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Deciphering Failure and Mechanical Properties of 3D Printed Concrete Using FE Models

Avinaya Tripathi, Ashutosh Maurya, Narayanan Neithalath and Subramaniam Rajan
School of Sustainable Engineering and the Built Environment
Arizona State University

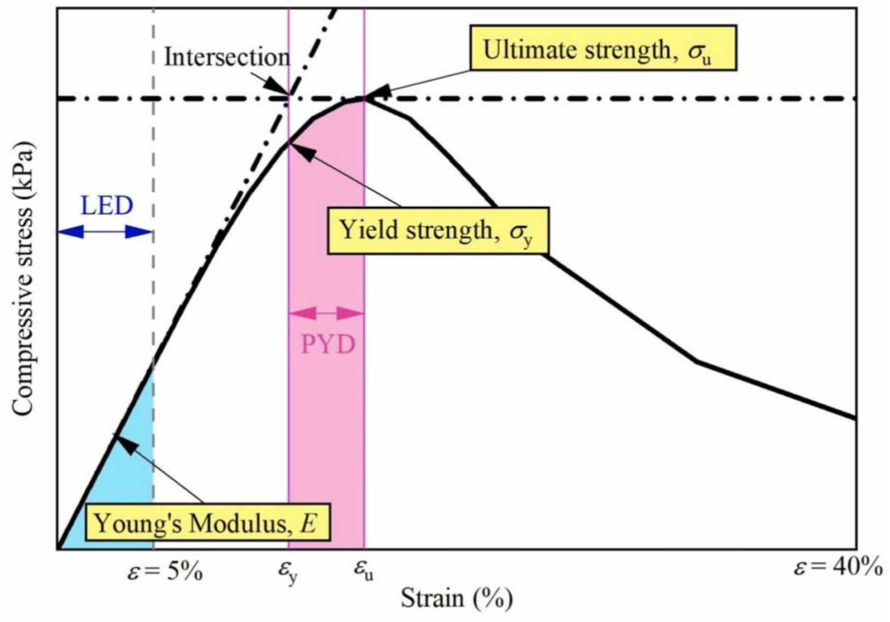
Presented by:
Avinaya Tripathi
Avinaya.Tripathi@asu.edu

Outline

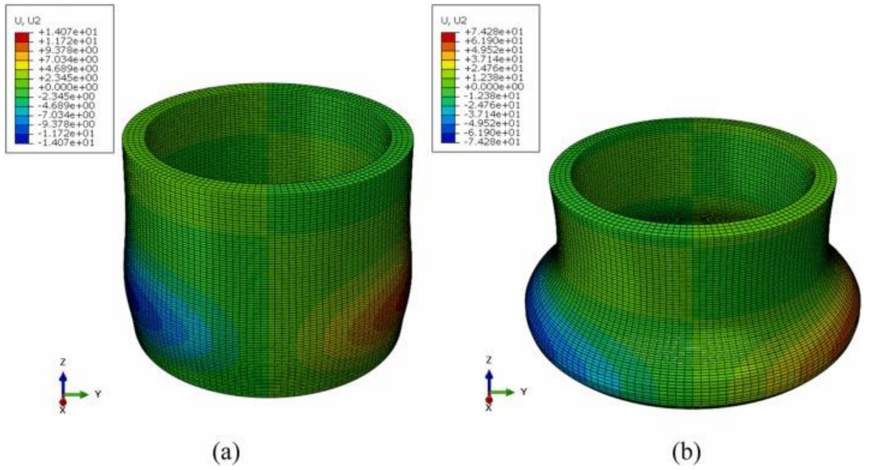
- 3D Printing of Concrete
- Characterizing orthotropic material behavior
- Building MAT_213 input data
- Numerical Examples
  - Compression Test
  - 4-Point Bending Test
- Future Work

