Tough Cementitious Mortar-Silicone Multi-Material Composite Enabled by Automated Multi-Material Additive Manufacturing

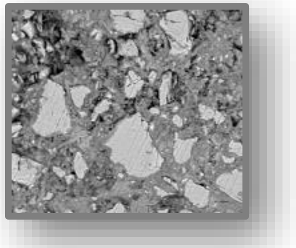
Aimane Najmeddine, Ph.D.
Associate Research Scholar

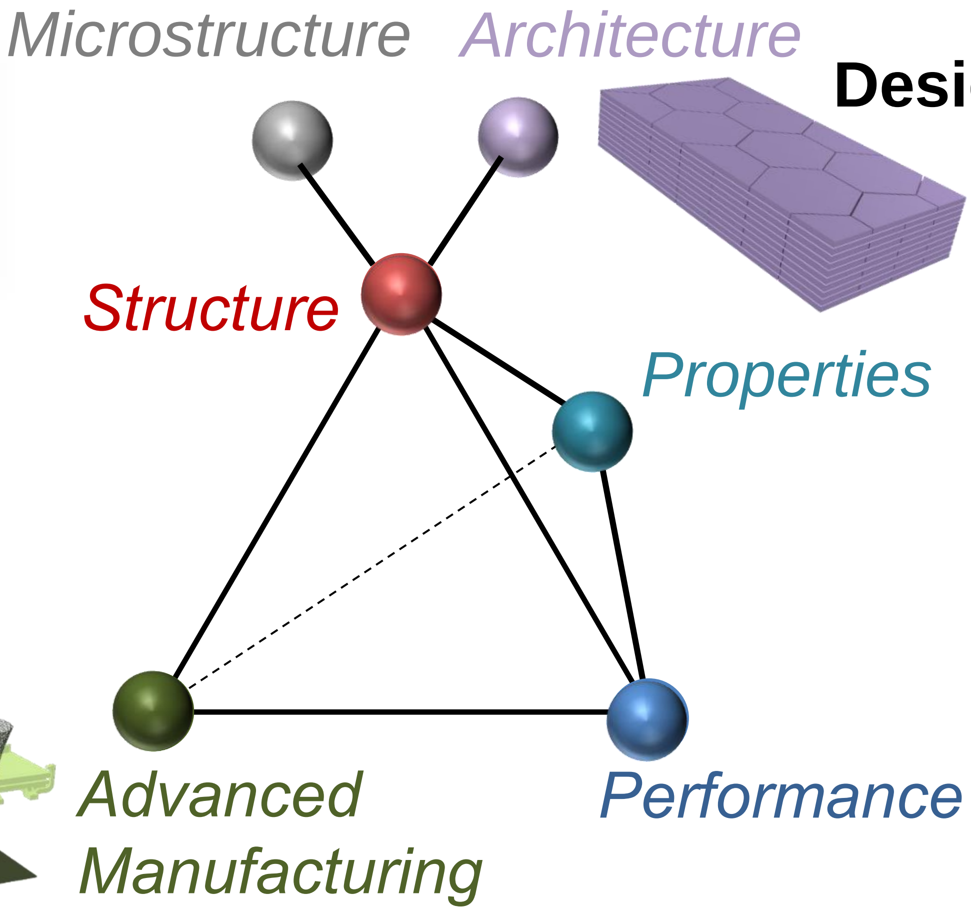
ARCHITECTED MATERIALS AND ADDITIVE MANUFACTURING LAB

PRINCETON ENGINEERING

Mechanics-Manufacturing-Design Synergy

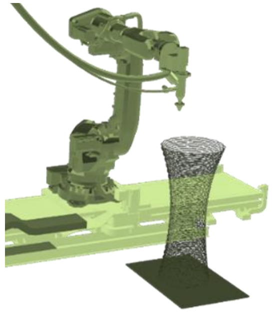
Design Freedom



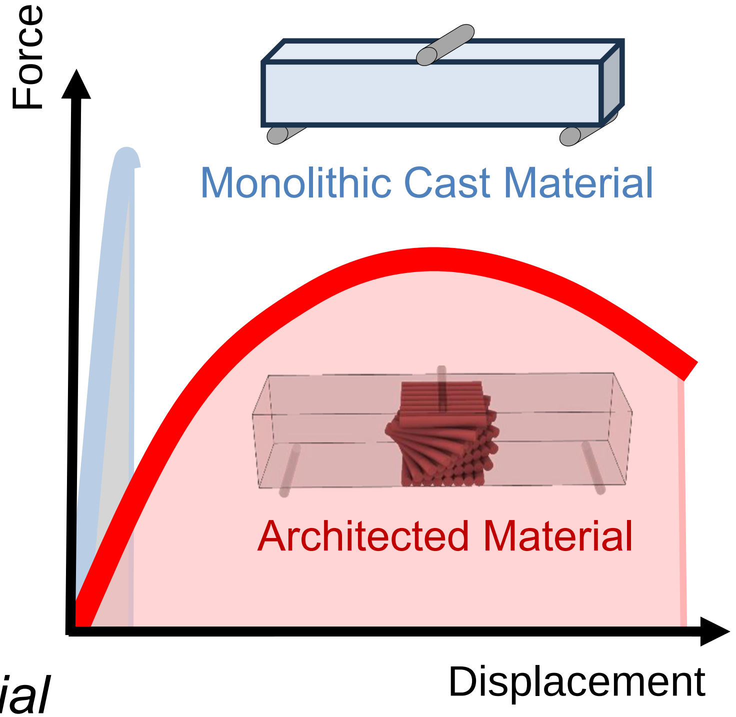


Manufacturing Freedom

- Additive
- Robotics
- Laser
- Formative



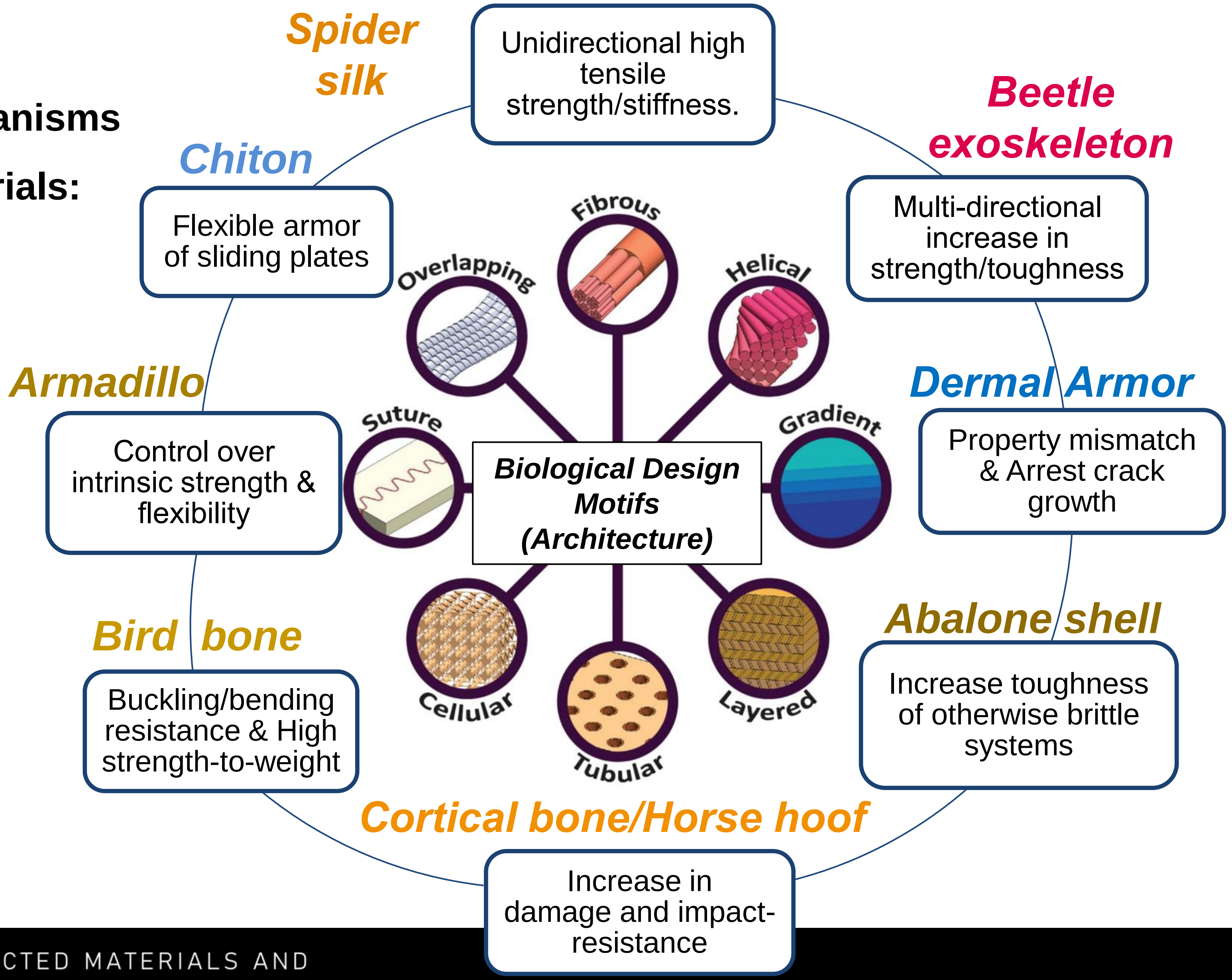
Enhanced Mechanics



Advanced Manufacturing can Enable New Designs of Architected Material

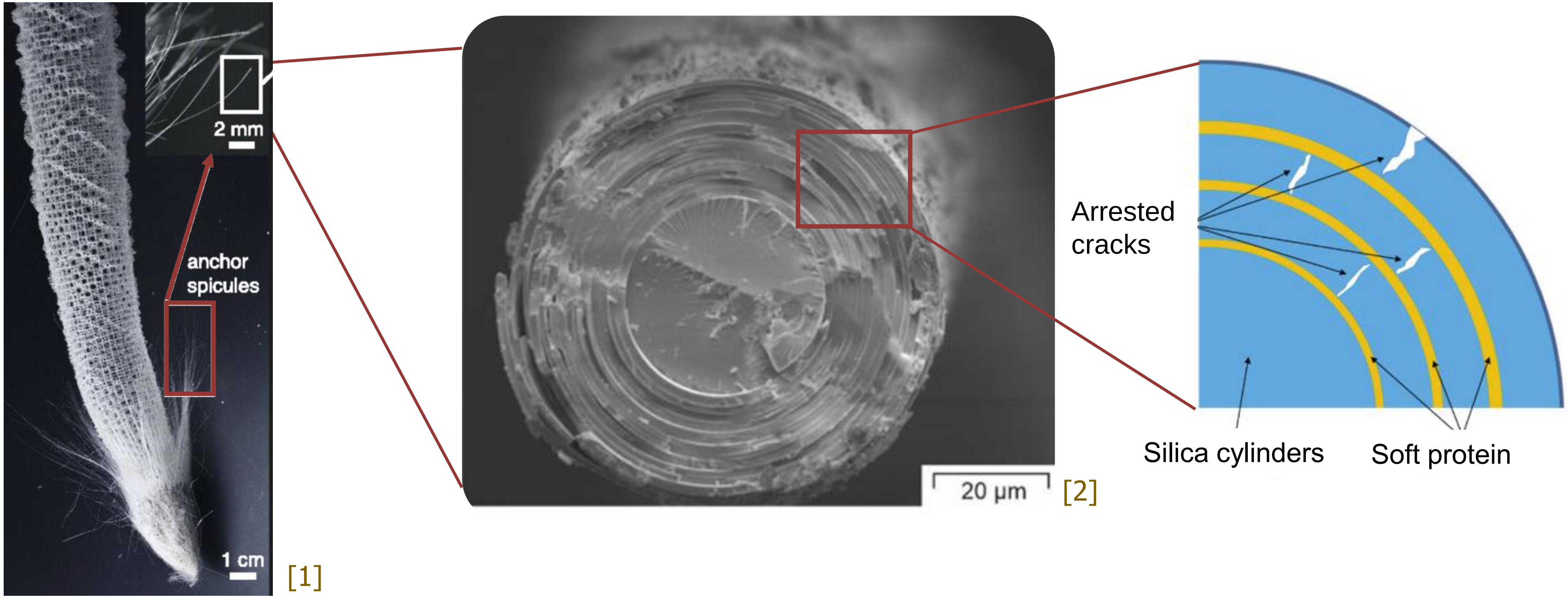
Nature Provides Numerous Examples of Purposeful Designs with Unique Mechanisms

Design Motifs and Toughening Mechanisms in Biological Materials:



