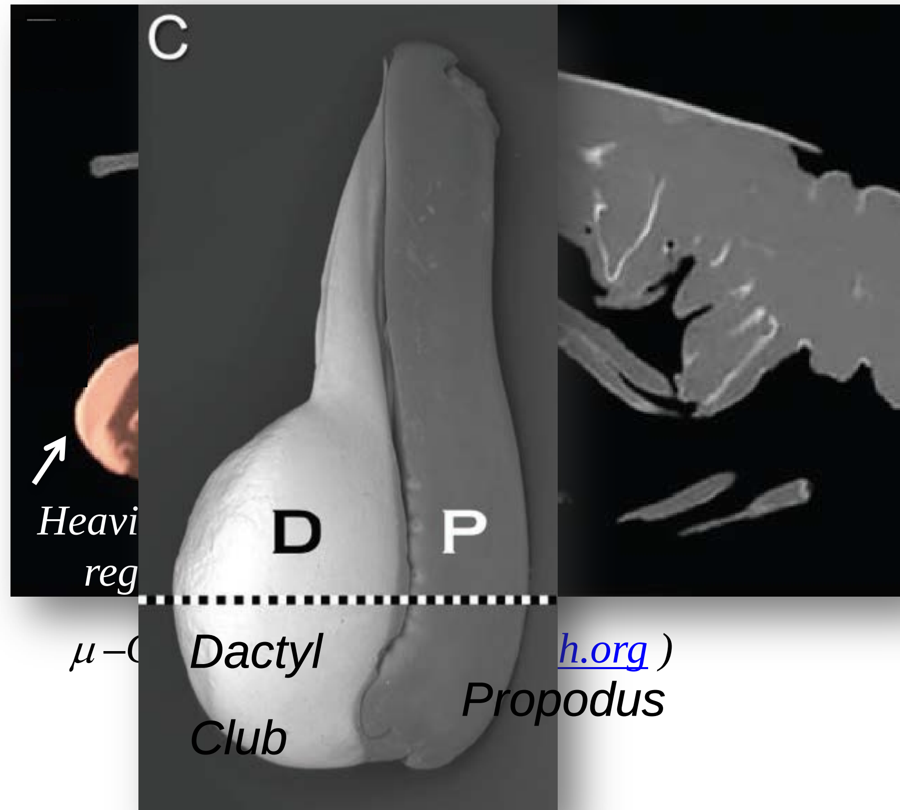
Stomatopod: Dactyl Club

Computational Multi-Scale
Materials Modeling Lab

Study of the structure-function relationships in this impact tolerant material



Sheila Patek, University of Massachusetts



Weaver et al., "The Stomatopod Dactyl Club: A Formidable Damage-Tolerant Biological Hammer," Science, 336 (2012) 1275-1280

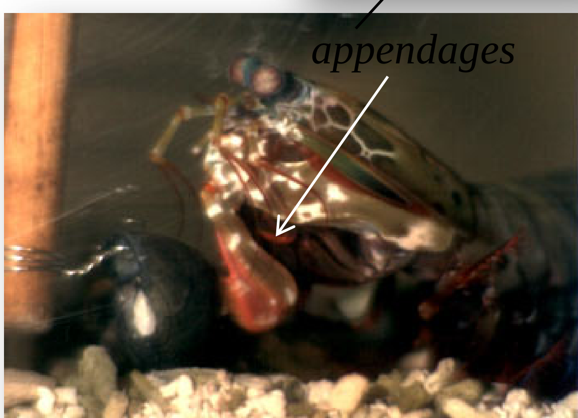
Stomatopod Dactyl Club

In Collaboration with Dr. David Kisailus,
University of California , Riverside

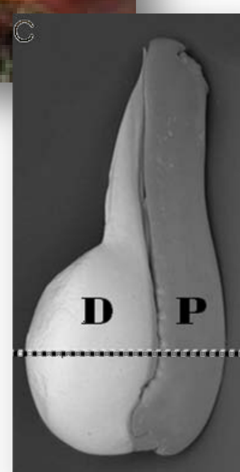
Computational Multi-Scale
Materials Modeling Lab

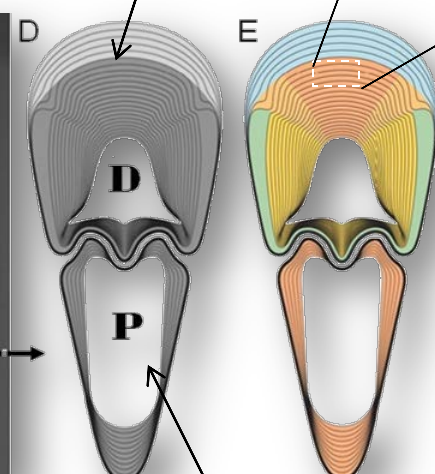
Study of the structure-function relationships in this impact tolerant material

Hydroxylapatite (HAP)
$CaCO_3$
α-Chitin



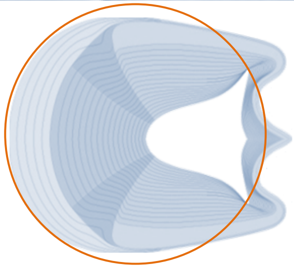
Sheila Patek, University of Massachusetts



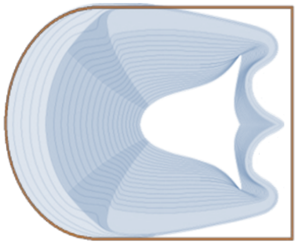


Weaver et al., Science, 336 (2012) 1275-1280

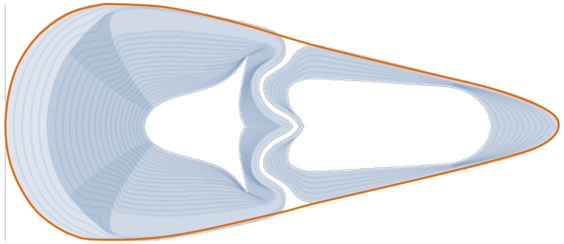
Stomatopod Dactyl Club



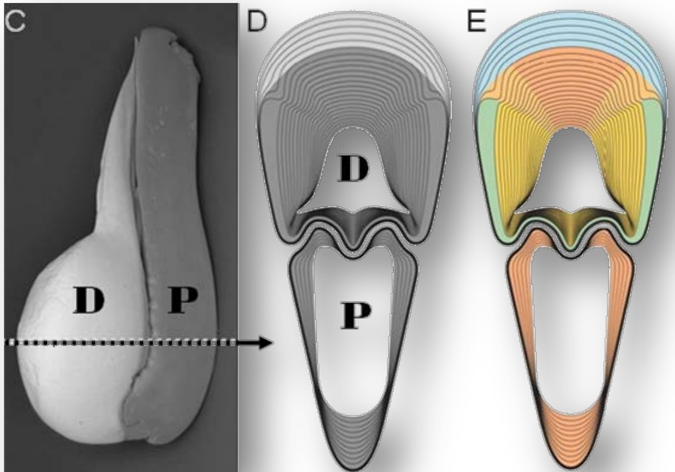
$C_d = 0.3$



$C_d = 0.295$



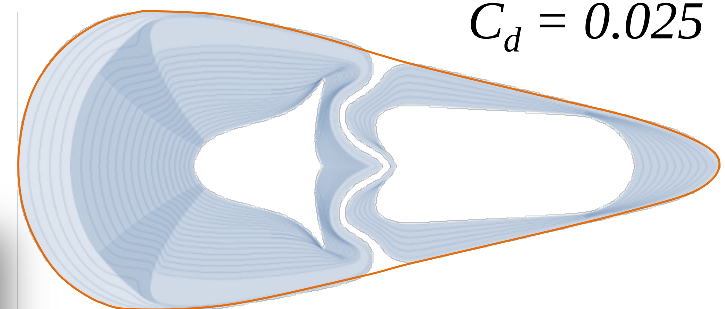
$C_d = 0.025$



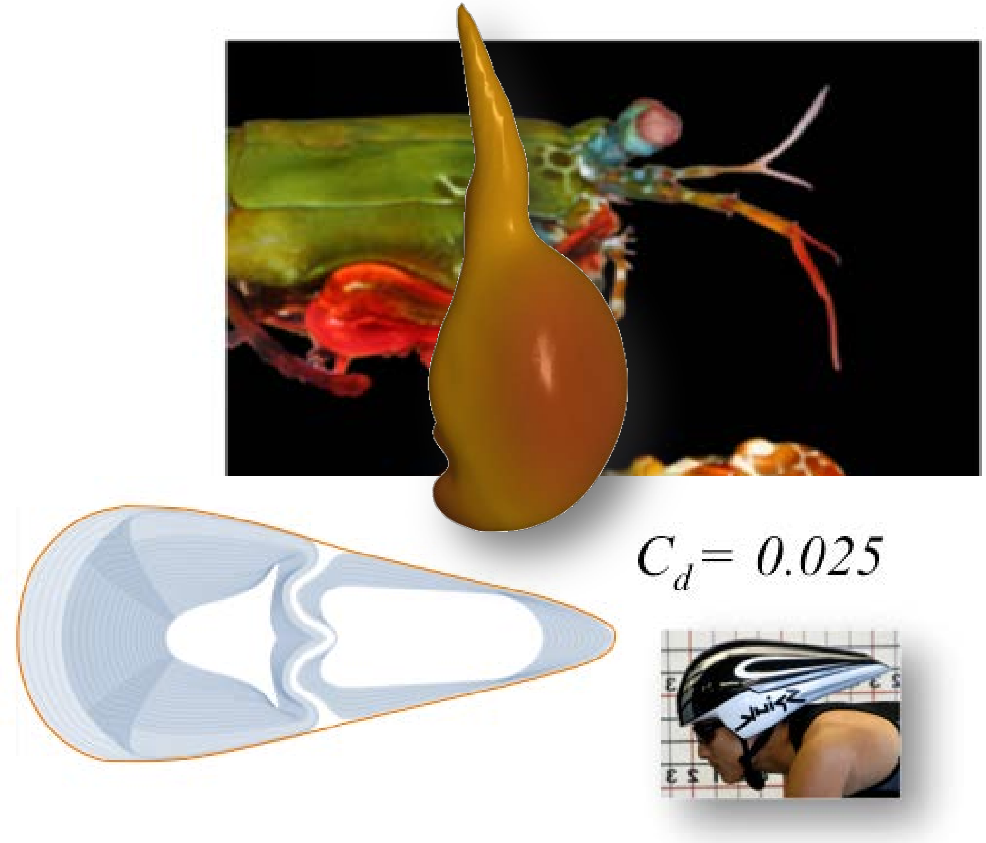
Grunenfelder,. Milliron, Herrera, Gallana, Suksangpanya, Yaraghi, Hughes,. Evans-Ludderodt, P. Zavattieri, D. Kisailus, to be submitted

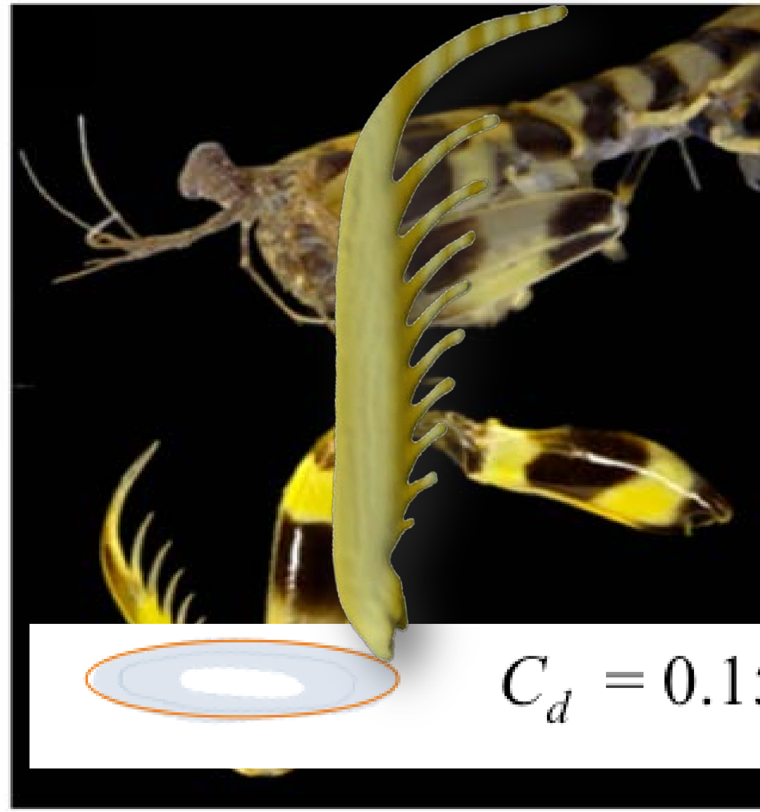
Stomatopod Dactyl Club

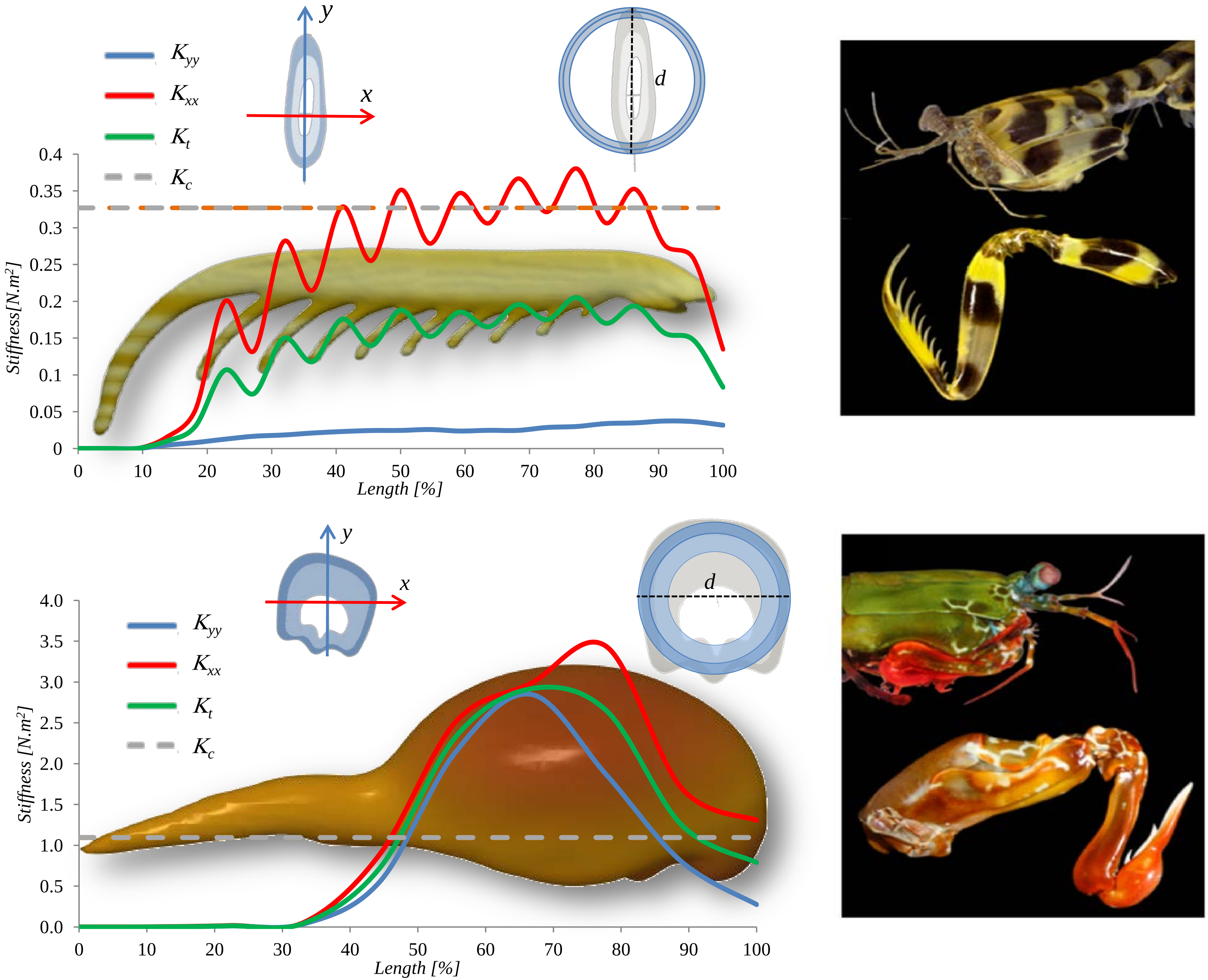
$C_d = 0.025$



$C_d = 0.028$


$C_d = 0.025$


$C_d = 0.15$

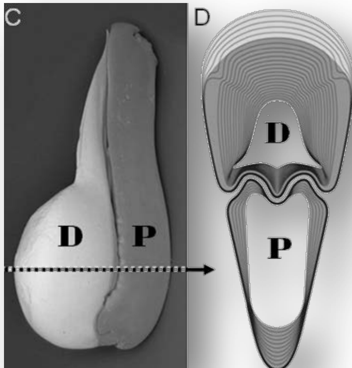


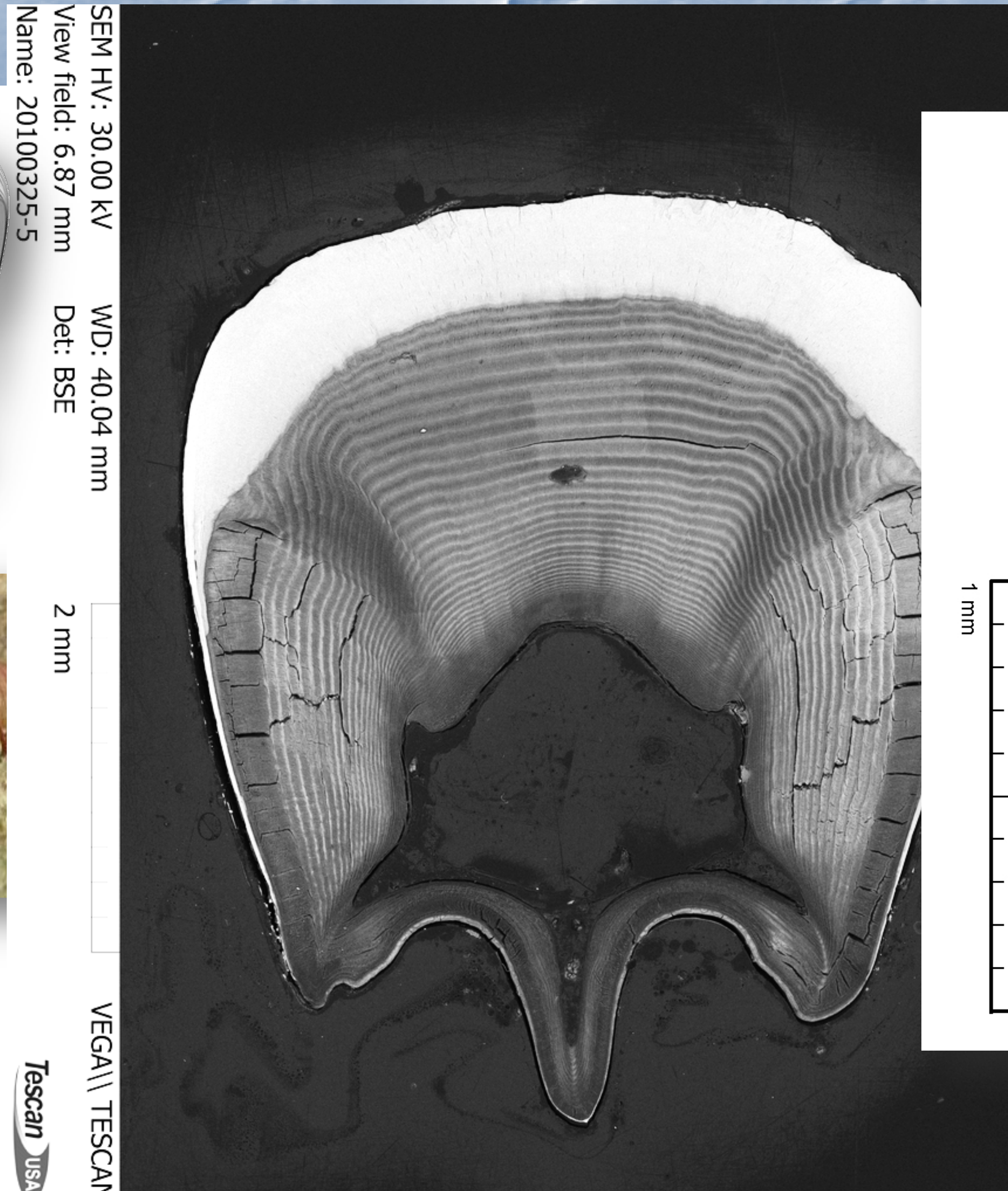
K_{yy}
K_{xx}
K_t
K_c
y
x
d
Stiffness[N.m²]
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0 10 20 30 40 50 60 70 80 90 100
Length [%]
K_{yy}
K_{xx}
K_t
K_c
y
x
d
Stiffness [N.m²]
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0 10 20 30 40 50 60 70 80 90 100
Length [%]

