# Mechanics of Tough Cortical Bone-Inspired 3D-Printed Architected Cement-Based Materials

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PRINCETON UNIVERSITY

aci CONCRETE CONVENTION
April 02, 2023

ARCHITECTED MATERIALS AND ADDITIVE MANUFACTURING LAB

# Motivation: There is a need for Resilient Civil Infrastructure


- Current Infrastructure in the U.S. need improved resilience

NAE GRAND CHALLENGES FOR ENGINEERING™

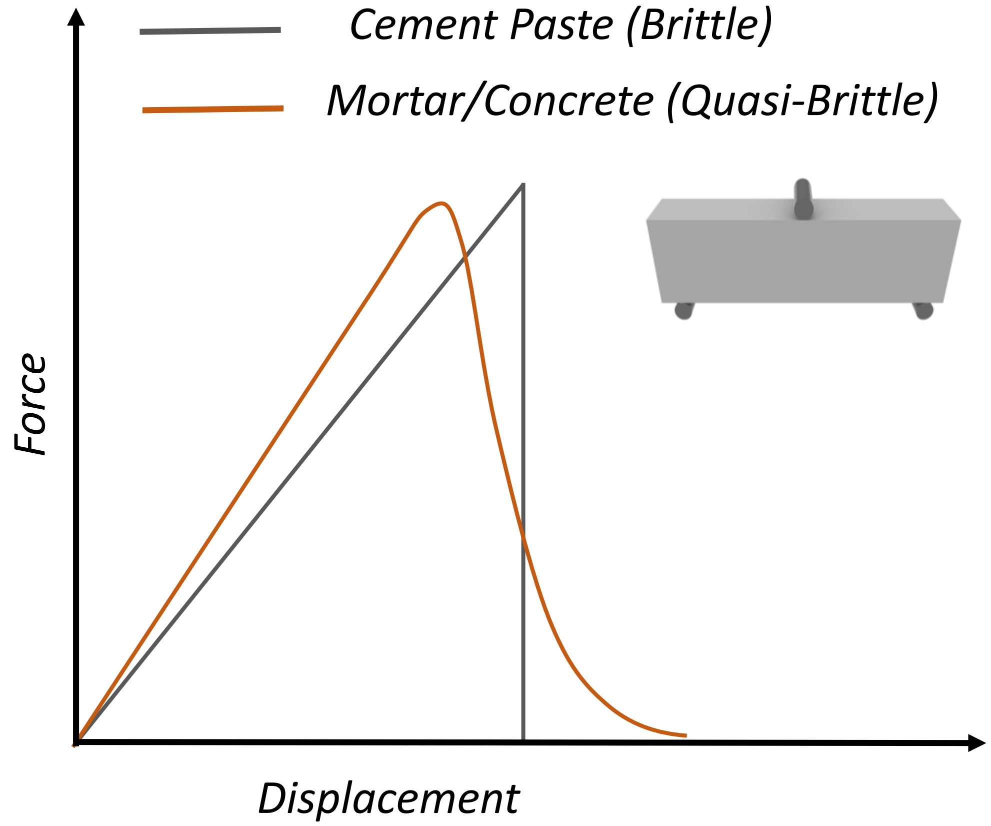
- Restore and Improve Urban Infrastructure

*Miami Bridge Failure (2018)*

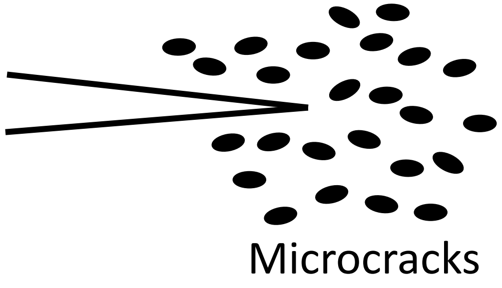
*Champlain Towers South Failure (2021)*

***Q. How do we quantify resiliency in concrete?***

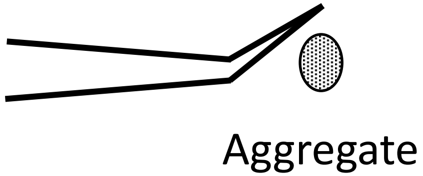
# Background: Damage and Fracture Mechanics of Concrete