[1] Adapted from: S. Naleway & M. Meyers, Adv. Mater., 2015

Deep sea sponge's layered soft-hard architecture makes it a tough material

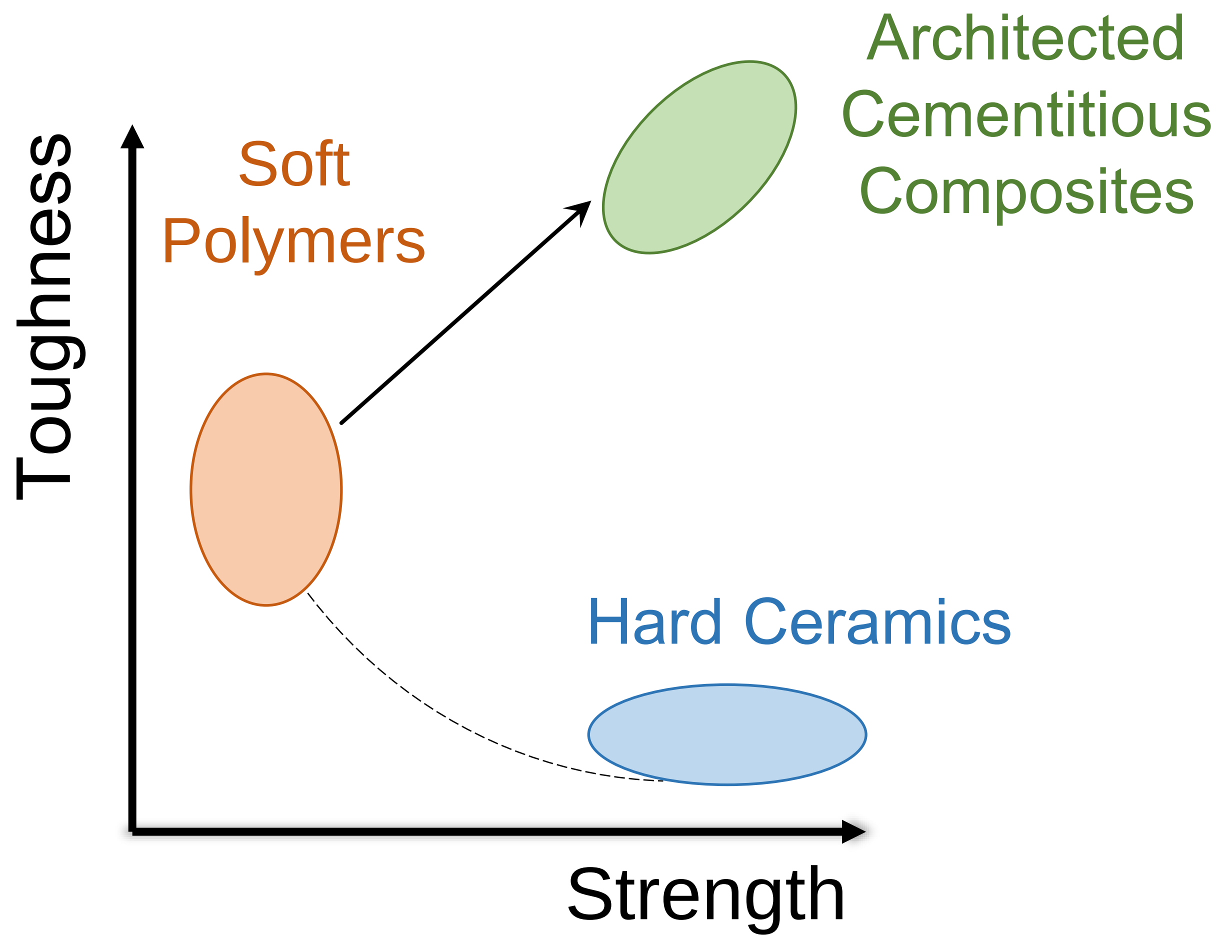


[1] PNAS 112 (2015) 4976–4981

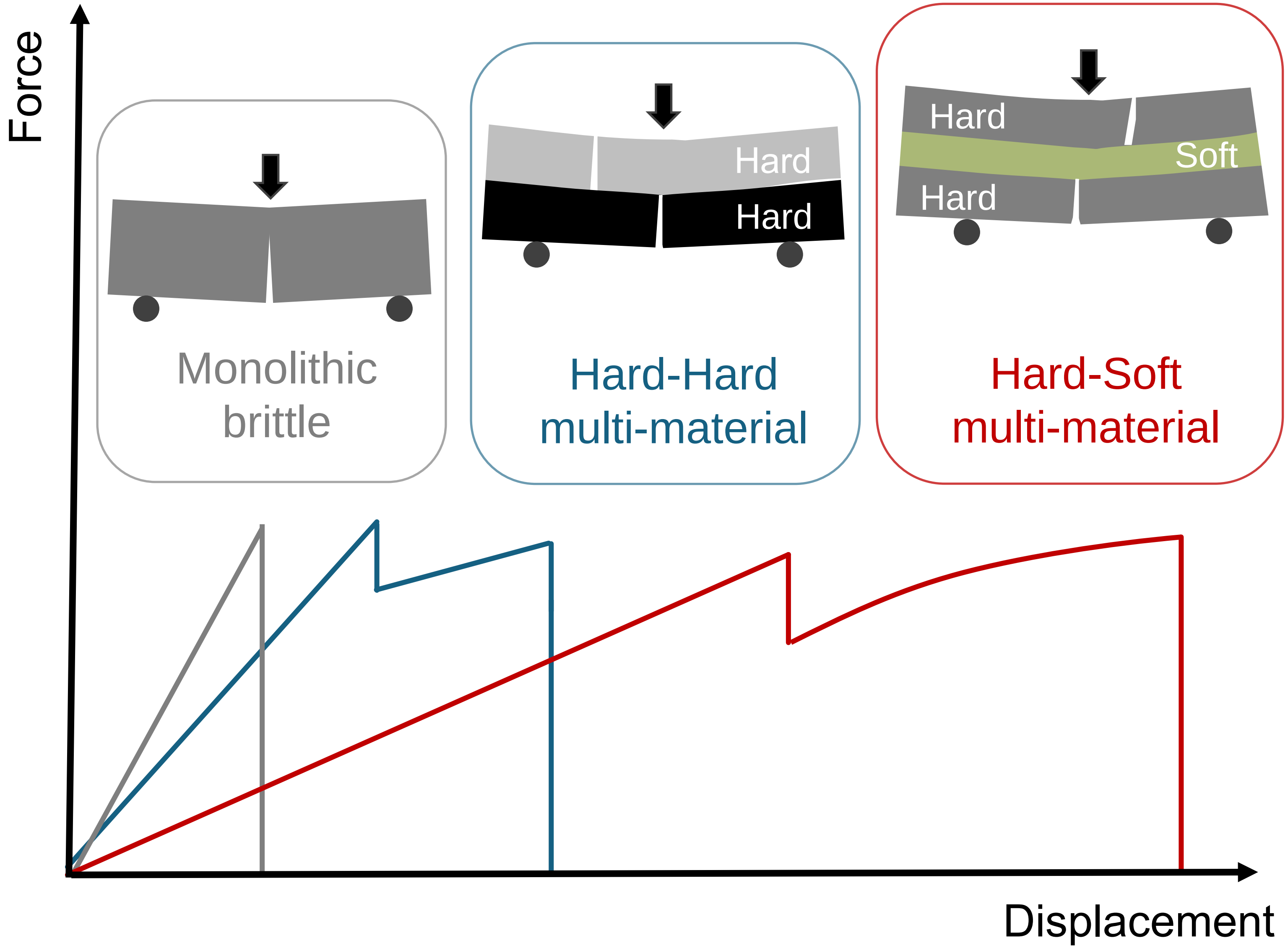
[2] Mechanics of Materials 140 (2020) 103243

Architected materials exhibit properties not found in monolithic materials

Improving **Toughness** *by Design*

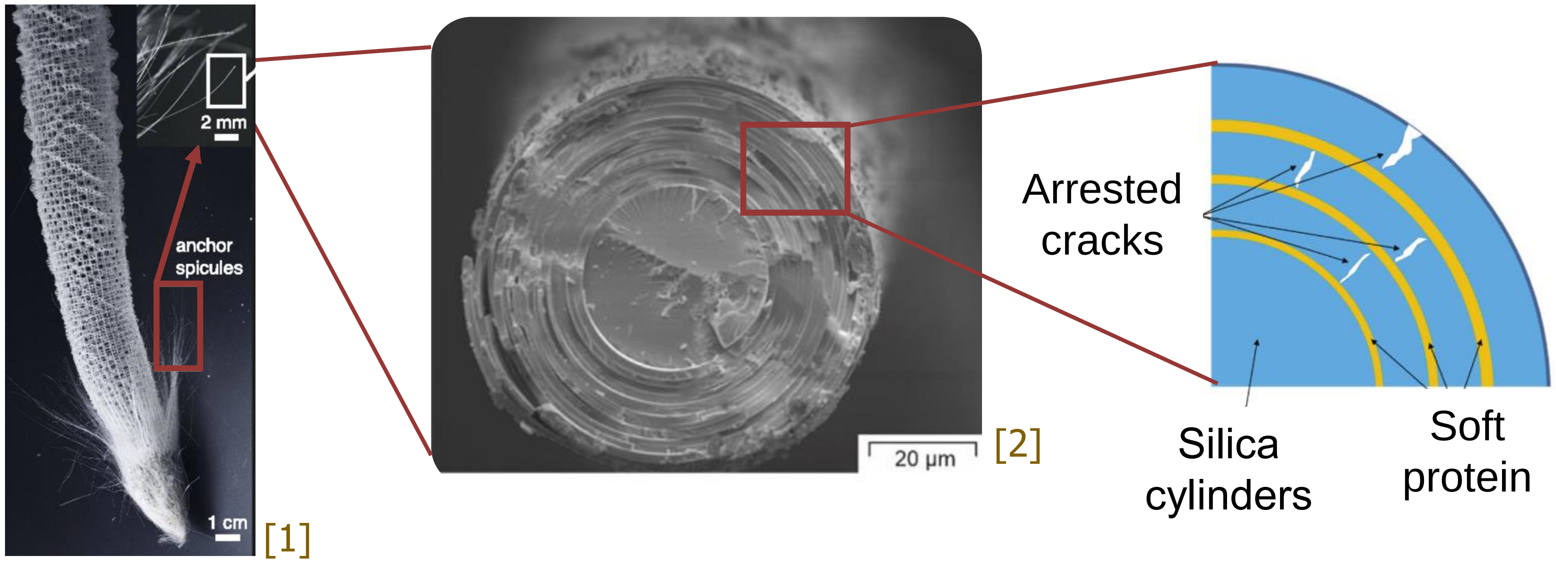


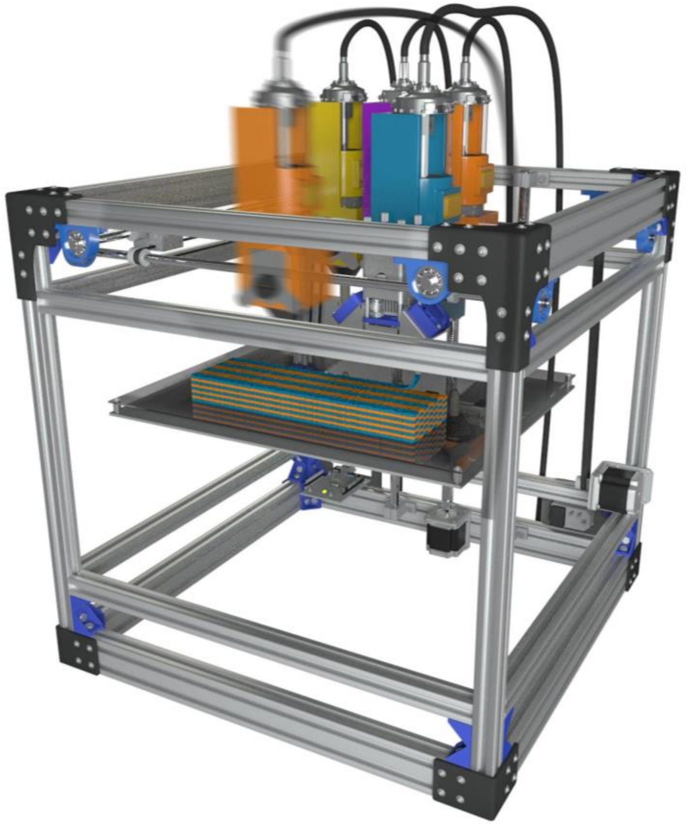
Hypothesis: engineered multi-material systems display improved mechanical performance



How can toughness be improved based on design?

Layered **Hard (mortar)-Soft (silicone)** Multi-Material Architectures Enabled by Additive Manufacturing

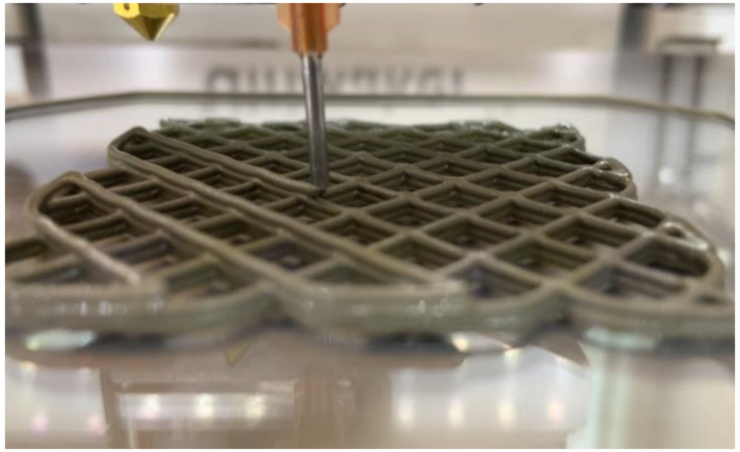




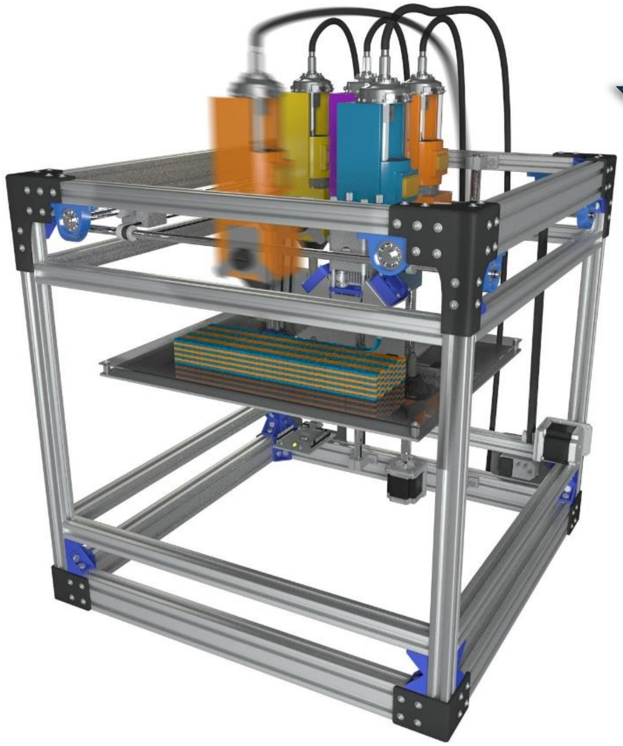
[1] PNAS 112 (2015) 4976–4981

[2] Mechanics of Materials 140 (2020) 103243

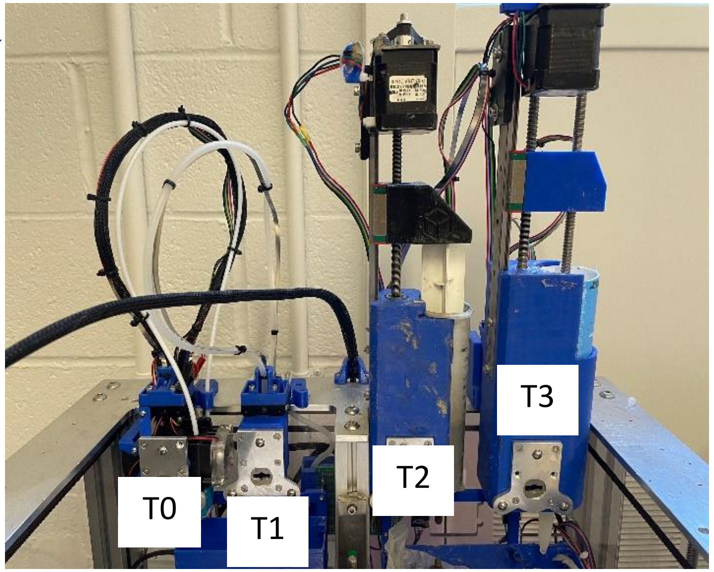
Advanced Manufacturing can Enable Architected Materials Across Scale and Help Study them