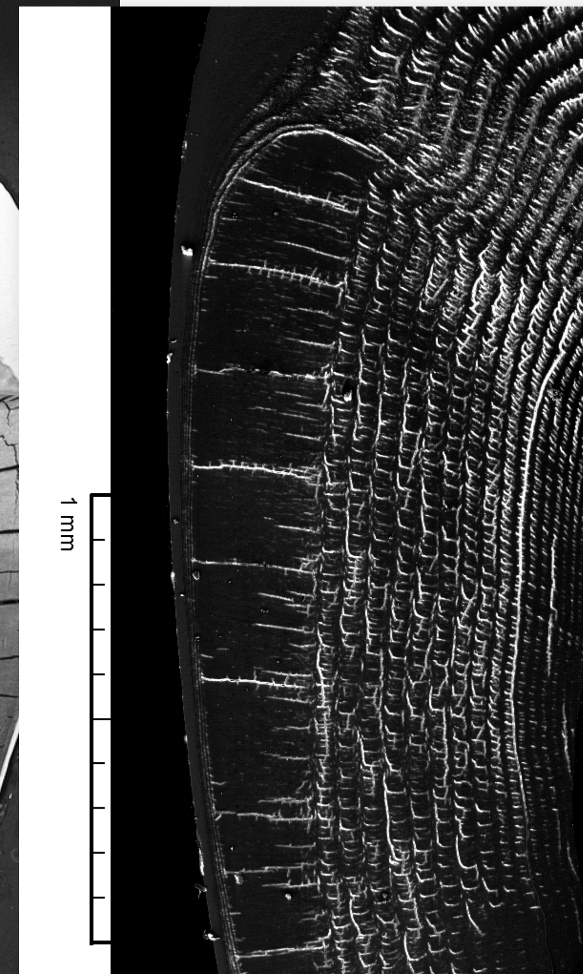
Dactyl Club: Ultrastructural Analysis

PURDUE ENGINEERING

Computational Multi-Scale Materials Modeling Lab







Post sonication back scattered electron micrograph.

Weaver, Milliron, Miserez, … Gallana, Zavattieri, DiMasi, and Kisailus, ***Science, 2012***