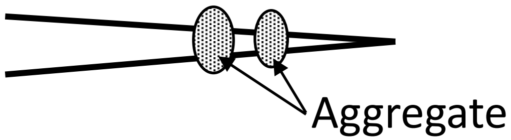

*Crack Shielding*



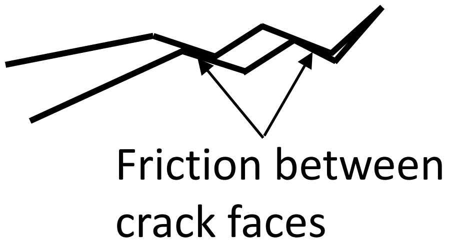

*Crack Deflection*




*Aggregate Bridging*



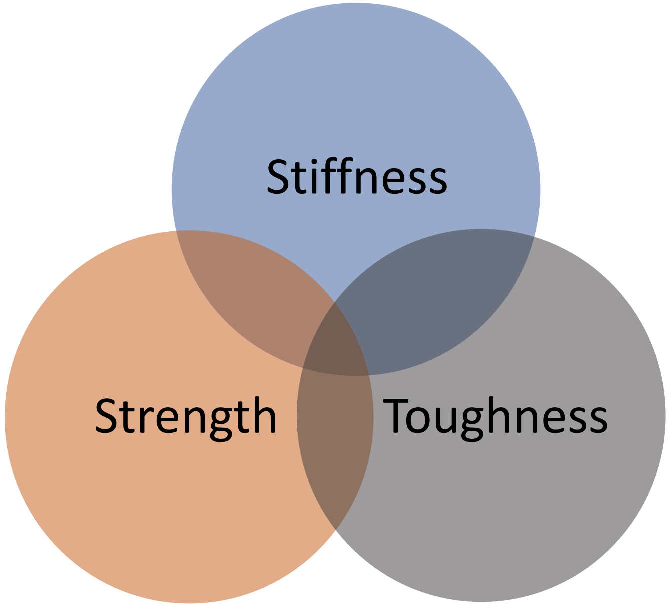

*Surface Roughness-induced closure*

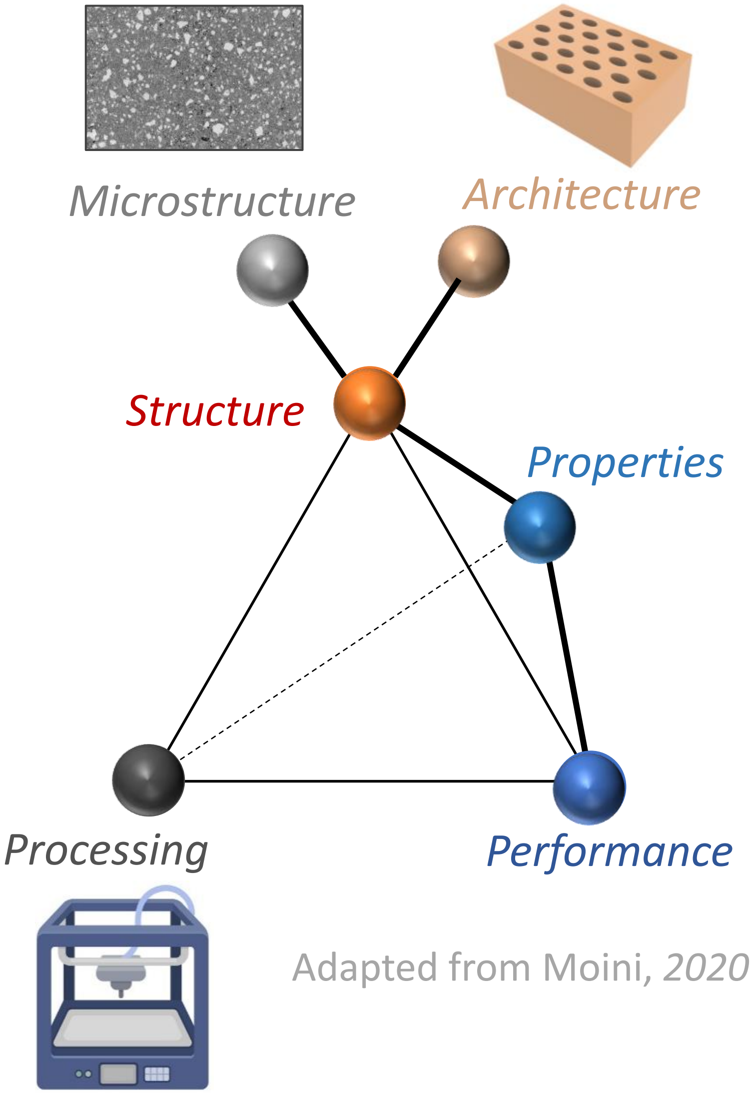



***Q. Can we develop tough concrete without changing composition?***

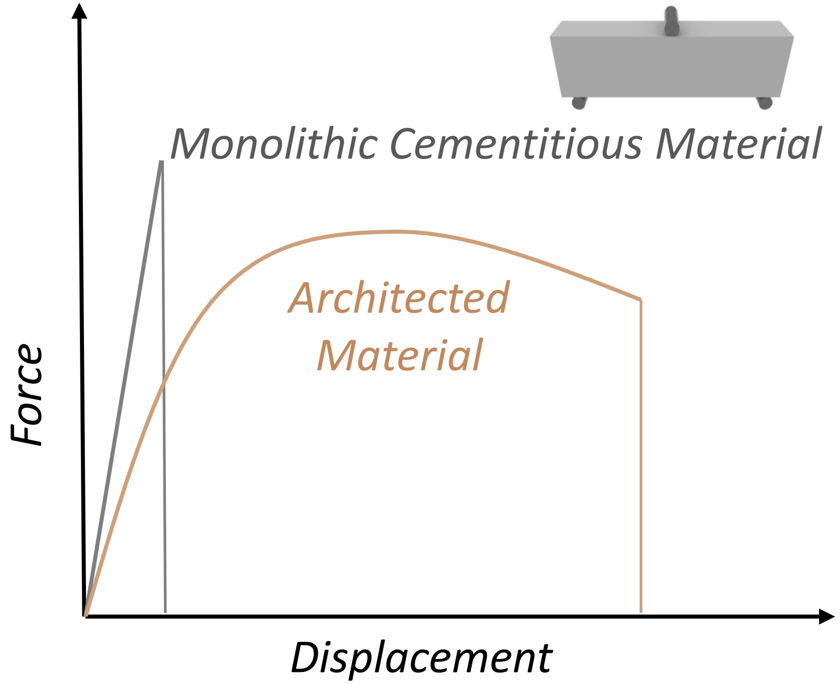
Adapted from Shah and Ouyang, 1994, Annu. Rev. Mater.

# How Do We Engineer Concrete to Have Damage-Resistance?

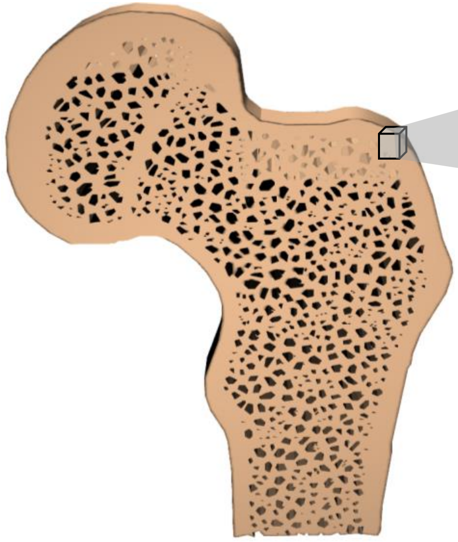


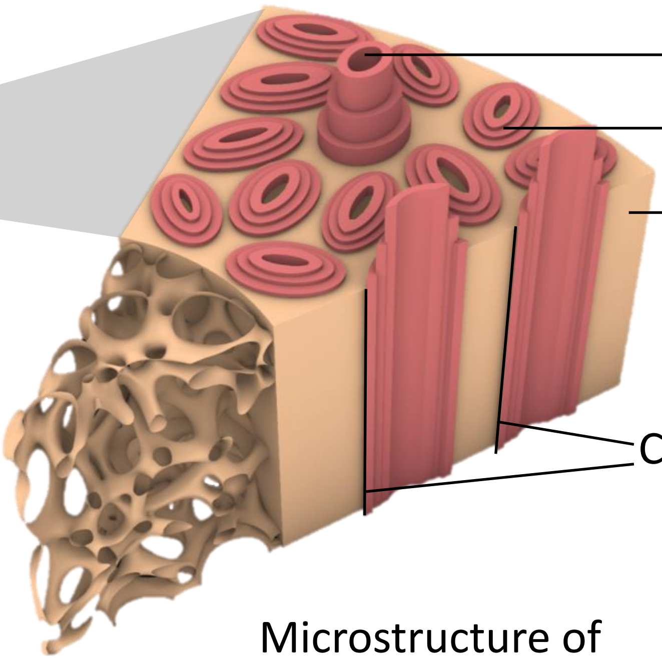

Adapted from Moini, *2020*



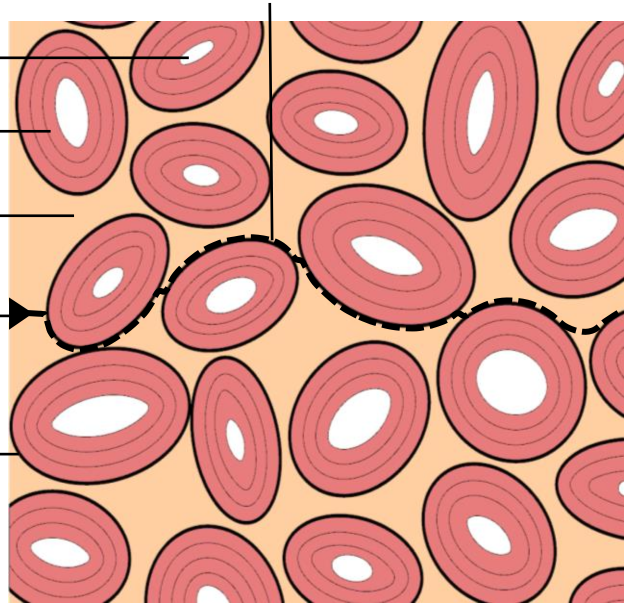
# Can we Learn From Nature? Let's Look at Microarchitecture of Bone



Schematic Cross-section of
Human Femur Bone




Microstructure of
cortical bone




Toughening Mechanism.

