Tough Bio-Inspired Architected Cement-Based Materials

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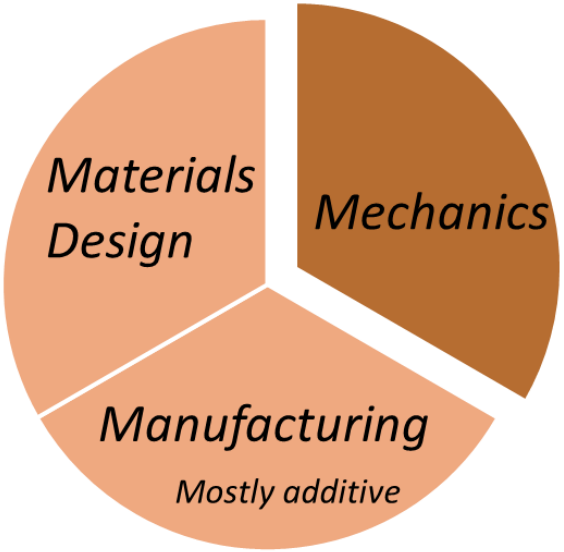
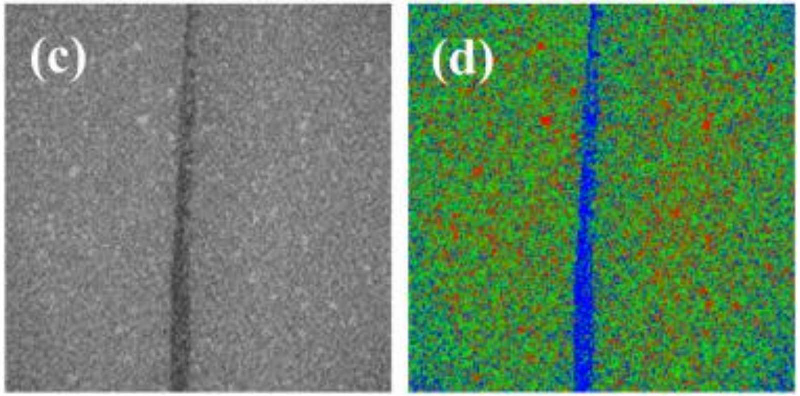


Additive Manufacturing of Cement-based Materials

- Layer-wise additive manufacturing (3D-printing) of cement-based printing represents an innovative manufacturing paradigm in the construction industry.
- This layer-by-layer process produces interfaces, heterogeneities and defects which govern the overall mechanical performance. Is this a challenge or opportunity?

The World's Largest 3D Printed Concrete Bridge is Completed in Shanghai (2021)



Moini – Cem Conc Res. (2021)

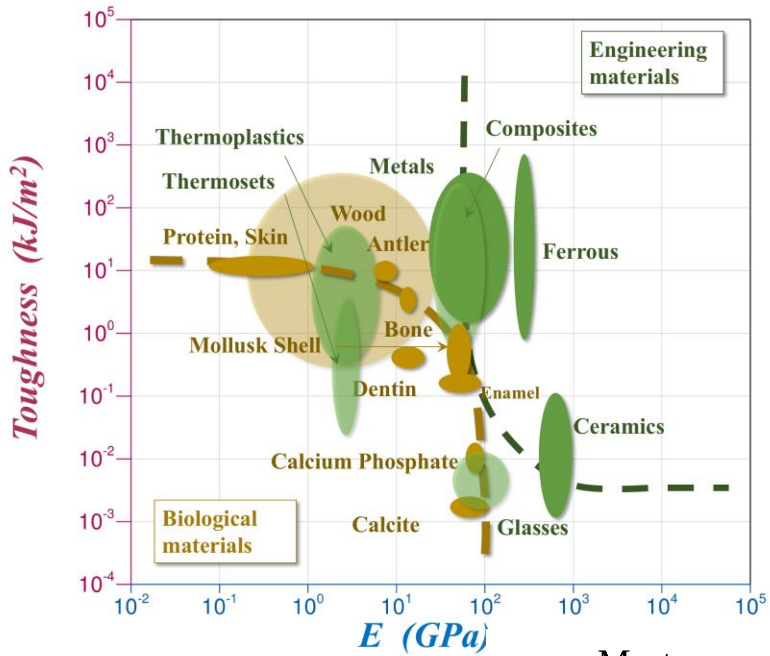
Architected Cement-Based Materials: Why?

It allows to develop prototypes for :

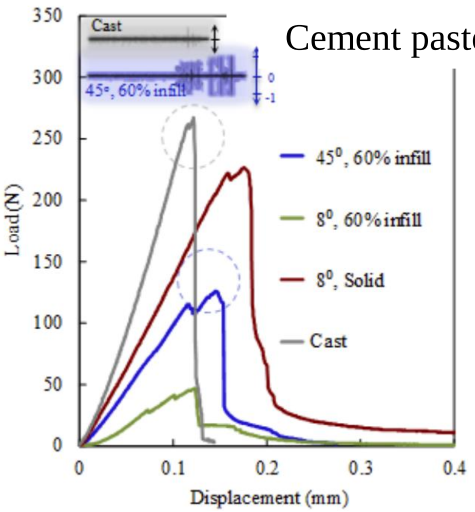
- ➢ Evaluating the intertwined Processing-Structure-Properties relationship
- ➢ Achieving novel **material architectures that are:**

