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BIOINSPIRED LAMINATED COMPOSITE CERAMIC STRUCTURES

Behnam Ashrafi, Ph.D., M.Eng.

H. Yazdani, C. Beausoleil, D. Backman, M. Genest
Novel Materials and Coating
Aerospace Manufacturing Technology Center
Aerospace Research Center

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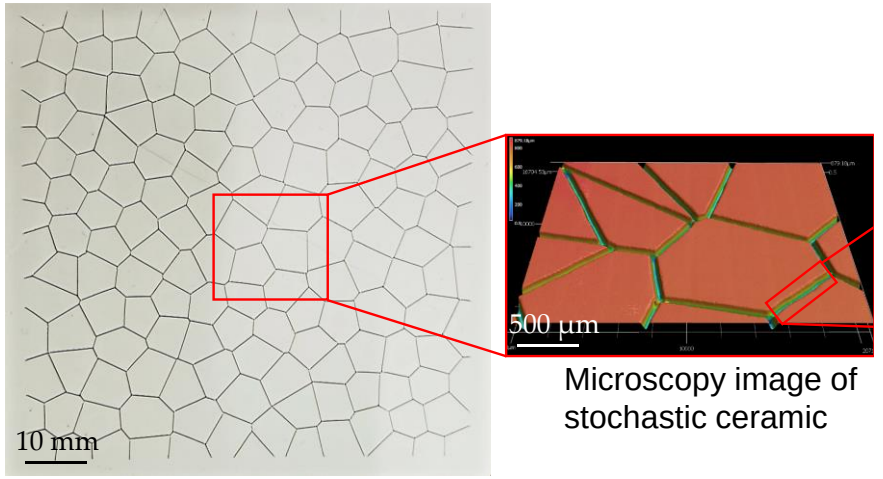
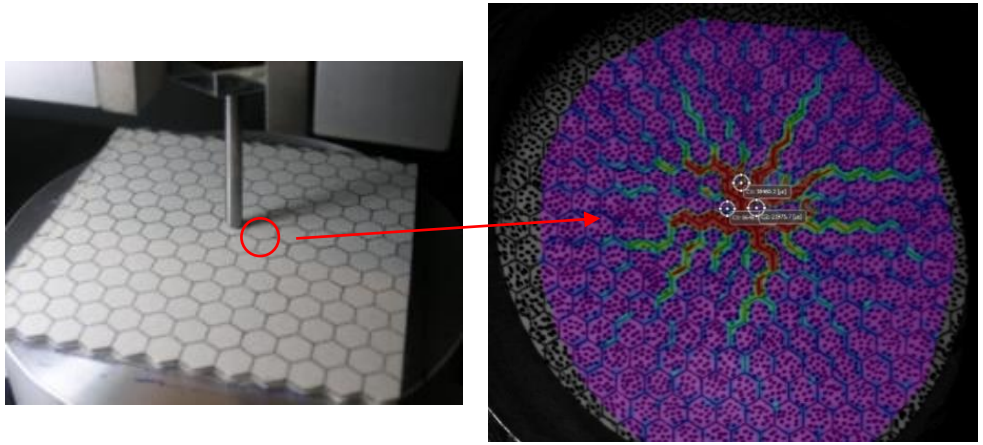
Outline

- Introduction
  - Ceramic Materials
  - Bio-inspired Approach
- Manufacturing Approaches
  - Laser-based architected ceramics
- Design and manufacturing
- Conclusion



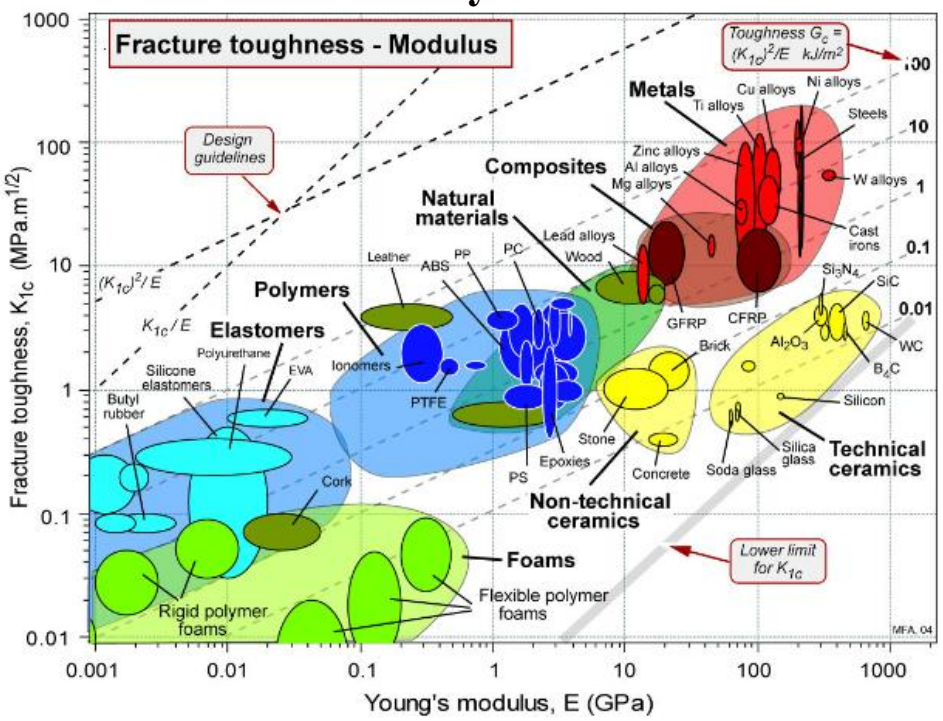
Microscopy image of stochastic ceramic



DIC image: crack propagation in architectured ceramics

Ceramic Materials and Structures

Ashby's Chart



Advantages of Ceramics

- ✓ High thermal stability
- ✓ High chemical resistance
- ✓ Relatively low density
- ✓ High stiffness
- ✓ High compressive strength