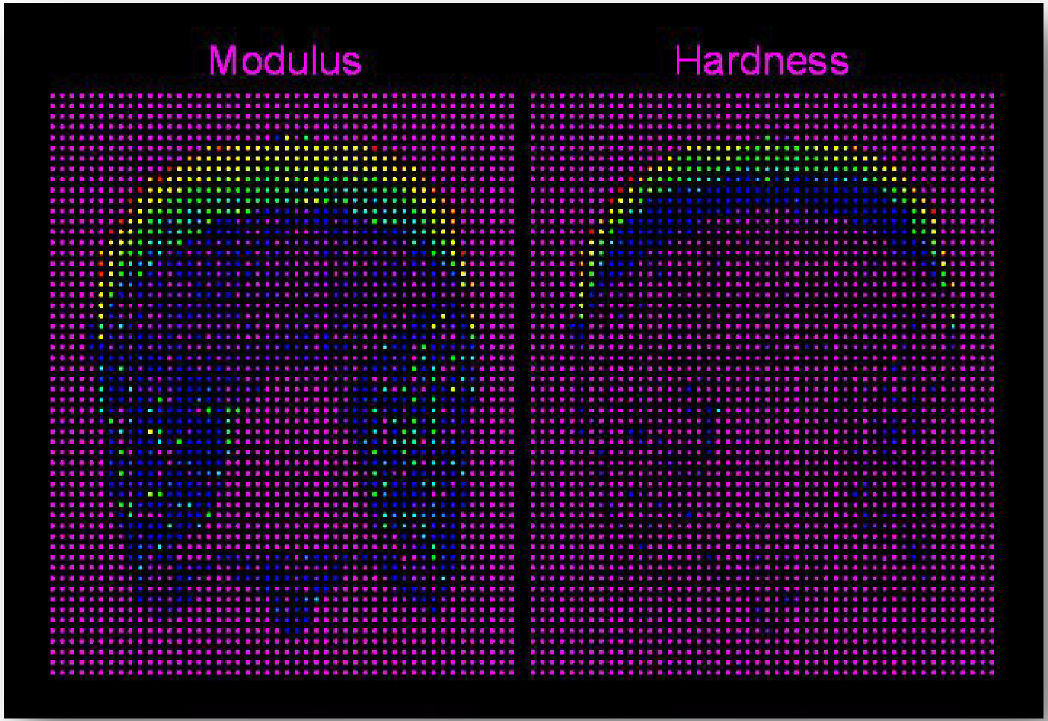
Dynamic modeling of impact

Target: Shell/Crab

Impact Region

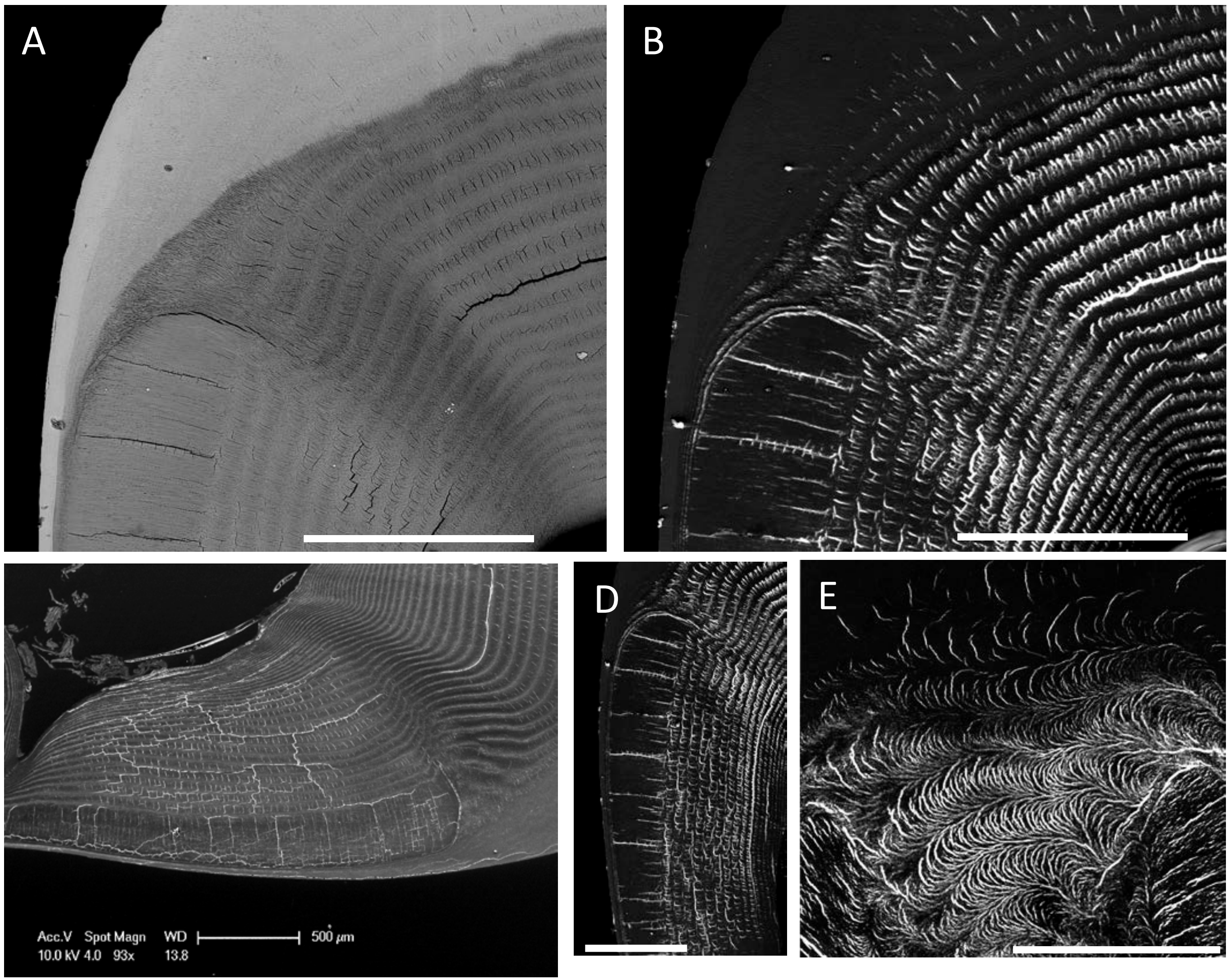
Periodic Region

Striated Region

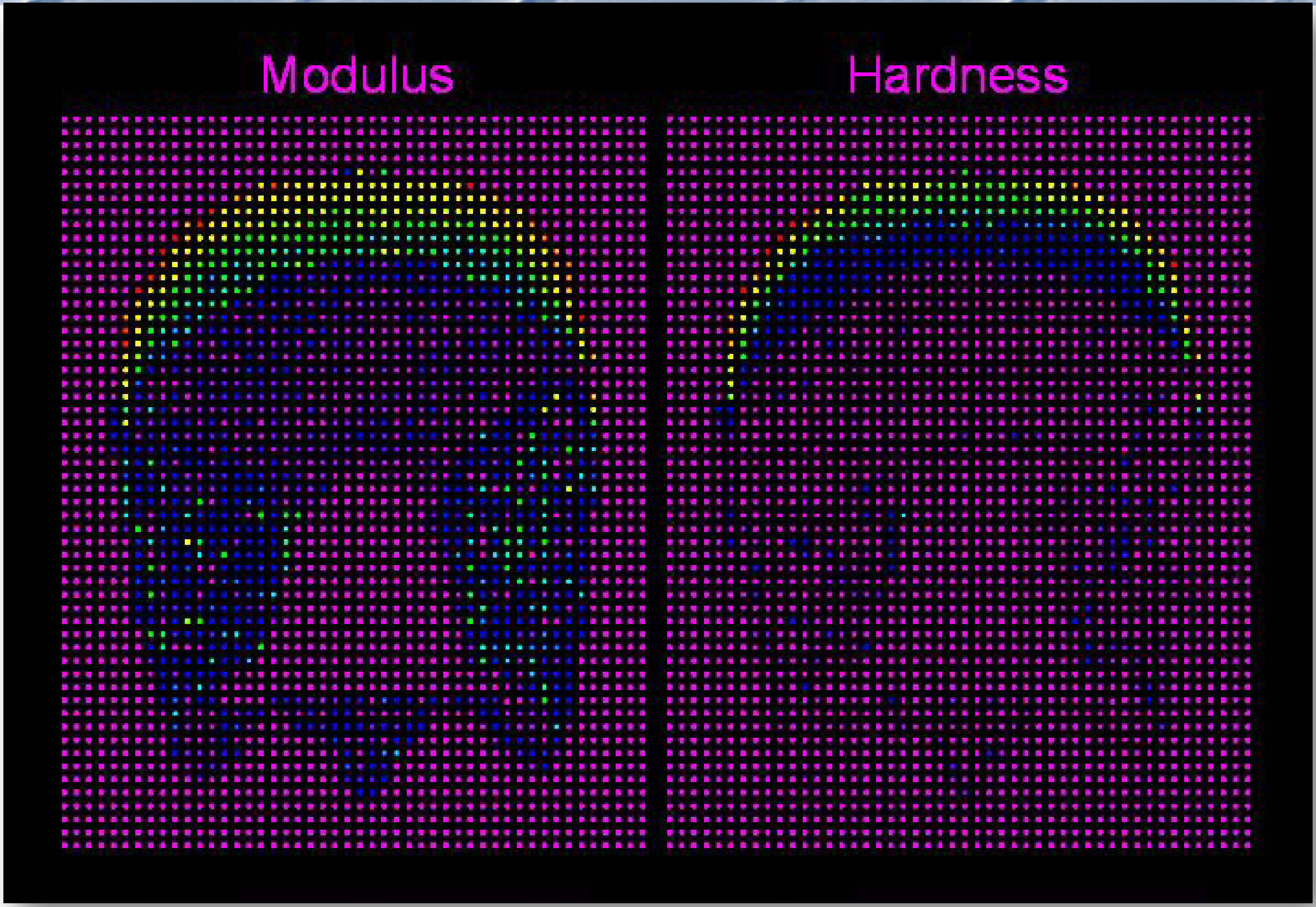


Ultra-toughening From Controlled Fracture

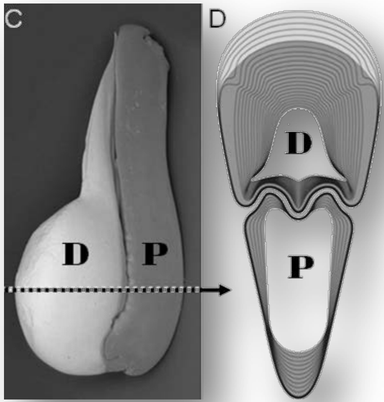
All scale bars are 500 microns

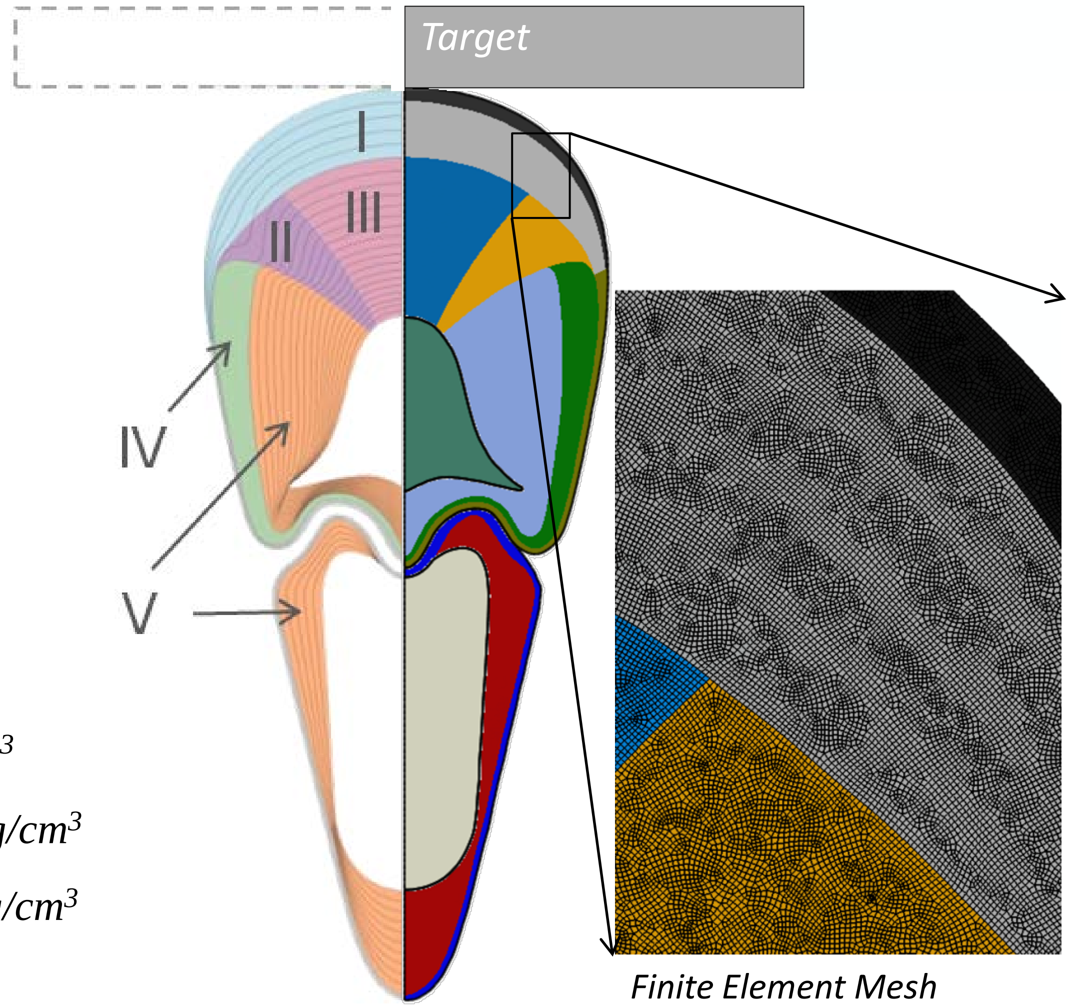


Micromechanical Characterization



Stomatopod Dactyl Club





Finite Element Mesh

Young's Modulus

$E_I = 40\text{-}70$ Gpa, $\rho = 3.16\ g/cm^3$

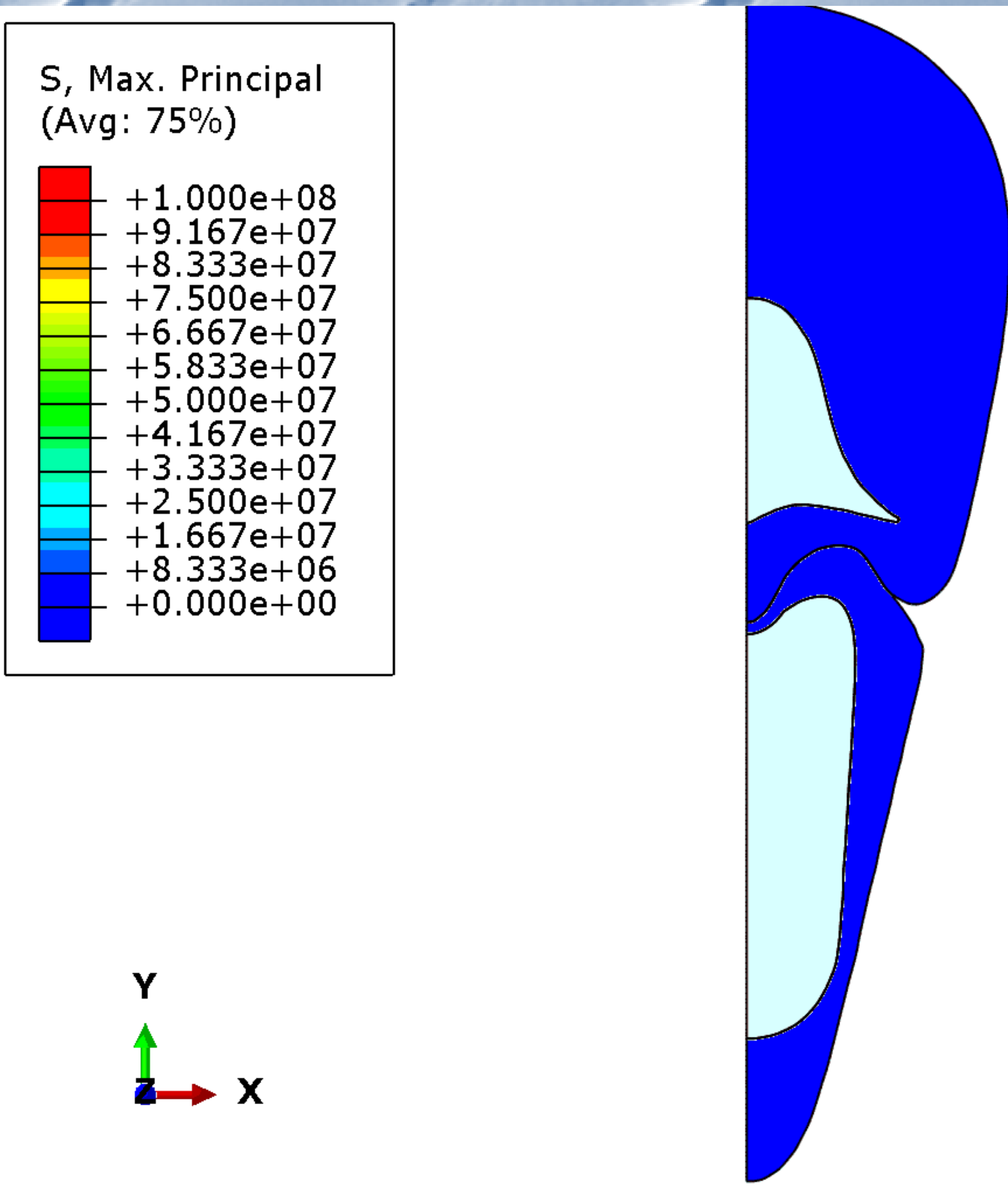
$E_{II} = E_{III} = 15$ GPa, $\rho = 2.50\ g/cm^3$

$E_{IV} = E_V = 25$ GPa. $\rho = 2.50\ g/cm^3$

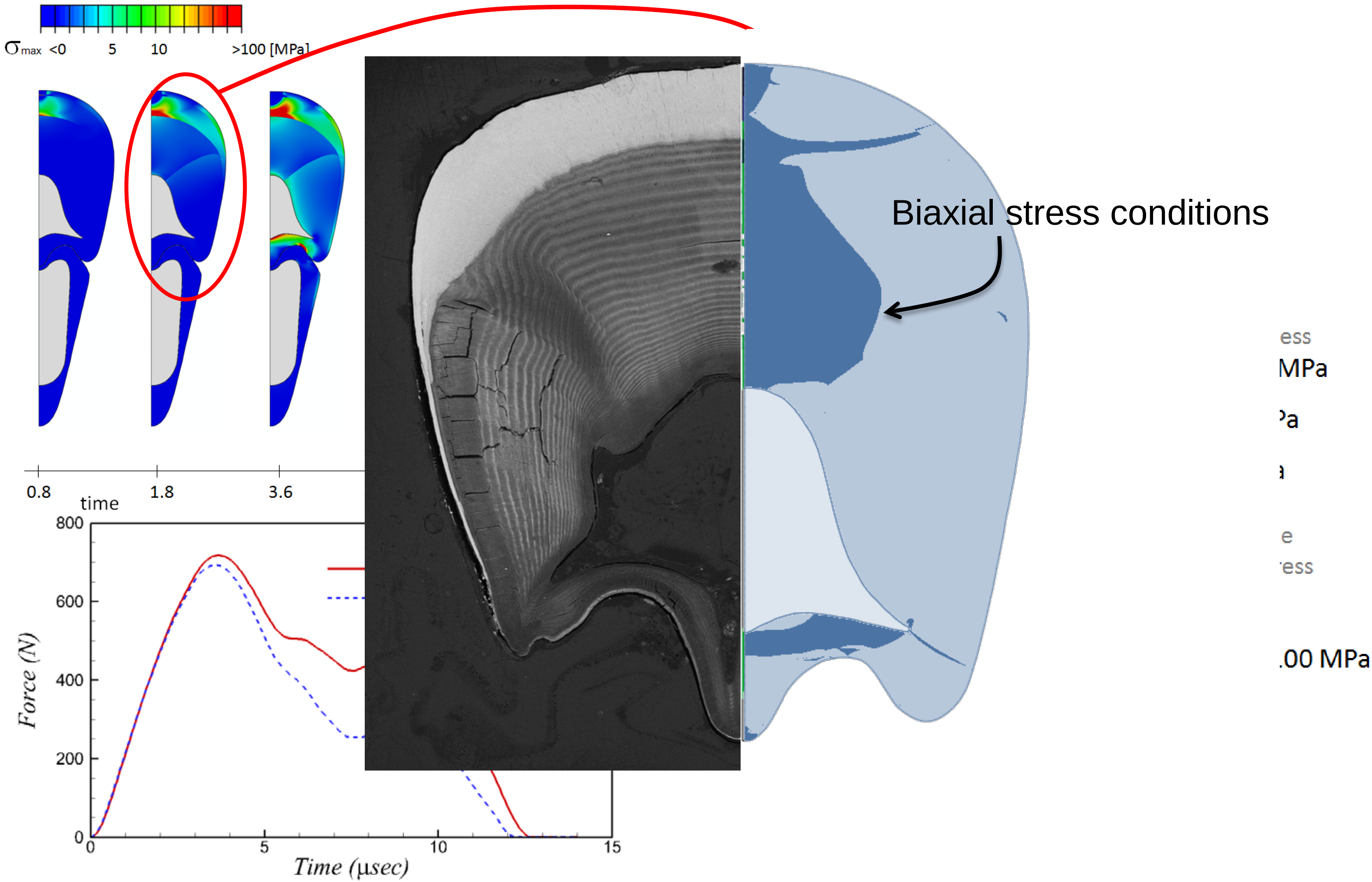
(based on nanoindentation and X-ray measurements)

Weaver, Milliron, Miserez, … Gallana, Zavattieri, DiMasi, and Kisailus, ***Science, 2012***