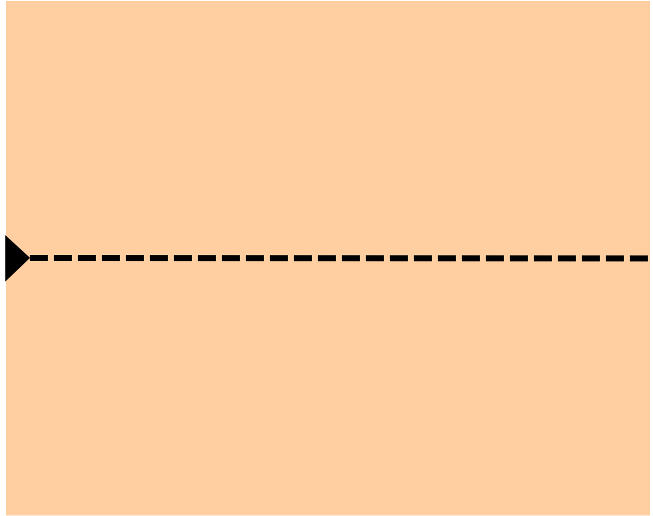
- Cement line – crack interaction
- Crack deflection through cement line

- Cortical bone forms tough outer shell of human femur bone
- Porosity – 3.5% [2], Osteon – 45-65% [3]
- Cement lines are 10 times weaker than osteons [4]

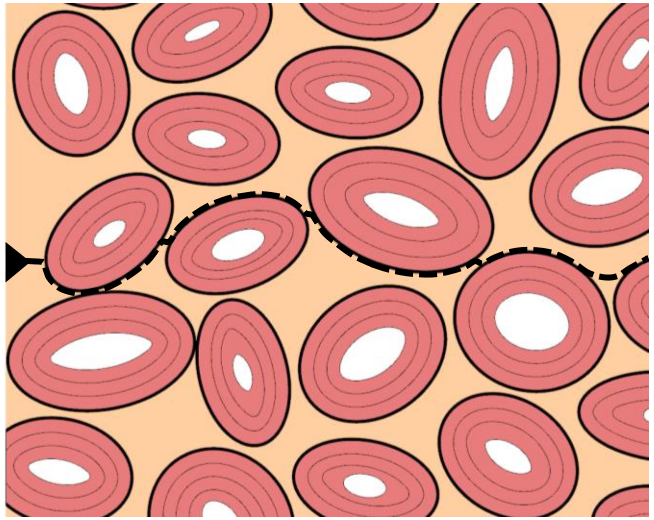
1. Nalla, R.K. *et al.*, 2003. Nat. Mater.
2. Renders, *et al.*, 2007. J. Anat.
3. Vahle *et al.,* 2015. In The Nonhuman Primate in Nonclinical Drug Development
4. Dong *et al.,* 2005, Mol. Cell. Biomech.

**Objective.**

*To engineer the bone-inspired* ***toughening mechanisms*** *in* ***brittle*** *cementitious material using tubular architecture*



*Brittle failure in monolithic cast*

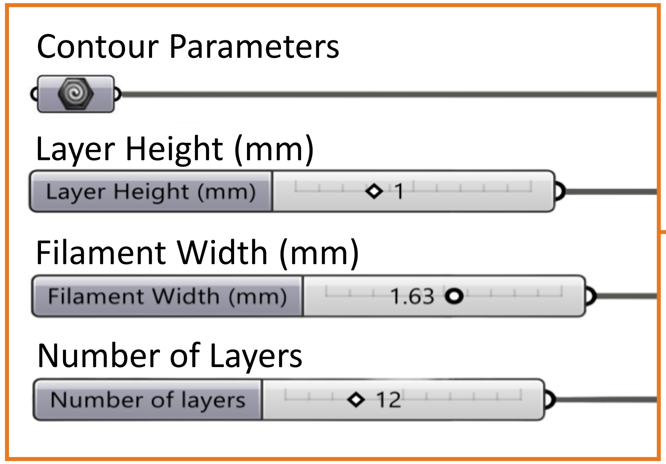


*Crack deflection in tubular architected material*

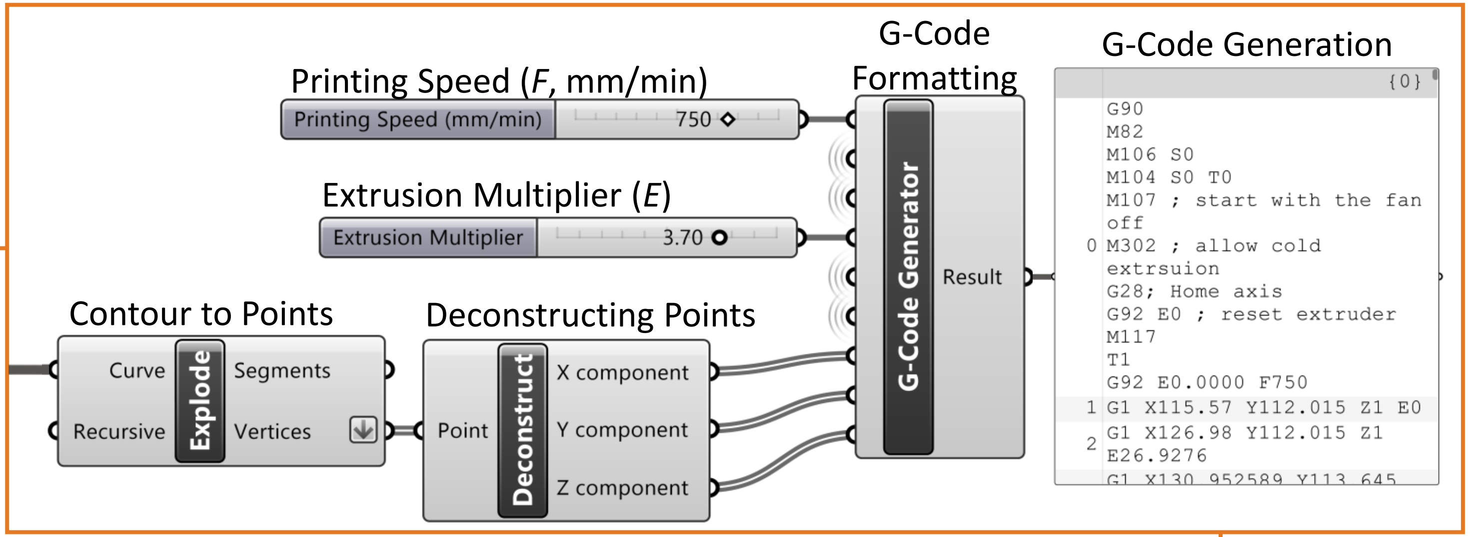
# How Do We Fabricate these Tubular Architected Cementitious Materials?

## Direct 3D-printing the Architecture:

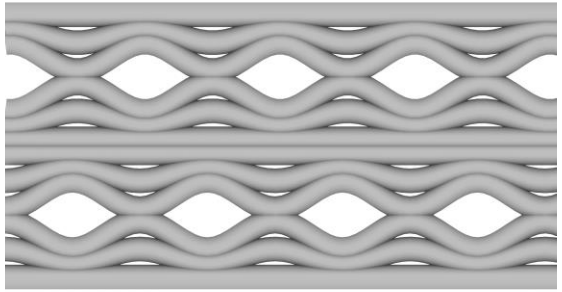
### Defining Input Geometrical Parameters