i. Engineered to have **new properties**

ii. Properties not offered by a single material or architecture alone

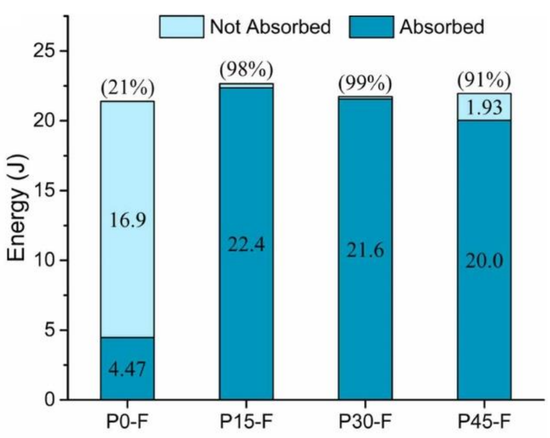


Cement paste



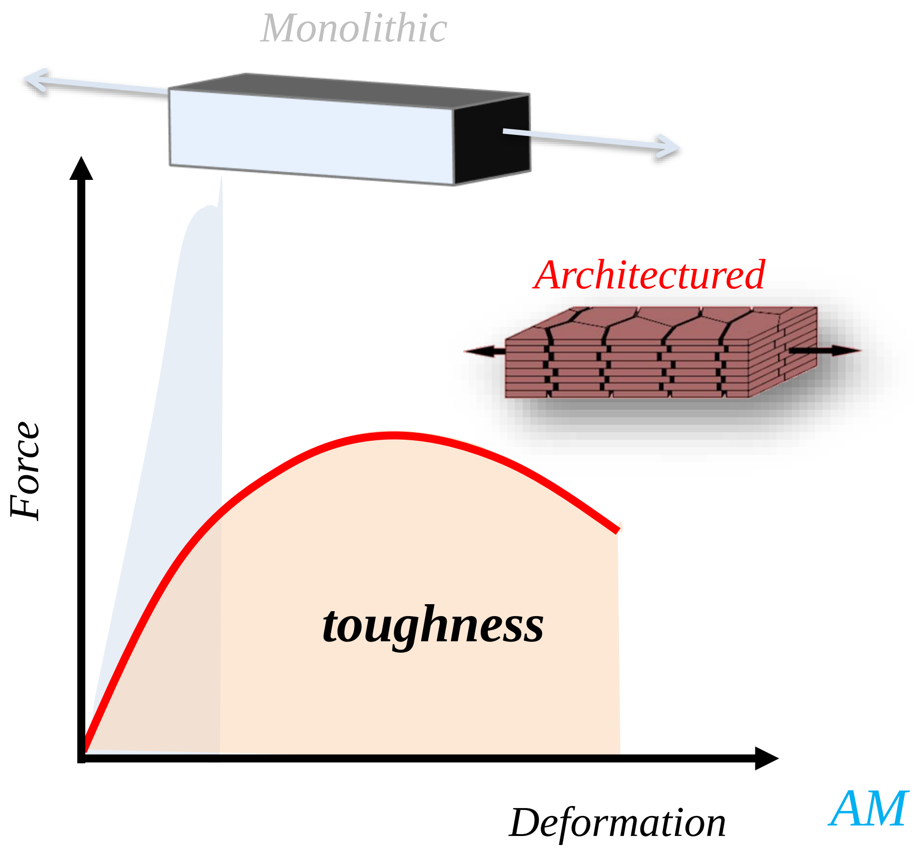
Moini et al. Adv. Mater. (2018)

Mortar

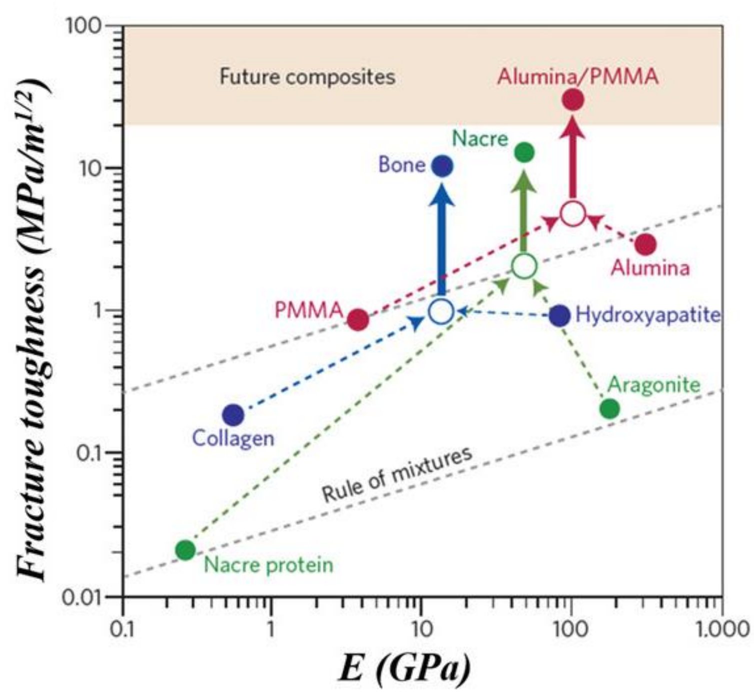


Liu et al. Add Manu (2022)

Can Bioinspired Design Contribute to Toughening of Mortar?



Control of mechanical properties through clever architectures and interfaces



Huang et al. (2018)

Problem:

AM process leaves behind processing-induced "Weak Interfaces"

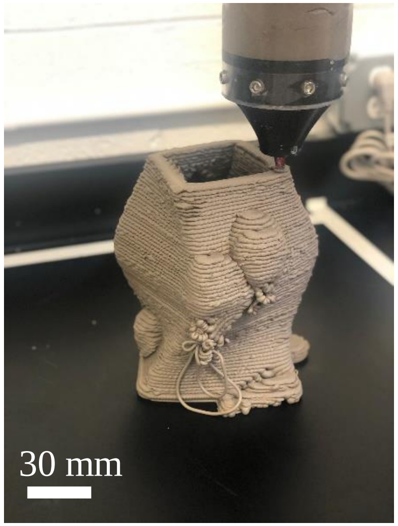
Question. *Can we harness the interplay between the weak interface and their spatial arrangement (architecture)?*

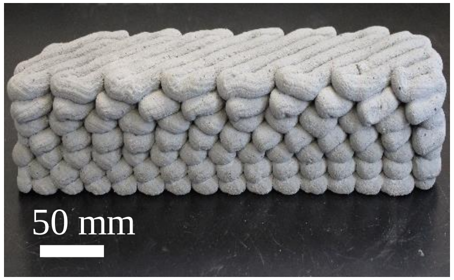
Selective Compliance Assembly Robotic Arm (SCARA)

- A Scara printer with two articulated single-joint arms was used to control the position of print head.
- Commonly used for clays and concrete.
- Calibrated and integrated the processing parameters with clay.
- Mortar ink development: 0.6 S/C ratio, VMA, HWRWA, etc., tailored for early-age deformations and specimens buildability.
- Relevant nozzle sizes were chosen.