Single-material extrusion

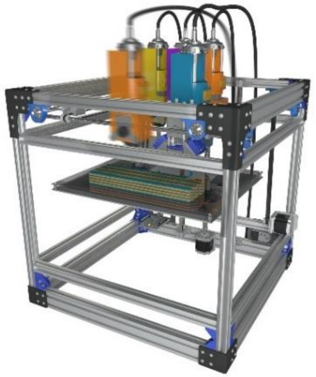


Multi-material extrusion



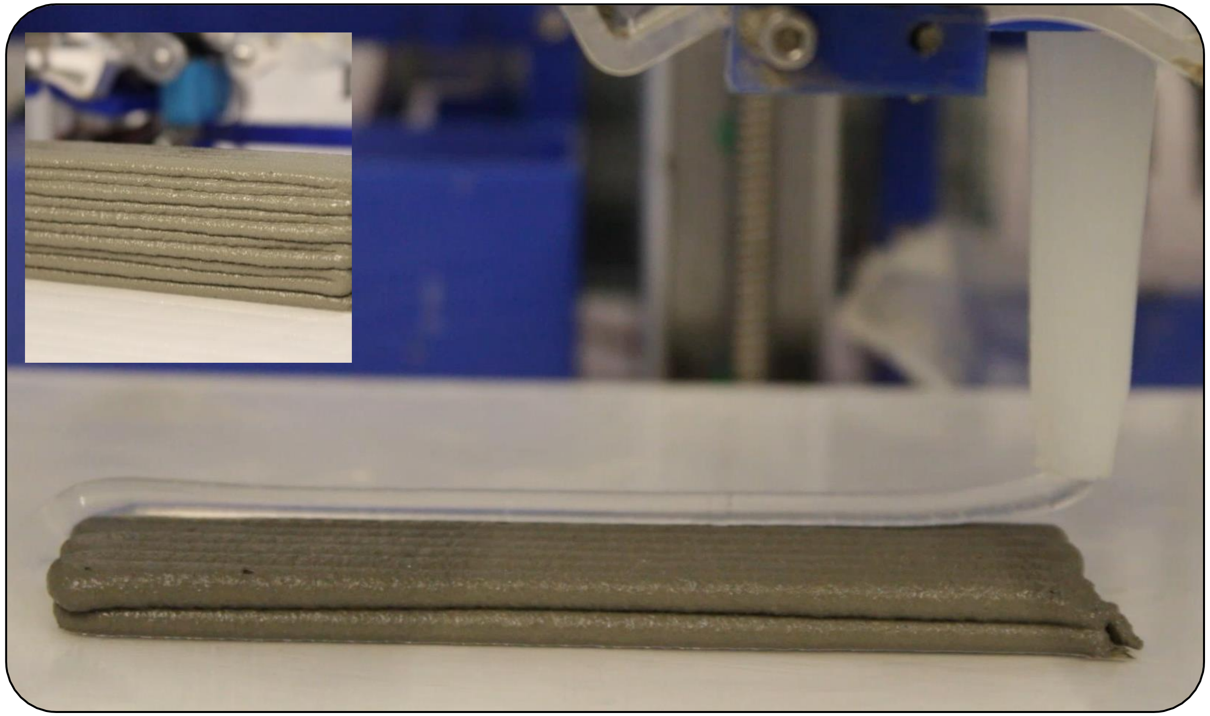
- **T0** – PLA filament extruder
- **T1** – Alternative filament extruder
- **T2** – Cement paste extruder (Hyrel)
- **T3** – Silicon extruder (Hyrel)

Additive manufacturing of hard(mortar)-soft(silicone) multi-material system

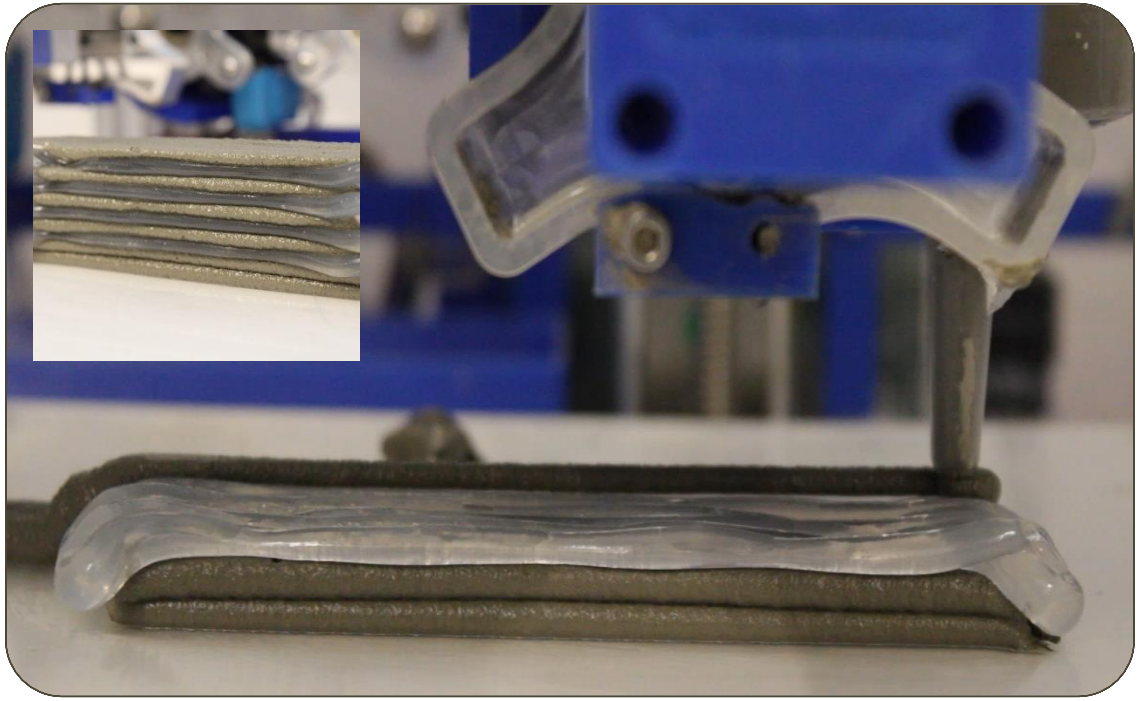


Multi-material extrusion for layered mortar-silicone multi-material composite

Silicone layer extrusion



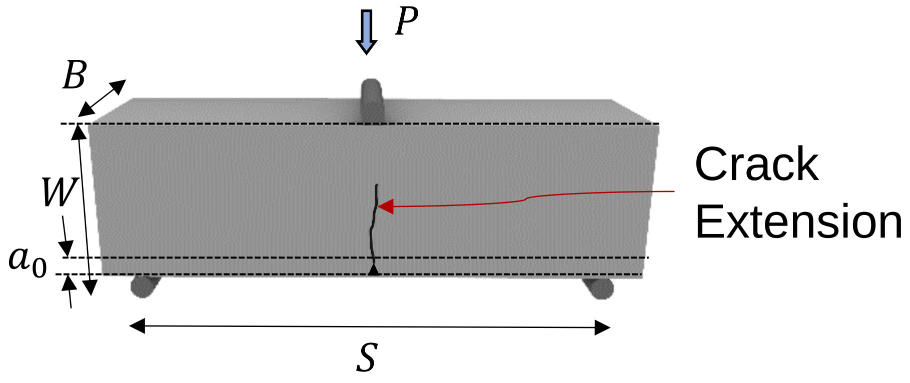
Mortar layer extrusion

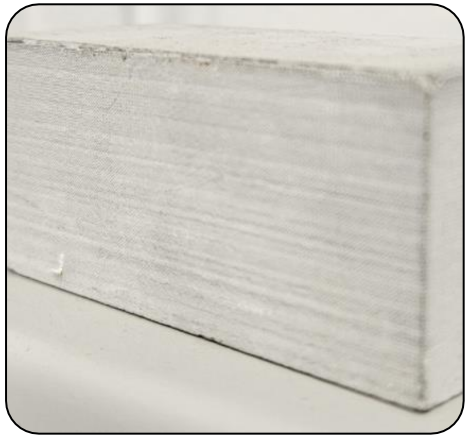


Fracture toughness was investigated experimentally for monolithic and layered systems

Monolithic Hard Materials (Mortar)

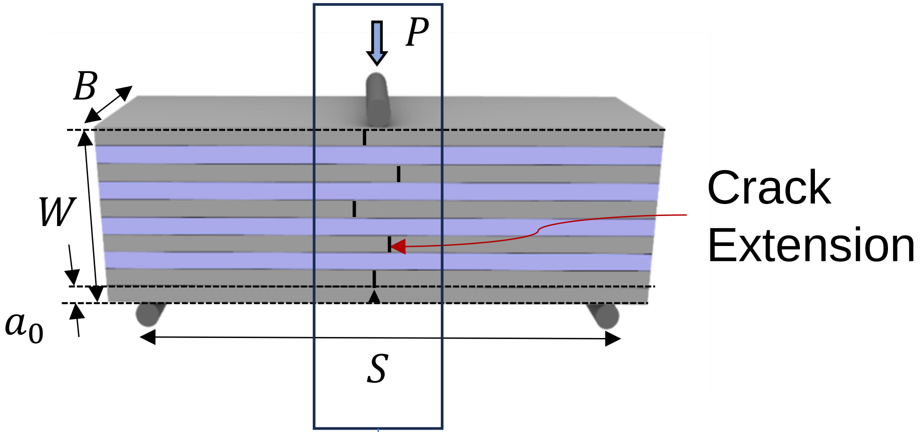
Single-edge Notched Bend (SENB) test

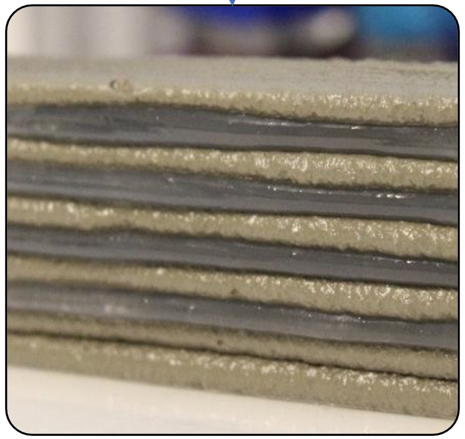




Layered hard-soft (Mortar/Silicone)

Single-edge Notched Bend (SENB) test



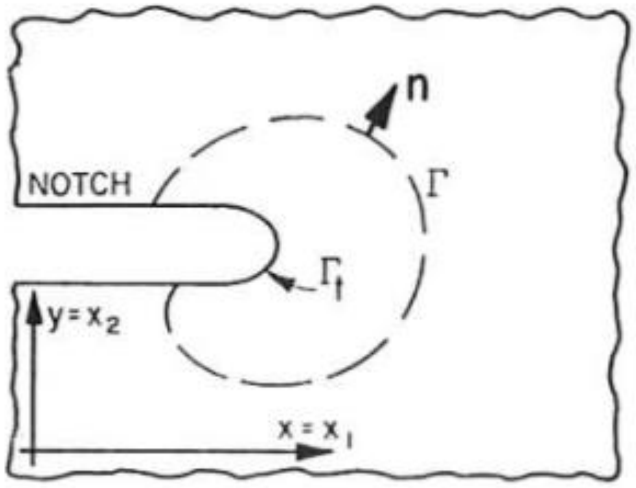


J-integral was used to quantify toughness (i.e., material resistance to crack extension)

Definition The J-integral is an integral equation that gives the amount of energy released in advancing a crack surface by a unit area.

$$J = \int_{\Gamma} \left(W dy - T \frac{\partial \boldsymbol{u}}{\partial x} ds \right)$$

Γ: Curve surrounding the notch tip
W: Strain-energy density
$\boldsymbol{T}$: Traction vector defined according to outward normal along Γ
$\boldsymbol{u}$: Displacement vector



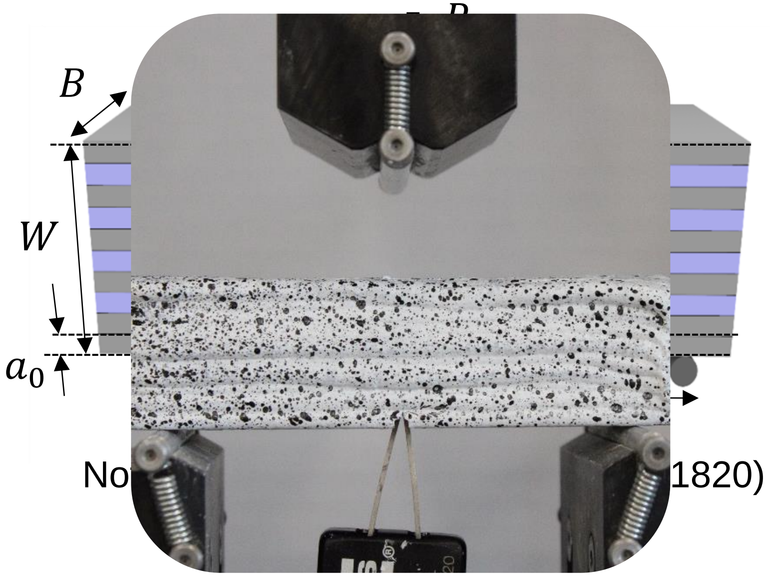
Flat surfaced notched in two-dimensional deformation field (all stresses depend only on x and y). Γ is any curve surrounding the notch tip; Γ_t denotes the curved notch tip [1]

[1] Rice. J., (1968). Journal of Applied Mechanics, 379-386.