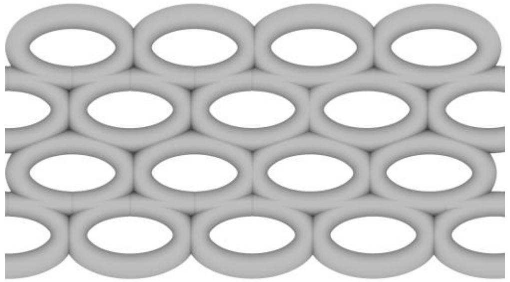

### Generating G-Code from the Contour




Graded Sinusoidal Contour

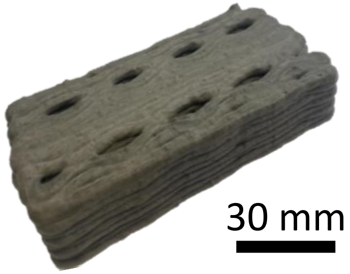


Elliptical Contour

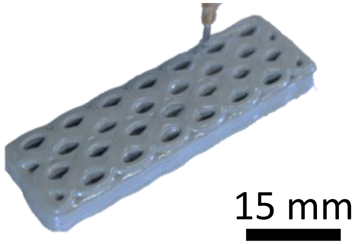


Parametric Contour

Graded Sinusoidal Toolpath



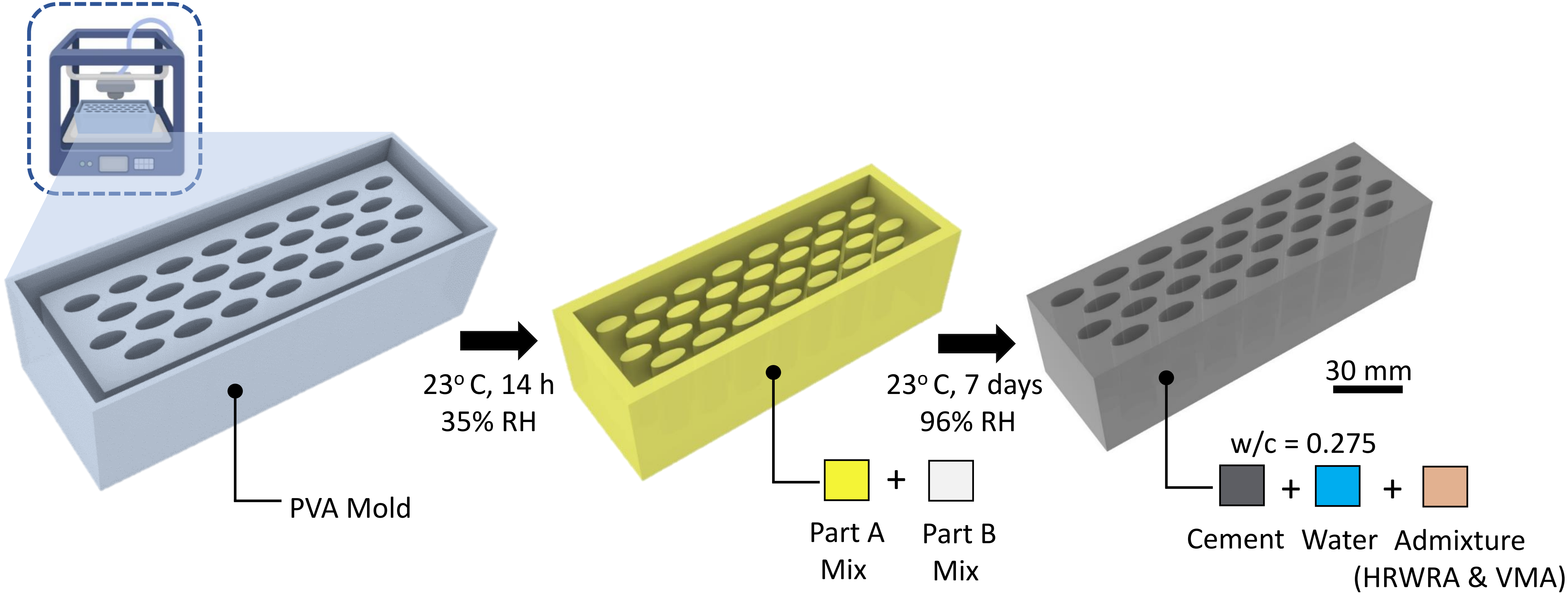

Elliptical Toolpath




3D-printed tubular architected materials

# How Do We Fabricate these Tubular Architected Cementitious Materials?

**Hybrid Cast-Additive Manufacturing Process:**



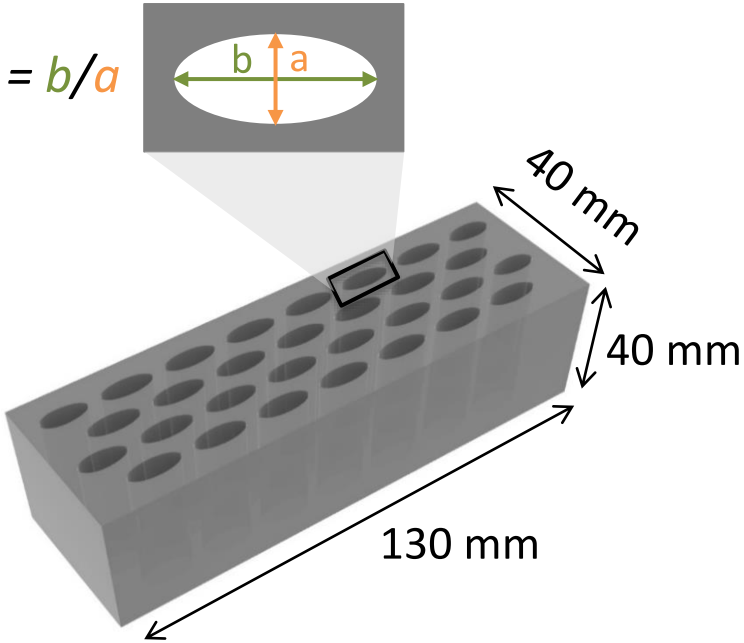

3D-Printing of PVA mold | Cured Urethane Rubber Mold | Tubular Architected Cementitious Material

*HRWRA – High range water reducing admixture; VMA – Viscosity Modifying agent

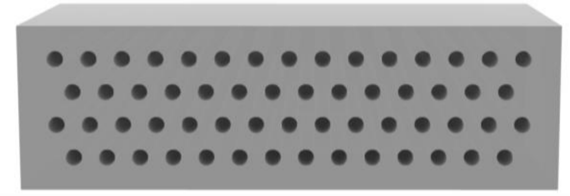
# What Design Parameters go into the Tubular Architecture?

| | Tubular architected material | Cortical Bone |
|---|---|---|
| Osteons/tube porosity (%) | 20 – 50% | 45 – 65%[1] |
| Aspect Ratio | 1 – 2.5 | 1.02 – 2.62[2] |

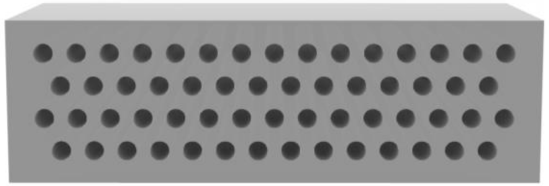
*Aspect ratio, e = b/a*



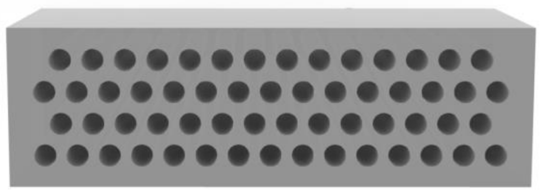

Solid



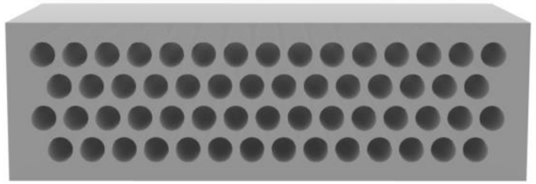
Circular 20%, *e = 1*



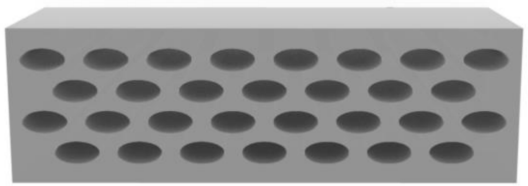
Circular 30%, *e = 1*



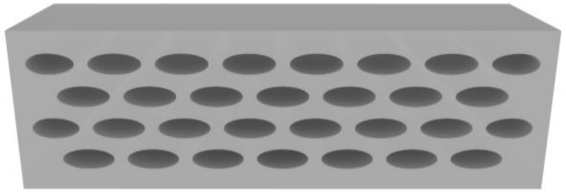
Circular 40%, *e = 1*



Circular 50%, *e = 1*



Elliptical 40%, *e = 2.0*



Elliptical 40%, *e = 2.5*

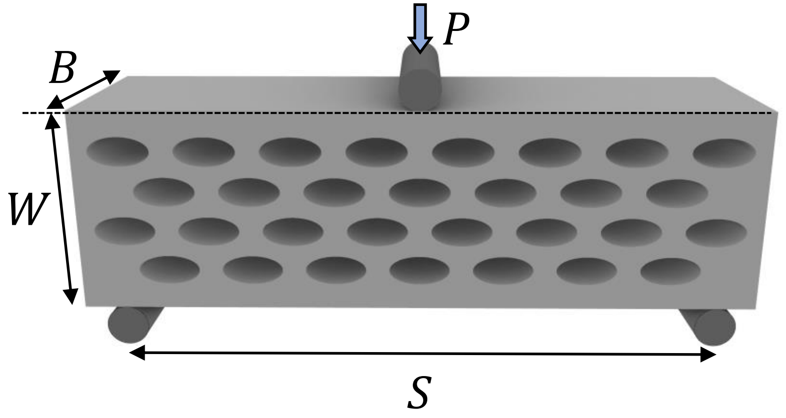

1. Vahle *et al.,* 2015. In The Nonhuman Primate in Nonclinical Drug Development
2. Keenan, *et al.*, 2017. Am. J. Phys. Anthropol.