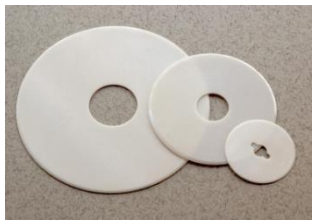
Main Disadvantage of Ceramics

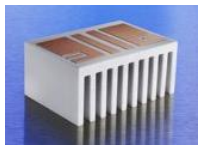
- Brittleness

Brittle fracture of glasses and ceramics

Applications

- ✓ Engines
- ✓ Thermal protection systems
- ✓ Electronics (insulators, heat sinks)
- ✓ Armour
- ✓ Dentistry
- ✓ Cutting tools



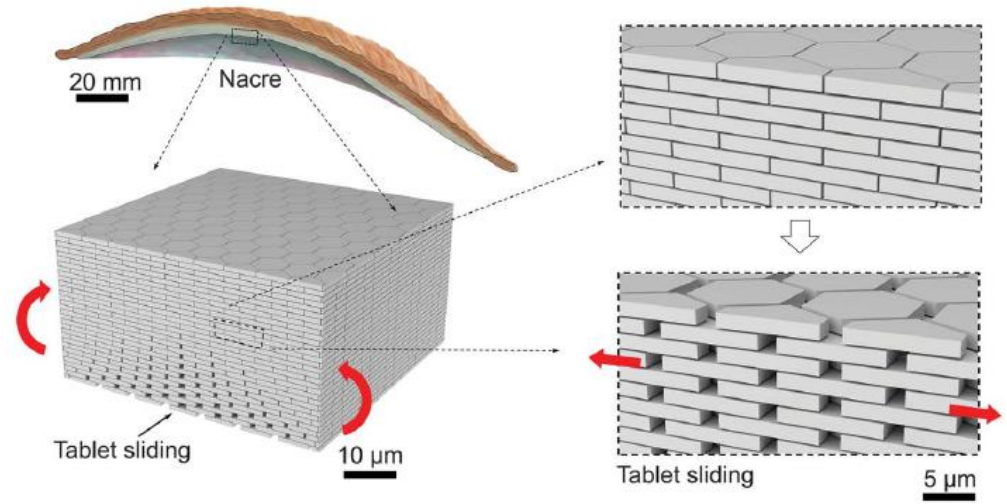


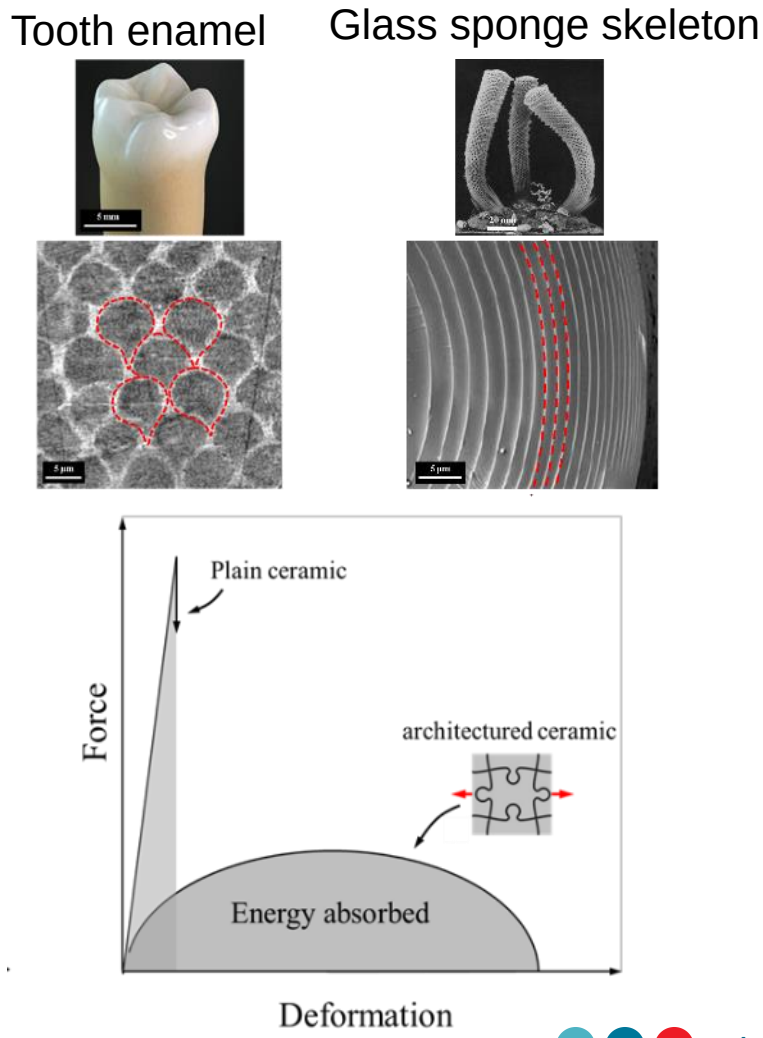
Why Architected Ceramics?