3D Potter V4

Nozzle diameter: 8 mm
Layer height: 8 mm

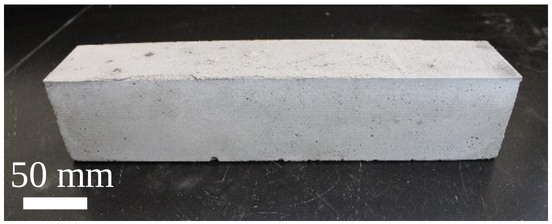




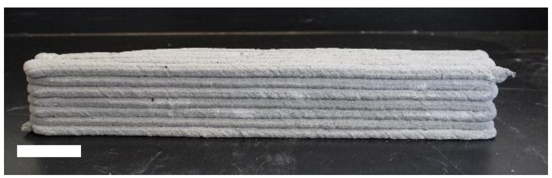
Prismatic mortar beam with a bioinspired design

Designs of Materials Architecture

Reference Samples



Cast mortar

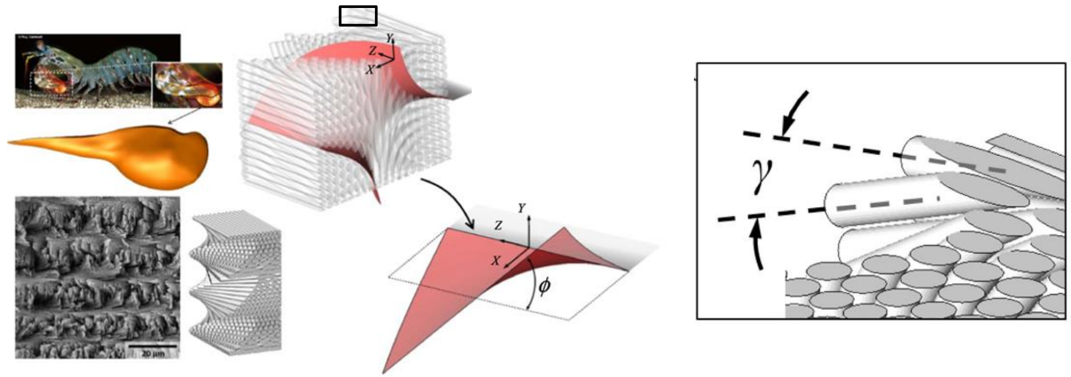


Lamellar architecture
Filament characterization

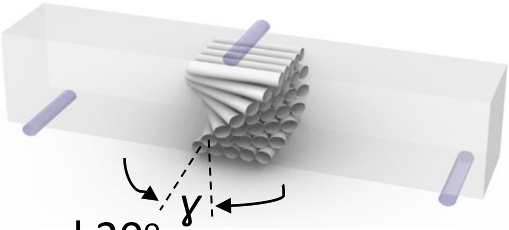
Lamellar architecture
Interface characterization

Architected samples using Bioinspired designs

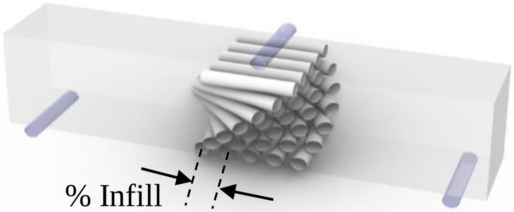
Bouligand architecture



Suksangpanya et al. (2017)



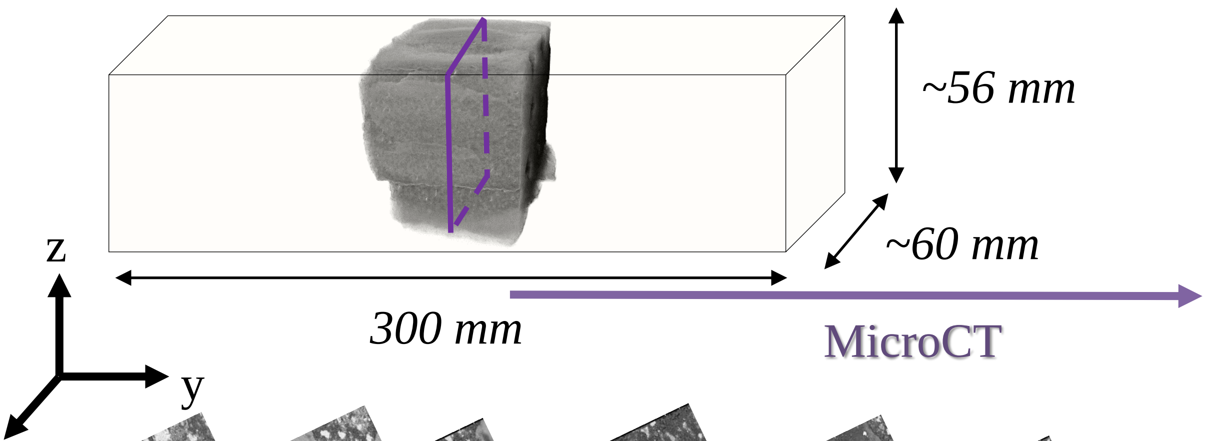
Solid Bouligand, γ = 1, 5, **10°**, and 20°