# How did We Characterize the Mechanical Response?

- Modulus of Rupture (MOR) was obtained from Three-point bend test (ASTM C78)

$$MOR = \frac{M \times y}{I}$$

where, $M$ is applied bending moment, $y$ and $I$ are the position of the neutral axis and second area on moment of the loading plane

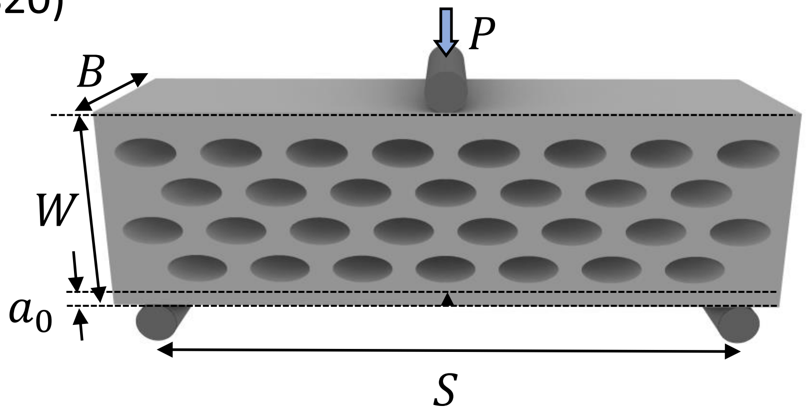



- Fracture Toughness was obtained from Single-edge notched bend test (ASTM E1820)

Crack Initiation Fracture Toughness, $K_{IC} = \left(\frac{PS}{B^{\frac{1}{2}}W^{\frac{3}{2}}}\right) f(a_0/W)$

Crack Propagation Fracture Toughness, $K_{Jc} = \sqrt{(J_{el} + J_{pl})E}$

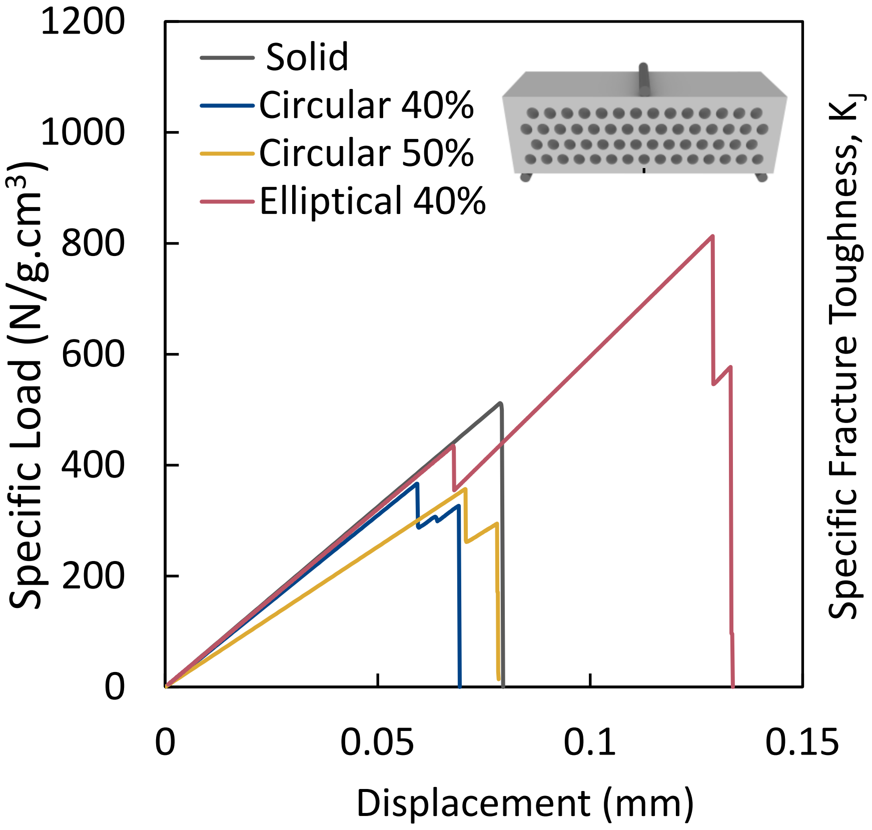
where, $J_{el} = \frac{K_{Ic}^2(1 - v^2)}{E}$ & $J_{pl} = \frac{n_{pl}A_{pl}}{b(d - a_0)}$



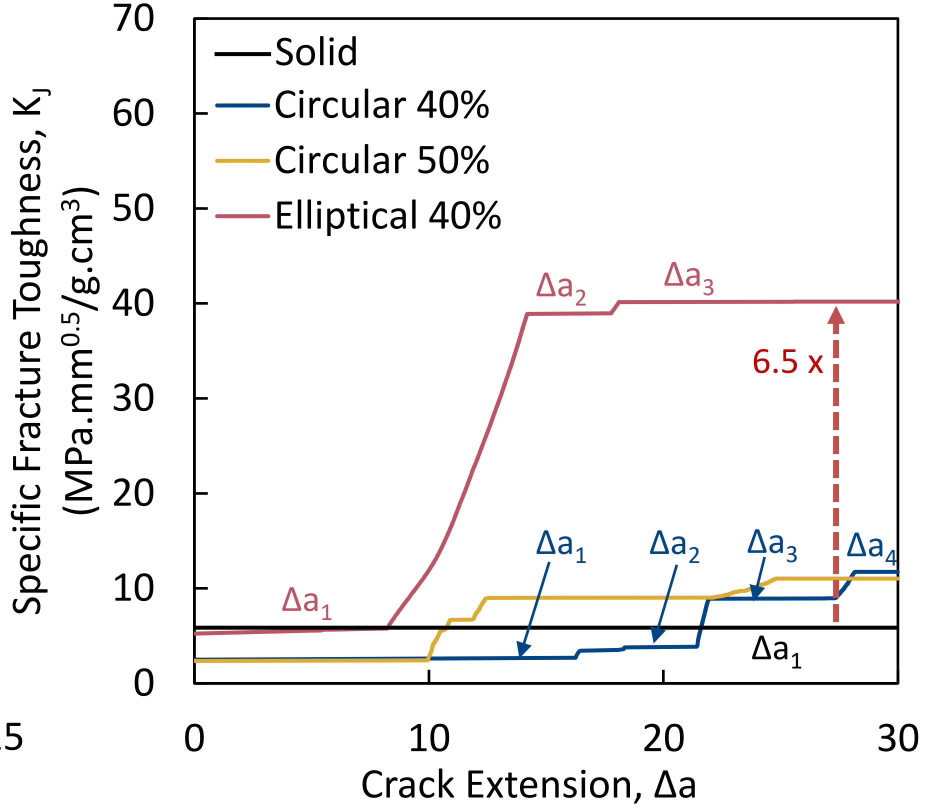

Where, $A_{pl}$ as the post-peak area under the notched load-displacement curve and $n_{pl}$ is given by ASTM E1820.