- Stiffness/strength and toughness are mutually exclusive in traditional engineering materials

- Biological materials use architecture and possess interesting combinations of properties

- ✓ Stiff and strong building blocks
- ✓ Designed architectures
- ✓ Weak interfaces





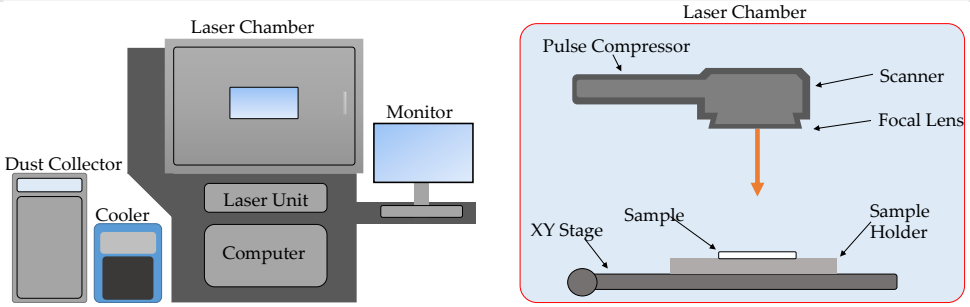
Barthelat et al. J. Mech. Phys. Sol. 2007, Aizenberg et al. science, 2005 , Habelitz et al. Archives of Oral Biology, 2009

Automated and Engineered Net Shaping of Ceramics

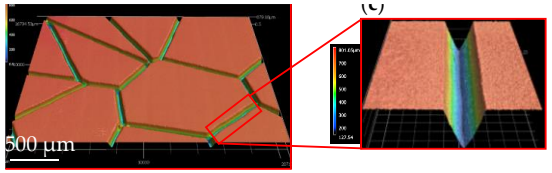
Goal: *Develop industrially scalable fabrication laser technique*

Why: *Ceramics have different applications such as heat shield systems for space vehicles, rocket propulsion components, and gas turbines. However, one of the main challenges with ceramic processing is the machinability of ceramics for producing complex parts. Unlike metals, ceramics are not able to maintain strength with traditional subtractive manufacturing techniques as the machined cuts are not damage-free.*

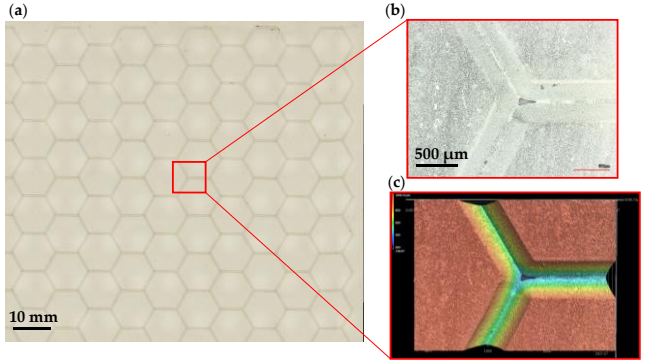
Outcome: *Developing a laser material removal system will allow the design of different advanced engineering applications and represent an effective and efficient manufacturing tool that can be incorporated in engineered net shaping systems.*



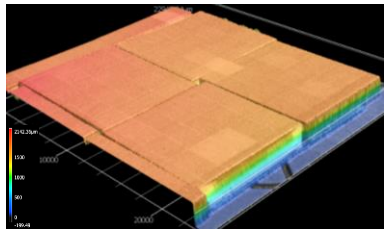
Schematic of NRC laser system facility



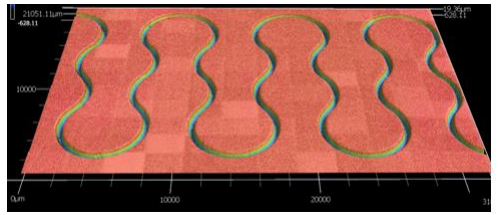
ceramic stochastic design: defect free and precise



microscopy images of laser machining of ceramic hexagonal design using picosecond fiber laser



Angle cut: tunable and defect free



Bioinspired cut: precise and programmable

I. Esmail, et al., Optics & Laser Technology 2021.
C. Beausoleil, et al., Ceramics International 2020.

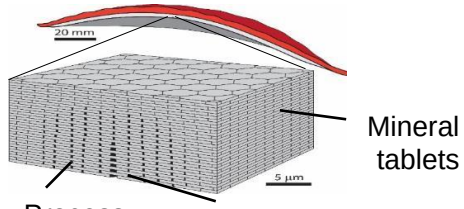
Bio-inspired Multi-layer Architectured Ceramic Composites with Multi-hit Capabilities

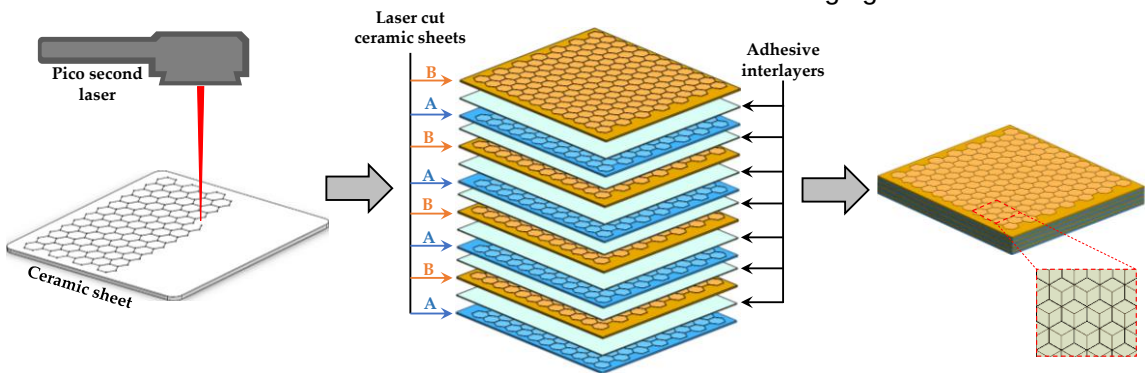
Goal: *Develop a high-toughness high-strength ceramics for ambient and high-temperature applications*