3D Printing at ASU

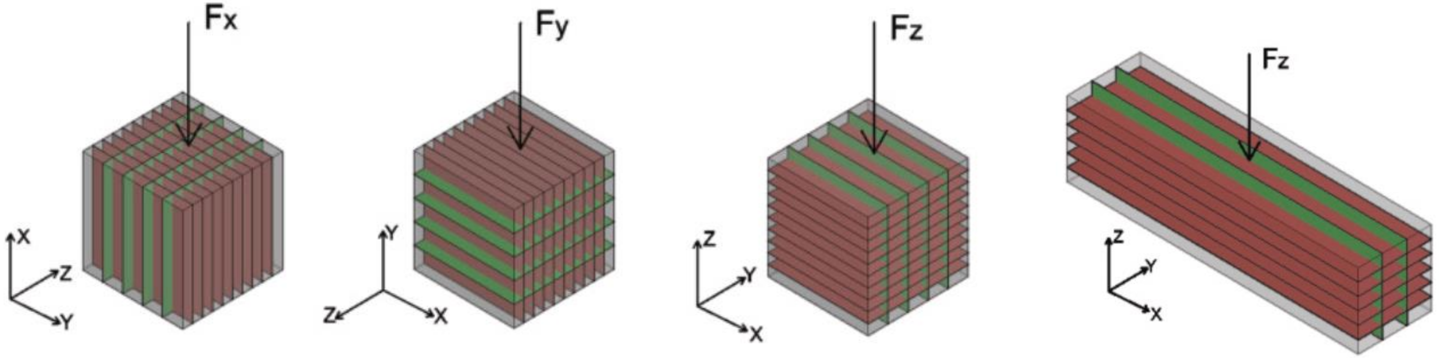
Challenges



Source: Liu et. al. (2023)

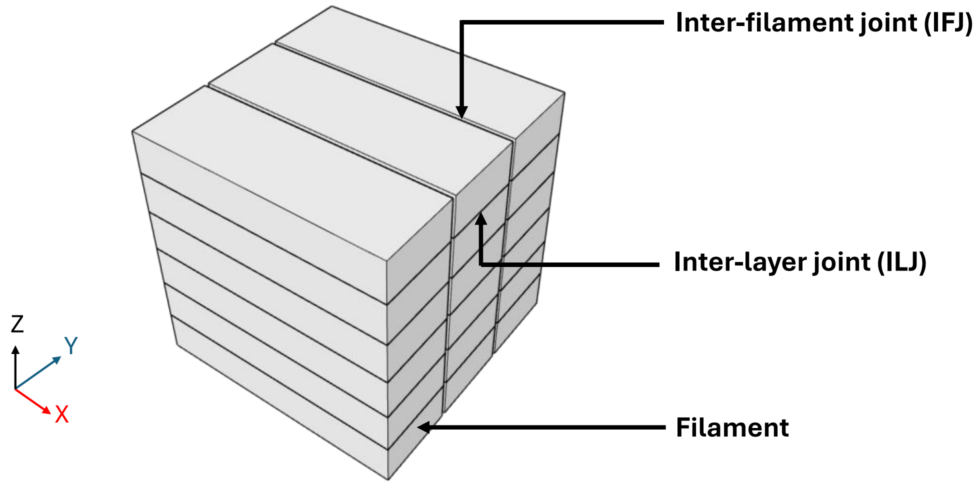


Source: Liu et. al. (2022)



Source: Xiao et. al. (2021)