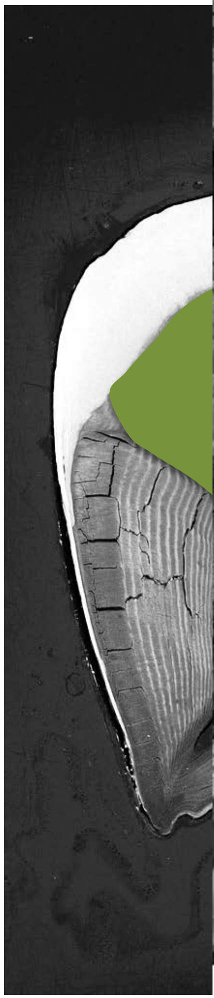
Stomatopod Dactyl Club:DFEA

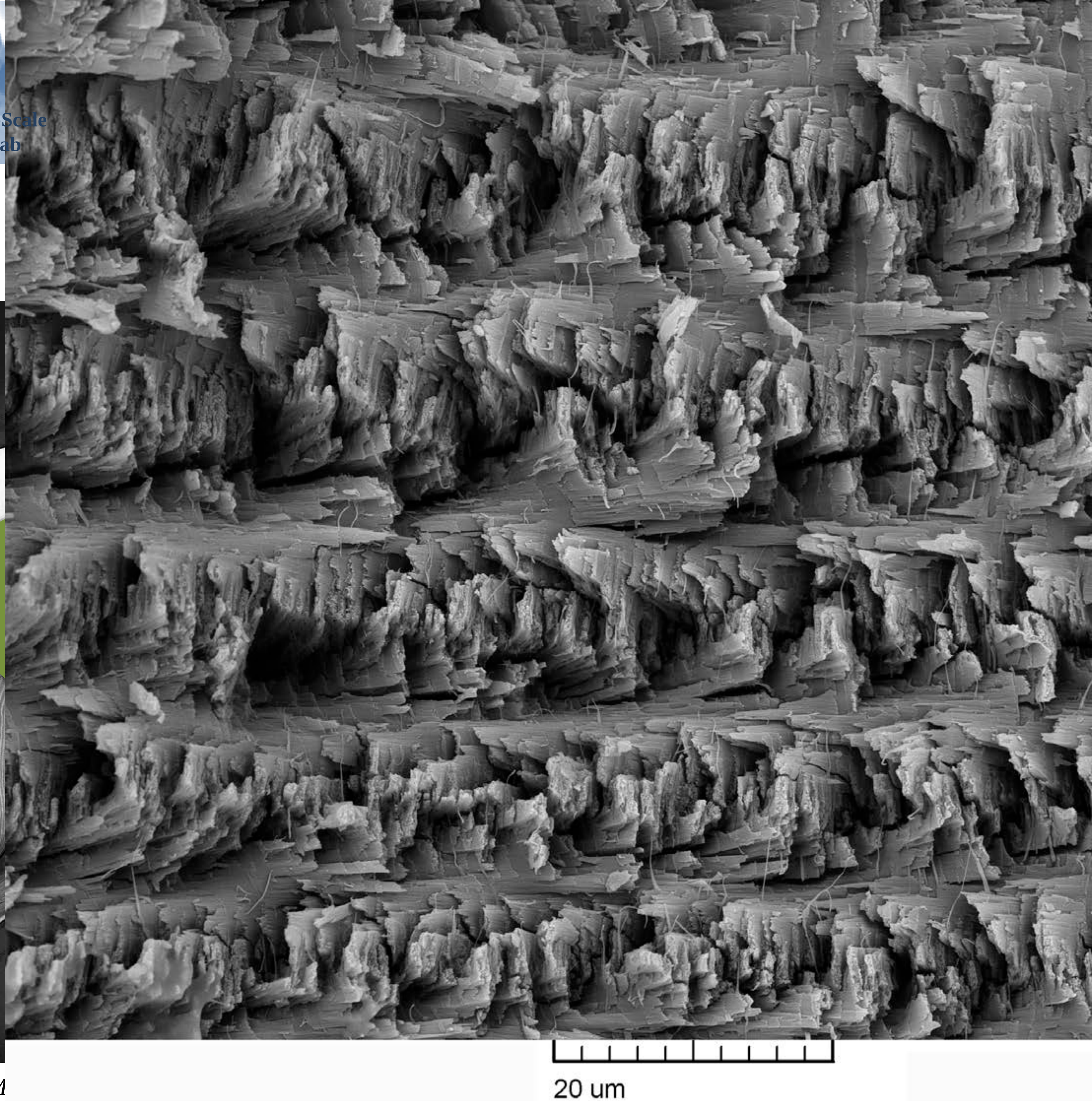


Stomatopod Dactyl Club



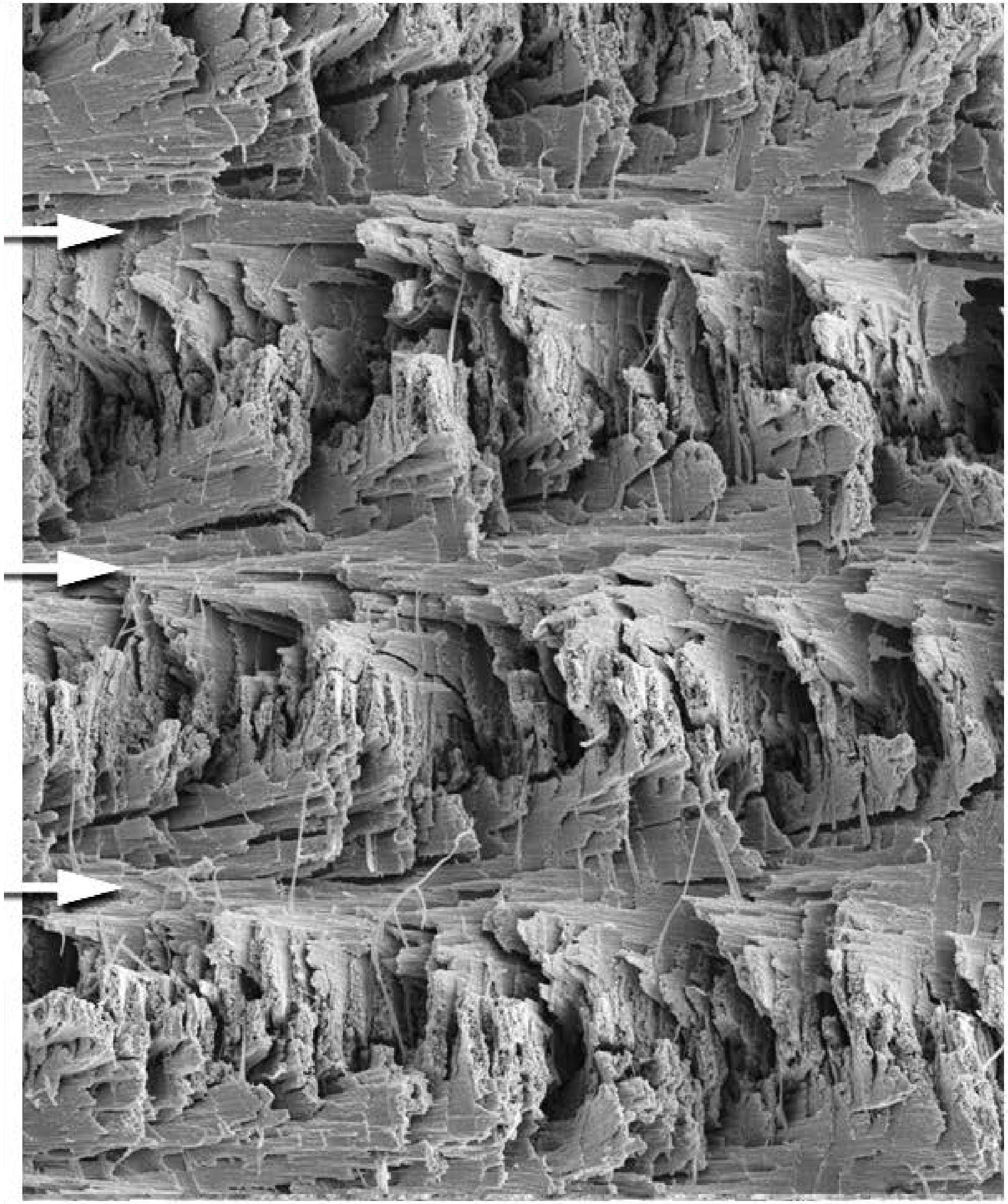
ion



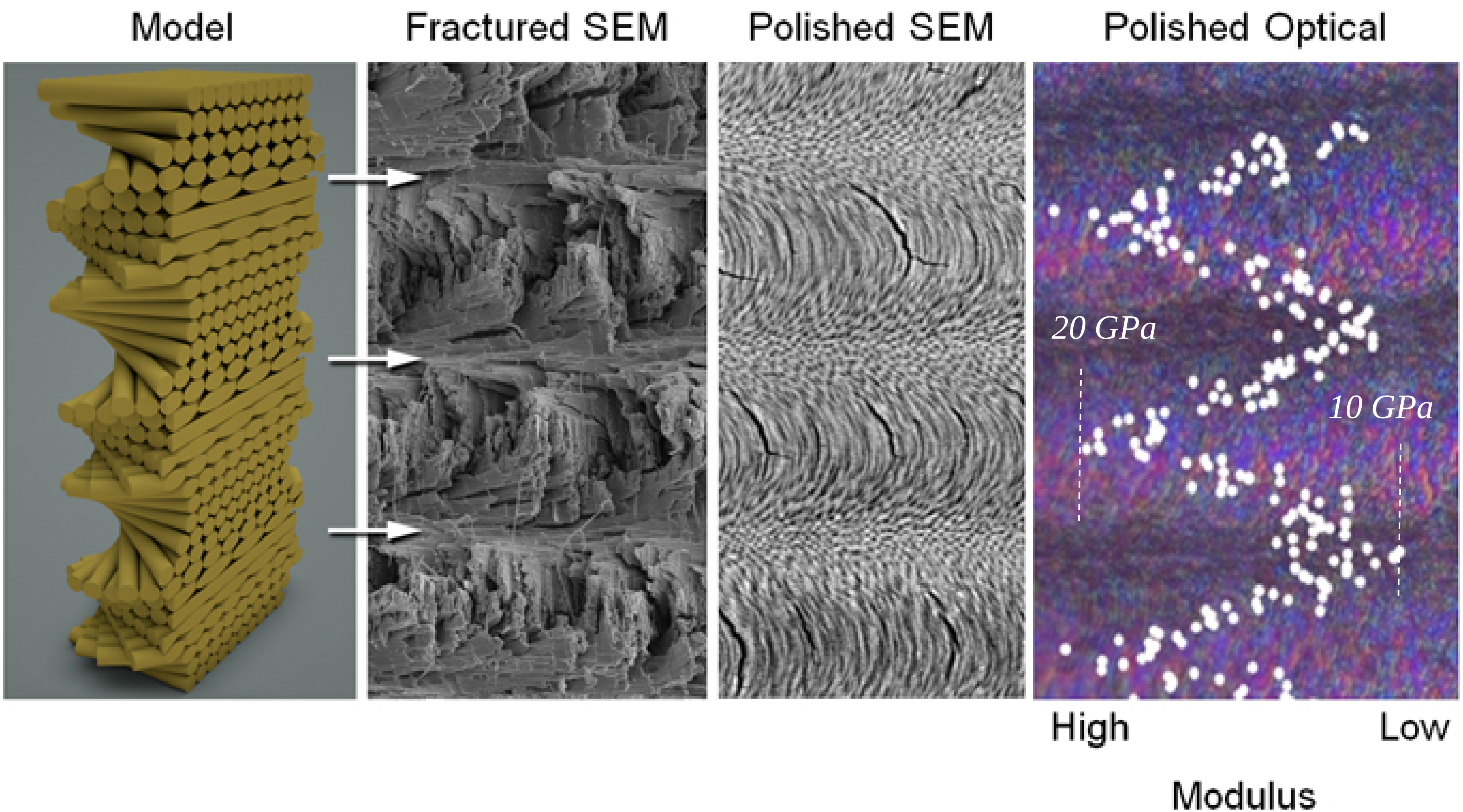


Weaver, Milliron, M

Ultrastructural Analysis – Periodic region



Stomatopod Dactyl Club



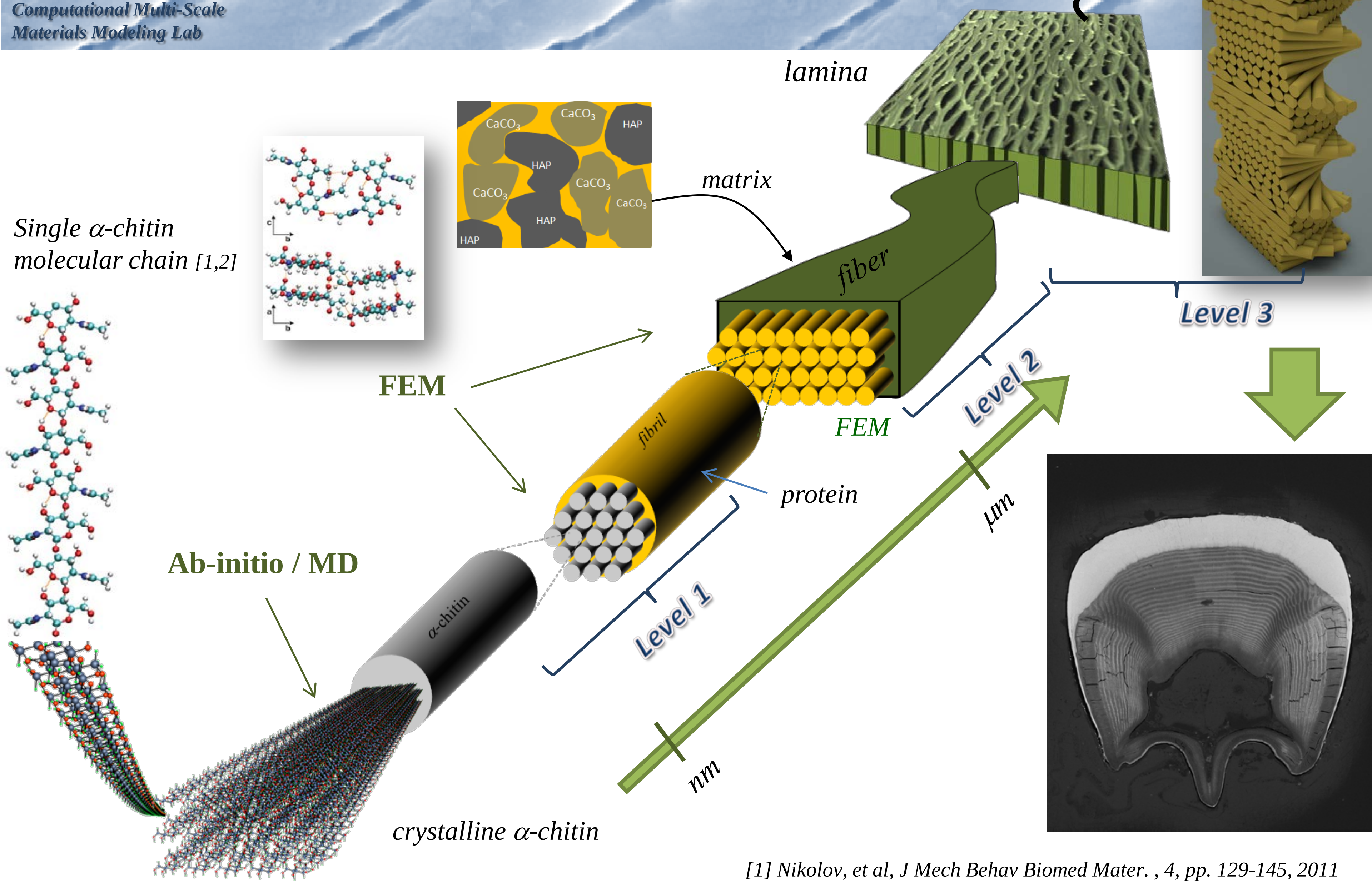
Nanoidentation measurements

Weaver, Milliron, Miserez, … Gallana, Zavattieri, DiMasi, and Kisailus, ***Science, 2012***

Hierarchical Structure

PURDUE ENGINEERING

Computational Multi-Scale Materials Modeling Lab

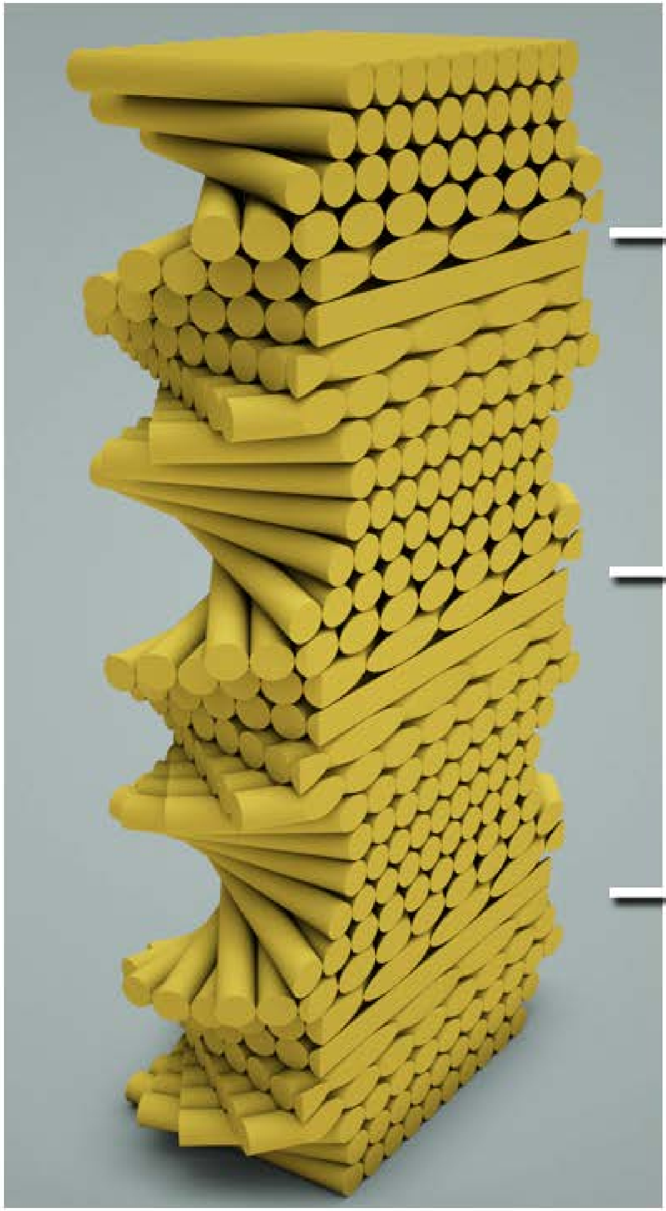


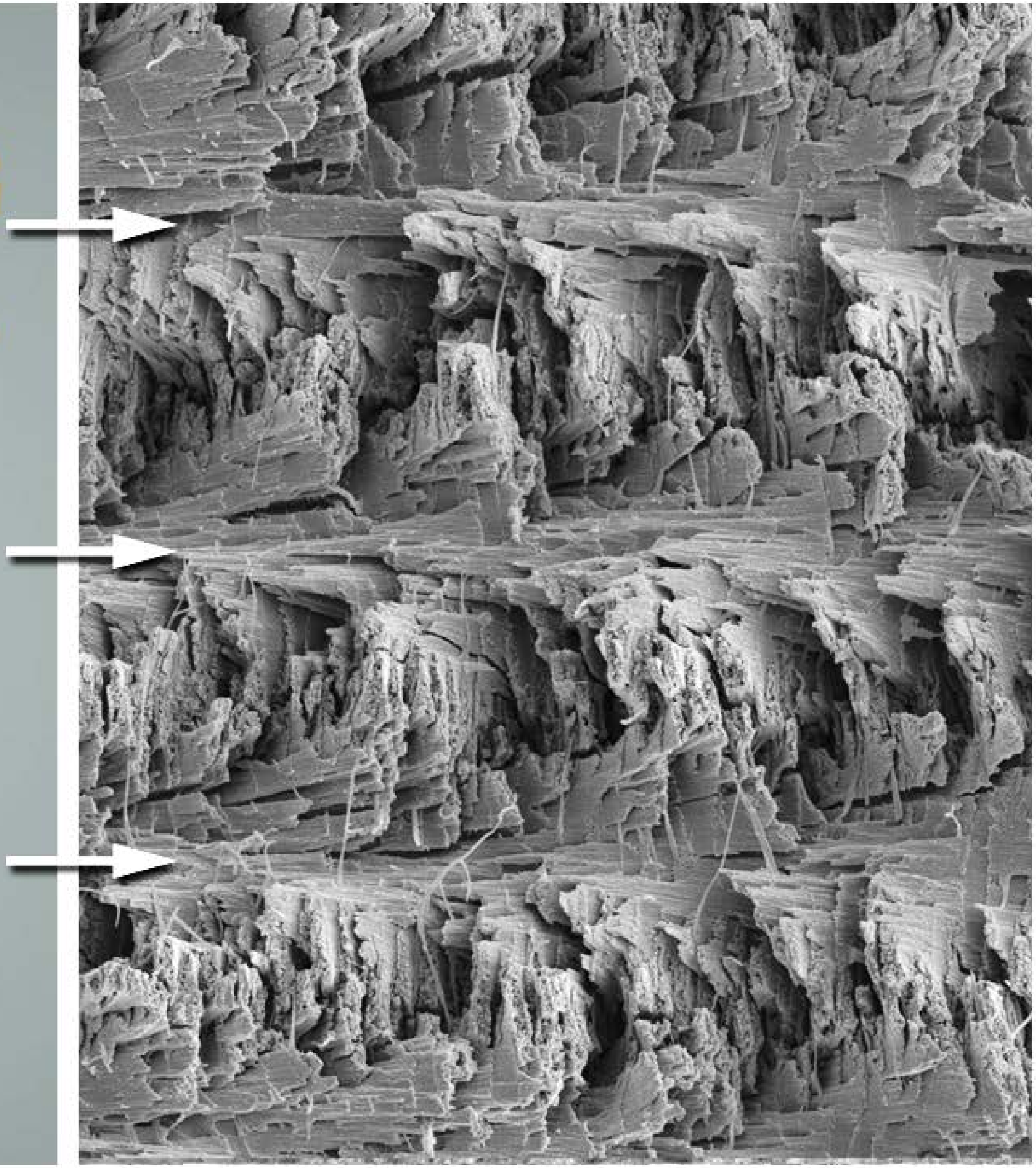
[1] Nikolov, et al, J Mech Behav Biomed Mater. , 4, pp. 129-145, 2011

[2] Nikolov, et al, Adv. Mater, 22, pp. 519-526, 2010.