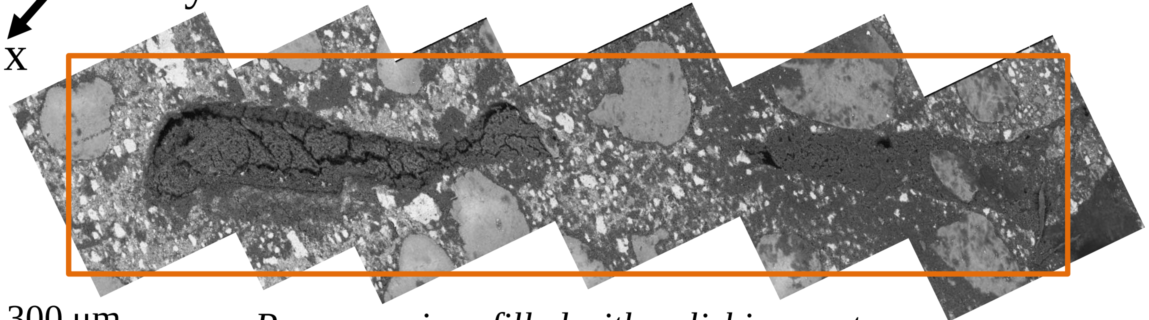


Cellular Bouligand, γ = **10°**

Qualitative characterization of intact lamellar architecture

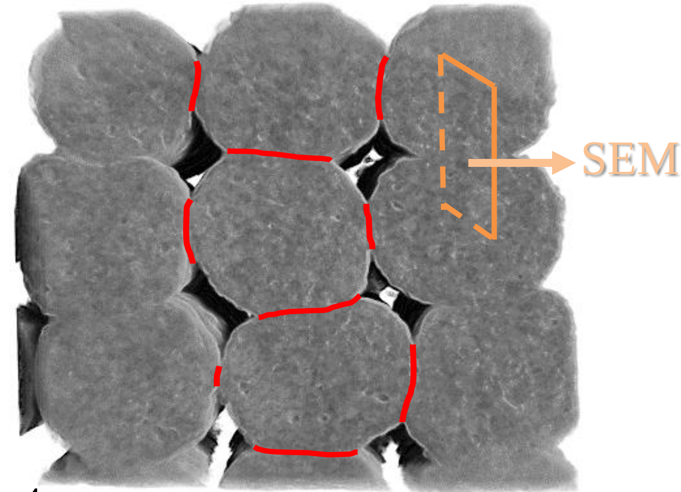
ROI = 44 × 25 × 36 mm





300 µm

Porous regions filled with polishing paste



XZ Plane

XZ Plane

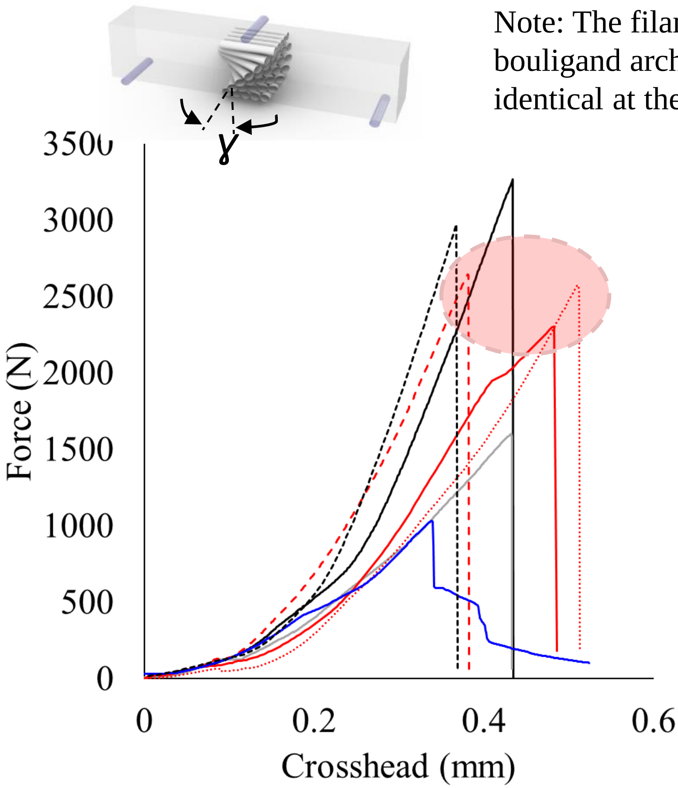
- **MicroCT 0.4x** shows large channels/pores (~ 4 *mm*) entrapped in between filaments.
- **SEM** highlights the highly porous interfaces between filament.

Role of Architecture on Mechanical Response – Strength

- Unnotched mortar prisms were tested under **3PB**.
- Specimens: 300 mm × 60 mm × 56 mm.

- This design allows for 7 layers (filament height is 8 mm).
- Modulus and strength were quantified for cast, bouligand, and cellular bouligand.

Note: The filament orientation of bouligand architectures and interface are identical at the bottom layer.