# Tubular Architecture Allow for Step-wise Cracking Toughening Mechanism

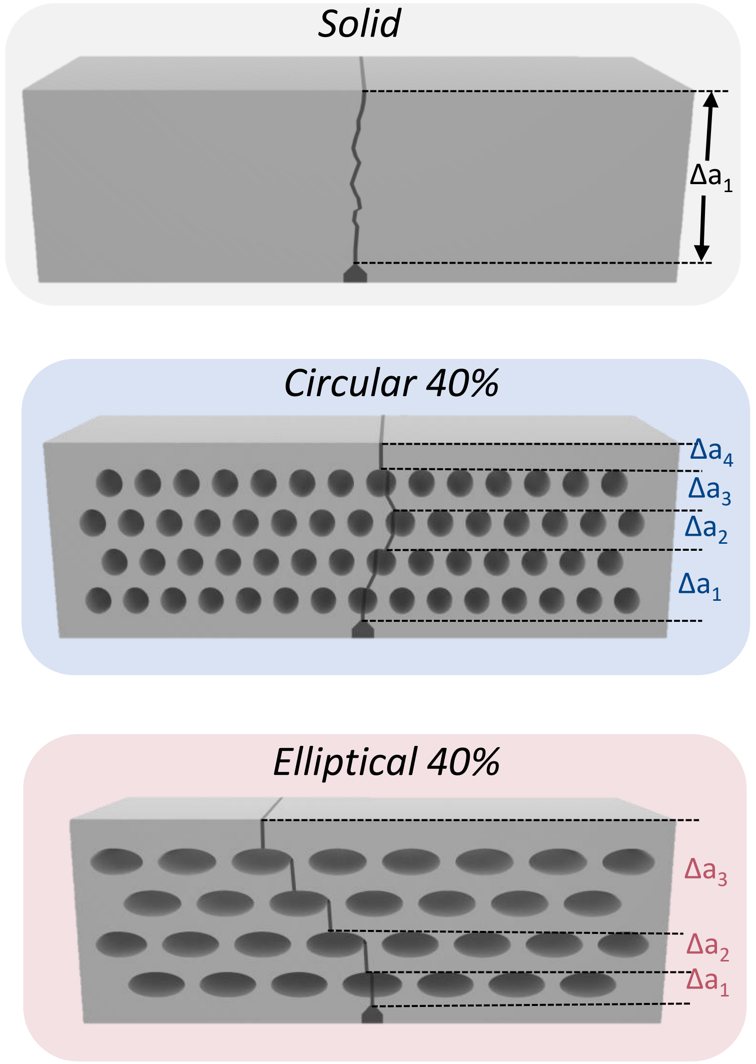
Load-Displacement Plot




Crack growth resistance curve

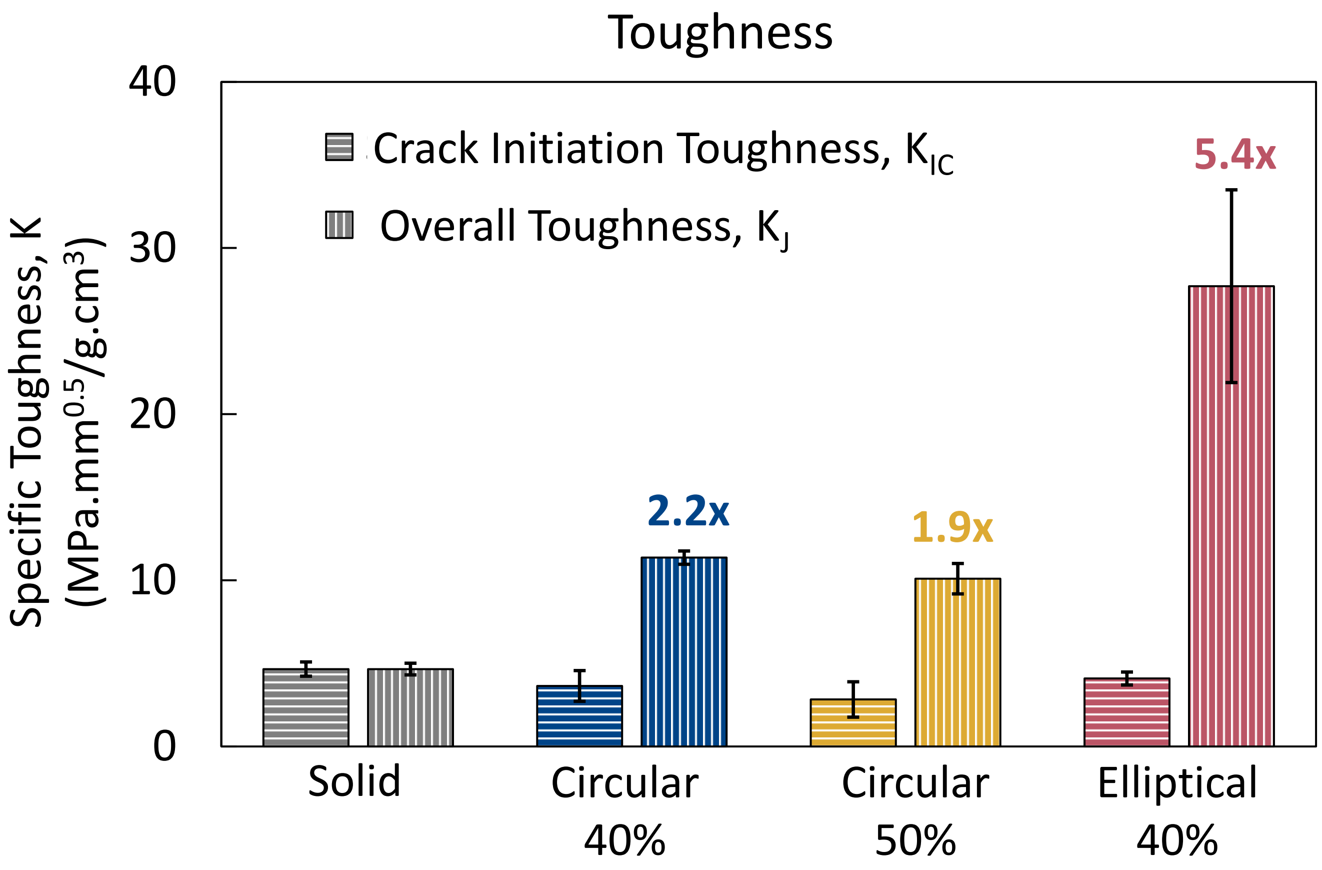


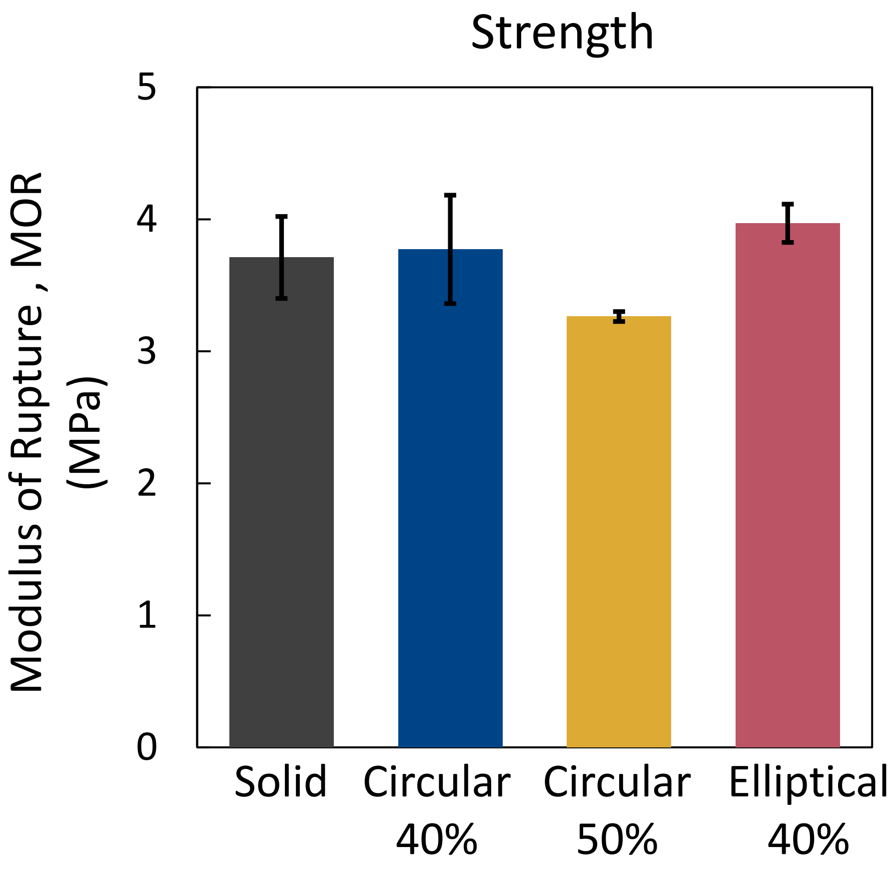

Crack Propagation




- Tubular architecture demonstrated step-wise load-displacement unlike brittle cast
- *Hypothesis:* Step-wise cracking and crack deflection are the toughening mechanisms

# Toughness is Enhanced by Five Folds Without Loss of Strength




- Crack initiation toughness ($K_{IC}$) and strength (MOR) remain constant with increasing porosity
- While crack propagation toughness ($K_J$) showed increase of 2-5 times from solid to tubular architecture

# How Can We Explain the Results using an Analytical Investigation?

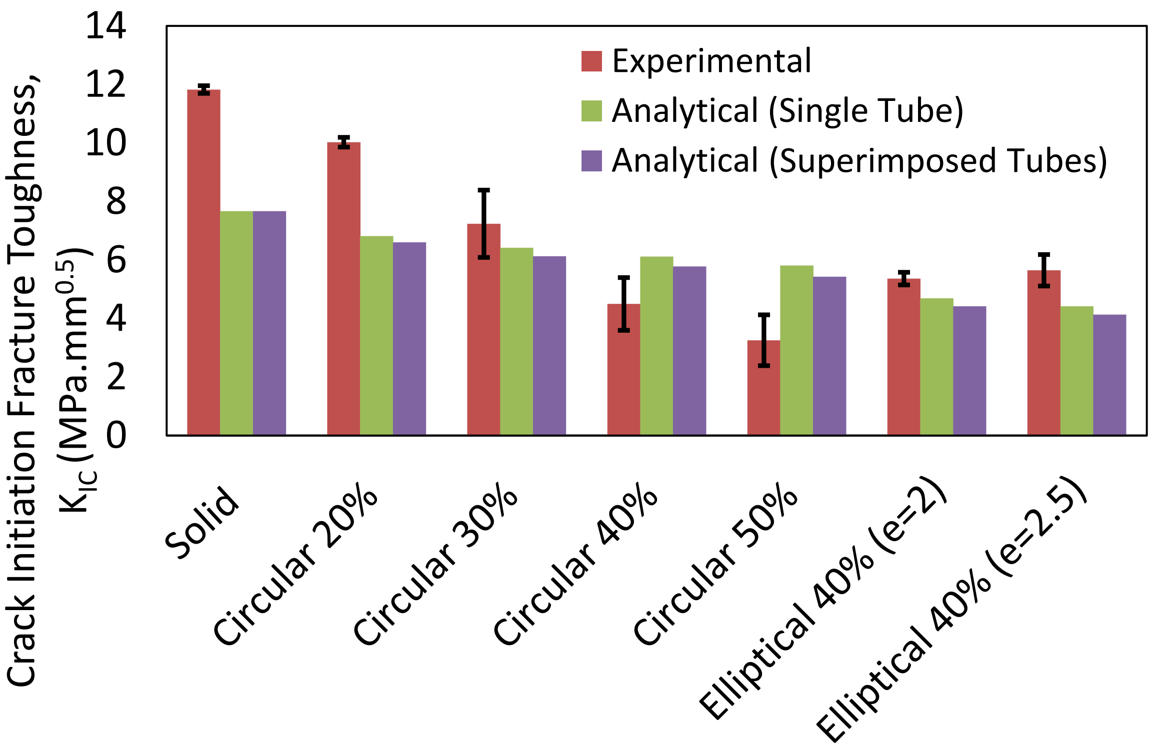
- Effect of tubes on the stress intensity factor and crack path can be determined using the Green function formulation