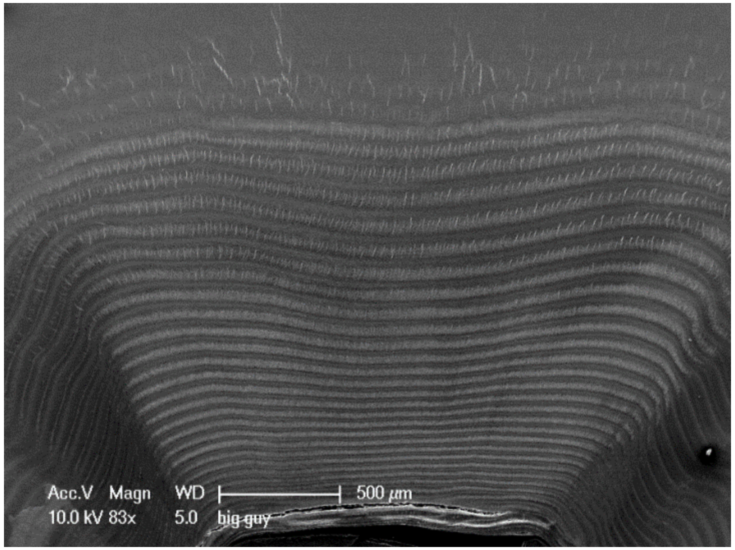
Isaias Gallana

Ultrastructural Analysis – Periodic region

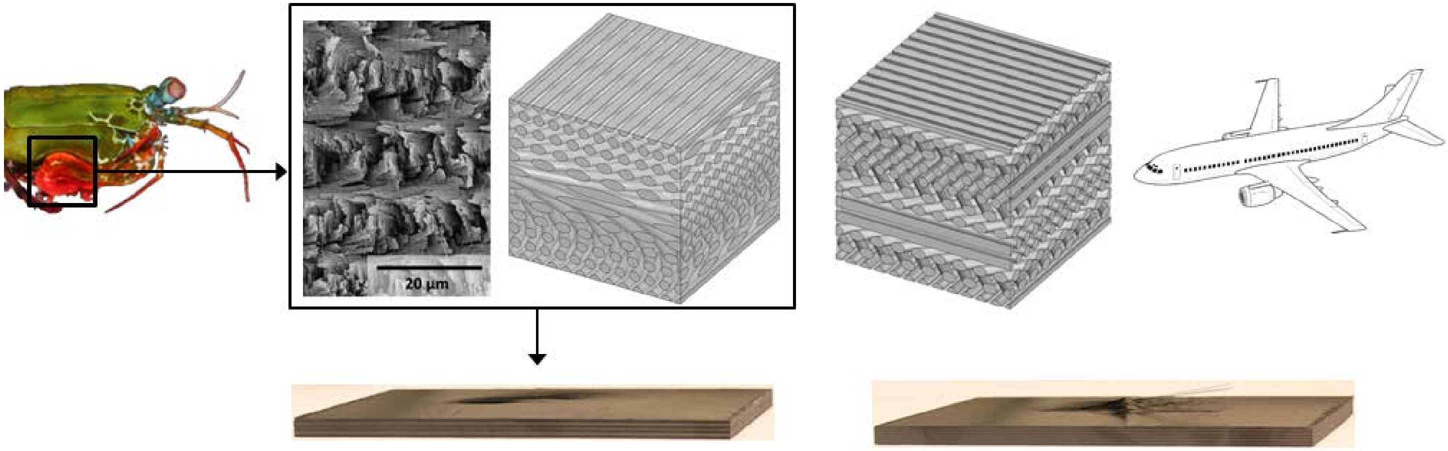




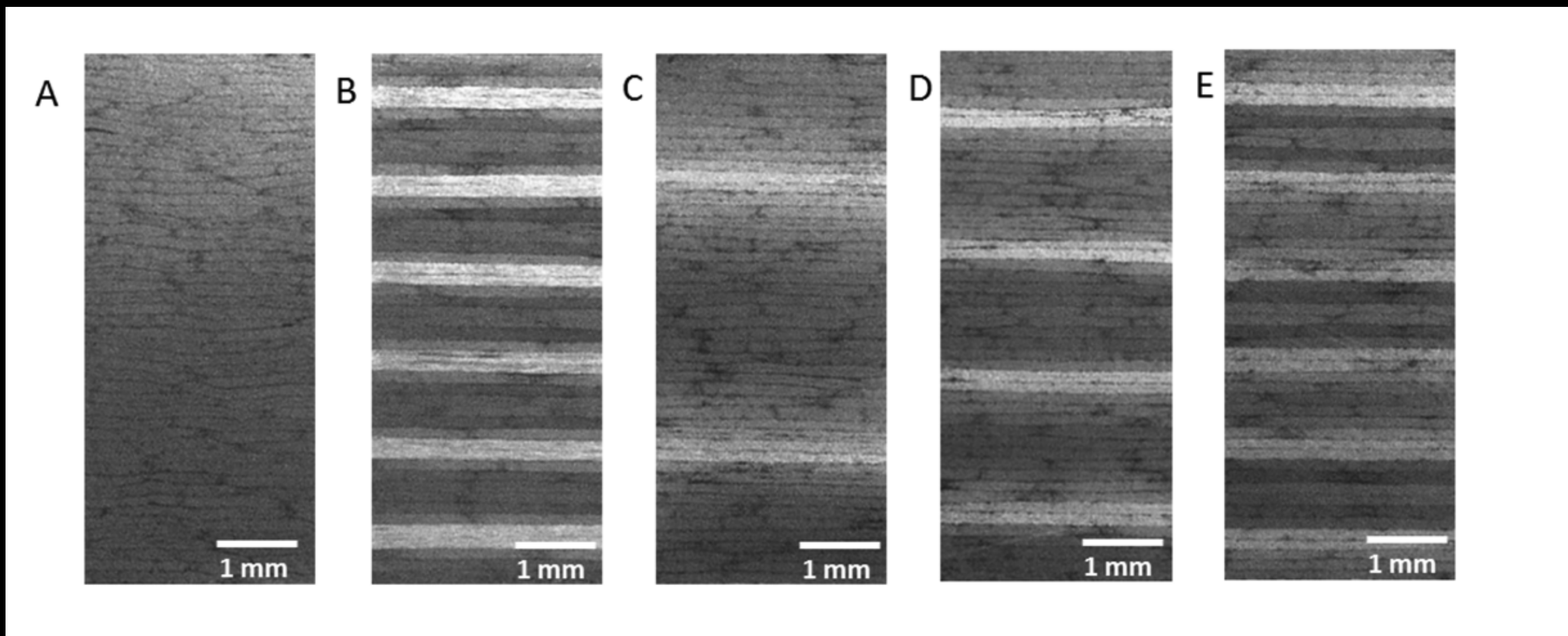
Stomatopod club: Periodic region

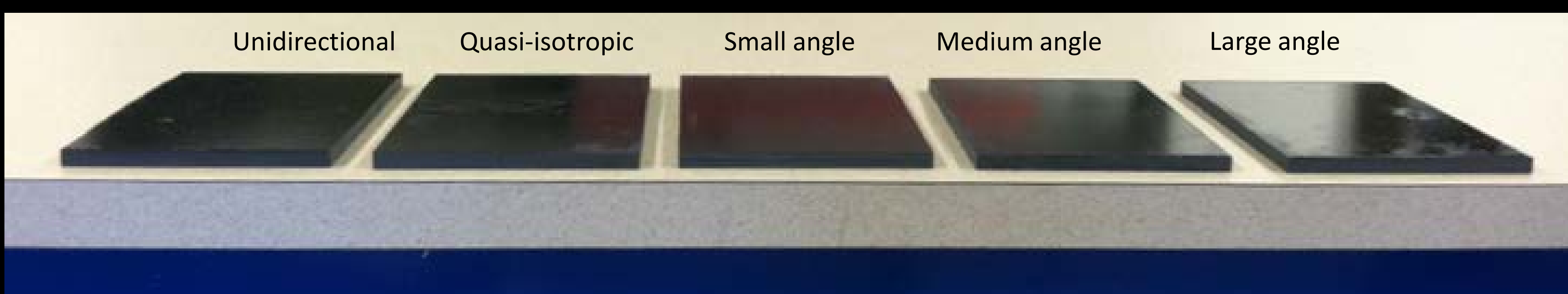


Composite mimic

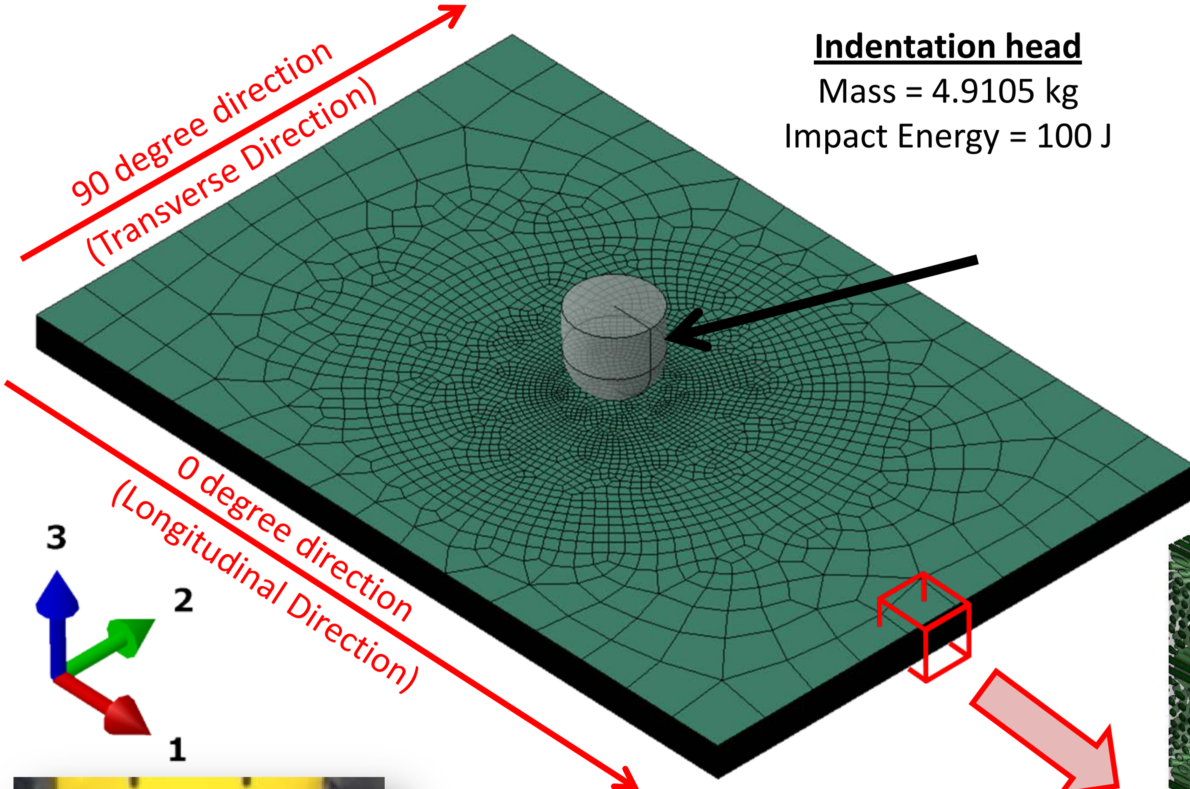


L.K. Grunenfelder, N. Suksangpanya, C. Salinas, G. Milliron, N. Yaraghi, S. Herrera, K. Evans-Lutterodt, S.R. Nutt, P. Zavattieri, D. Kisailus,"Bio-Inspired Impact Resistant Composites", **Acta Biomaterialia, 2014.**


A
B
C
D
E
1 mm
1 mm
1 mm
1 mm
1 mm

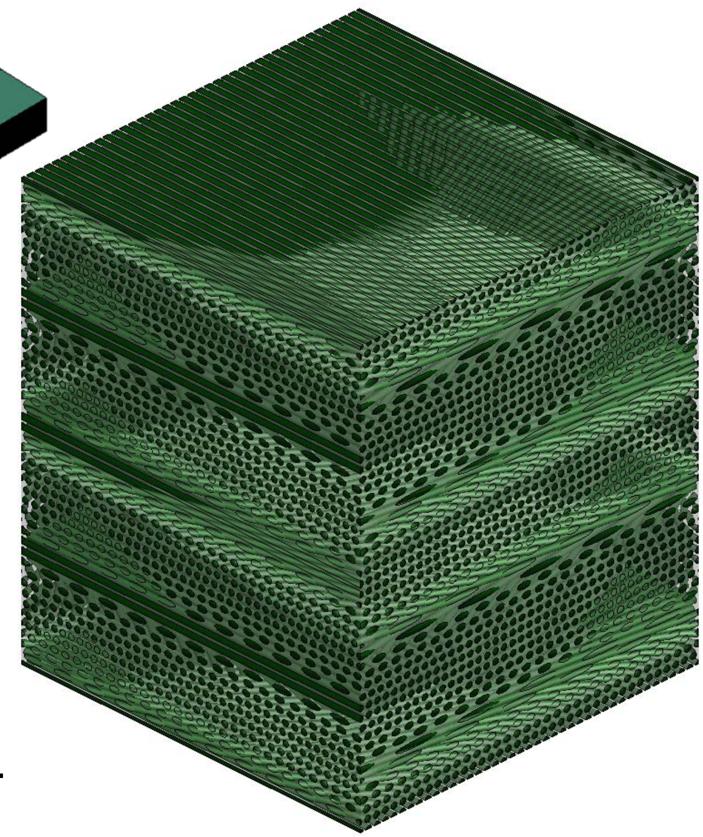

Unidirectional
Quasi-isotropic
Small angle
Medium angle
Large angle

DROP TOWER TEST MODEL



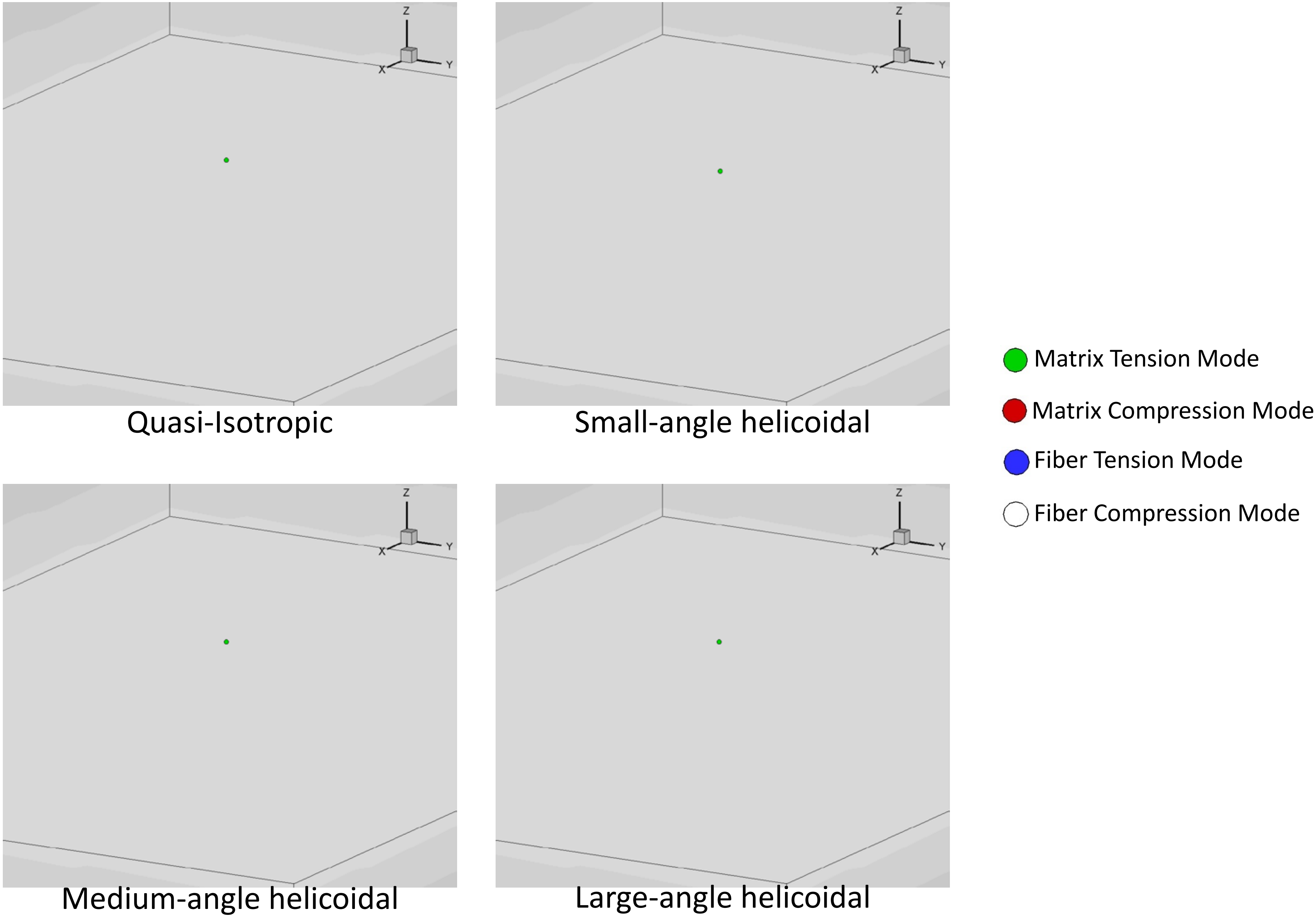
Indentation head
Mass = 4.9105 kg
Impact Energy = 100 J

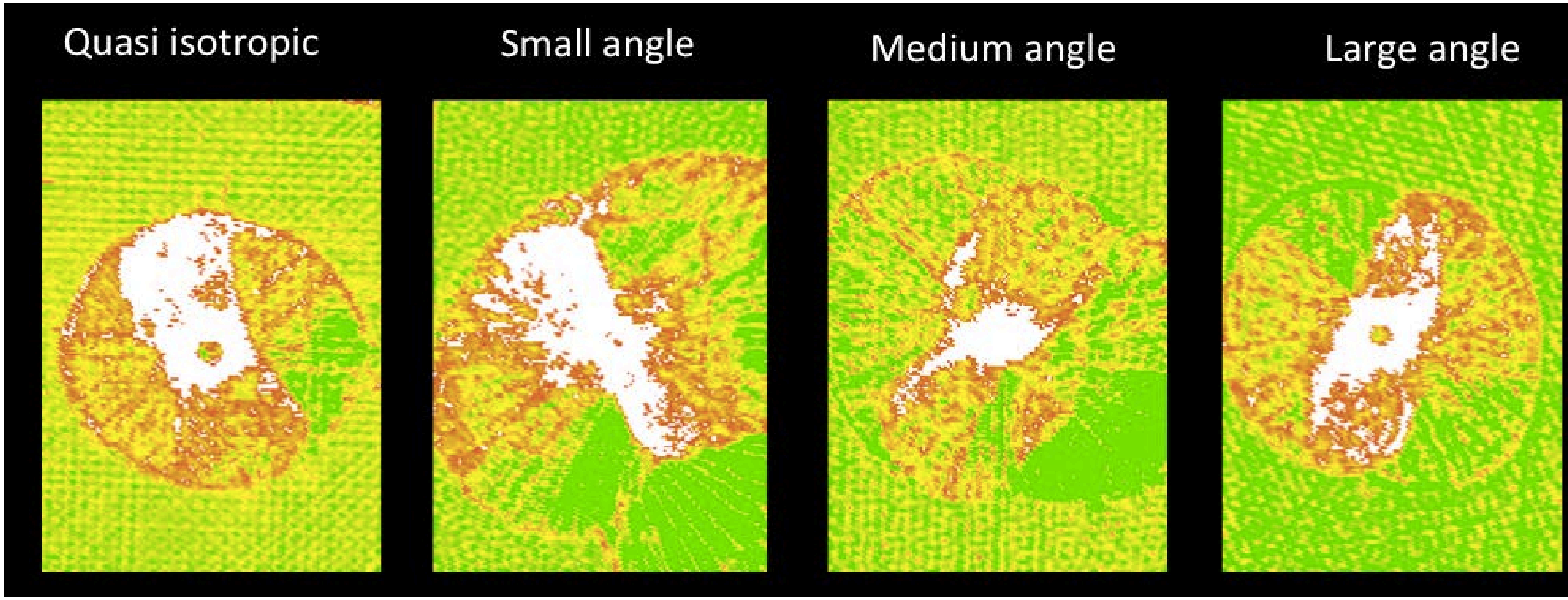
48-ply composite:
- Quasi-Isotropic
- Small-angle helicoidal
- Medium-angle helicoidal
- Large-angle helicoidal

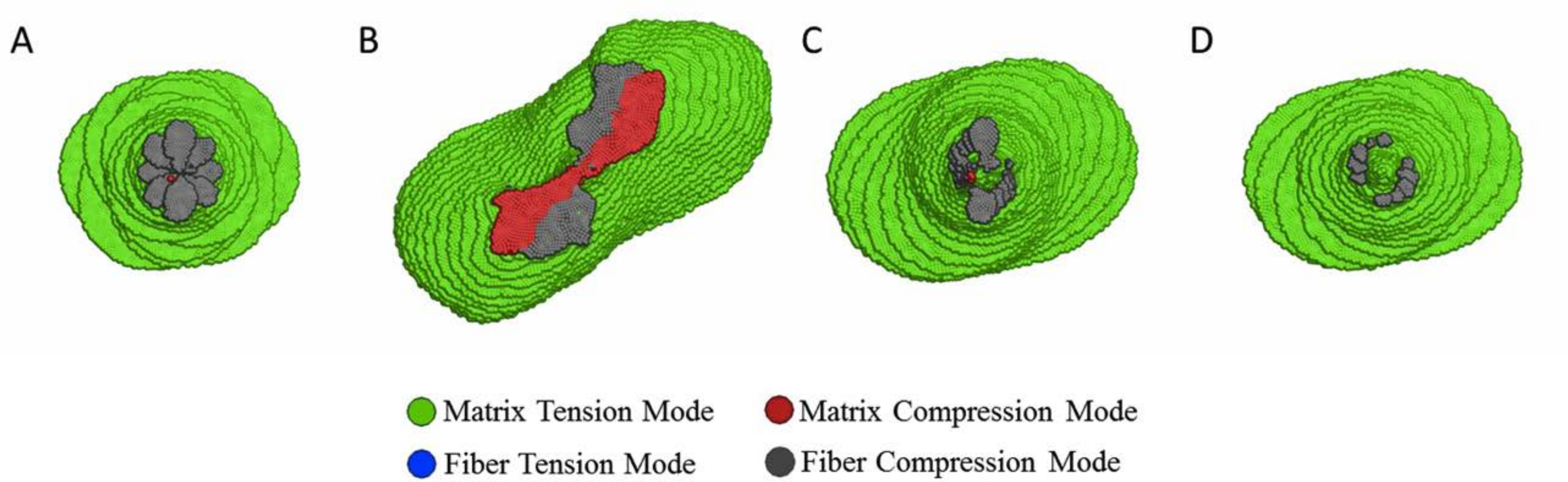


Hashin anisotropic damage model

Points represent node at which the Hashin criteria meets at different times

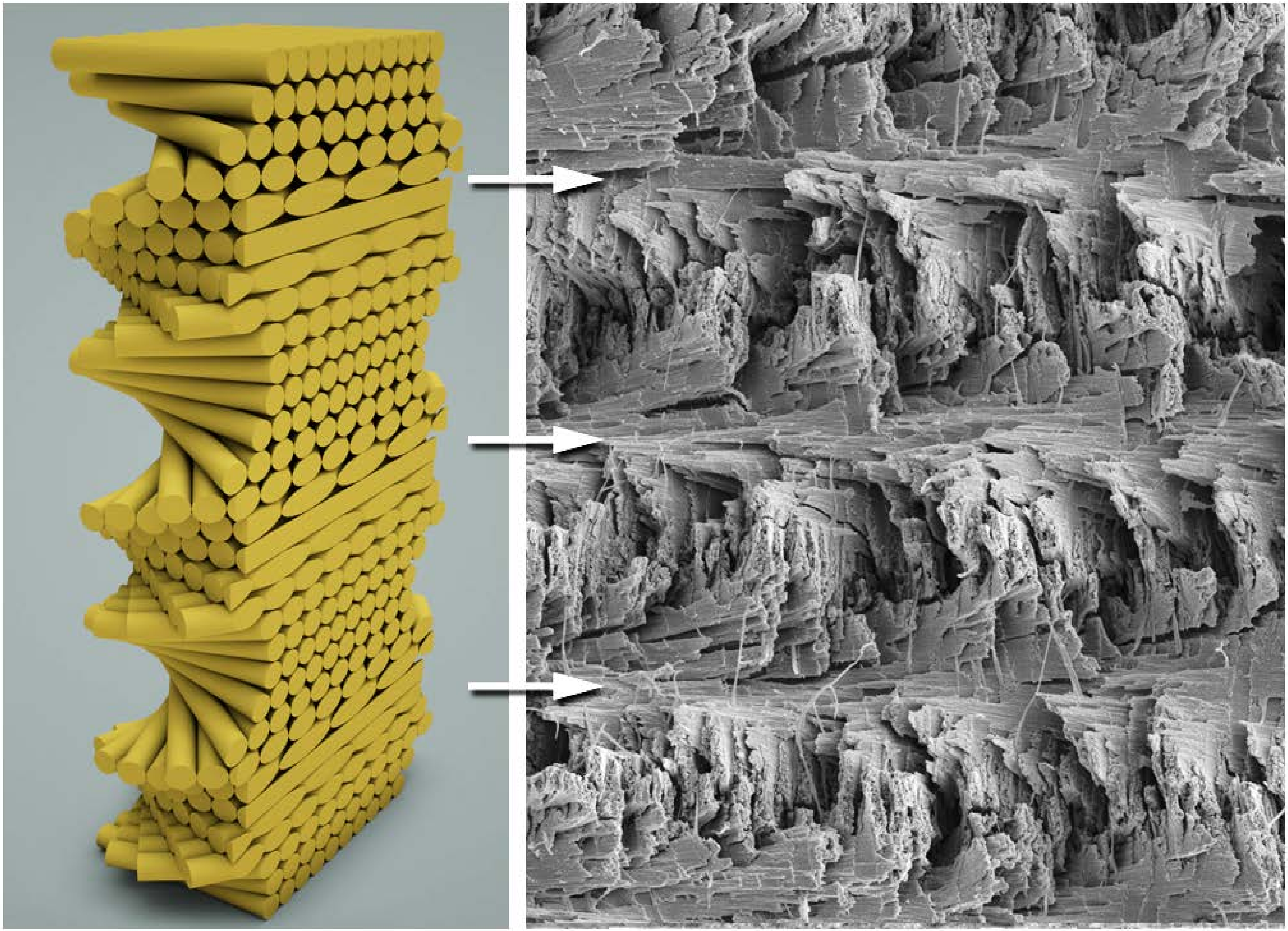






L.K. Grunenfelder, N. Suksangpanya, C. Salinas, G. Milliron, N. Yaraghi, S. Herrera, K. Evans-Lutterodt, S.R. Nutt, P. Zavattieri, D. Kisailus,"Bio-Inspired Impact Resistant Composites", **Acta Biomaterialia, 2014.**