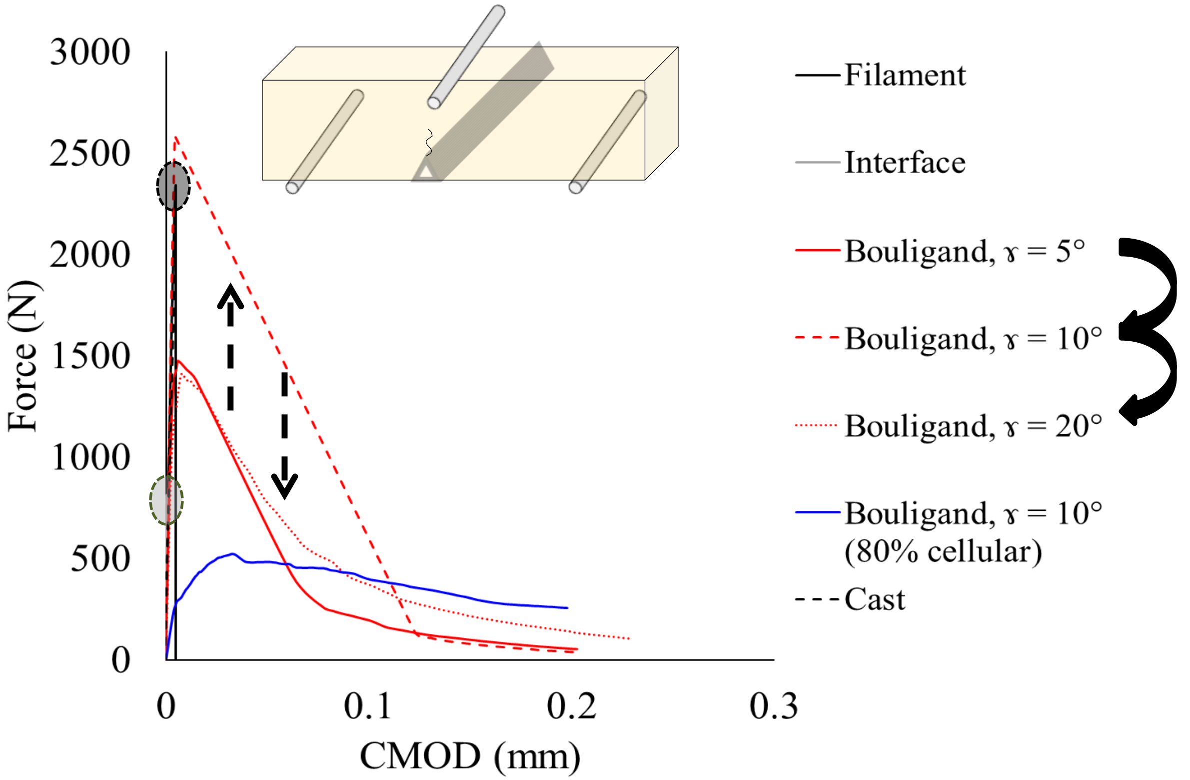
❖ Increased compliance was in interface and bouligand architectures compared to their filament/cast counterpart.

❖ Interface was about three times weaker than filament.

❖ No sacrifice of strength for solid bouligand.

Role of Architecture on Fracture Response – Toughness

- Notched mortar beams were tested under **3PB**.
- **J-integral** versus crack extension was calculated.
- K_{IC} and K_{JC} was calculated based on elastic and plastic components of J-Integral.



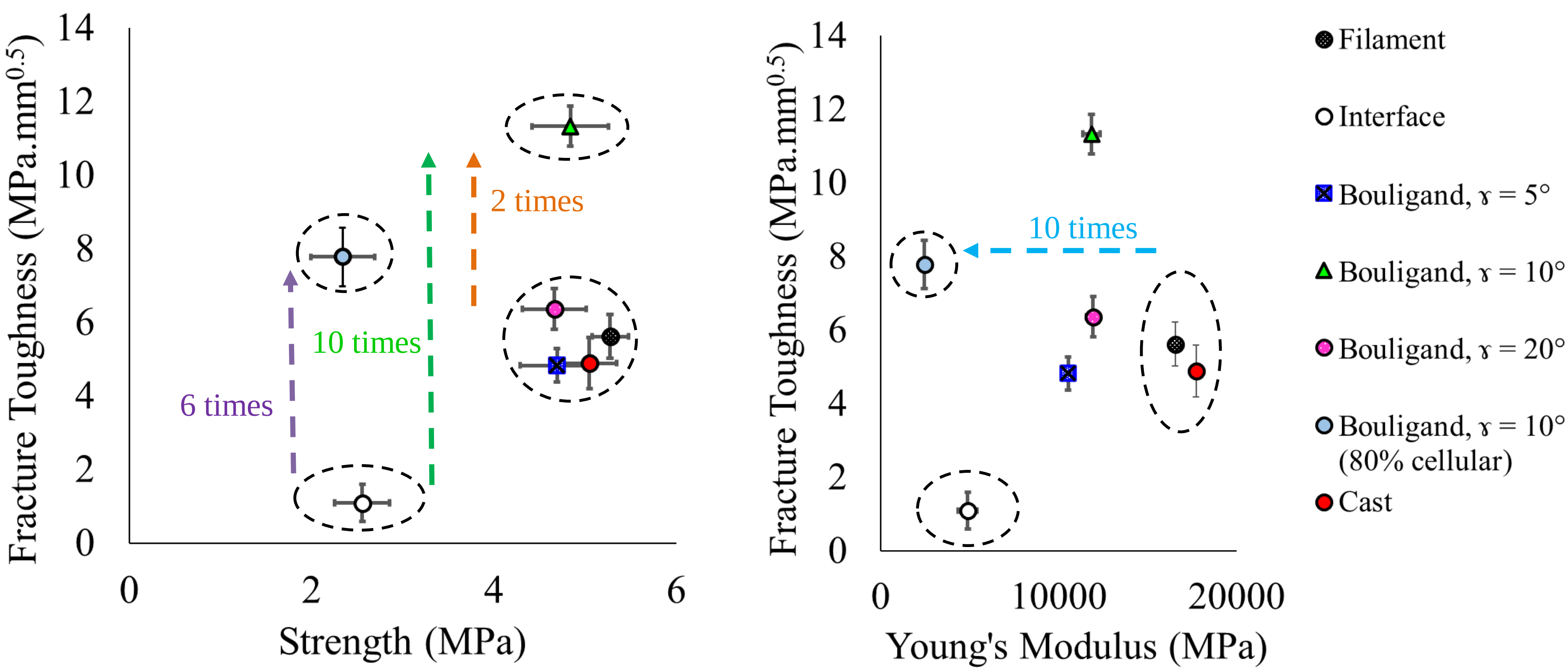
❖ $K_{IC} = K_{JC}$ for cast, filament, and interface samples.