Reasons for Orthotropic Behavior

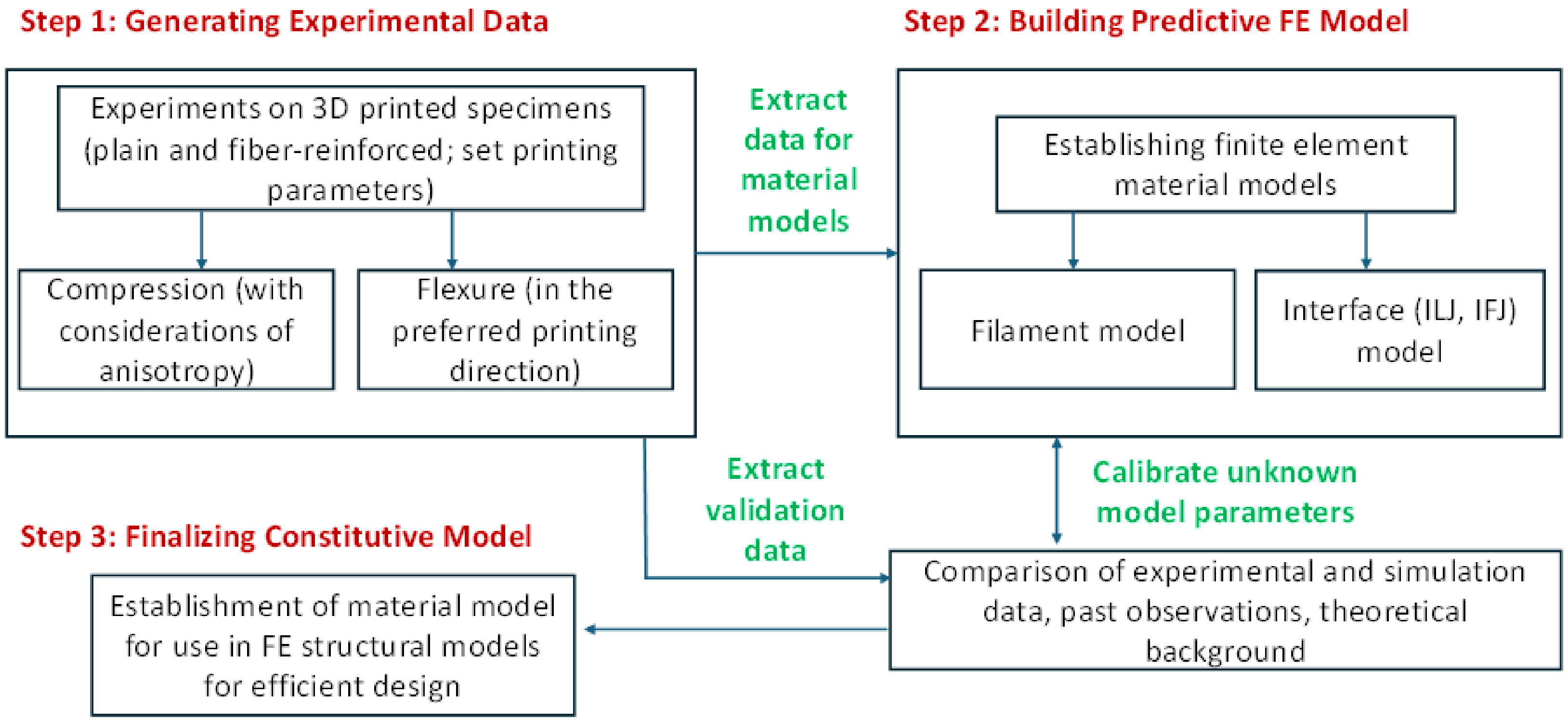


Direction:

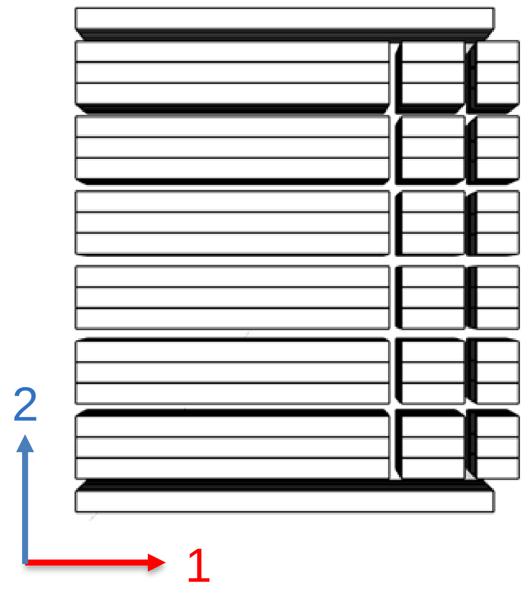
- X-axis (Principal direction 1) along the print direction.
- Y-axis (Principal direction 2) perpendicular to the print direction and parallel to the print layer plane.
- Z-axis (Principal direction 3) perpendicular to both the print direction and the print layer, parallel to build-up direction.