Compliance based method to calculate J-integral

❖ J-integral is given by: $J = J_{init} + J_{prop}$

initiation propagation



For plane-strain notched bend test

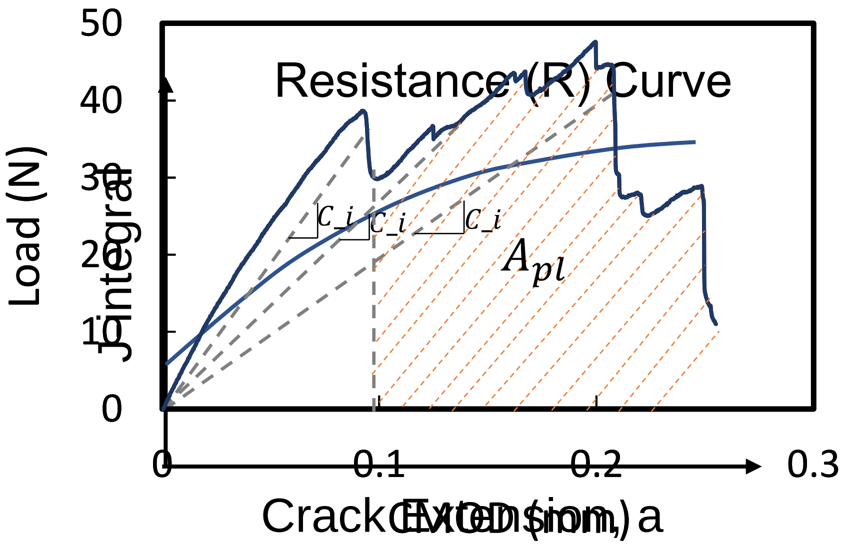
$$J_{init} = \frac{K_{Ic}^2(1-v^2)}{E}, \quad J_{pl_i} = \left[J_{pl_{i-1}} + \left(\frac{\eta_i}{W-a_i}\right)\left(\frac{A_{pl_i} - A_{pl_{i-1}}}{B}\right)\right]$$ [1]

$$K_{IC} = \left(\frac{PS}{BW^{\frac{3}{2}}}\right) f(a_0/W) \quad \text{where} \quad f(x) = \frac{3(x)^{\frac{1}{2}}[1.99 - x(1-x)(2.15 - 3.93x + 2.7x^2)]}{2(1+2x)(1-x)^{\frac{3}{2}}}$$

and A_{pl_i} is the post-peak area under the notched load-displacement curve

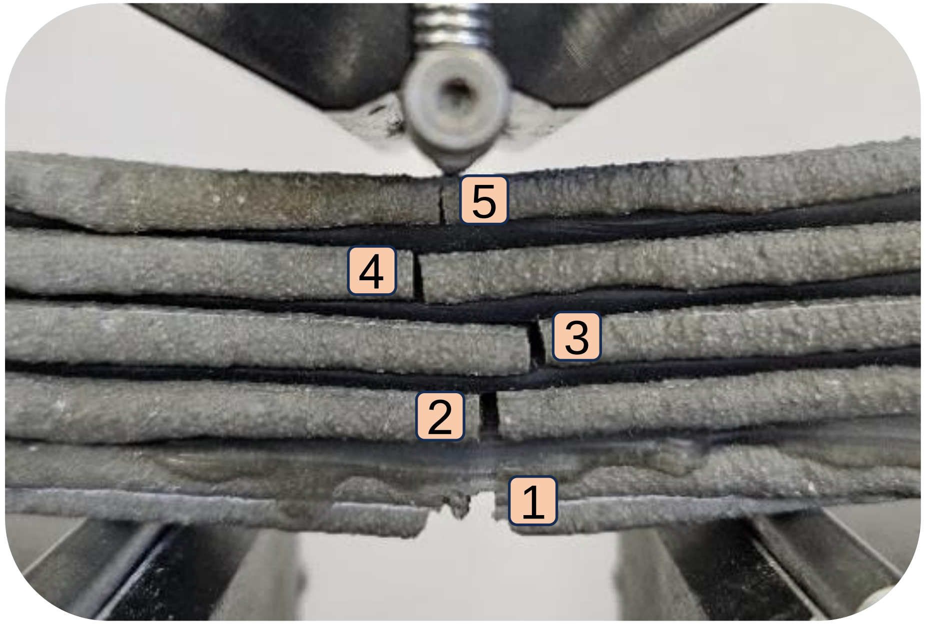
❖ Crack Extension, $a_i = \frac{C_i}{C_0} a_0 \frac{V\left(\frac{a_0}{W}\right)}{V\left(\frac{a_i}{W}\right)}$ [2] $\quad V(x) = 0.8 - 1.7(x) + 2.4x^2 + \frac{0.66}{1-x^2}$

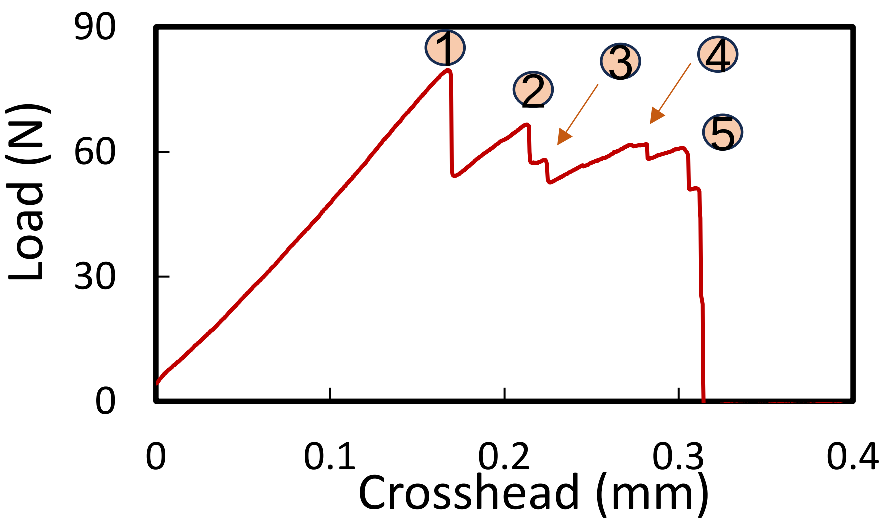
where, C_n is the instantaneous compliance of sample

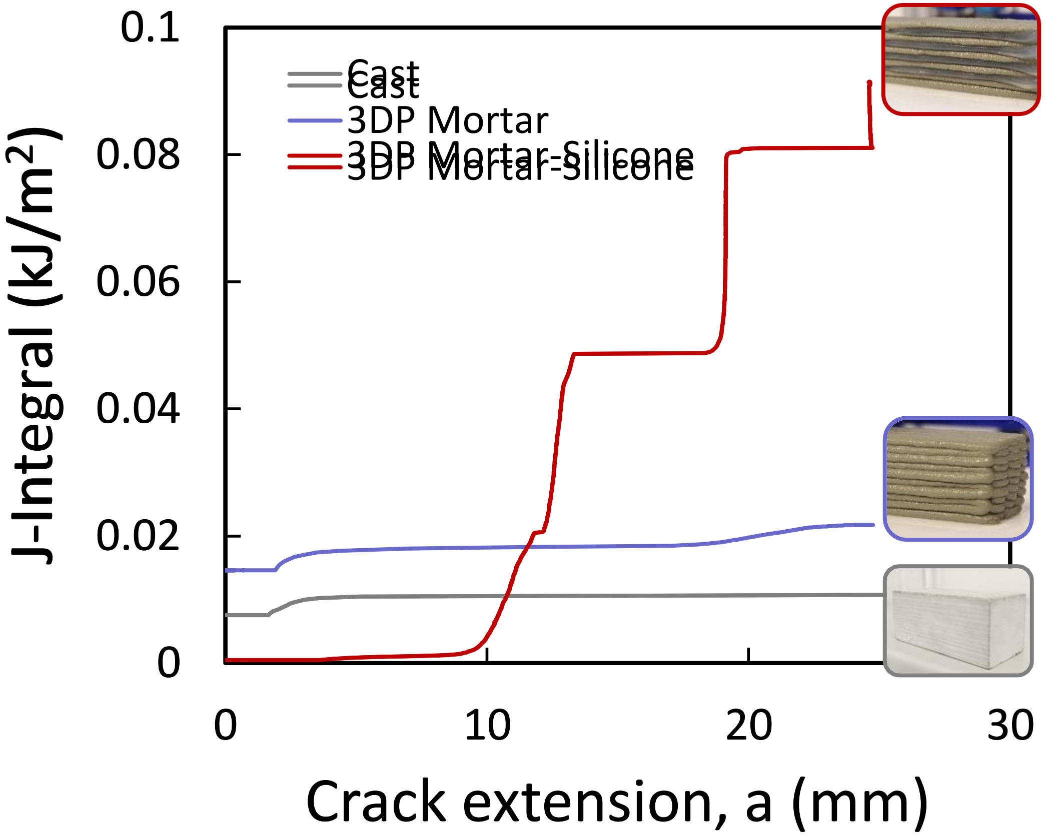


[1] ASTM E1820-24 - Standard Test Method for Measurement of Fracture Toughness
[2] Banthia and Sheng (1995) Two Parameter Fracture Model for Concrete

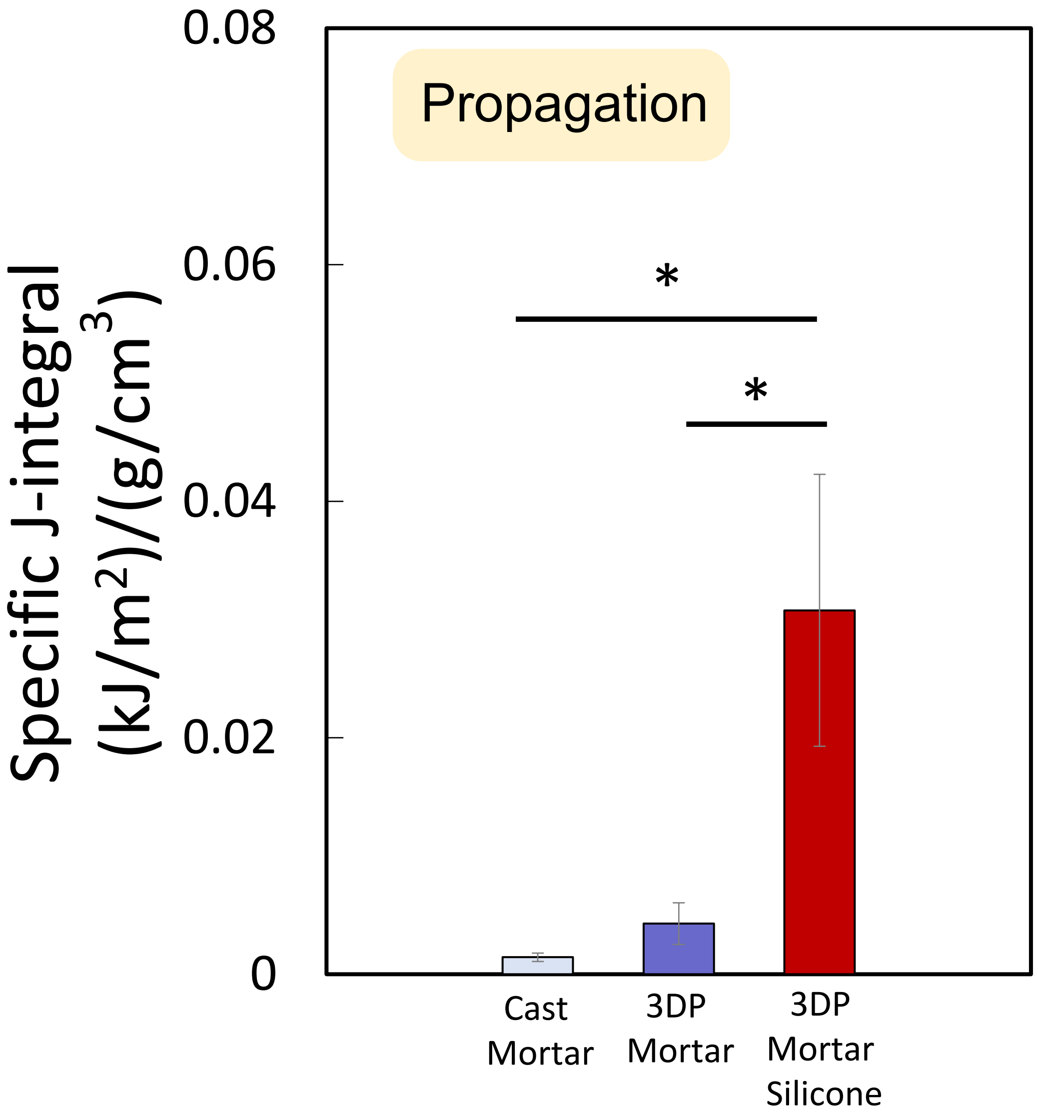
Layered multi-material shows pronounced toughening compared to monolithic and cast