- Muskhelishvili Equations predict stress fields in elastic medium ($\sigma_{xx}$, $\sigma_{yy}, and\ \sigma_{xy}$) as the function of complex potentials, $\phi$ & $\psi$

$$\sigma_{xx} + \sigma_{yy} = 2\left[\phi'(z, b_n, b_t) + \overline{\phi'(z, b_n, b_t)}\right]$$
$$\sigma_{yy} - \sigma_{xx} + 2\sigma_{xy} = 2[\bar{z}\phi''(z, b_n, b_t) + \psi'(z, b_n, b_t)]$$

- Complex potentials ($\phi$ & $\psi$ ) are the functions of the distribution of dislocations along crack due to elliptical tube ($b_n, b_t$) [1]
- Stresses due to crack-tube interactions are superimposed upon the stress due to the distribution of dislocation along the arbitrary crack
- Cauchy integral equations, with external stresses ($f_n$, $f_t$), can be solved numerically to determine the stress intensity factors [1]

$$\int_{z_1}^{z_2} \frac{b_n(z_0)}{z - z_0} dz_0 + \int_{z_1}^{z_2} \sigma_n(z, z_0) b_n(z_0)\, dz_0 = f_n(z)$$
$$\int_{z_1}^{z_2} \frac{b_t(z_0)}{z - z_0} dz_0 + \int_{z_1}^{z_2} \sigma_t(z, z_0) b_t(z_0)\, dz_0 = f_t(z)$$