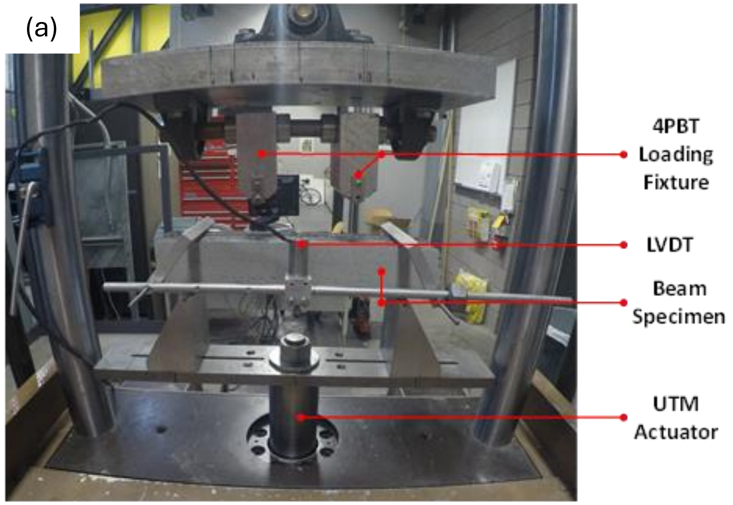
Mixture ID	Mass fraction of ingredients					Water-to-binder ratio (w/b) by mass	SP % to powder ratio (w/b) by mass
	Cement (OPC)	Limestone (L)	Fly Ash (F)	Slag (S)	Sand (M)		
L_{30}	0.35	0.15	-	-	0.5	0.35	0.35
UB	0.42	0.06	0.06	0.06	0.4	0.18	1.1

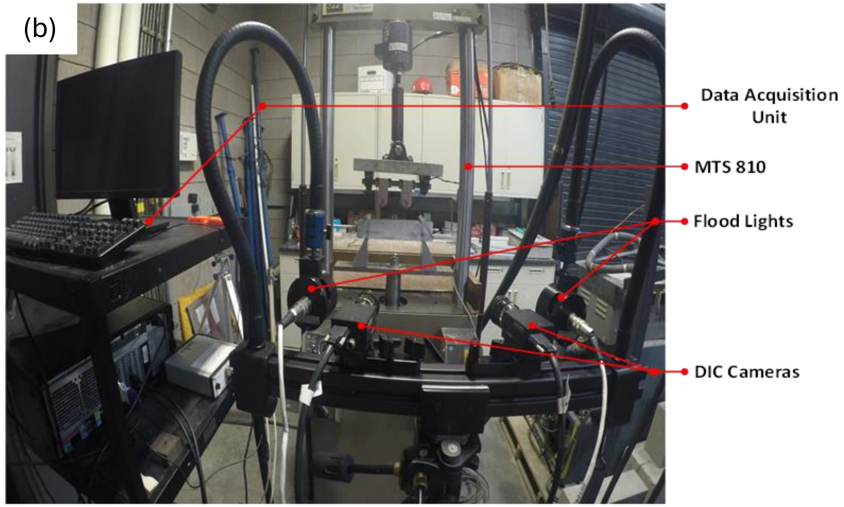
Overview


Step 1: Generating Experimental Data
Experiments on 3D printed specimens (plain and fiber-reinforced; set printing parameters)
Compression (with considerations of anisotropy)
Flexure (in the preferred printing direction)
Extract data for material models
Step 2: Building Predictive FE Model
Establishing finite element material models
Filament model
Interface (ILJ, IFJ) model
Extract validation data
Calibrate unknown model parameters
Step 3: Finalizing Constitutive Model
Establishment of material model for use in FE structural models for efficient design
Comparison of experimental and simulation data, past observations, theoretical background