❖ Similar K_{IC} was quantified for filament and cast, while interface shows a lower K_{IC}.

❖ Bouligand architectures receive significant contribution from plastic component.

❖ K_{JC} of Bouligand, $\gamma = 10^o$ was significantly larger than any other.

Fracture Toughness and Compliance Increases by Architecture



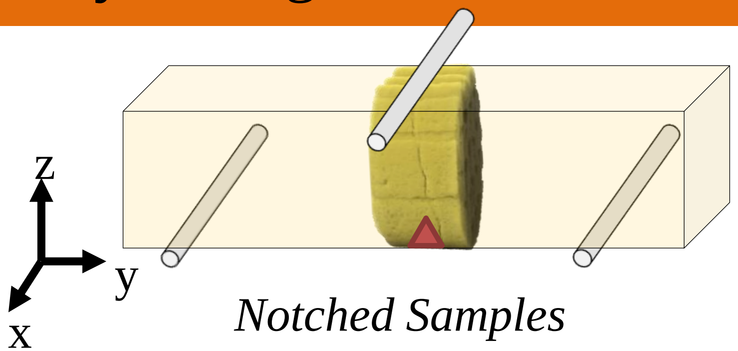
Fracture toughness of solid Bouligand, γ =10° is

- **10-times higher** than interface counterpart and
- **2-times higher** than printed unidirectional filament and cast counterpart.

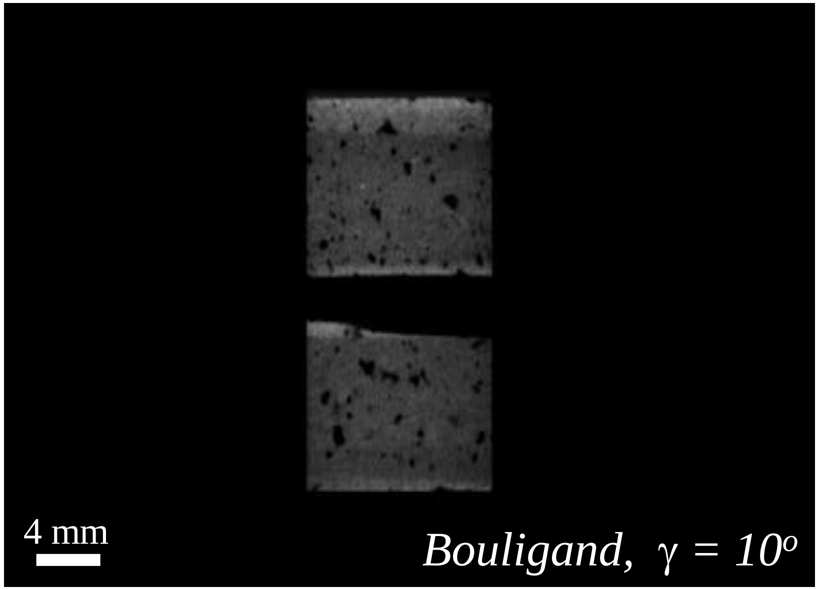
Cellular Bouligand, γ =10° is

- **6-times tougher** than interface counterpart
- **10-times more compliant** than unidirectional filament counterparts.

Why Bouligand Architecture Makes the Sample Tougher?



Notched Samples

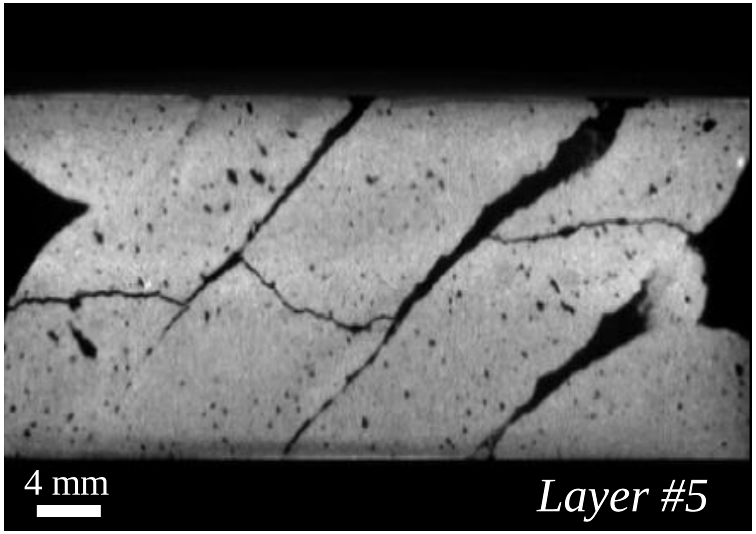


Bouligand architecture promoted damage mechanism such as:

- ❑ Interfacial cracking
- ❑ Crack twisting

Therefore, it allows for:

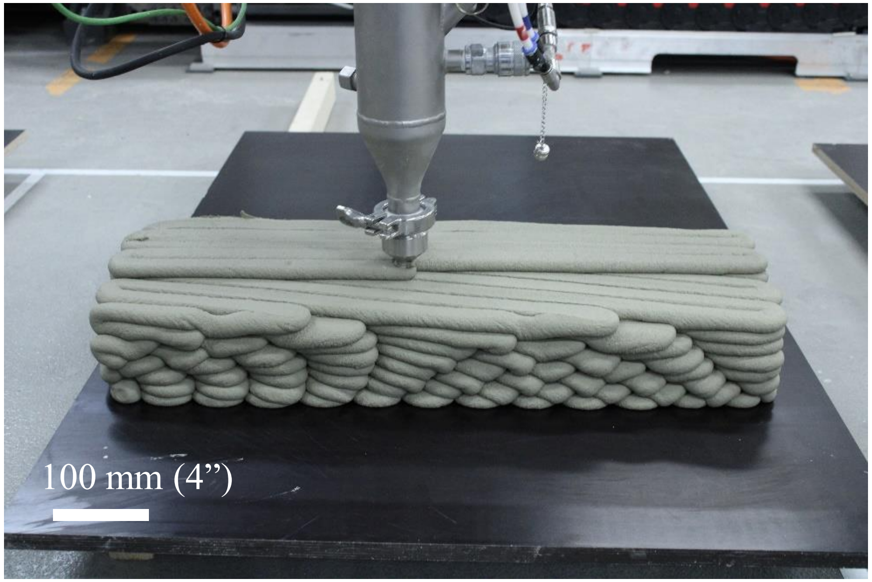
- ❑ Controlled fracture and crack growth at interface and Enhanced energy dissipation and toughness