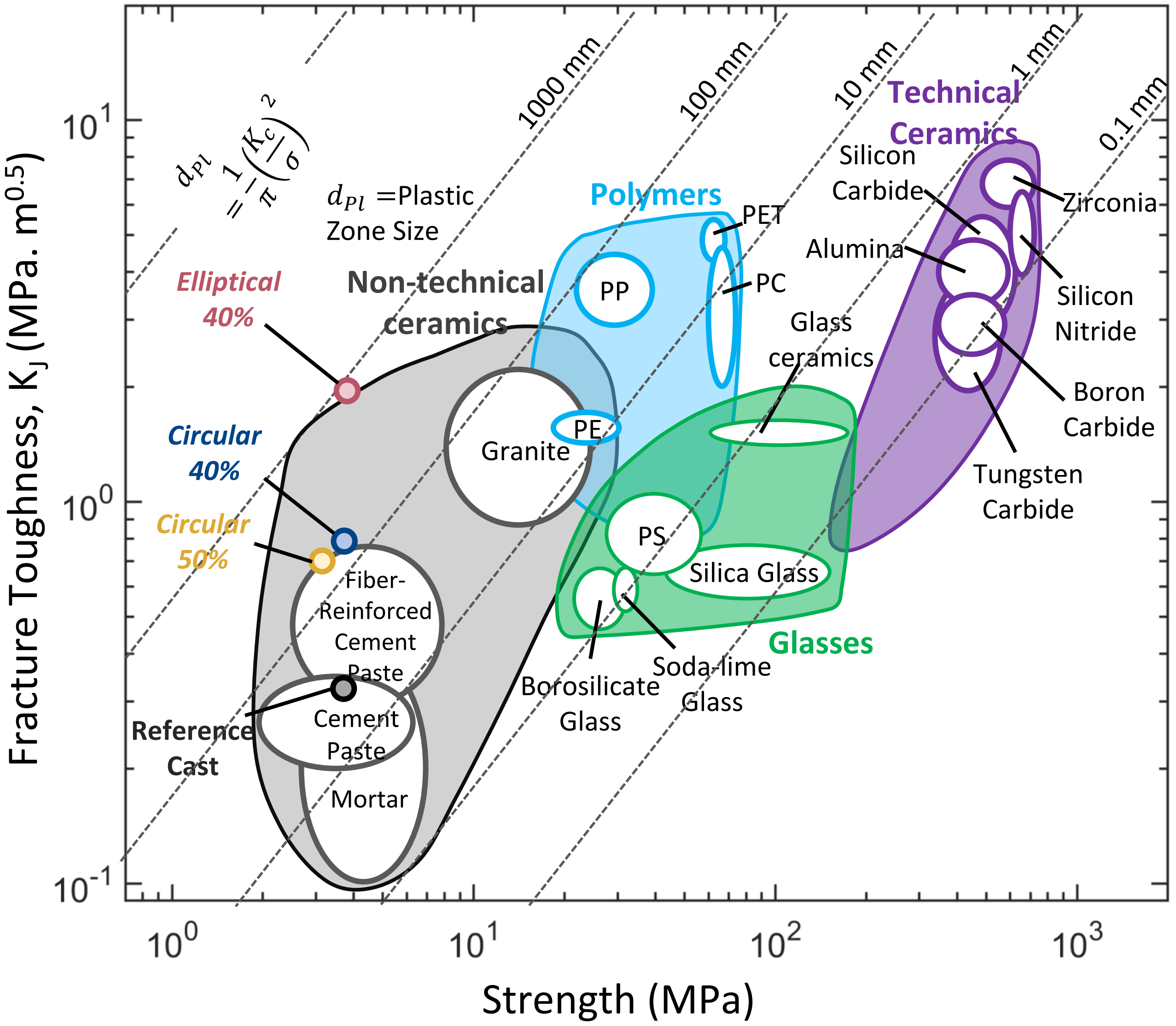
Analytical (Single Tube) Analytical (Superimposed tubes)



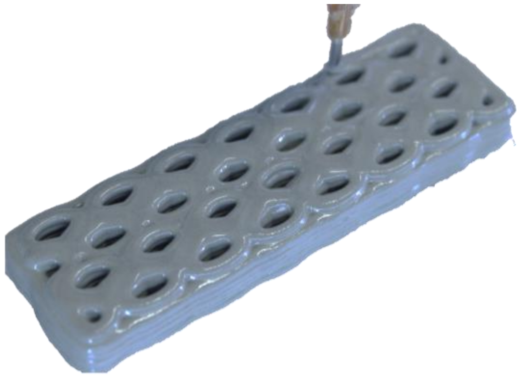

1. Patton, E.M. and Santare, M.H., 1993. Crack path prediction near an elliptical inclusion. Engineering fracture mechanics.

# Where did the Tubular Architected Cementitious Material land?

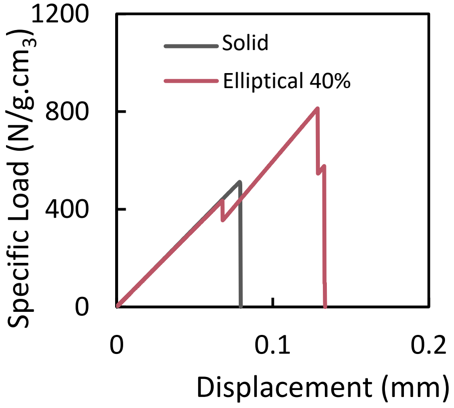
- Elliptical 40% showed fracture toughnesss comparable to granite and glass ceramic
- Circular 40% and Circular 50% showed fracture toughness close to upper boundary of fiber-reinforced cement paste



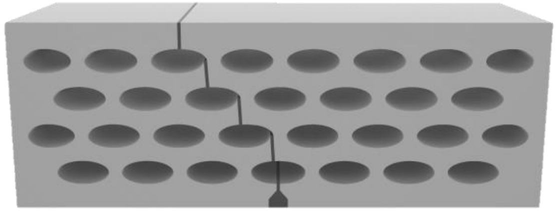
# Concluding Remarks



- Additive manufacturing can be used in a variety of ways (3DP, hybrid) to architect materials, and further work on scaling up is necessary
- Exploiting *Step-wise crack propagation & crack deflection* toughening mechanism inspired from bone can enhance the fracture toughness by 5 times

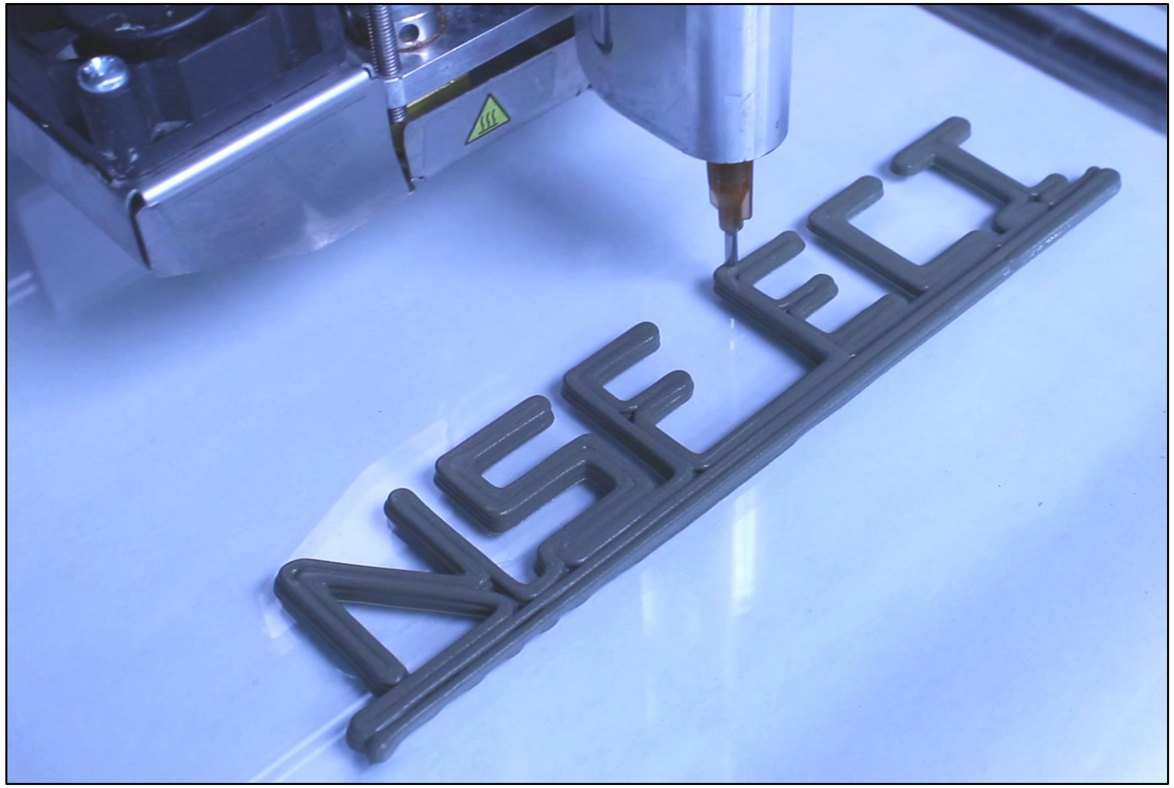



- The improvement in toughnesss-strength trade-off was achieved without changing the composition (adding fiber)



# Acknowledgements


- We would like to acknowledge the support for our lab by NSF-Engineering Civil Infrastructure and NSF-Advanced Manufacturing programs of the CMMI.

# Thank you, Questions!