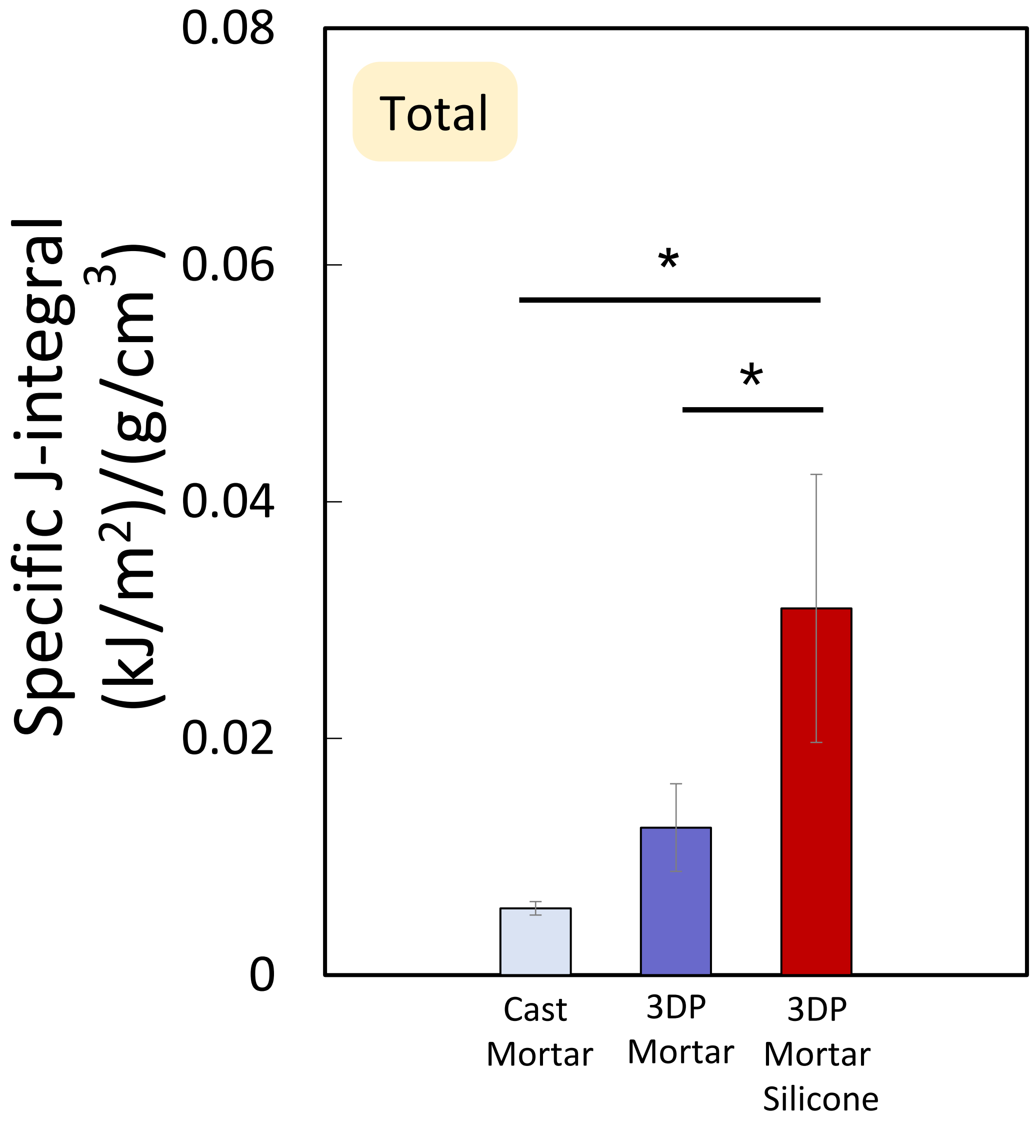






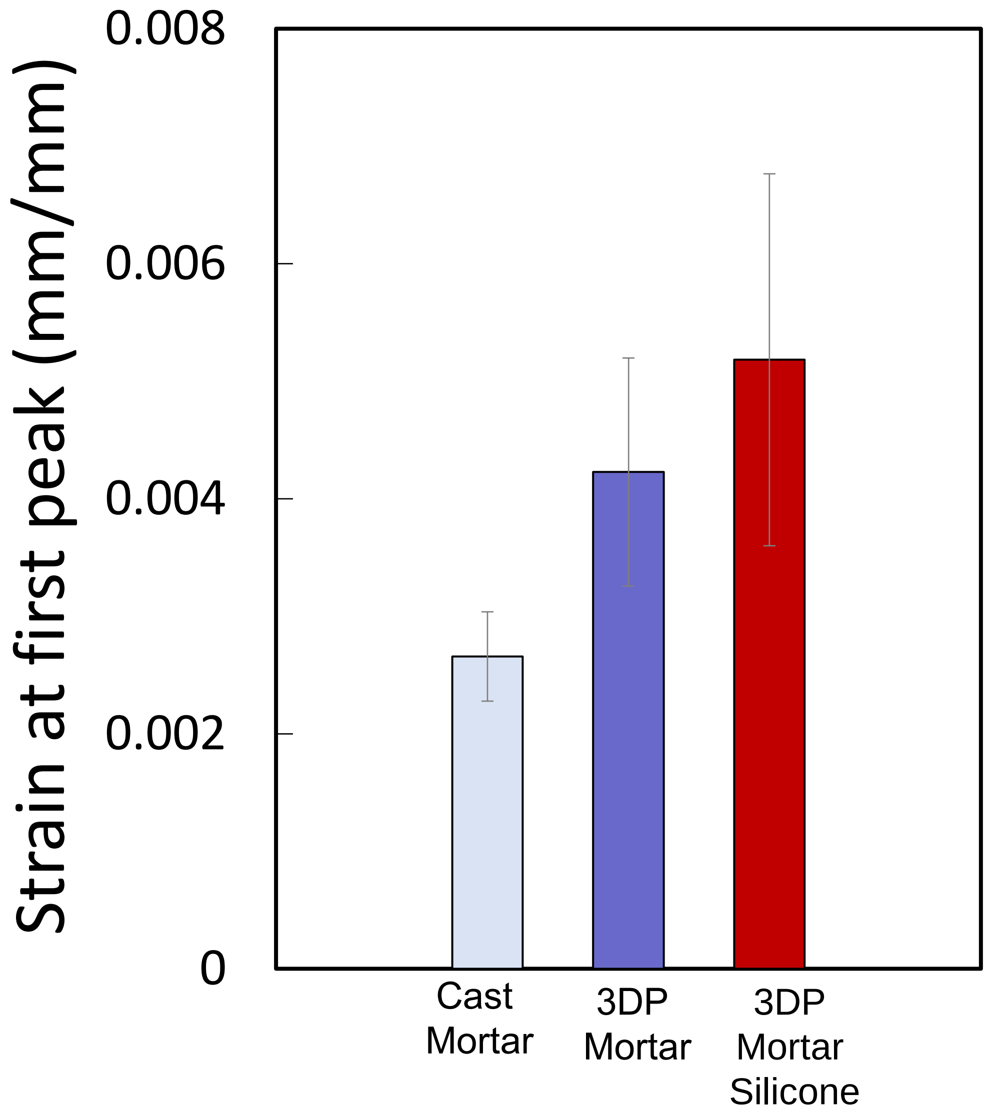
Layered multi-material shows pronounced toughening compared to monolithic and cast

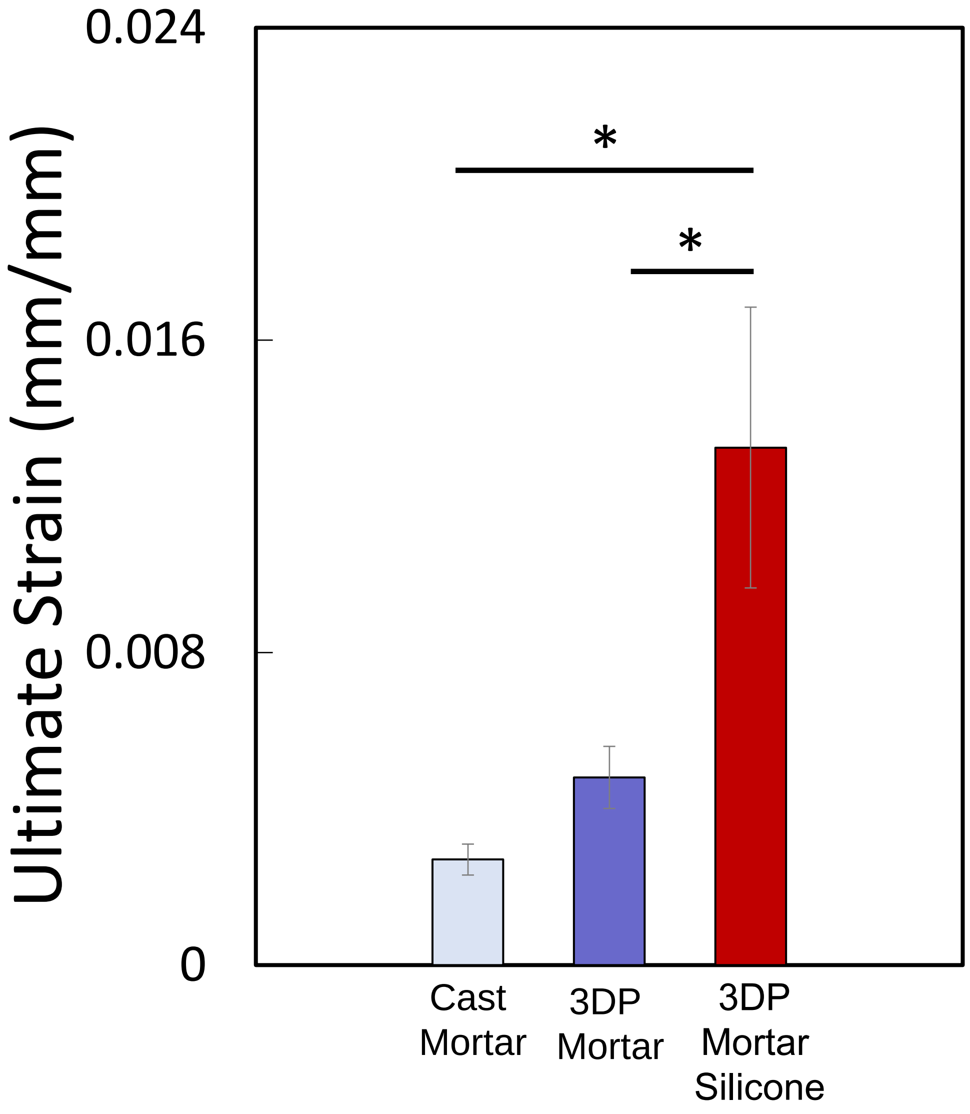




* Symbols indicate significance with t-test thresholds of 0.05

Enhanced ductility was achieved for layered multi-material compared to monolithic and cast

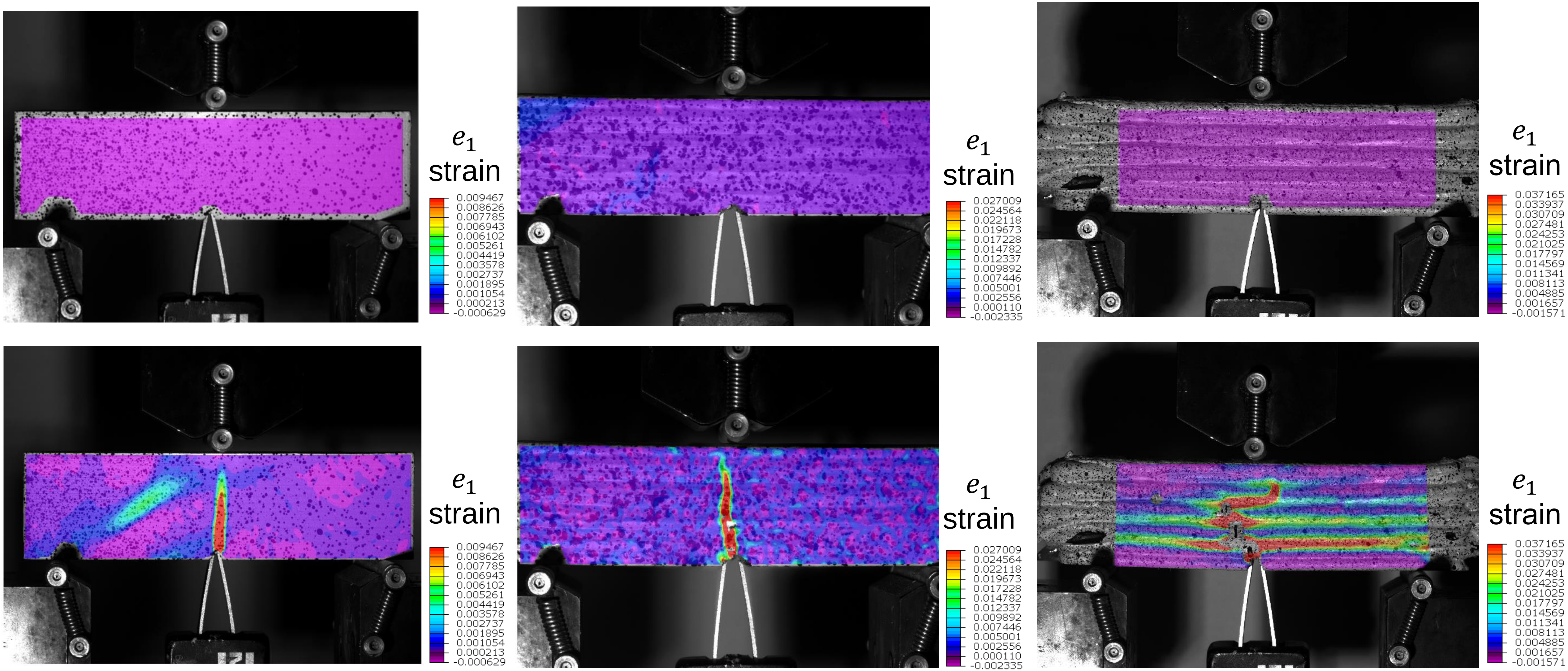




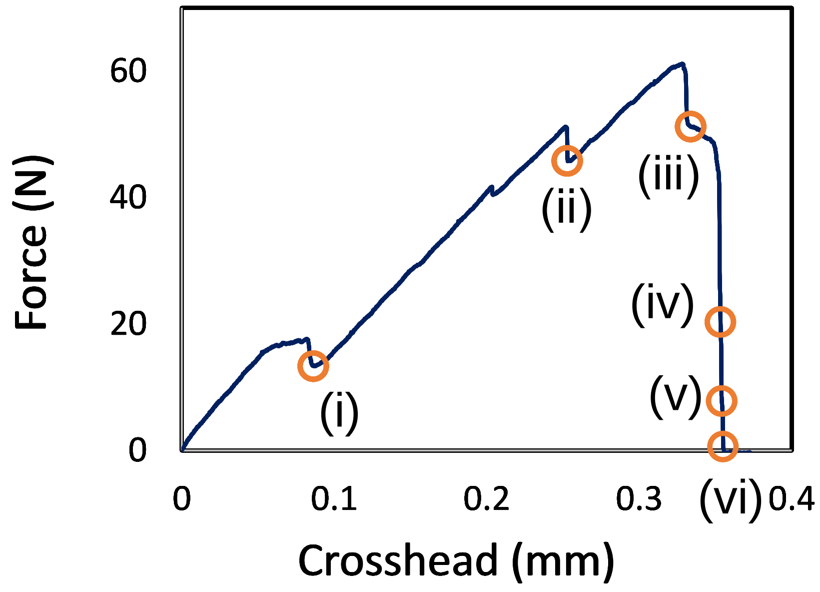
* Symbols indicate significance with t-test thresholds of 0.05

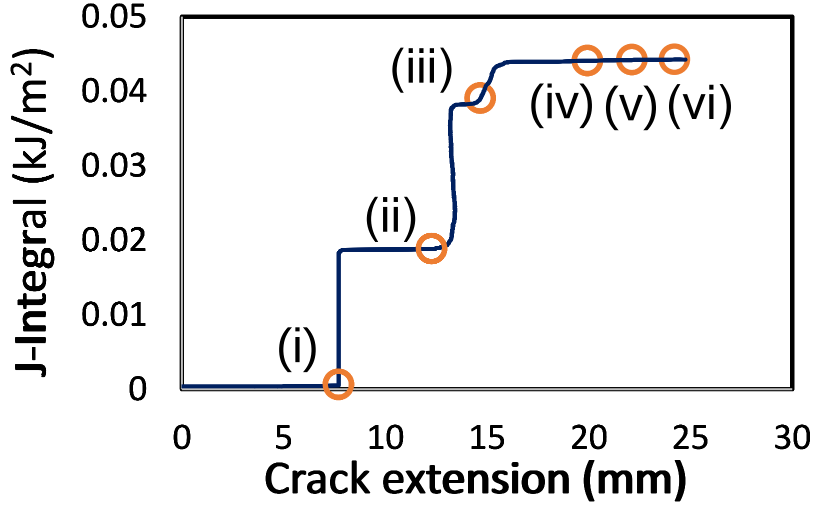
Vastly varying crack propagation mechanism responsible for toughening observed