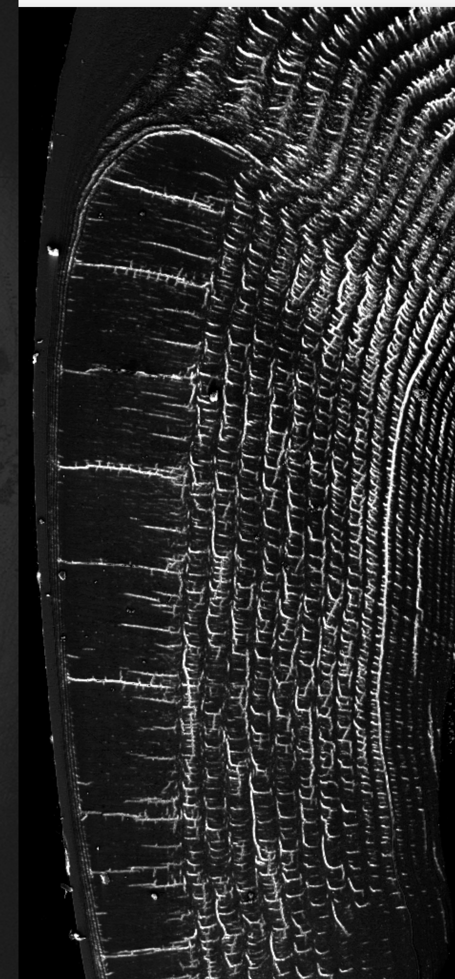
Fracture Analysis – Periodic region



PURDUE ENGINEERING

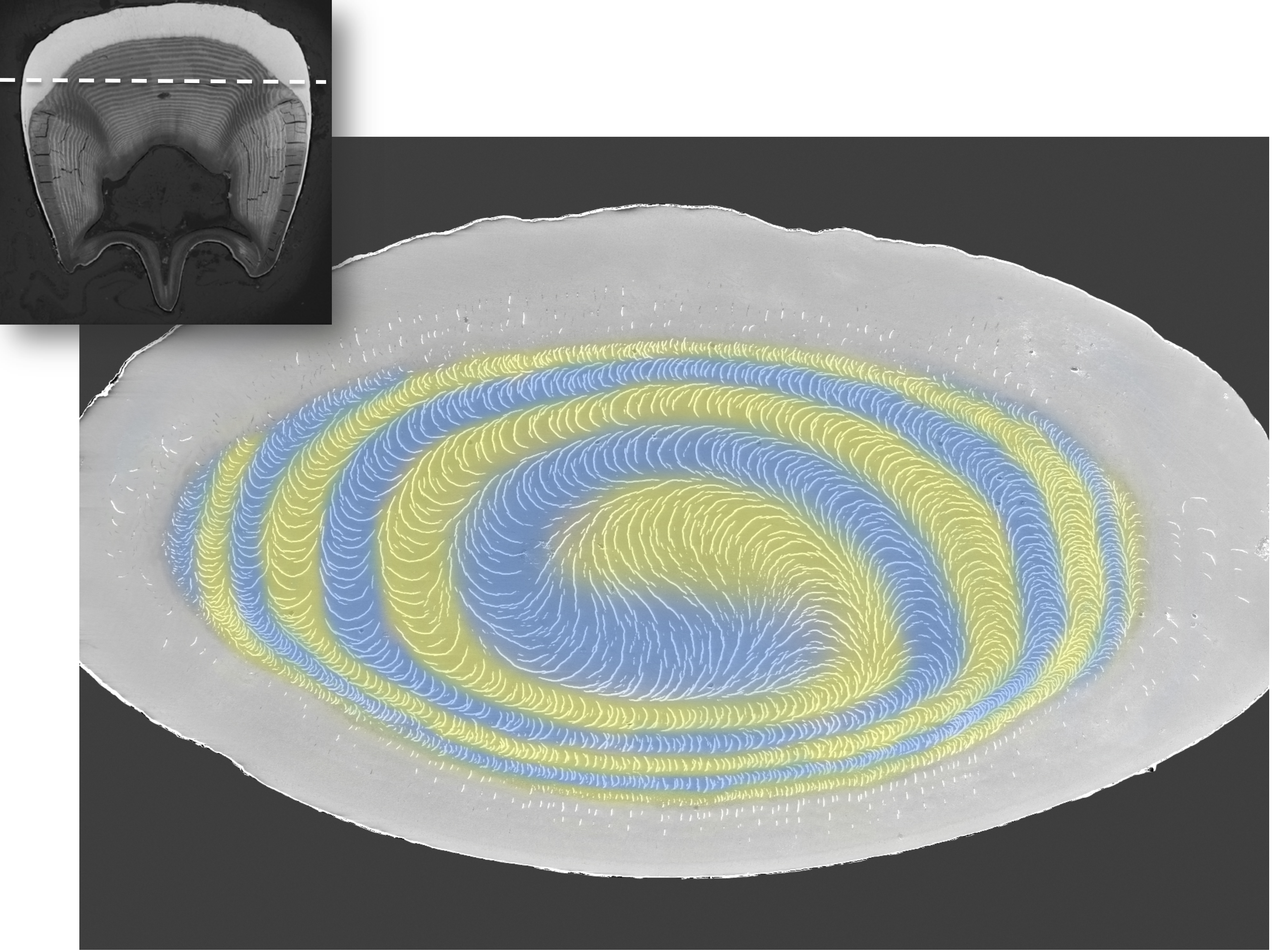
Computational Multi-Scale Materials Modeling Lab

Dactyl Club: Ultrastructural Analysis

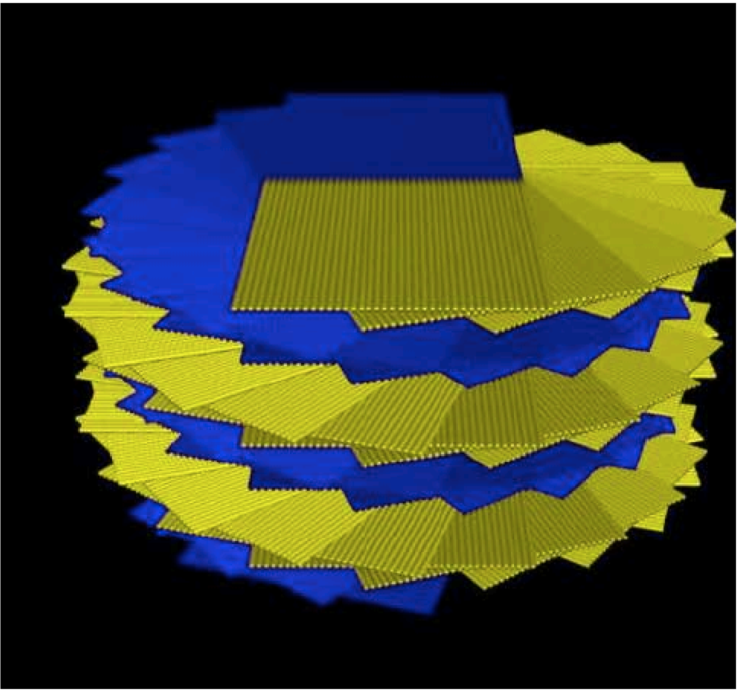


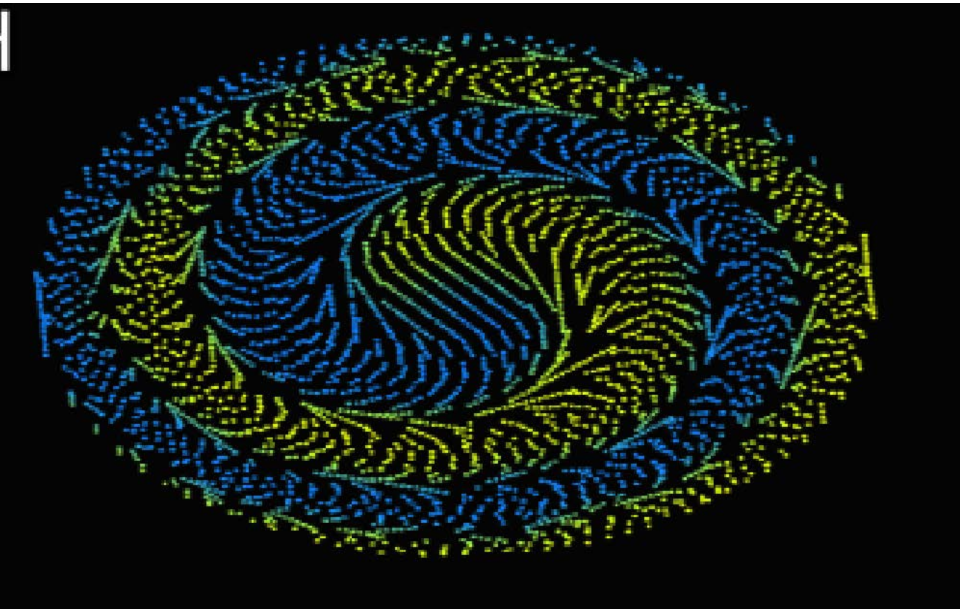
Post sonication back scattered electron micrograph.

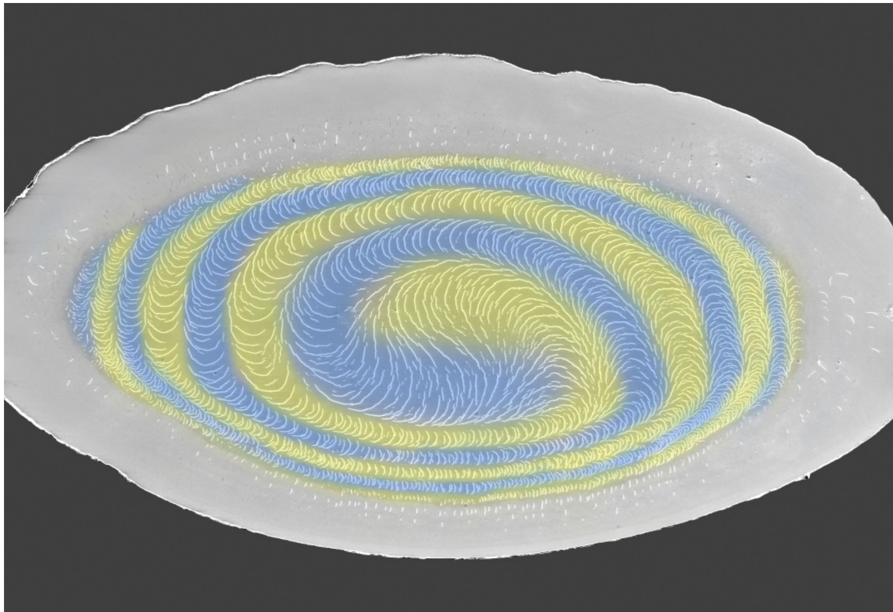
Weaver et al, ***Science, 2012***



D. Kisailus, J. Weaver, G. Milliron, UC Riverside,

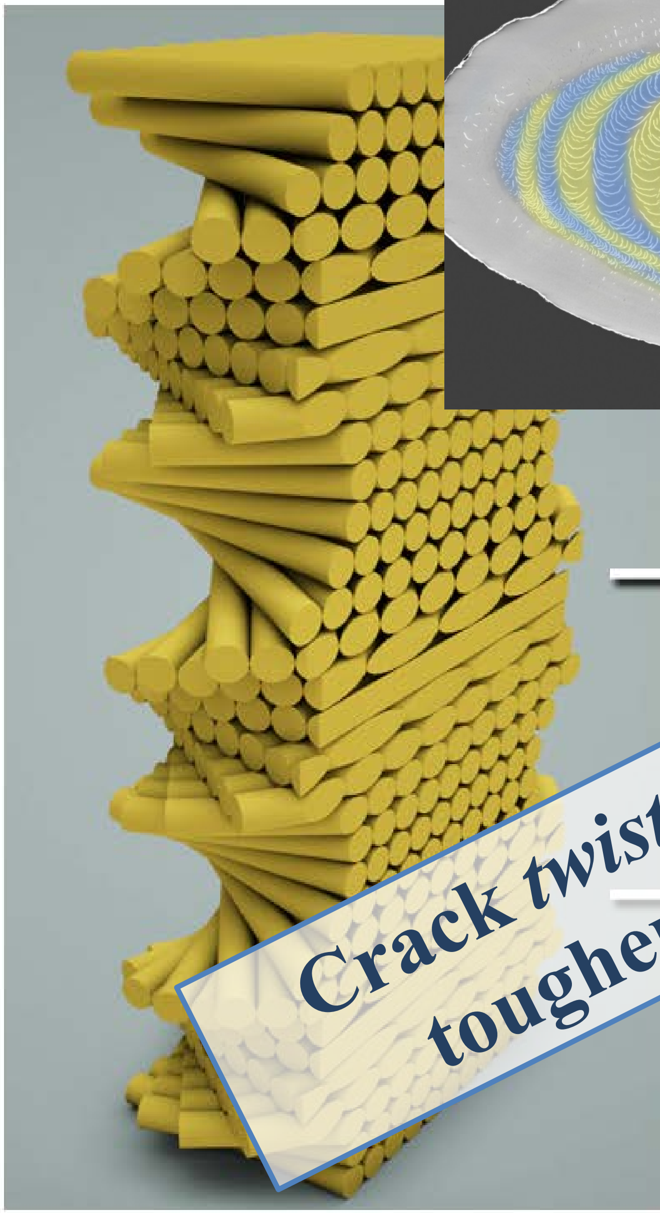


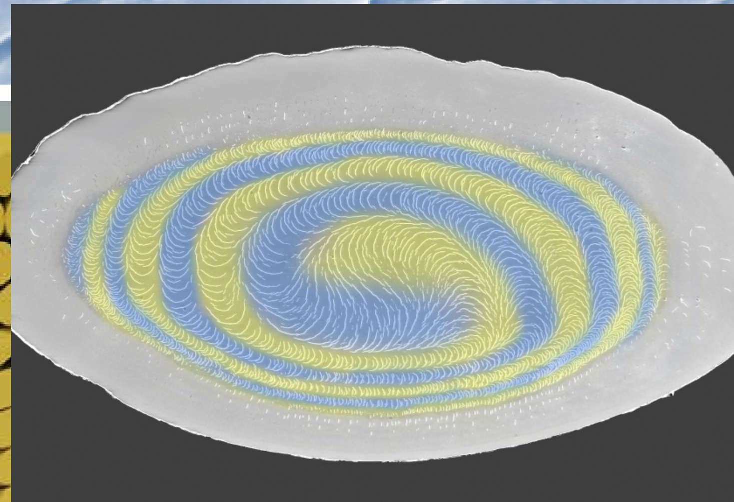




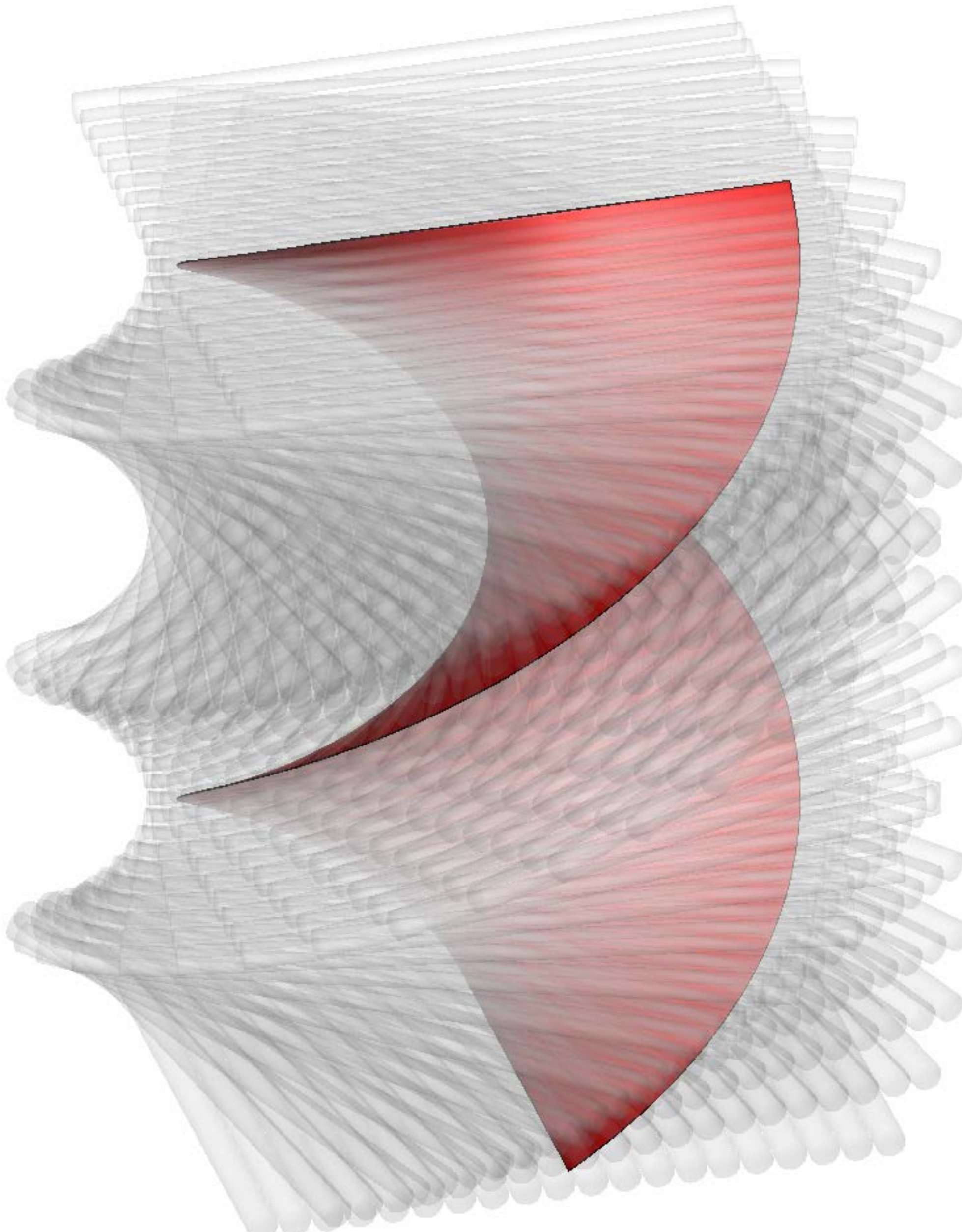
Ultrastructural Analysis – Periodic region