Why: *Ceramics suffer from low tensile strength and brittle fracture behavior, which limit their range of applications where high toughness is required.*

How: *Nature's inspiring motifs and unique design concepts can open new avenues to solve ceramics' brittleness. Many biological materials such as mollusk shells, and teeth are comprised of hard and stiff yet brittle building blocks bonded by tougher and weaker interfaces.*

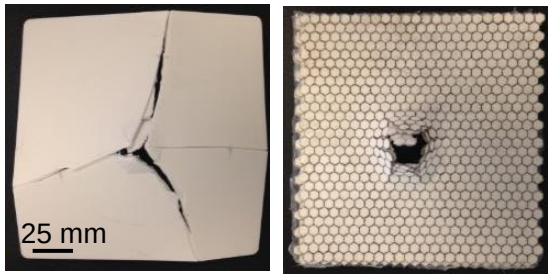
Outcome: *Improving multi-hit capability of bio-inspired ceramics; extending design space of ceramics by tuning architectures using NRC subtractive manufacturing capabilities. The developed techniques could be applied to personnel armor systems and vehicles.*





Manufacturing steps: Laser machining ceramic tiles and simplified lamination.

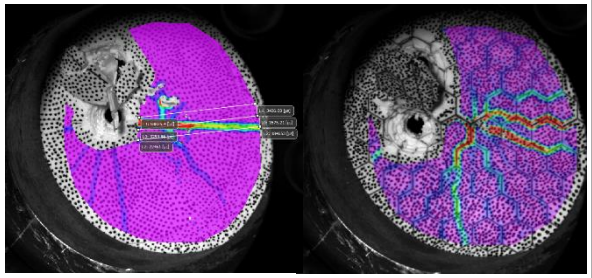
Multi-hit capability



Plain ceramic

Architectured ceramic

DIC image: crack propagation

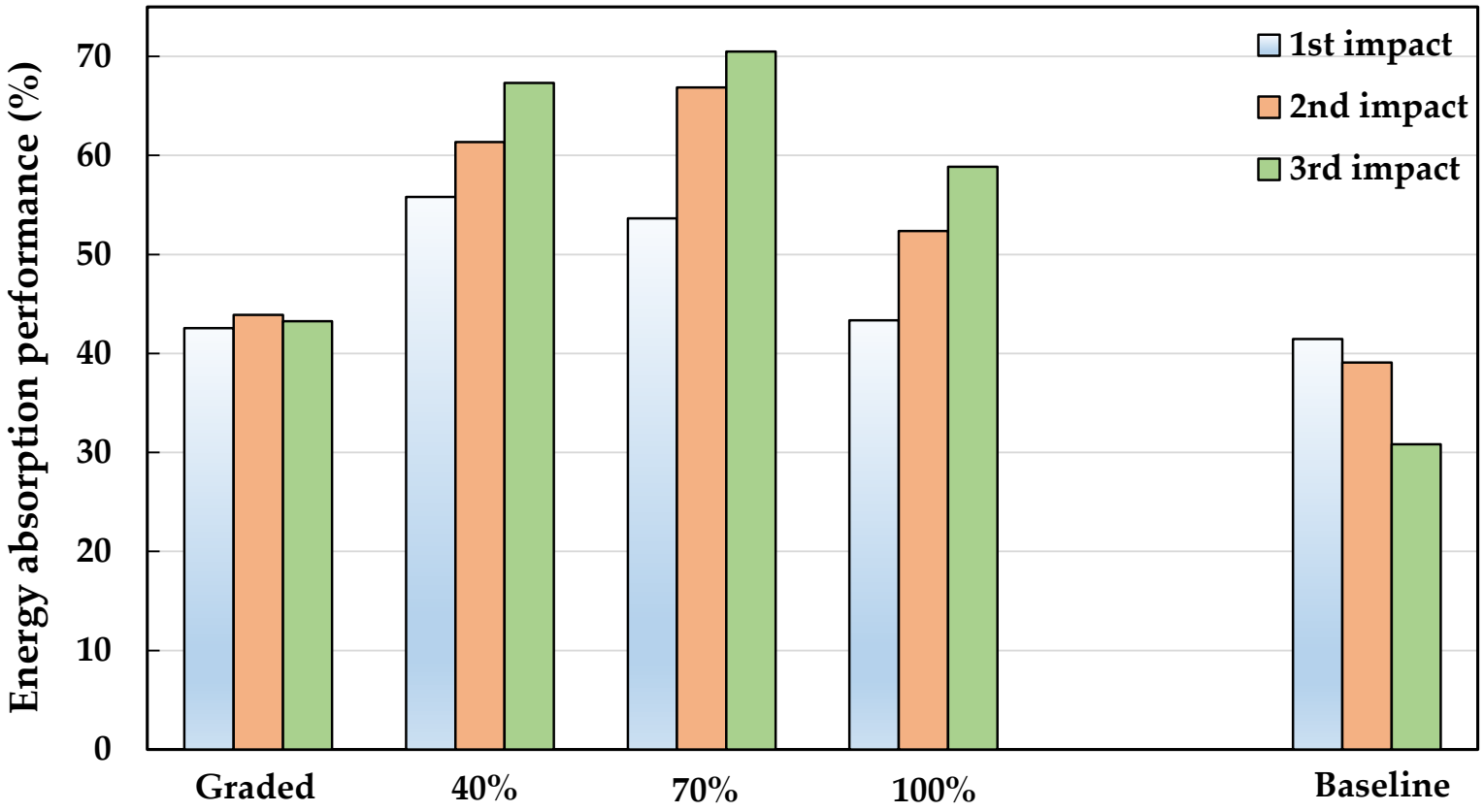


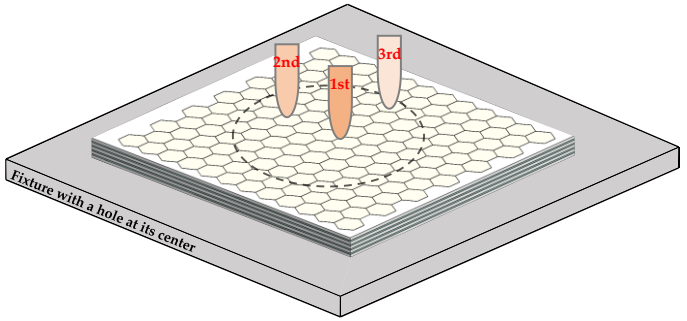
Plain ceramic

Architectured ceramic

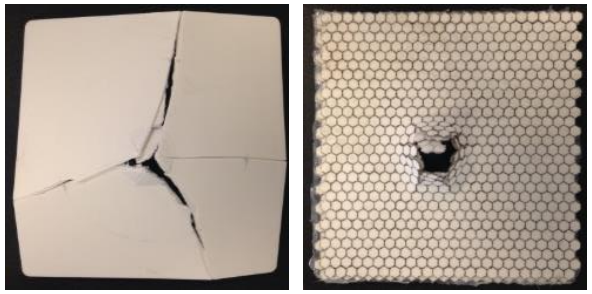
H. Yazdani, et al., Extreme Mechanics Letters 2020.

Partially vs. Fully Cut Architectures – Energy Absorption





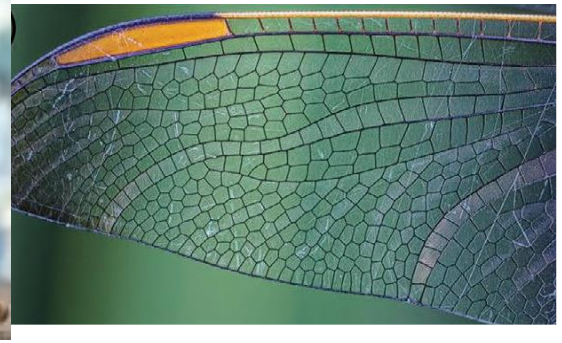
Multi-hit Capability



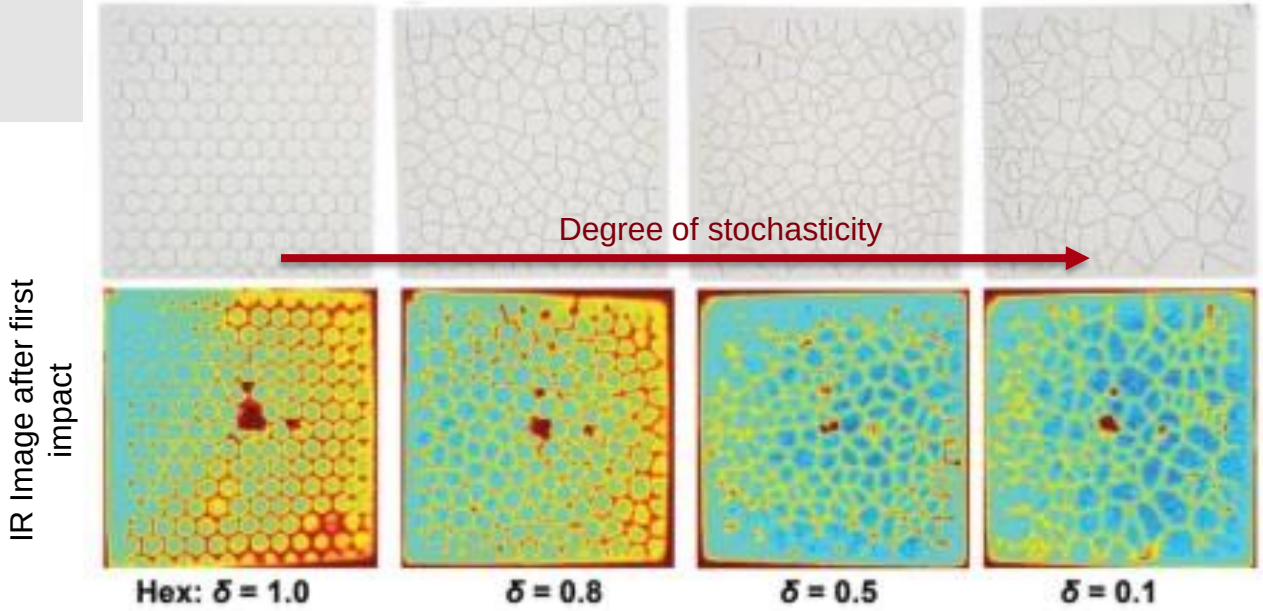
Yazdani et al, Extreme Mechanics Letters, 2020