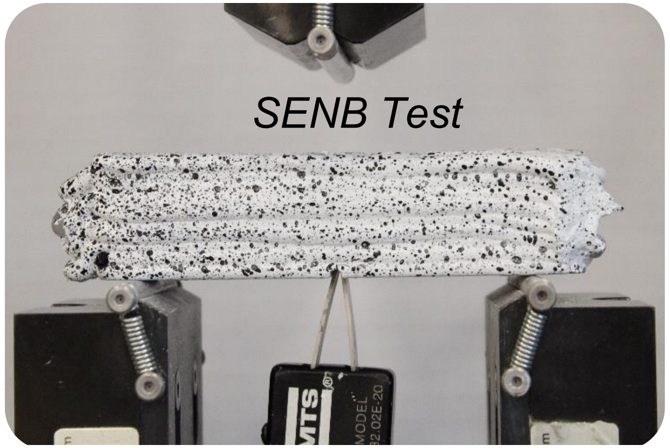
Cast | 3DP Mortar | 3DP Mortar-Silicone

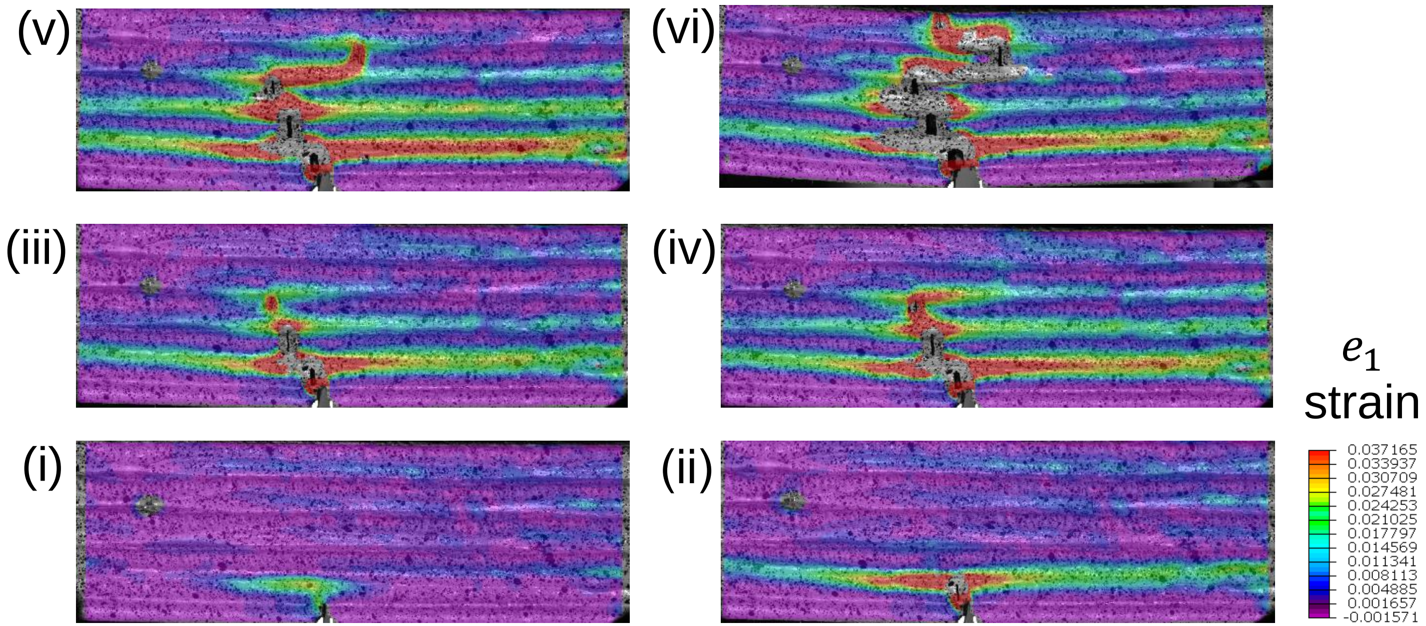


Step-wise cracking responsible for significant sequential energy dissipation across layers









How do we numerically investigate fracture in hard-soft multi-material assemblies?

Coupled phase-field CZM model developed to numerically investigate crack prop in MMs

Updated crack surface energy

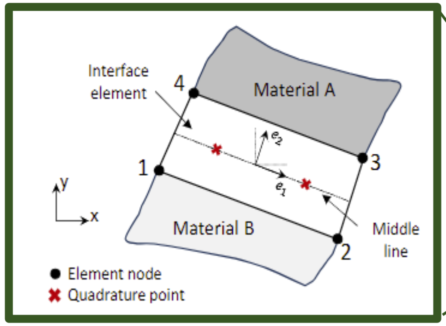
$$\int_{\Omega_0} G_c^b \gamma(d, \nabla d)\mathrm{d}V + \int_{\Gamma_0} G^i \mathrm{dA}$$

Bulk | Interface

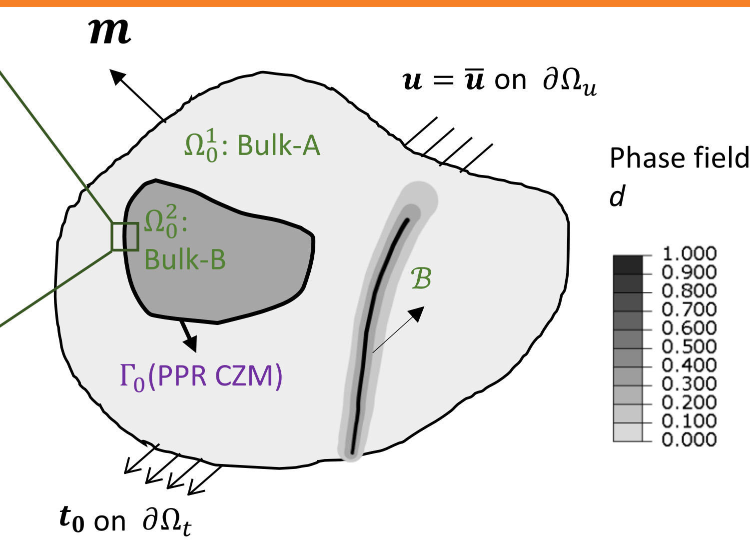
G_c^b: fracture energy of the bulk material

G^i: fracture energy dissipated at the interface

$$\int_{\Gamma_0} G^i \mathrm{dA} = \int_{\Gamma_0} (\Delta\mathbf{u})^{\mathrm{T}} \mathbf{T} \mathrm{dA}$$



$\Delta\mathbf{u} = \mathbf{u_1} - \mathbf{u_2}$ displacement jump vector



$\mathcal{B}$: smeared crack – modeled by Phase-field

Γ_0: Interface – modeled by PPR CZM

Updated total potential energy of the system

Displacement field | Phase-field | Strain energy density | CZM | Body forces | Applied traction

$$\underbrace{\Pi(\mathbf{u}, d)}_{\textit{total potential}} = \underbrace{\int_{\Omega_0} g(d)\psi_0(\mathbf{F})dV}_{\textit{strain energy}} + \underbrace{\int_{\Omega_0} G_c^b \gamma(d, \nabla d)\mathrm{d}V + \int_{\Gamma_0} \overbrace{(\Delta\mathbf{u})^{\mathrm{T}}\mathbf{T}}\ \mathrm{dA}}_{\textit{crack surface energy}} - \underbrace{\left(\int_{\Omega_0} \boldsymbol{b_0} \cdot \mathbf{u}dV + \int_{\Gamma_0} \mathbf{t_0} \cdot \mathbf{u}dA\right)}_{\textit{external energy}}$$

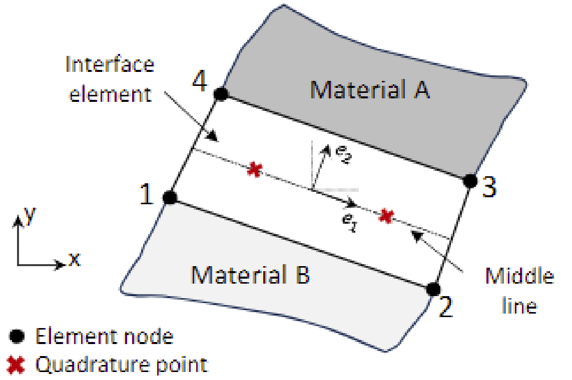
Bulk | Interface

Park-Paulino-Roesler (PPR) [1] used to capture dissipated energy at interfacial zones

User-Element Subroutine (UEL) for Abaqus

$$\phi(\Delta\mathbf{u}_n,\Delta\mathbf{u}_t)=\min\left(G_c^{int}{}_n,G_c^{int}{}_t\right)+\left[\Gamma_n\left(1-\frac{\Delta\mathbf{u}_n}{\delta_n}\right)^{\alpha}\left(\frac{m}{\alpha}+\frac{\Delta\mathbf{u}_n}{\delta_n}\right)^{m}+\left\langle\boxed{G_c^{int}{}_n}-\boxed{G_c^{int}{}_t}\right\rangle\right]\mathrm{x}\left[\Gamma_t\left(1-\frac{|\Delta\mathbf{u}_t|}{\delta_t}\right)^{\beta}\left(\frac{n}{\beta}+\frac{|\Delta\mathbf{u}_t|}{\delta_t}\right)^{n}+\left\langle\boxed{G_c^{int}{}_t}-\boxed{G_c^{int}{}_n}\right\rangle\right]$$

$G_c^{int}{}_n, G_c^{int}{}_t$: Energies for mode I and mode II fracture, respectively
Γ_n, Γ_t: Energy constants
$\Delta\mathbf{u}_n, \Delta\mathbf{u}_t$: Normal and tangential components of the displacement jump
δ_n, δ_t: Final crack openings representing complete failure in the normal and tangential directions, respectively
α, β: shape parameters



- Normal traction force

$$T_n(\Delta\mathbf{u}_n,\Delta\mathbf{u}_t)=\frac{\Gamma_n}{\delta_n}\left[m\left(1-\frac{\Delta\mathbf{u}_n}{\delta_n}\right)^{\alpha}\left(\frac{m}{\alpha}+\frac{\Delta\mathbf{u}_n}{\delta_n}\right)^{m-1}-\alpha\left(1-\frac{\Delta\mathbf{u}_n}{\delta_n}\right)^{\alpha-1}\left(\frac{m}{\alpha}+\frac{\Delta\mathbf{u}_n}{\delta_n}\right)^{m}\right]\mathrm{x}$$

$$\boxed{T_n(\delta_{nc},0)=\sigma_{max}}$$

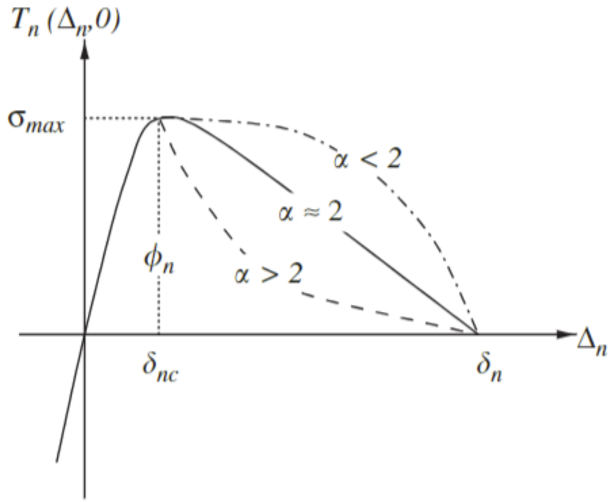
$$\left[\Gamma_t\left(1-\frac{|\Delta\mathbf{u}_t|}{\delta_t}\right)^{\beta}\left(\frac{n}{\beta}+\frac{|\Delta\mathbf{u}_t|}{\delta_t}\right)^{n}+\left\langle G_c^{int}{}_t-G_c^{int}{}_n\right\rangle\right]$$

- Tangential traction force

$$T_t(\Delta\mathbf{u}_n,\Delta\mathbf{u}_t)=\frac{\Gamma_t}{\delta_t}\left[n\left(1-\frac{|\Delta\mathbf{u}_t|}{\delta_t}\right)^{\beta}\left(\frac{n}{\beta}+\frac{|\Delta\mathbf{u}_t|}{\delta_t}\right)^{n-1}-\beta\left(1-\frac{|\Delta\mathbf{u}_t|}{\delta_t}\right)^{\beta-1}\left(\frac{n}{\beta}+\frac{|\Delta\mathbf{u}_t|}{\delta_t}\right)^{n}\right]$$

$$\boxed{T_t(0,\delta_{tc})=\tau_{max}}$$

$$\mathrm{x}\left[\Gamma_n\left(1-\frac{\Delta\mathbf{u}_n}{\delta_n}\right)^{\alpha}\left(\frac{m}{\alpha}+\frac{\Delta\mathbf{u}_n}{\delta_n}\right)^{m}+\left\langle G_c^{int}{}_t-G_c^{int}{}_n\right\rangle\right]\left(\frac{\Delta\mathbf{u}_t}{|\Delta\mathbf{u}_t|}\right)$$