We can Infer: *Bioinspired Bouligand Architectures* + "*Weak Interfaces*" promote interfacial damage and allow for *enhancing the fracture response.*

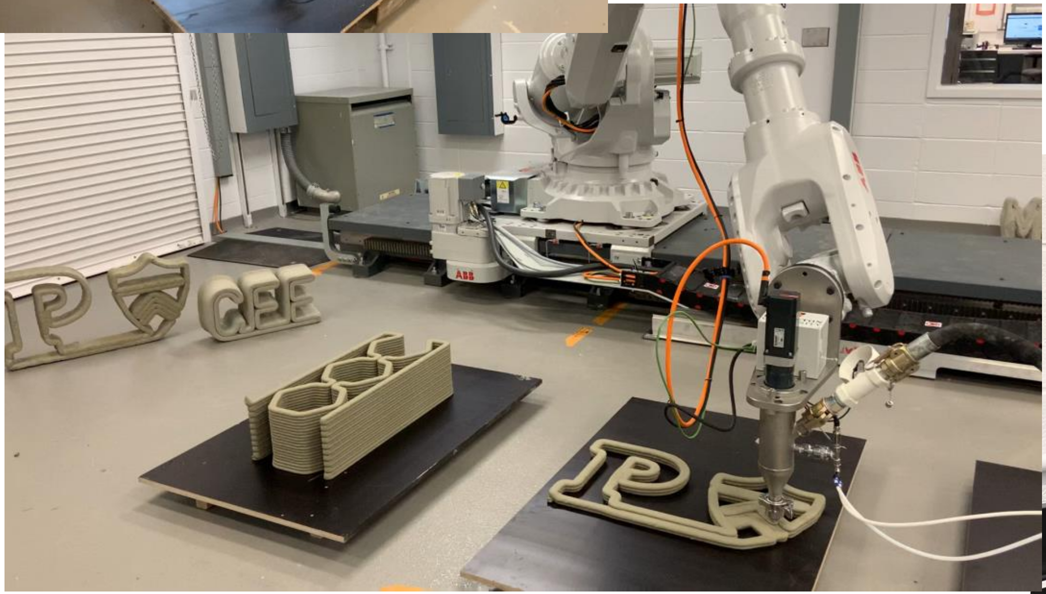
Scale-up the Findings via Robotic Processing Platforms

- A 7-axis robot arm capable of **real-time proportioning** of raw-material and **in-situ monitoring of processing parameters (Q, P, T)** has been developed.
- Several material compositions are being development for intricate architectures.
- Design freedom of meter-scale samples with controlled architecture.
- All to **scale up** the understanding the synergy between interface and architecture.