Stochastic Designs of Architected Ceramics

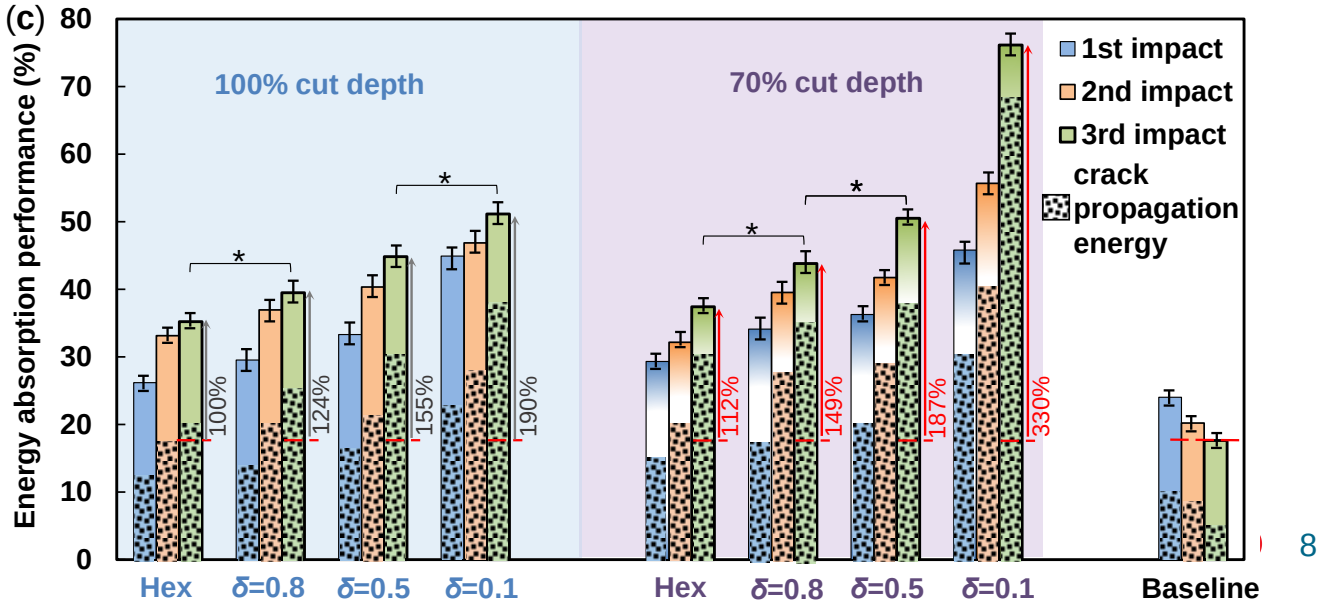
Armadillo



Dragonfly wing

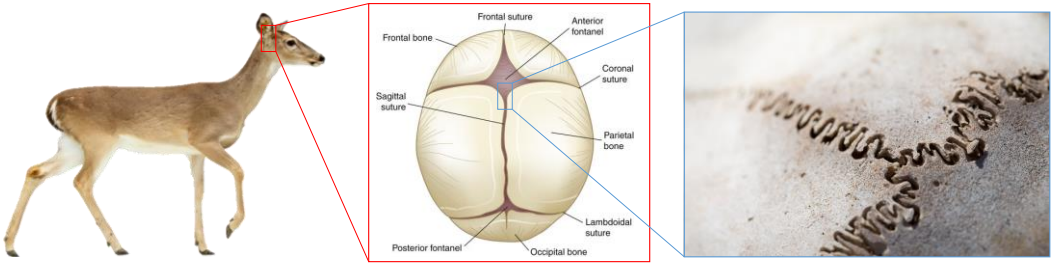


- ✓ Toughness enhancement scales with the degree of stochasticity
- ✓ Up to 330% toughness improvement compared to the baseline
- ✓ Further demonstration of enhanced protection

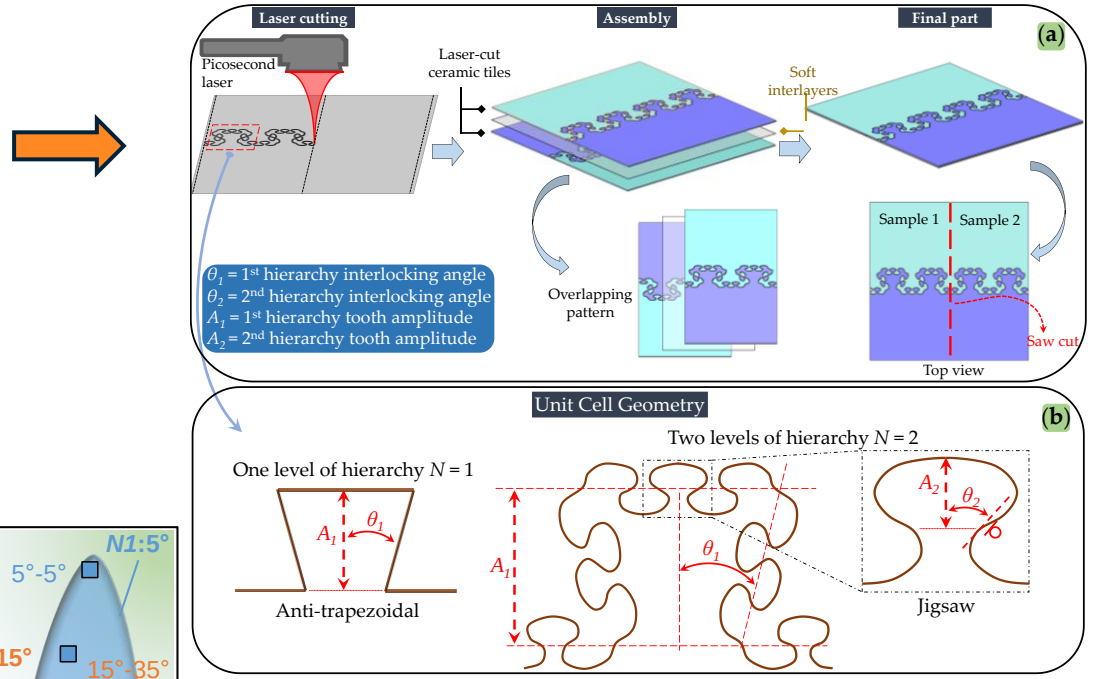


Yazdani et al., Advanced Functional Materials (2021)