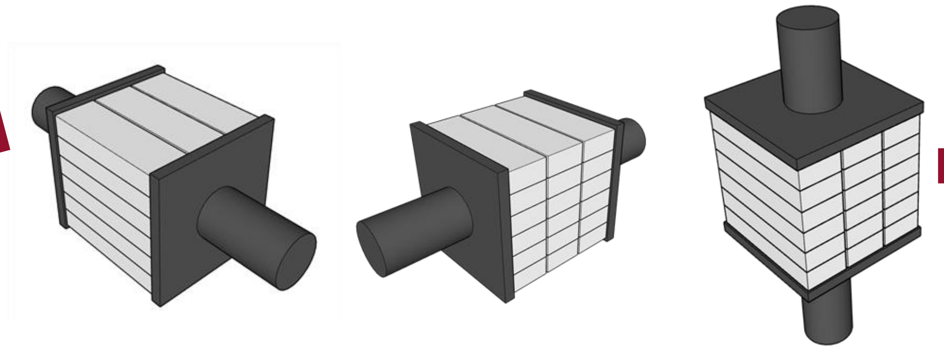
Validation Tests



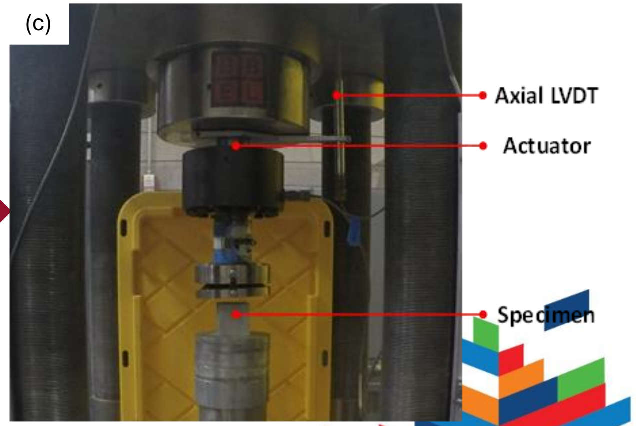




4-point bend testing (Beams of 60 × 60 × 300 mm size)



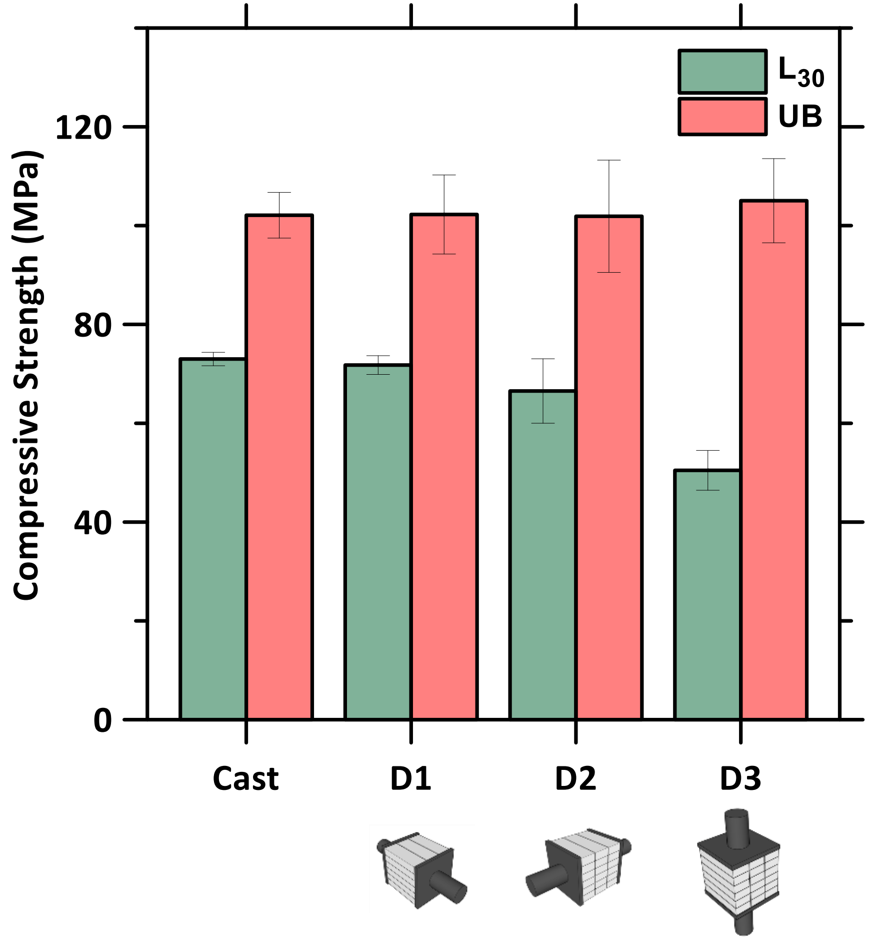
Direction-1 (D1) **Direction-2 (D2)** **Direction-3 (D3)**

