Materials by Design:
3-Dimensional Architected Nanostructured Meta-Materials

Julia R. Greer

Division of Engineering and Applied Science
California Institute of Technology
Boeing 747-8
Max Weight at Take-Off: 970,000 pounds

Boeing 787 Dreamliner
502,500 pounds. Uses 20% less fuel

Lightweight: Weak, Easy to Damage and Tear

Strong: Heavy and Expensive

Specialized: Heavy and Brittle
All manufacturing routes known today produce materials that are either **strong** and heavy or light and weak. 

Correlation between strength and density: **A HUGE PROBLEM** for every technology.
Great Pyramid of Giza
largest man-made stone monument

Original height: 147 m
• Weight: $5.75 \times 10^6$ tons
• Constructed of 2.3 million limestone blocks
• Weight at base: 10,500 tons/m²

Height: 324 m
• Weight: $9.4 \times 10^3$ tons
• Force on foundation: 45,000 kg/m²

twice-as-tall engineered structure
Creating ultra-light, strong, and fracture tolerant materials

Architected structures with nano-sized solids merge structural and material properties into a single meta-material

Hughes Research Lab

Different architectures Contain 99.9% Air!

YES, THESE ARE REAL!
Fabrication of 3D Architected Nanoscale Meta-Materials

From prototype to scalable manufacturing: How?

HRL/Architected Materials

Sometimes materials get stronger
Other times they get weaker
And sometimes they stop breaking...
ONLY at nanoscale
Tough and Recoverable Ceramic Nanolattices

50nm-Thick Walled Nanotruss:
- High strength
- Brittle catastrophic failure
- Low toughness

10nm-Thick Walled Nanotruss:
- Ductile-like failure
- No strain bursts
- High toughness
- Recoverable!
Critical Wall Thickness Drives Deformation Mode

10nm Wall Thickness
\[ t/a = 0.016 < (t/a)_{cr} \]

20nm Wall Thickness
\[ t/a = 0.031 \approx (t/a)_{cr} \]

40nm Wall Thickness
\[ t/a = 0.063 > (t/a)_{cr} \]

60nm Wall Thickness
\[ t/a = 0.094 > (t/a)_{cr} \]
Did We Hit the White Space?

⇒ **STRENGTH, TOUGHNESS** and **RECOVERABILITY** controlled by **architecture, nanomaterials, and microstructure**
⇒ Possible to **DESIGN NEW CLASSES** of **MATERIALS**

Building up Hierarchy

A

0th order

L

1st order

N

2nd order

3rd order

B Octahedron of Octahedra

C Octahedron of Octets

D Octet of Octahedra

E Octet of Octets

F

G

H

Hierarchy Brings Scaling to Ideal

![Graph showing Young's Modulus vs. Relative Density](image)

- **1st Order Lattice**
- **2nd Order Half-Cell**
- **2nd Order Full Lattice**
- **3rd Order Half-Cell**
- **Simulation Data**

- Hollow 20mm Al2O3
- Composite Polymer + Al2O3
- Solid Polymer

![Graph showing Yield Strength vs. Relative Density](image)

- Young's Modulus (N/m²)
- Yield Strength (N/m²)
- Relative Density (ρ)

L.R. Meza, A. Mateo, A. Zelhofer, D. Kochmann, J.R. Greer (isubmitted, 2015)
In-situ Nanomechanical Experiments: \textit{InSEM (SEMENTOR)}

We make indenter tips with desired geometry and functionality:

- Tension-Compression Tip
- Double Tension Grips
- Wedge Tip

Suspended graphene transistors, electrodes, and carbon nanotubes.
A few words on fracture (lack thereof...)

L. Montemayor, et al. (isubmitted, 2015)
Presence of Notch doesn’t Affect Failure

UN-NOTCHED

NOTCHED

Collaboration with M. Wong Wei Hin and Y.-W. Zhang (IHP)

Notch-Insensitive and Tough!

A smorgasbord of research pursuits for relevant technologies

**ENERGY STORAGE:**
Lightweight and Structurally Robust Electrodes

Si: **4200mAh/g** gravimetric charge capacity vs. C: **372mAh/g**

Damage-resistant nanostructured electrodes by designing proper architecture

Ph.D. students: Chen Xu, Xiaoxing Xia, Dylan Tozier
Collaboration w/ M. Ortiz, W.A. Goddard (Caltech) => Bosch, LiOx
A smorgasbord of research pursuits for relevant technologies

**ENERGY STORAGE: BIO-MIMICKING:**
Ultra-Strong, Tough, and Lightweight Materials

---

**Fracture Strength**

\[ \sigma_f = \frac{K_c}{\sqrt{\pi t}} \]

Theoretical Limiting Strength

\[ \sigma_f \propto \left( \frac{1}{t} \right)^{1/m} \]

---

**Liguidust**

---

**Damage-resistant nanostructured electrodes (no cracking!)** by designing proper architecture

Lightweight and Structurally Robust

---

**Students:** Lucas Meza, Lauren Montemayor, Arturo Mateos, and Nigel Clarke
Collaboration with D. Kochmann (Caltech) and HRL => NASA, DARPA
Diatoms: Primitive Organism, Exceptional Damage Tolerance

Valve

Girdle bands

Cribellum + Cribrum

Foramen

5 µm

5 µm

4 µm

Fracture Experiments and Modeling Reveal...

EXTREME STRENGTH AND DAMAGE TOLERANCE!

Strength $\sigma_F$ (MPa) vs. Density $\rho$ (kg/m$^3$)

- Diatom Frustule
- Theoretical Maximum
- Cellulose
- Silk
- Compact bone
- Antler
- Fully Dense Hydroxyapatite
- Natural Polymers
- Natural Elastomers
- Natural Ceramics
- Enamel
- Nacre

SUMMARY

- Can be made of just about any material
- Offer extremely lightweight properties
- Decouple properties that have always been linked together

Nano-lattices merge structural and material properties into a single "meta-material"

For details/publications: http://jrgreer.caltech.edu
We are Helium-free!

Chocolate Nano-trusses
100% Taste, 99.9% Air, 0.01% Calories! No Halium, it's real!
Acknowledgements of Awesome "Resources"

For details/publications: http://jrgreer.caltech.edu

Great Collaborators:
C. Weinberger (Sandia)
H. Gao's group (Brown)
A. Needleman (UNT)
Z. Wu, Y.-W. Zhang, D. Srolovitz (IHCP Singapore)
D. Kochmann, M. Ortiz (Caltech)
F. Greer, D. Hofmann (JPL)
B. Carter, A. Jacobsen, T. Schaedler (HRL)
L. Valdevit (UCI)

NSF CAREER DMR-0748267 DMR-1204864 and CMMI-12343640

Space Technology Early Career Faculty Award

Caltech Innovation Initiative (CI2)
Dow-Resnick Institute

Young Faculty Award

MCMA Program

Young Investigator

National Science Foundation
WHERE DISCOVERIES BEGIN

Office of Naval Research
N000140910883

DARPA
Defense Sciences Office
HRL

NASA
United States of America

NASA
United States of America

NASA
United States of America

NASA
United States of America

NASA
United States of America

NASA
United States of America
Having Fun with Nanoscribe...