PURDUE ENGINEERING
Computational Multi-Scale
Materials Modeling Lab



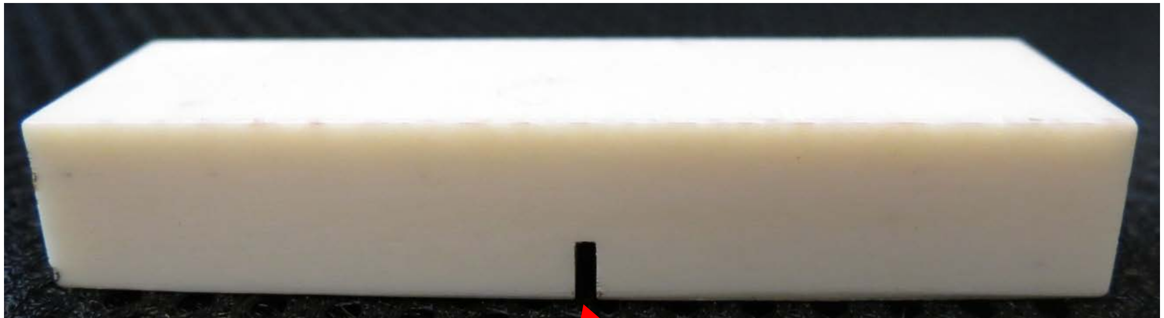


Crack *twisting* as a potential toughening mechanism



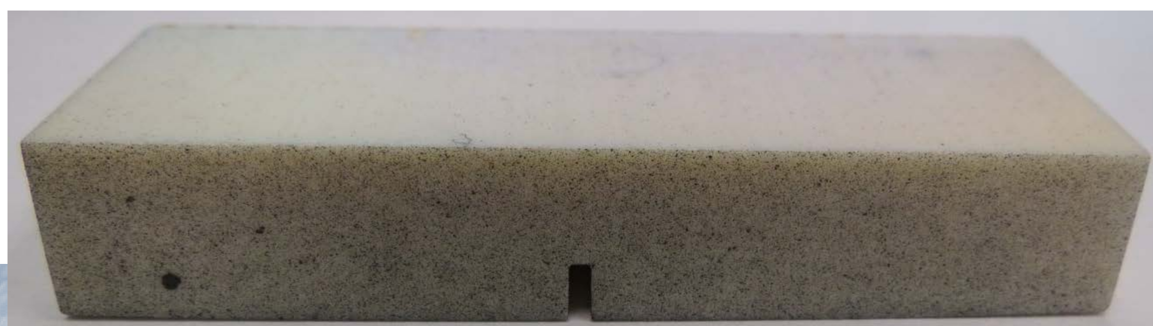
Epoxy-glass fiber composites

Then, cutting the notch to the length determined earlier.

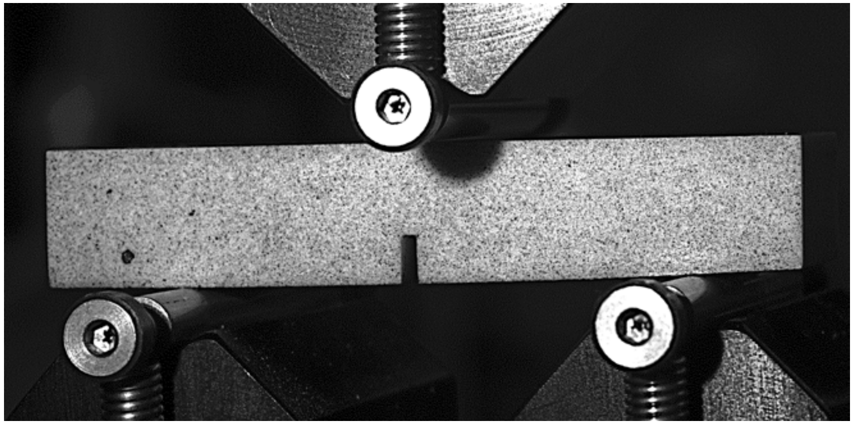


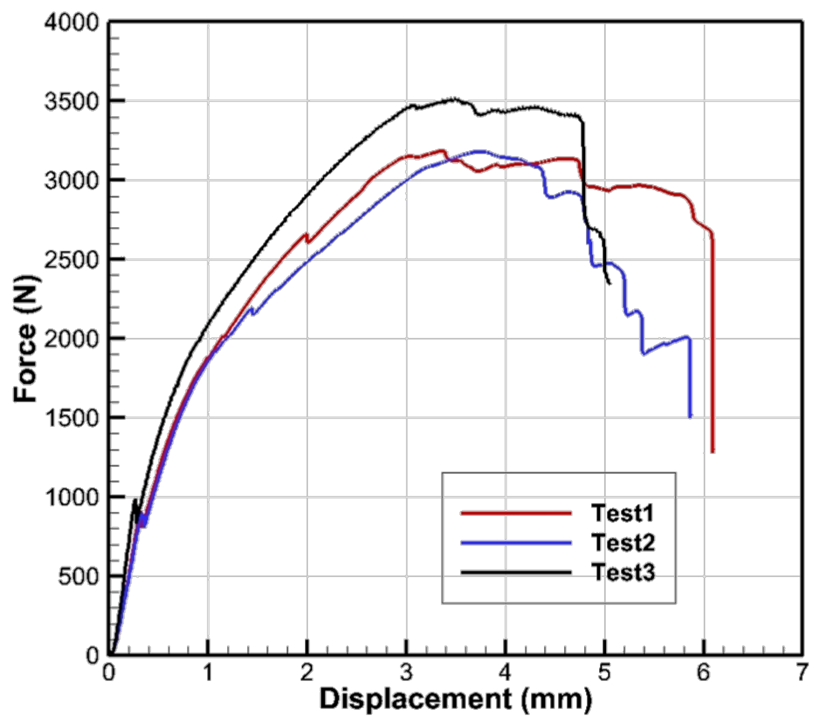
Initial Crack
3.784 mm Length
1.778 mm Width (= Blade thickness)

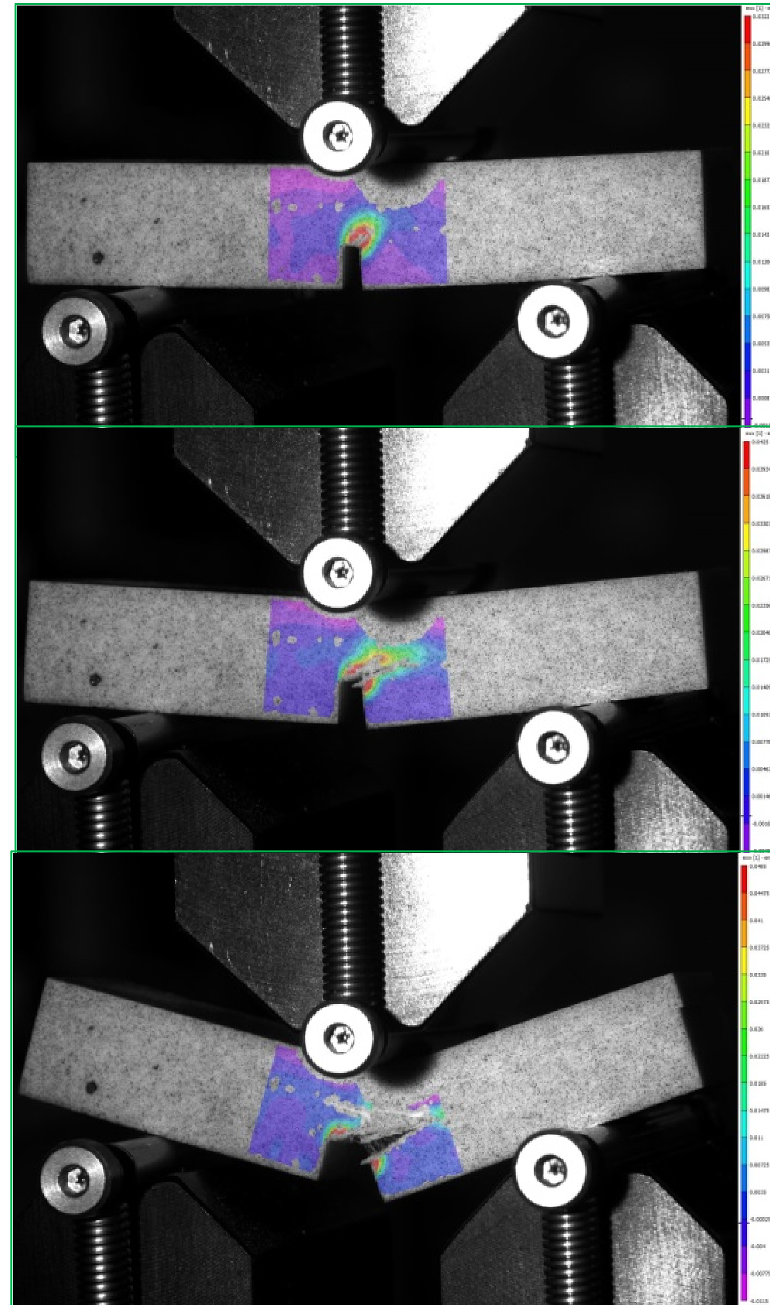
After that, preparing the sample for Digital Image Correlation (DIC) analysis by spraying the surface of sample.



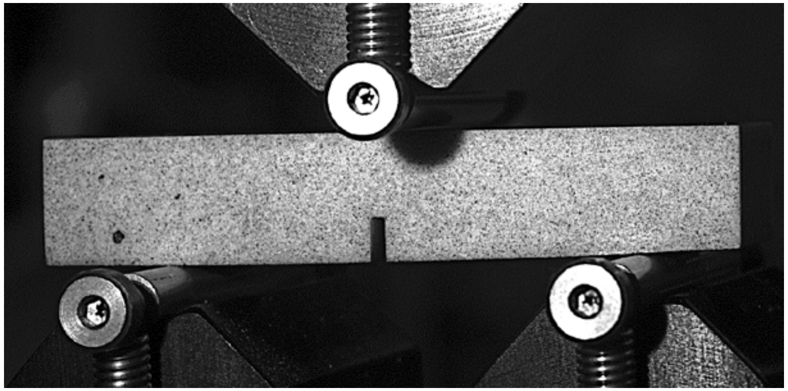
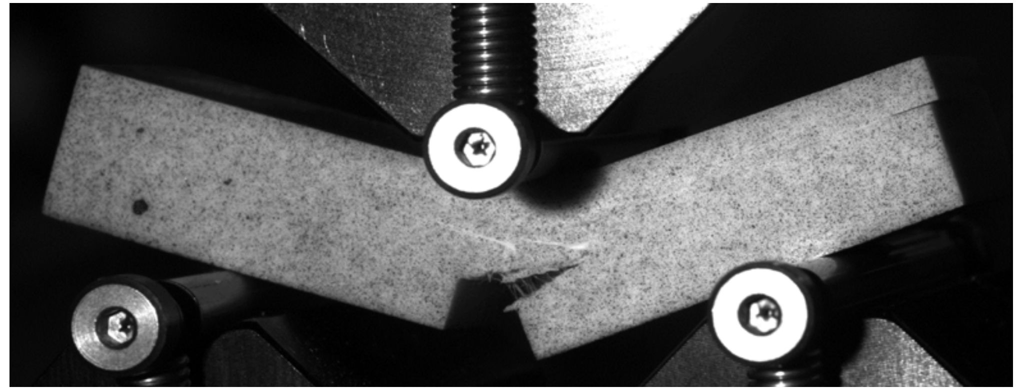
Testing of Composite Biomimetics