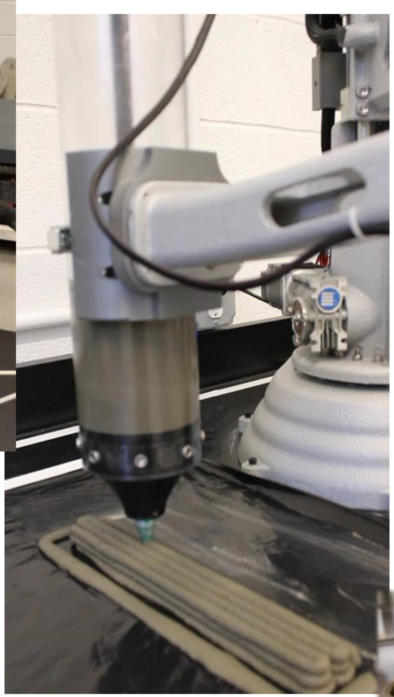


Recent efforts to scale up – mm to m

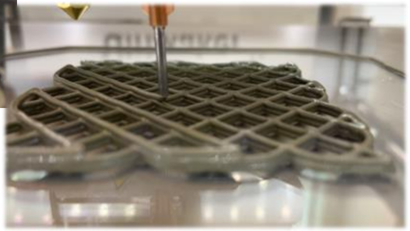
Robotic (IRB 4600)
Mono-extrusion



Robotic (IRB 6700)
Two-component extrusion



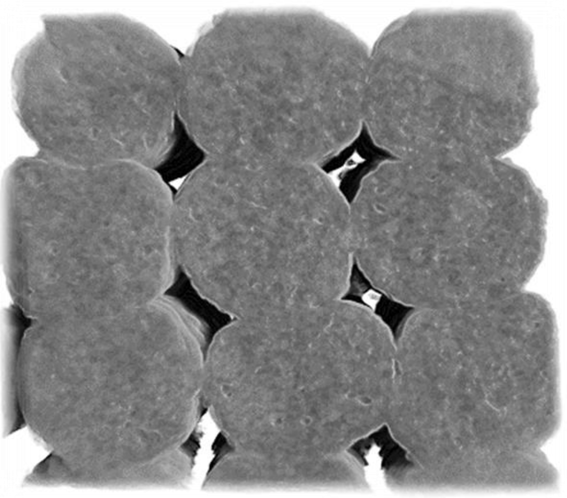
Scara V4
Mono-extrusion

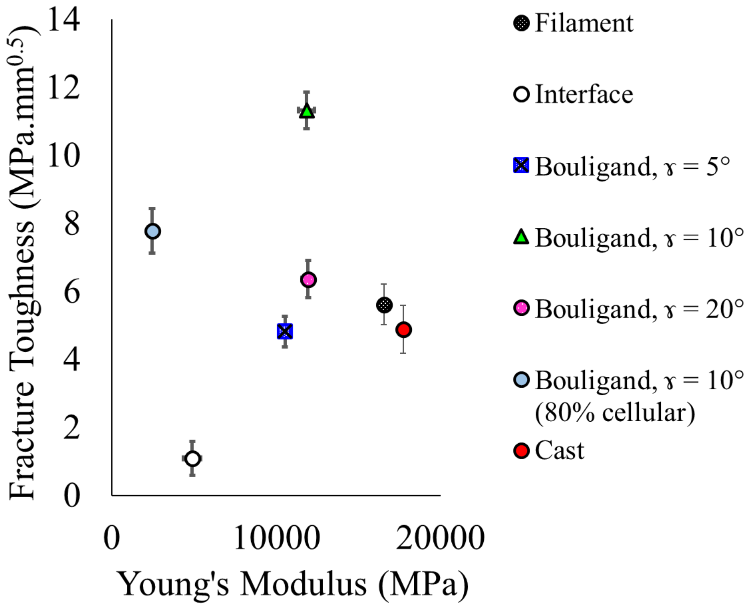


Conclusions and Findings

We studied the effect of a bioinspired architecture (Bouligand) controlling the spatial arrangement of weak interfaces on mechanical and fracture properties:

- *Promotion of unique* ***damage mechanisms****, such as <u>interfacial cracking</u> and <u>crack twisting</u>*
- *Increase fracture toughness by* ***10-times***
- *Increase of compliance by* ***10-times***





Patterning material is free of cost!

Drawing patterns from nature could inform new design approaches for tougher and resilient construction materials and structures

Acknowledgment

- ➢ *Engineering Fracture Response and Transport Behavior in Additively Manufactured, Layered Concrete Materials*

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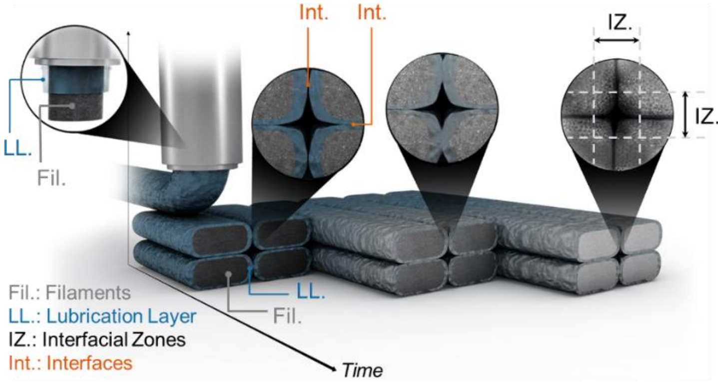
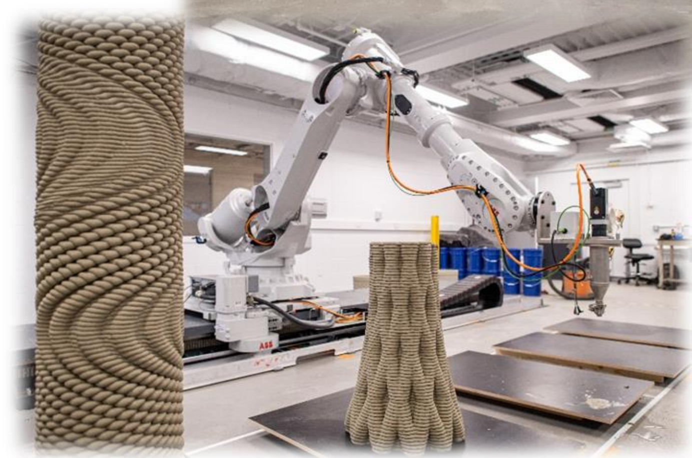
In collaboration with OSU

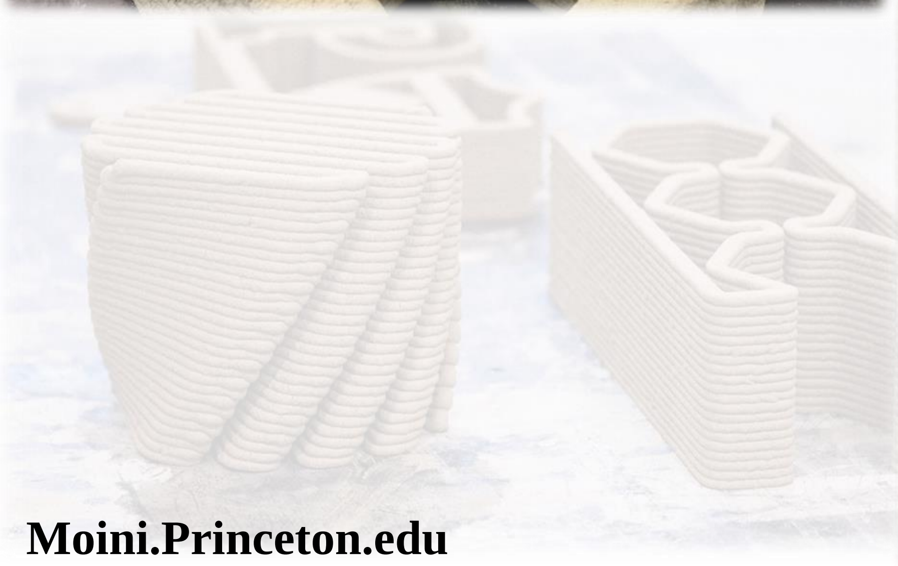


- ➢ *Princeton University, Department of Civil and Environmental Engineering (CEE)*



Thank you

Questions?



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