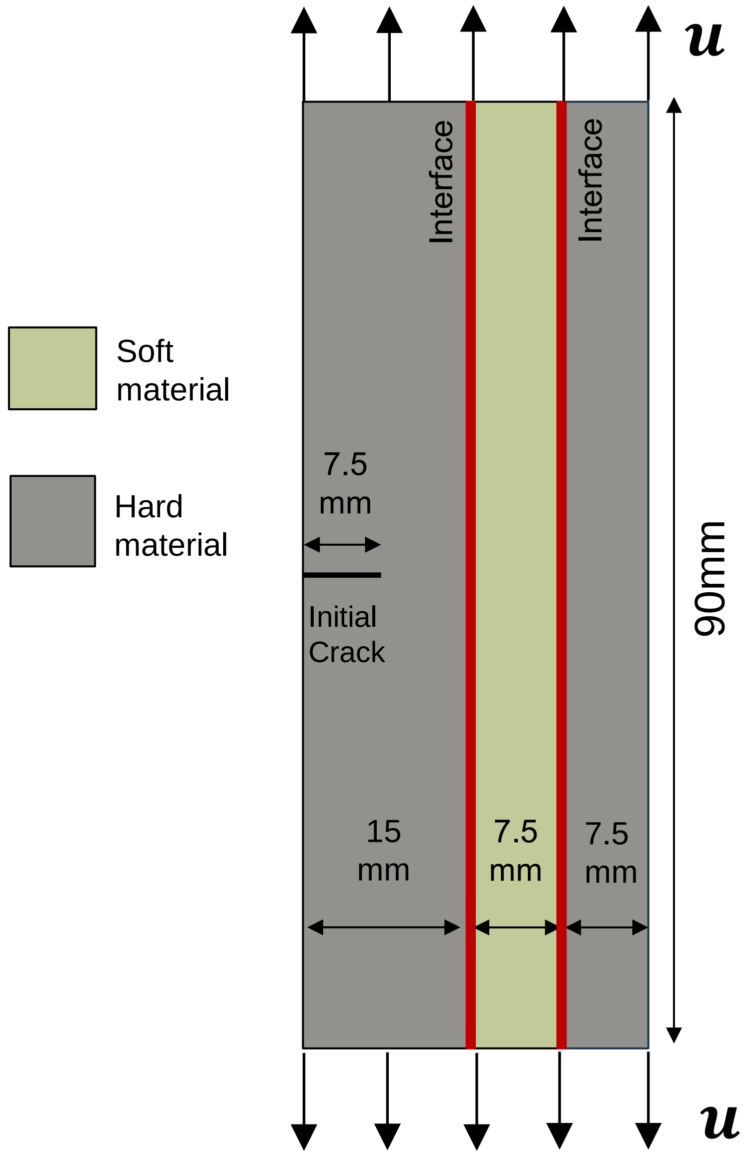
Updated crack surface energy

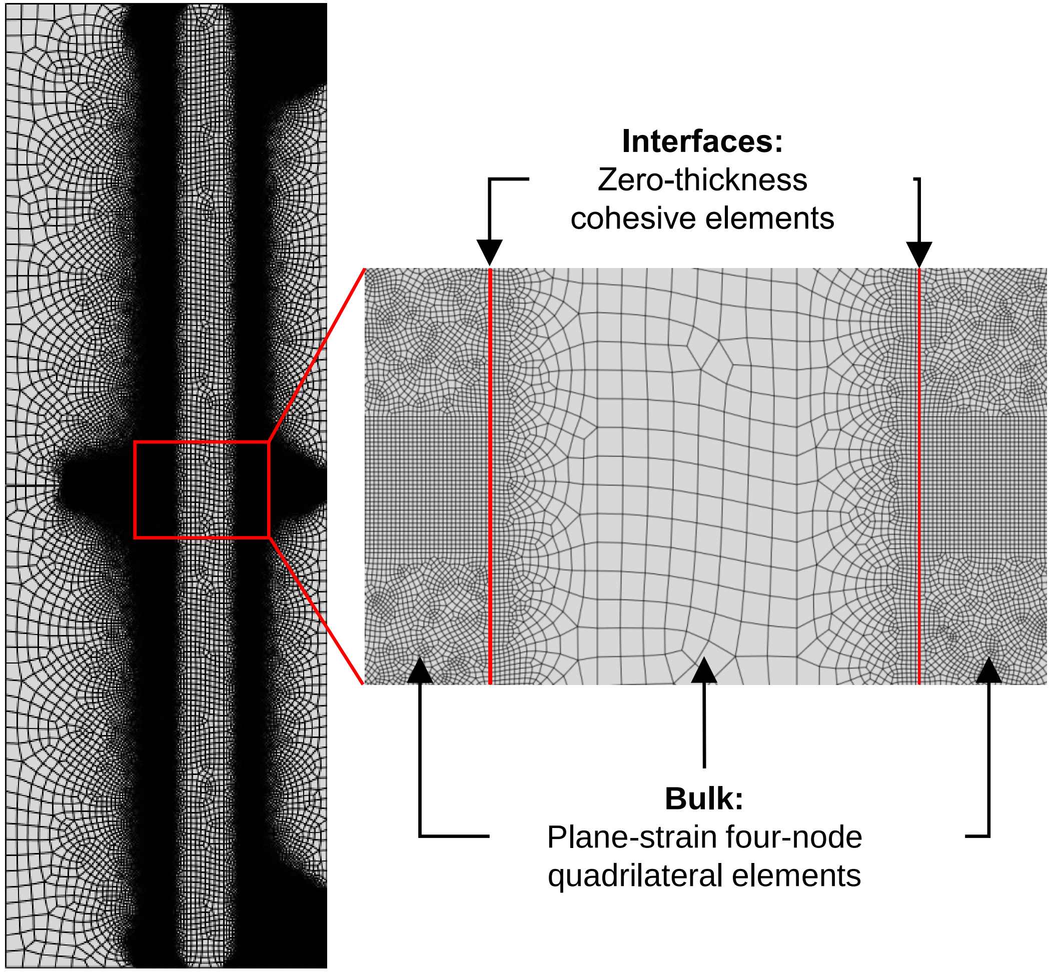
$$\int_{\Gamma_0} G^i \mathrm{dA} = \int_{\Gamma_0} \boxed{(\Delta\mathbf{u})^{\mathrm{T}}}\,\boxed{\mathbf{T}}\,\mathrm{dA} \quad \text{where} \quad \boxed{\Delta\mathbf{u}=\mathbf{u_1}-\mathbf{u_2}} \quad \text{and} \quad \boxed{\mathbf{T}=(T_n,T_t)}$$

Displacement jump

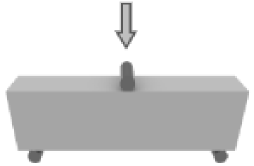
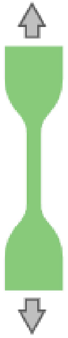
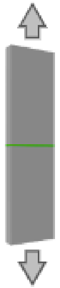
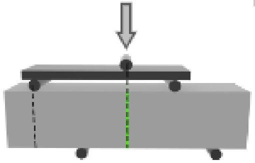
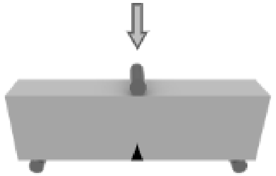
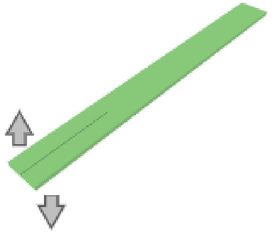
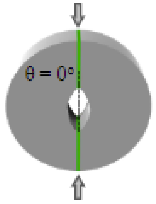
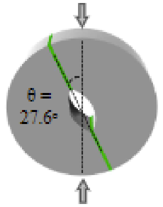
Traction force vector

Zero-thickness cohesive elements used for interface - 4-node quadrilateral plane strain elements used for bulk





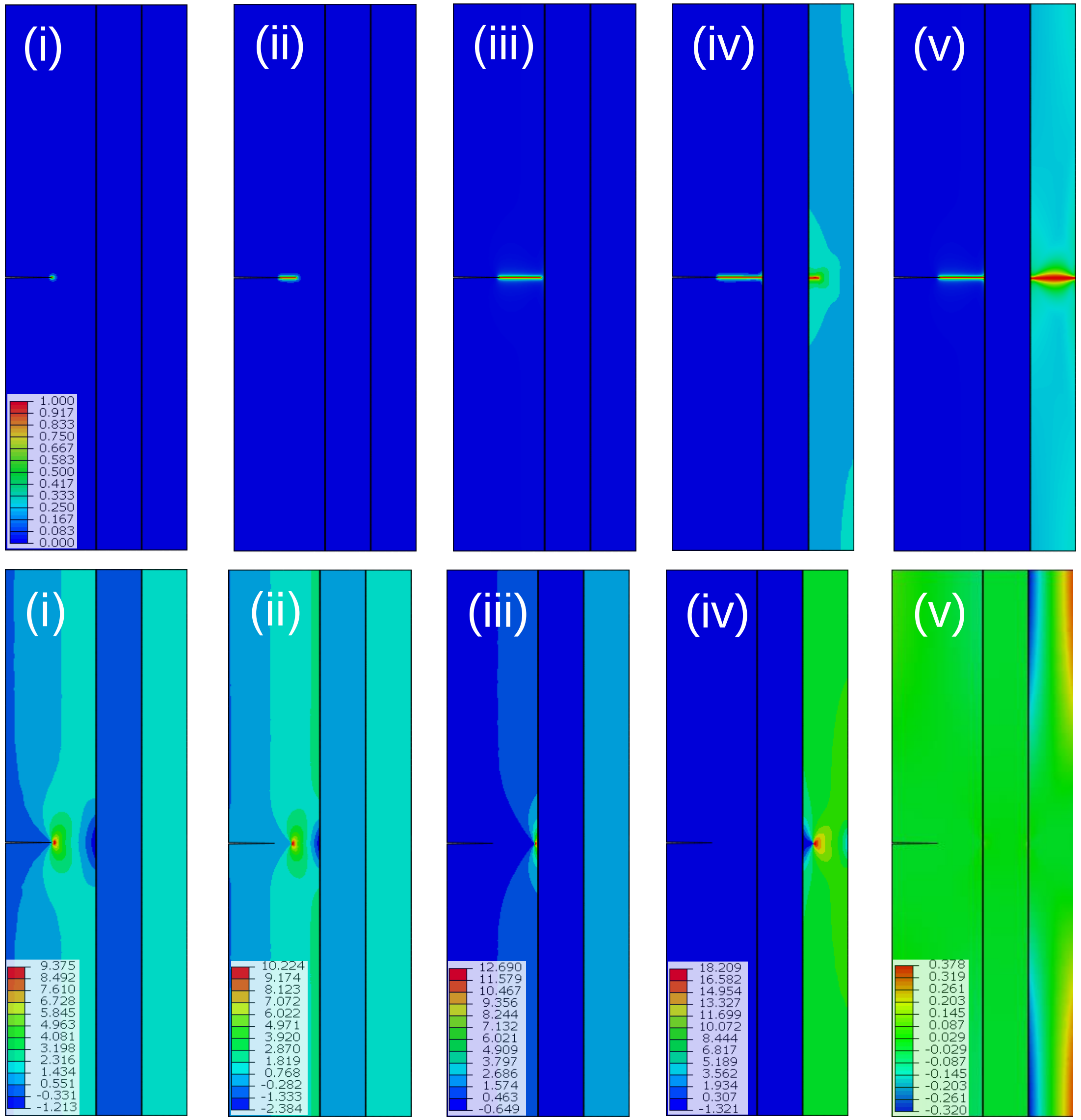
Material properties were determined using specific mechanical characterization tests

	Hardened Cement Paste	PVS	Interface
Mechanical properties	 Modulus of rupture σ_c (MPa) = 3.36 Modulus of elasticity[a] E_c (MPa) = $2.2e^4$ Poisson's ratio[a] $\nu_c = 0.22$	 Tensile strength σ_p (MPa) = 1.06 Rubber modulus μ_p (MPa) = 0.4 Poisson's ratio[b] $\nu_p = 0.49$	 Normal strength σ_n (MPa) = 0.16  Tangential strength σ_t (MPa) = 0.29
Fracture properties	 Fracture toughness G_{c_c} (N/mm) = $4.47e^{-3}$	 Fracture toughness G_{c_p} (N/mm) = 1.29	Mode-I Fracture toughness G_{c_I} (N/mm) = 1.23  Mode-II Fracture toughness $G_{c_{II}}$(N/mm) = 1.29 

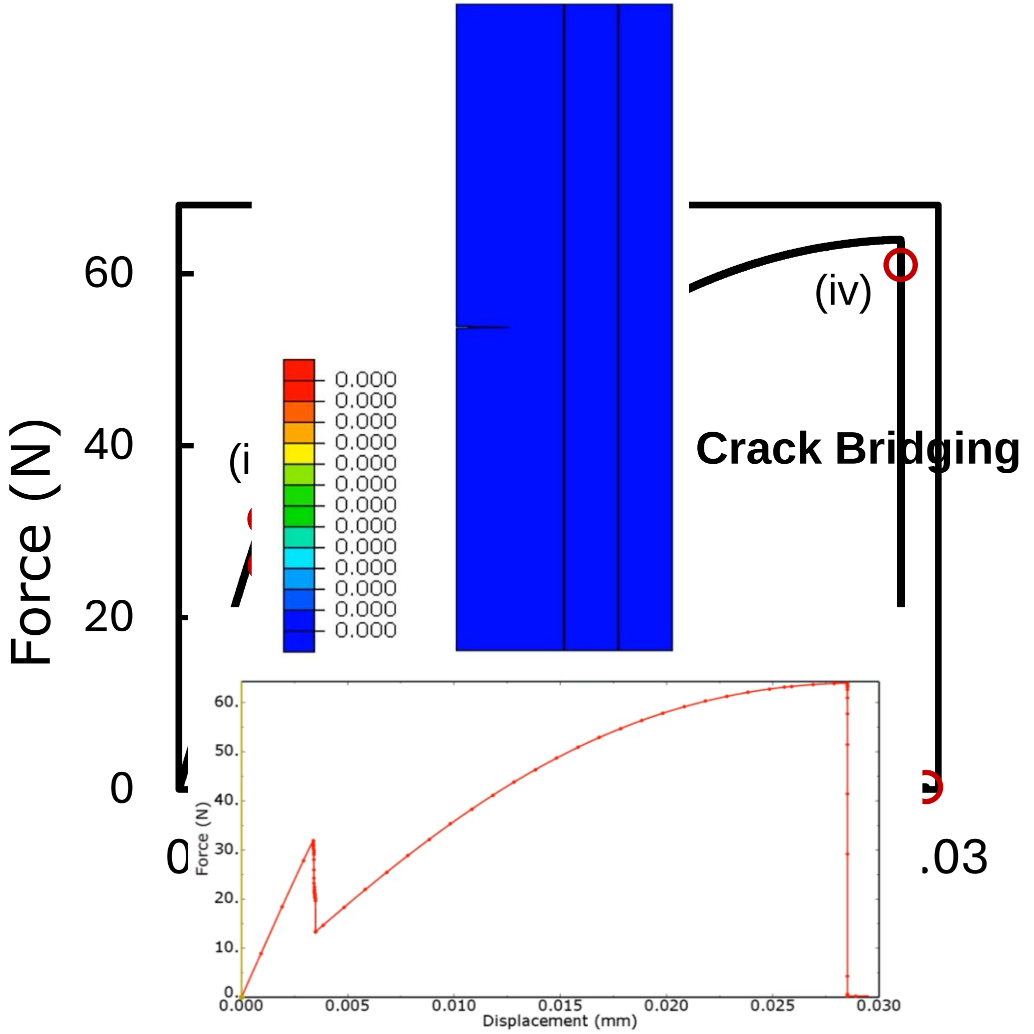
Crack propagation mechanism in tri-layer hard-soft-hard composite