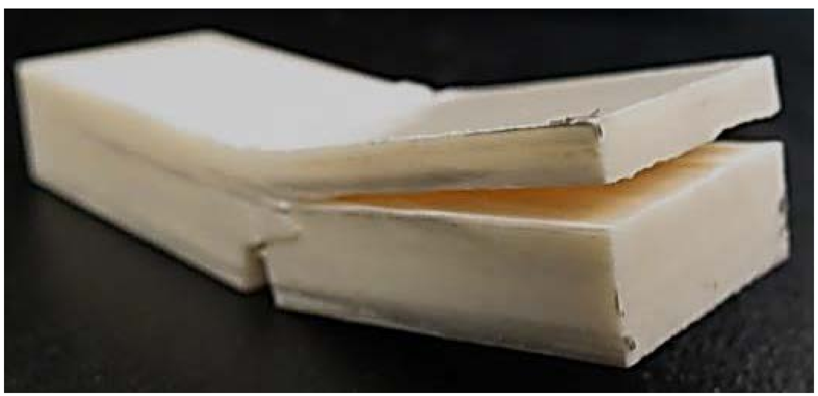




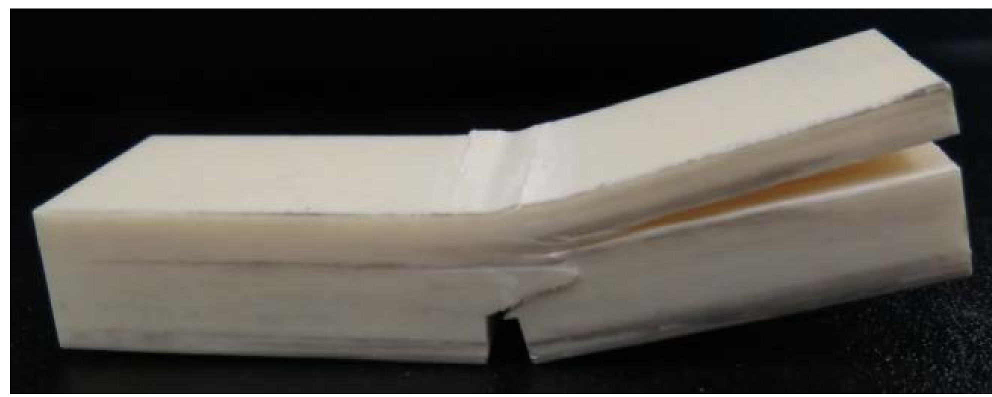


Testing of Composite Biomimetics



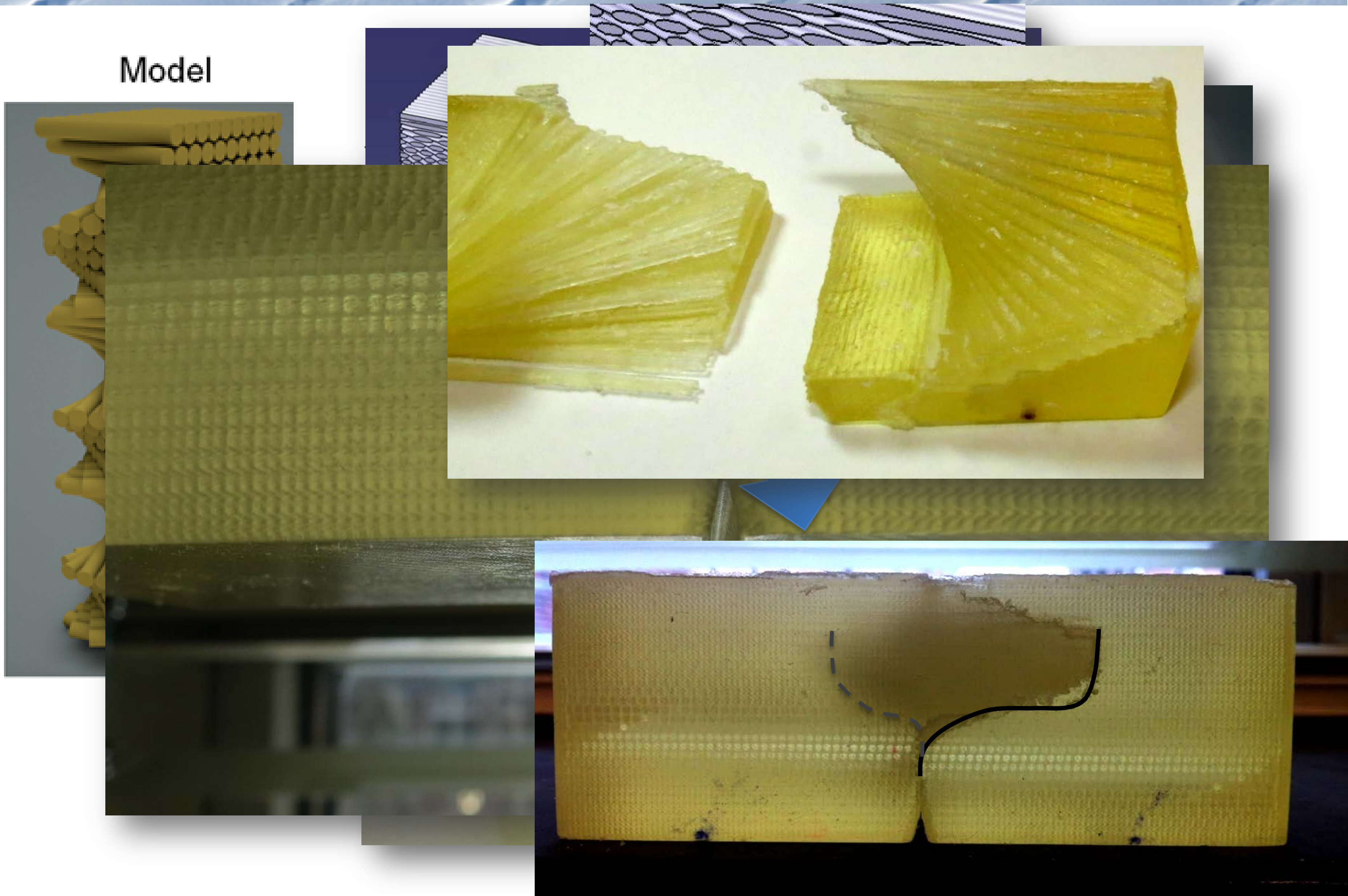
Front view

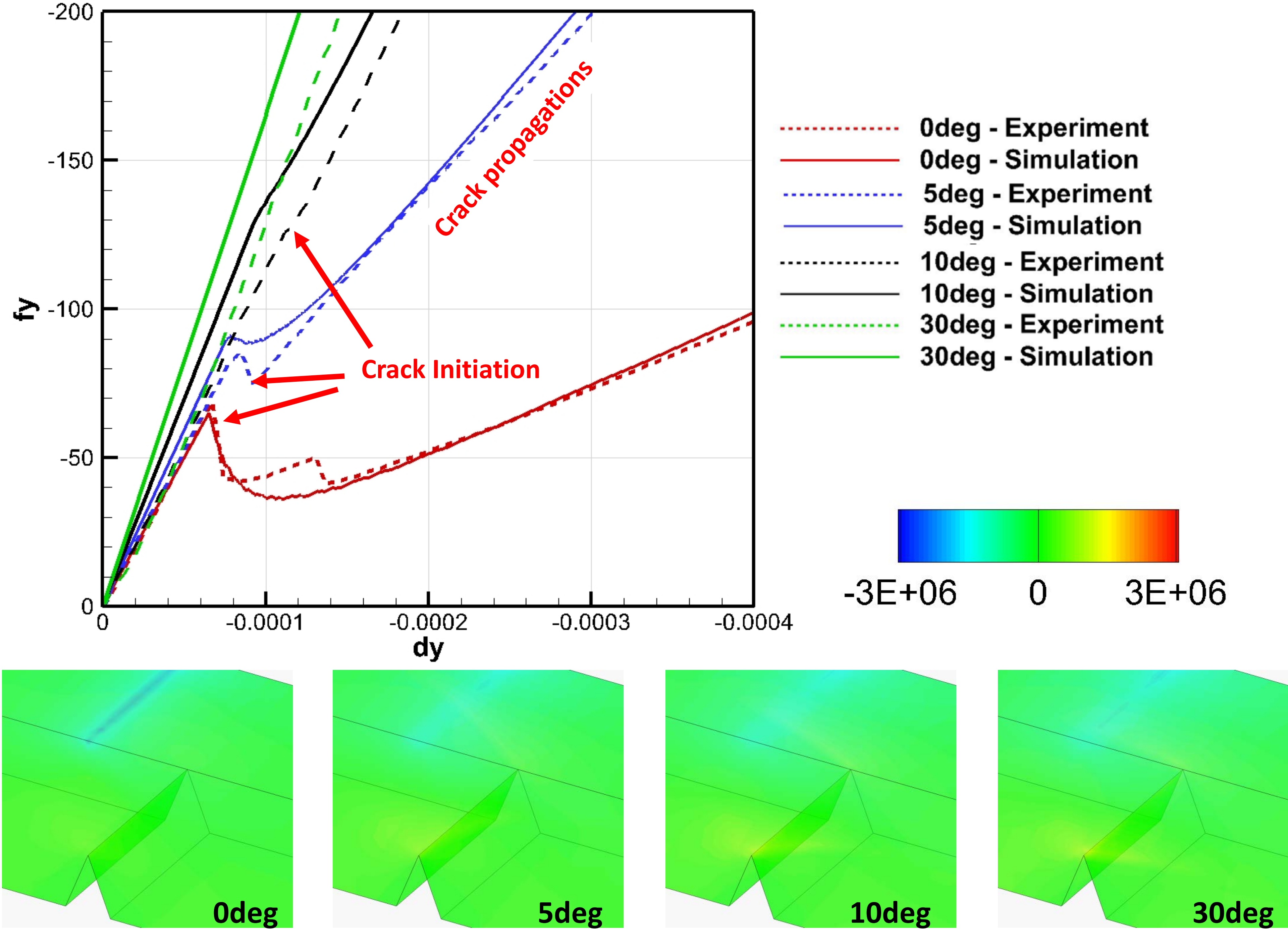


Back view

Biomimetics: 3D printing

Model





-200
-150
-100
-50
0
fy
0
-0.0001
-0.0002
-0.0003
-0.0004
dy
Crack propagations
Crack Initiation
0deg - Experiment
0deg - Simulation
5deg - Experiment
5deg - Simulation
10deg - Experiment
10deg - Simulation
30deg - Experiment
30deg - Simulation
-3E+06
0
3E+06
0deg
5deg
10deg
30deg

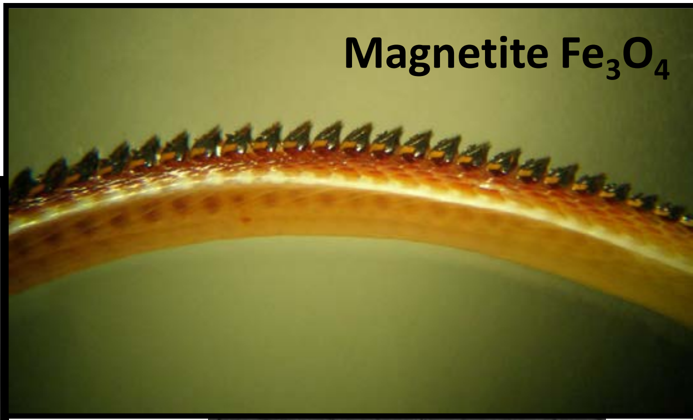
Palau's Rock Islands (Pacific Ocean) http://travel.nationalgeographic.com/travel/countries/palau-photos/

Computational Multi-Scale Materials Modeling Lab

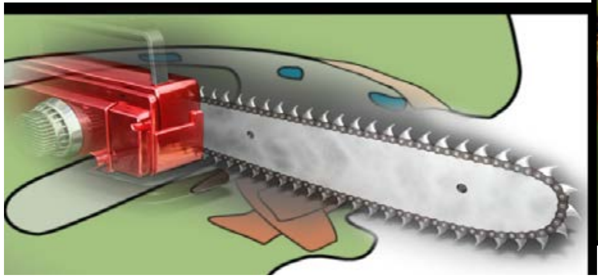
Chiton's teeth

In Collaboration with Dr. David Kisailus, Qianqian Wang, University of California Riverside

Chiton's teeth (*C. stelleri*)



Chitons, a group of elongated mollusks that graze on (and erode) hard substrates for algae.



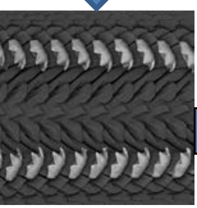
Kisailus and coworkers Materials Today, 2010

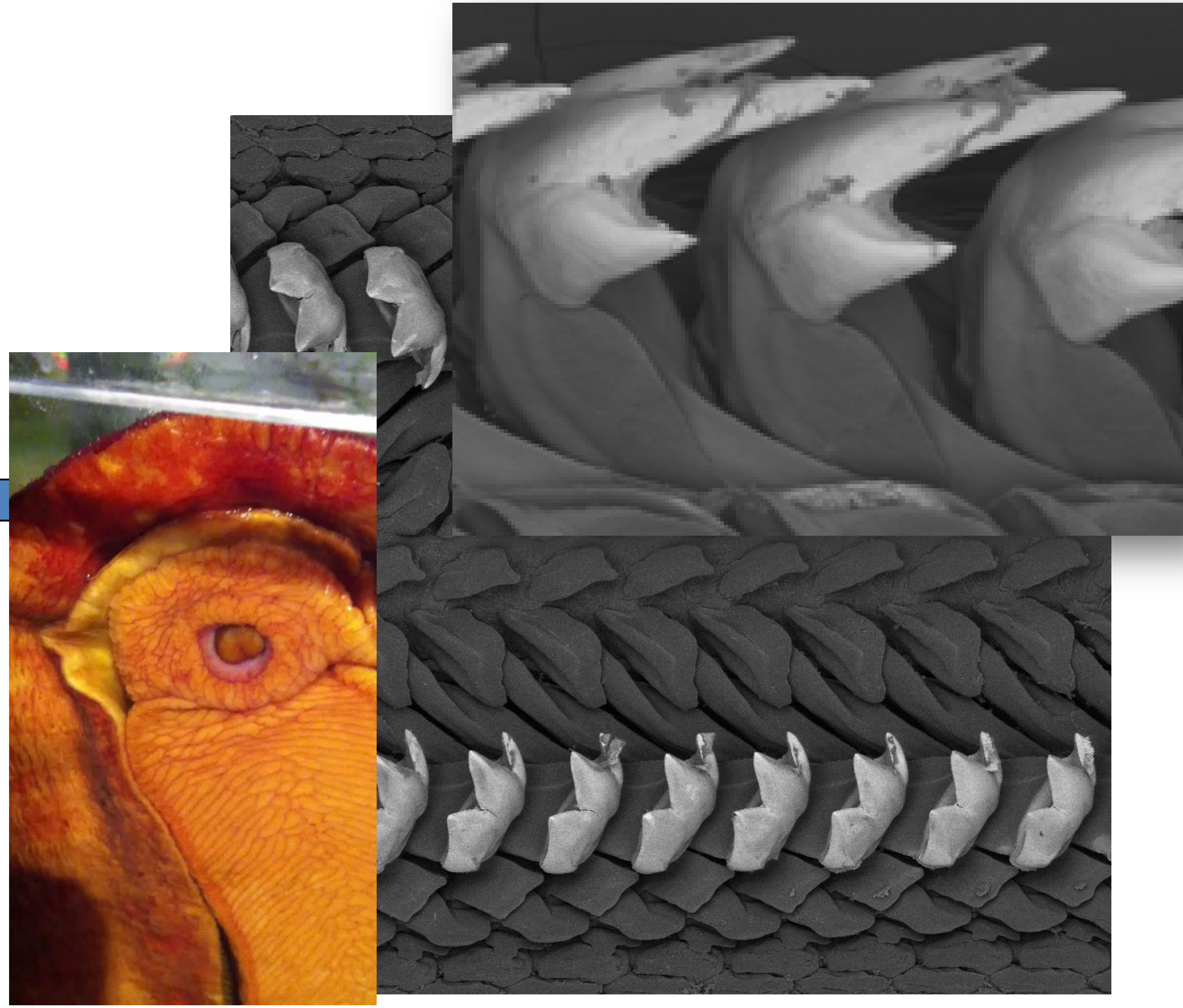
mineralized radular teeth

Chiton's teeth

Chiton's teeth (*C. stelleri*)

Chitons, a group of elongated mollusks that graze on (and erode) hard substrates for algae.



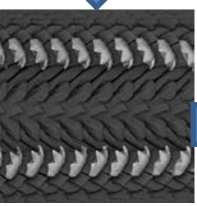


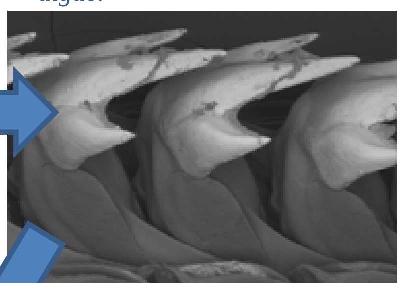
Chiton's teeth

In Collaboration with Dr. David Kisailus,
University of California , Riverside

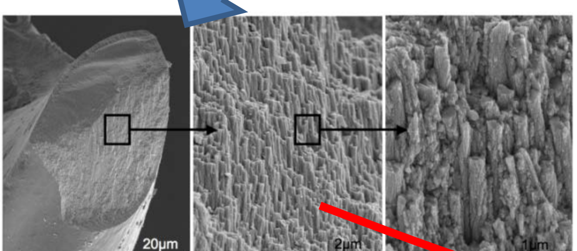
Chiton's teeth (*C. stelleri*)

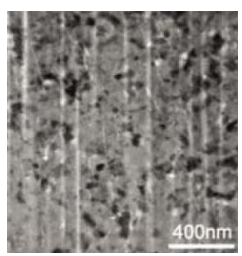
Chitons, a group of elongated mollusks that graze on (and erode) hard substrates for algae.





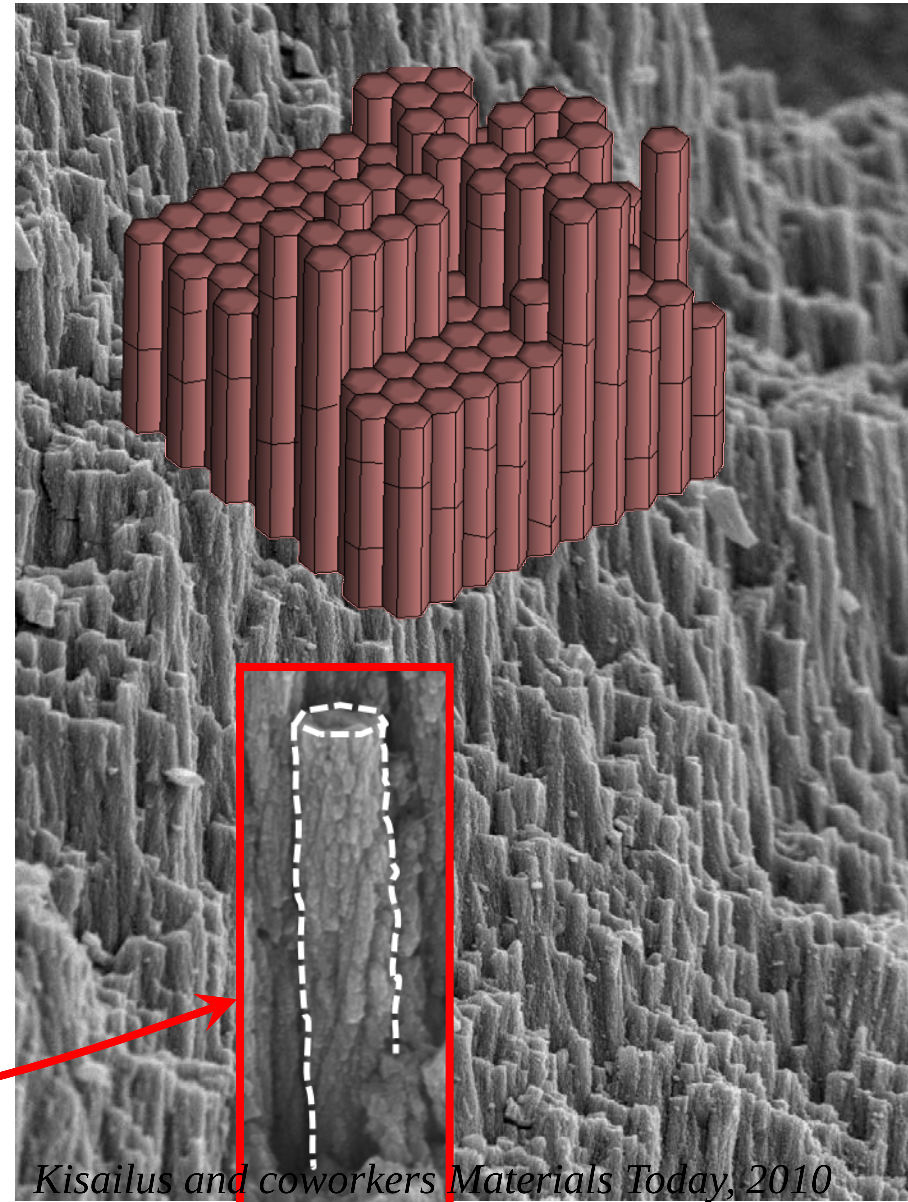
mineralized radular teeth





Hierarchical structure of Chiton's tooth.

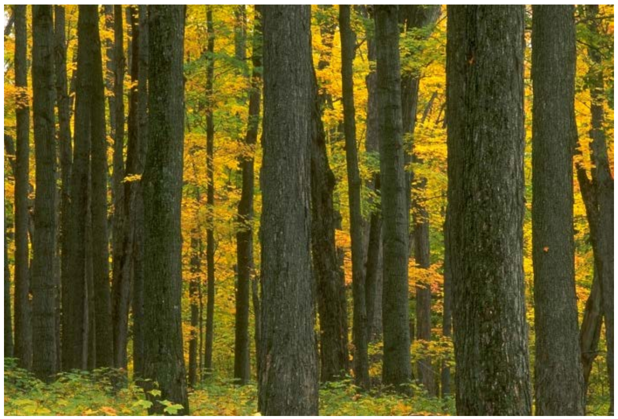
SEM picture: Rod-like ultrastructure, TEM: magnetite nanograins.



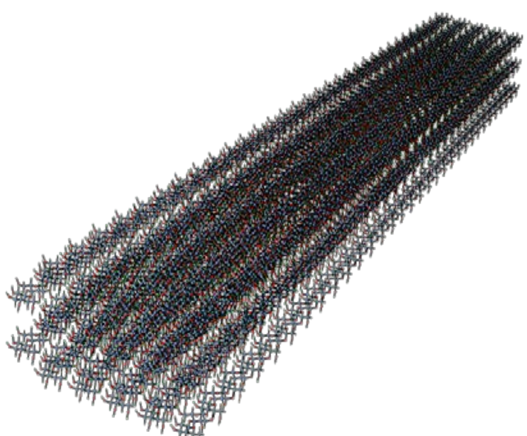
Kisailus and coworkers Materials Today, 2010

Other related projects

What do marine creatures have in common with trees?



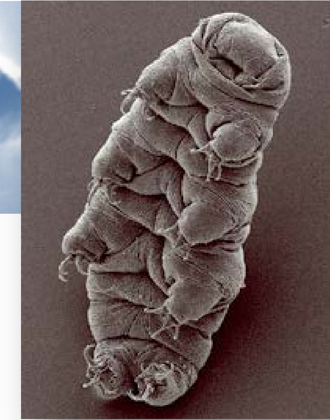
Polysaccharides



Cellulose

Chitin

Extremophiles



- They can withstand $-200^{o}C$ to $150^{o}C$
- They can survive high pressure.
- They survived the vacuum of outer space.
- They resist solar radiation, gamma radiation, ionic radiation— at doses hundreds of times higher than would kill a person.
- They can go without food or water for nearly 120 years, drying out to the point where they are 3% or less water, only to rehydrate, forage, and reproduce

Biomimetics Approach

The study of the Structure-Function relationship requires:

1. Study of the typical loading conditions.
2. Microscopy Study to understand the internal structure.
3. Experimental observations
4. Speculations
5. Hypothesis
6. New ideas for biomimetic material design

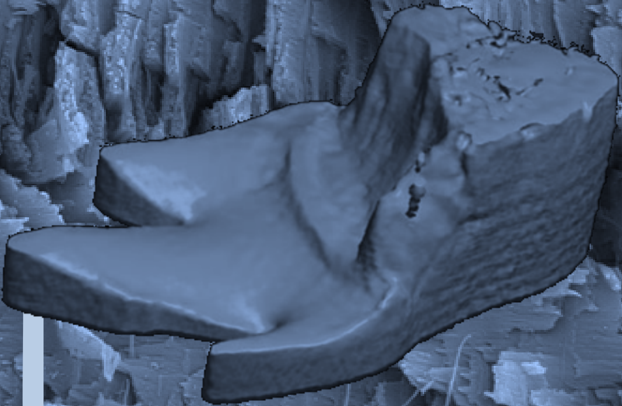
Acknowledgement

Acknowledgments:

Students:, Enrique Escobar, Isaias Gallana, Nicolas Guarin, Chan Jeong, Nobphadon Suksangpanya, Di Wang, Yunlan Zhang

Collaborators: David Kisailus, UC-Riverside, Horacio Espinosa, Northwestern, Joanna McKittrick, UC-San Diego

Funding: AFOSR, AFOSR MURI, USFS, NSF CAREER



Thanks!

Questions?

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