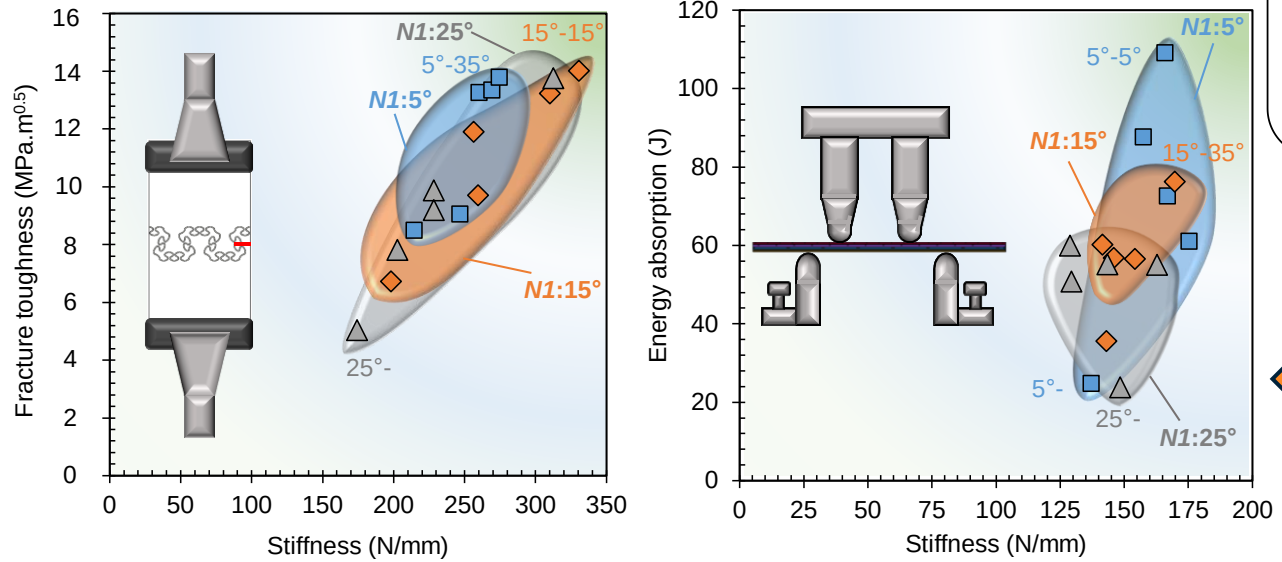
Suture Ceramics for Flexible Ceramics



White-tailed Deer

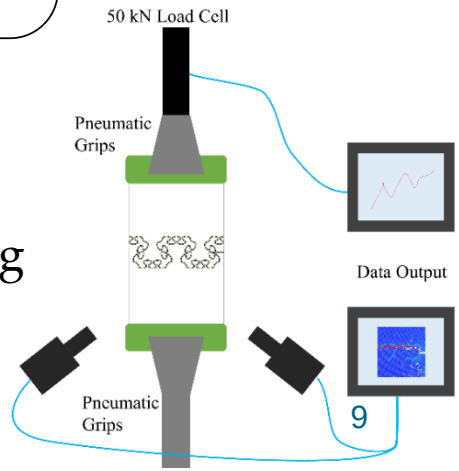


Design & Manufacturing

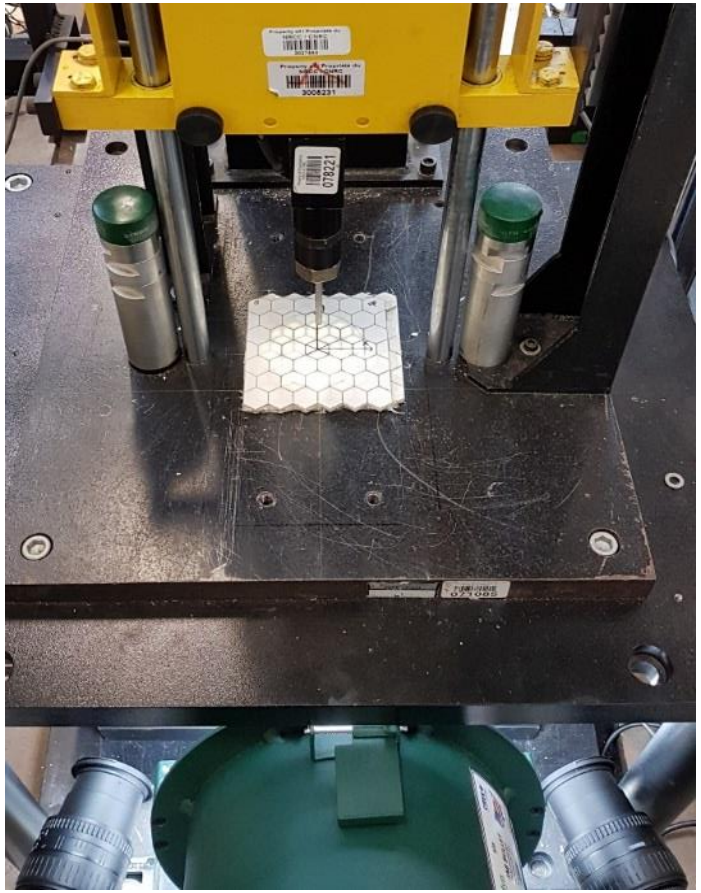


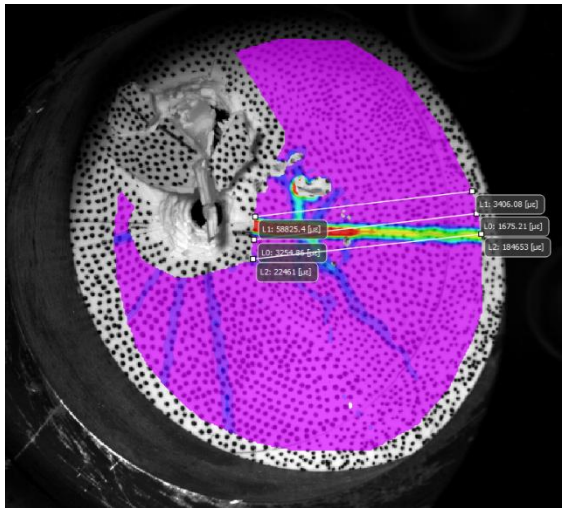
Katz, Z. et al., Advanced Materials Interfaces, 2023.

Testing



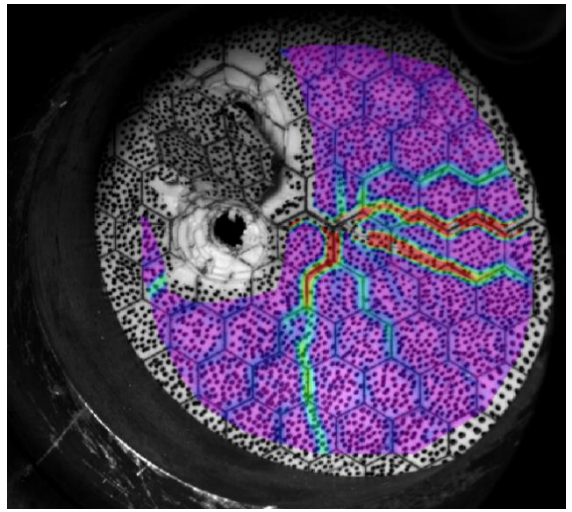
Experimental Mechanics: Digital Image Correlation (DIC)



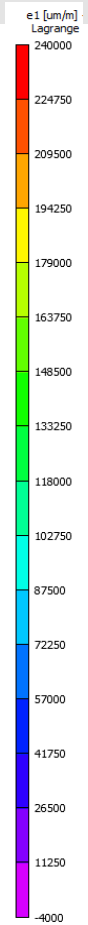


Plain ceramic

Catastrophic



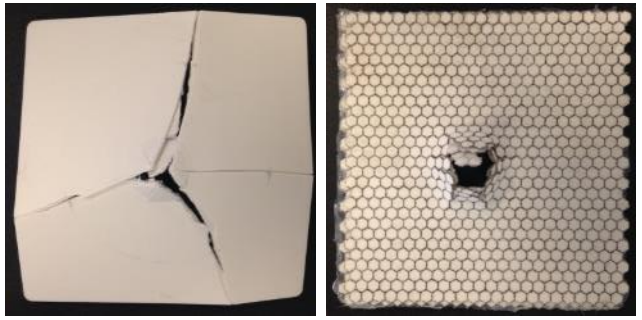
Architectured ceramic
(L = 5 mm)



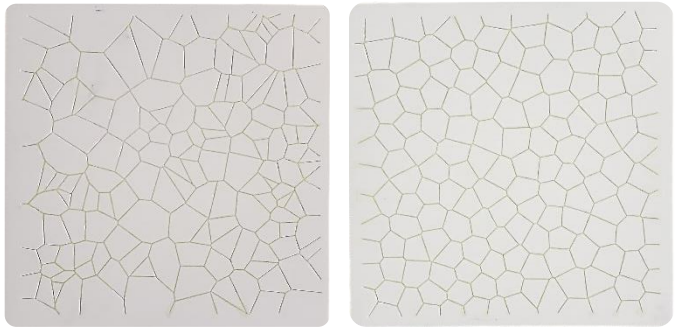
- To capture the failure initiation and propagation during the loading
- The deformation is spread in the architectured ceramics unlike the plain ceramic

Concluding Remarks

- ✓ Bio-inspiration: an approach to overcome brittleness of ceramics
- ✓ Deep, high precision subtractive manufacturing of industrial ceramics: a necessary step towards fabrication of toughened ceramics
- ✓ A combination of finite element analysis and experimental approaches: a cost effective/quick solution to identify optimal designs for a target application
- ✓ Fabrication of single-layer and multi-layer architected ceramics based on subtractive manufacturing



Demonstration of Multi-hit Capability



$\delta = 0.1$ $\delta = 0.8$

Stochastic multilayered ceramics

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M. Hojjati
F. Shadmehri

Behnam Ashrafi
Senior Research Officer
AMTC, Montreal, QC
Behnam.Ashrafi@nrc-cnrc.gc.ca