Phase-field

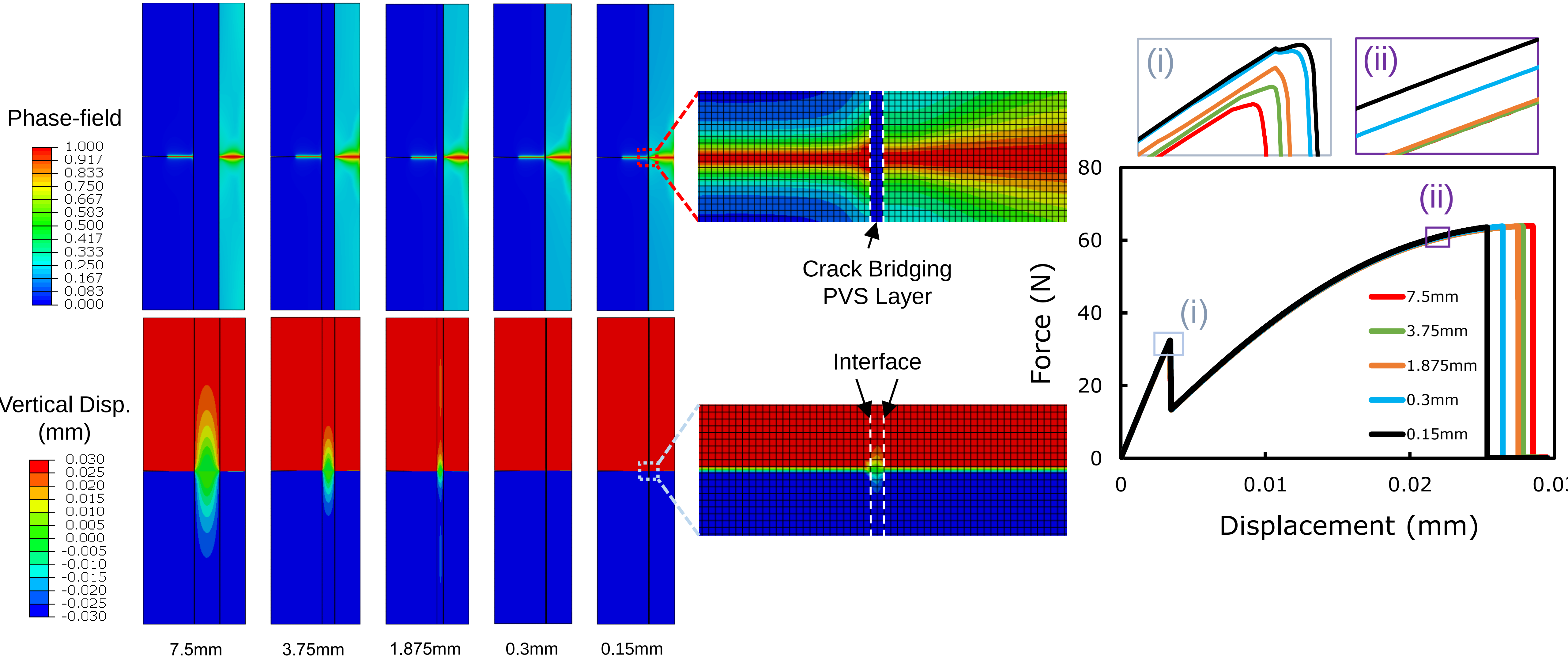
Stress S_{22} (MPa)



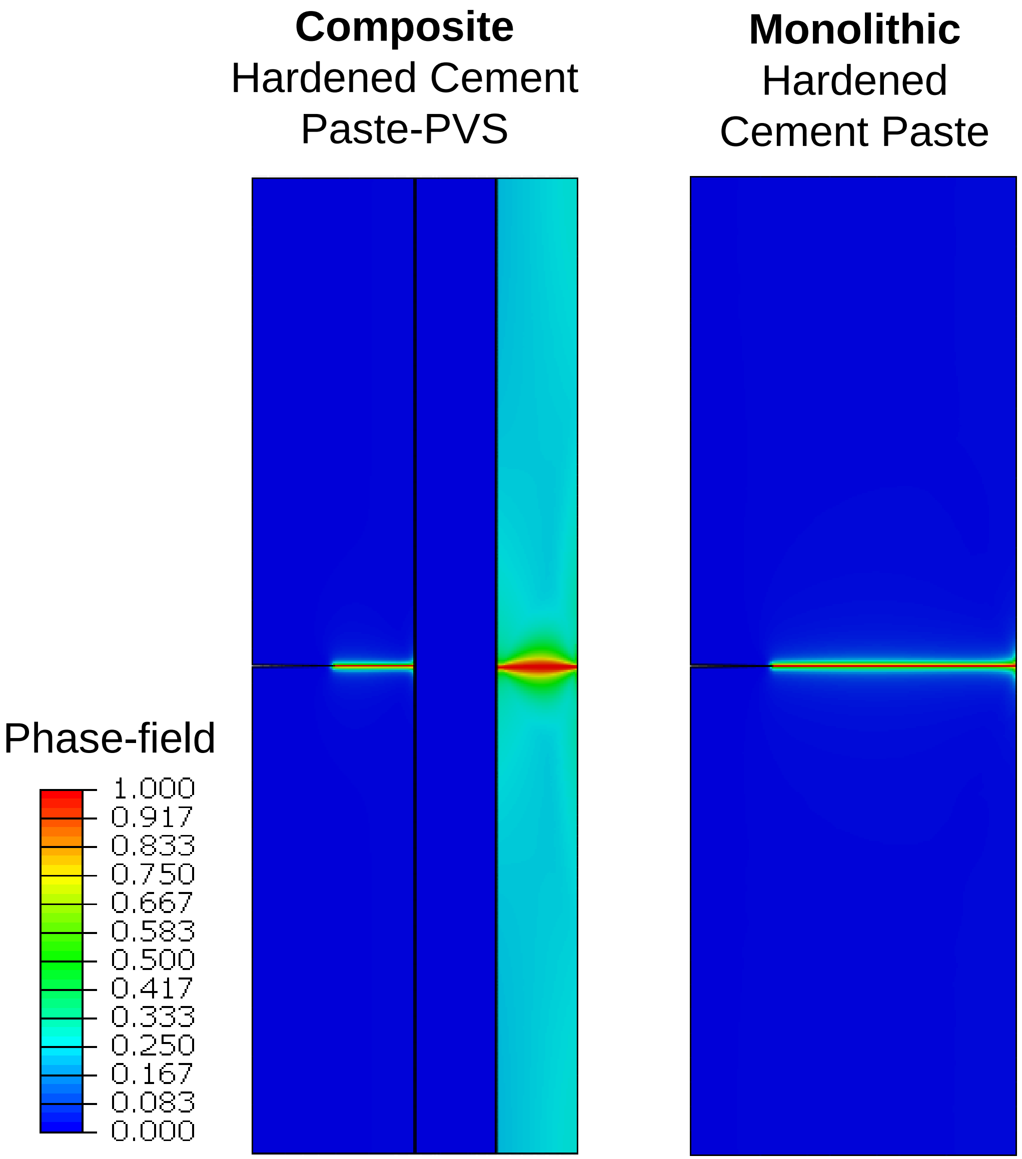
Toughening Mechanisms in Hard-Soft Composites

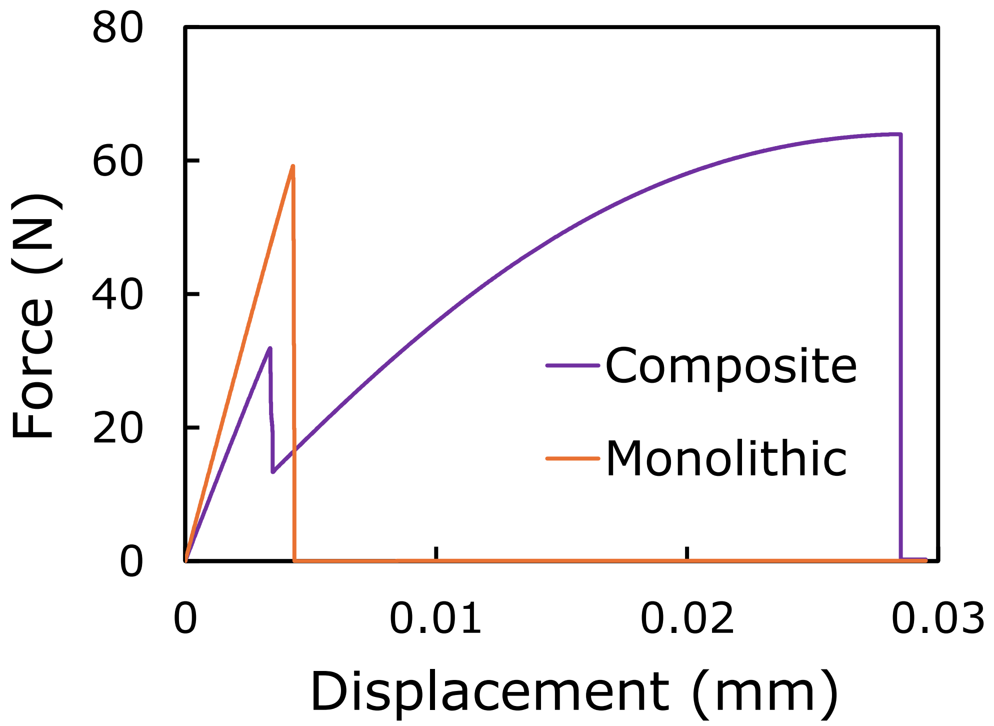


Effect of thickness on overall performance



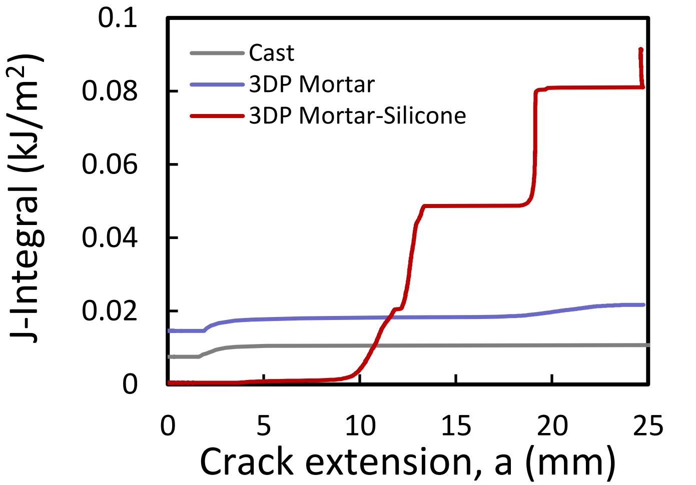
Hardened cement-PVS composite show significant increase in toughness vs. monolithic

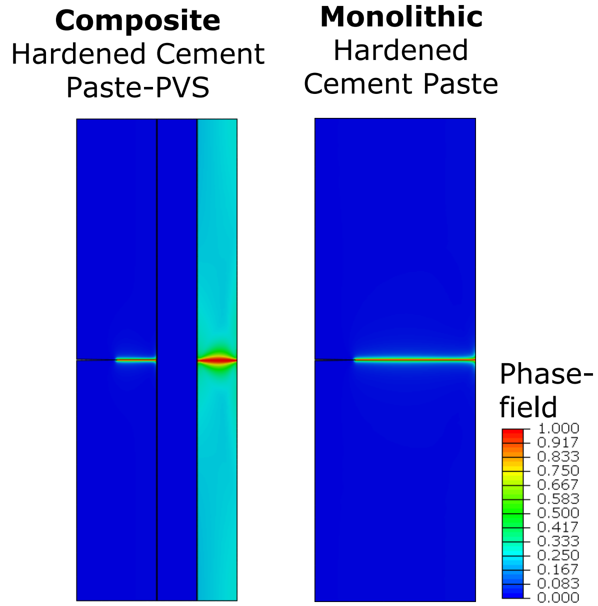


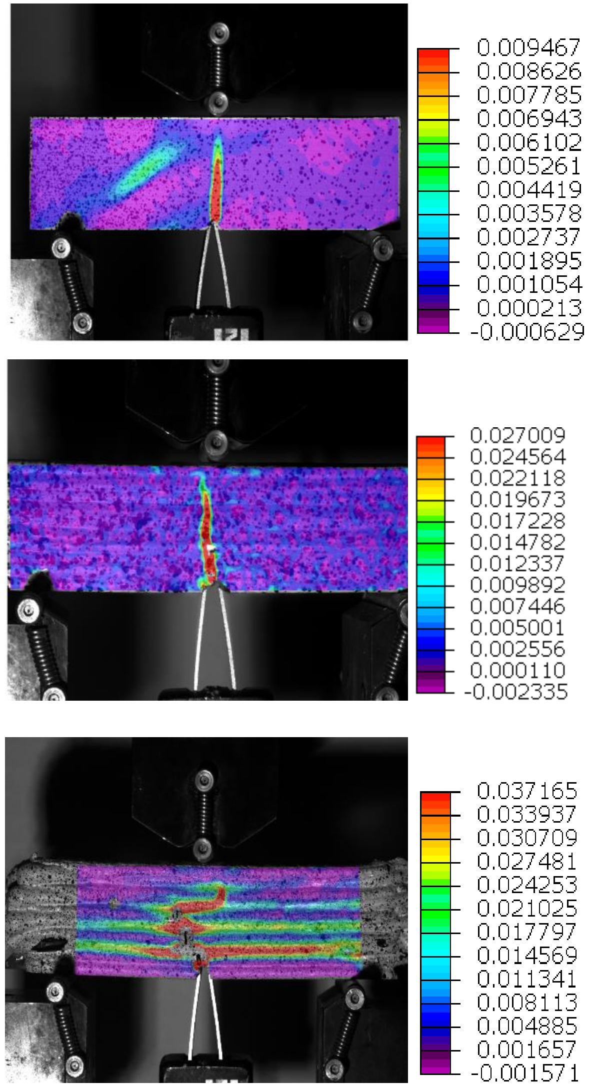


Conclusions and outlook

- Concrete can be re-imagined as a composite material
- Engineering new constitutive properties in concrete materials is possible using advanced manufacturing
- Substantial improvement in toughness achieved for layered hard(mortar)-soft(silicone) multi-material systems compared to their monolithic and cast counterparts
- Numerical investigation of fracture can help further explain toughening mechanisms observed in such multi-material systems







Thank you for your attention! Questions?