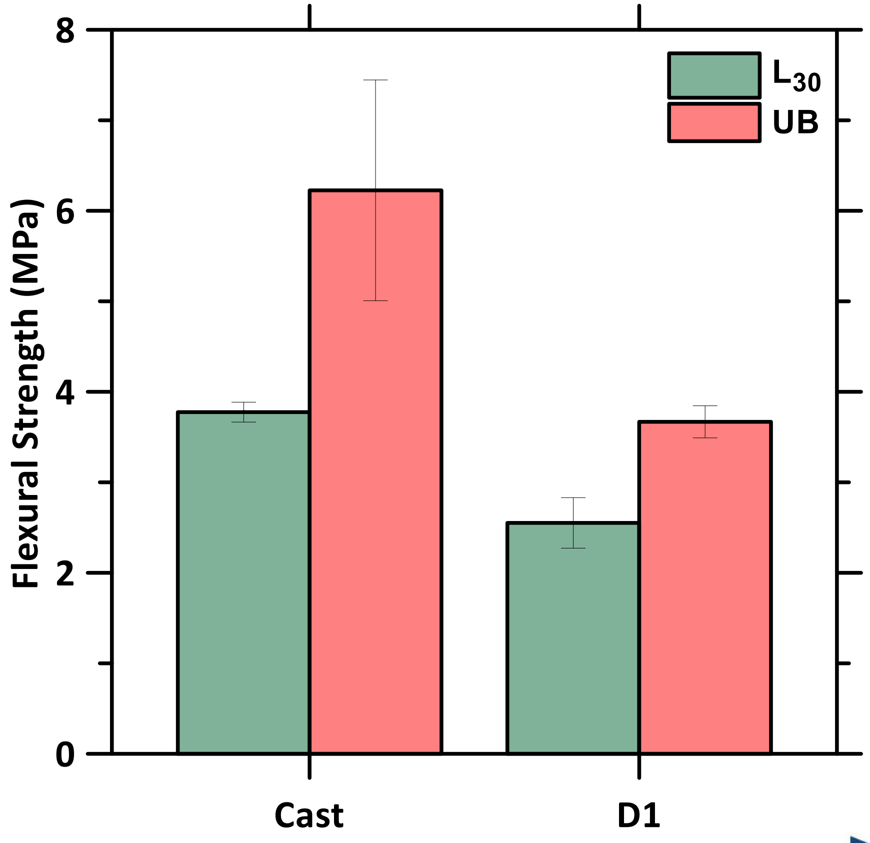


- Layer Height (LH): 10 mm
- Filament Width (FW): 20 mm

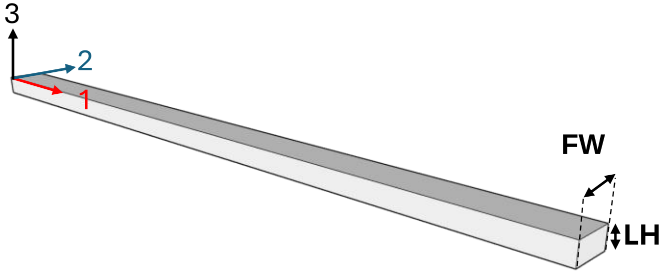
Uniaxial Compression (Cubes of 60 × 60 × 60 mm size)

Material Characterization Test

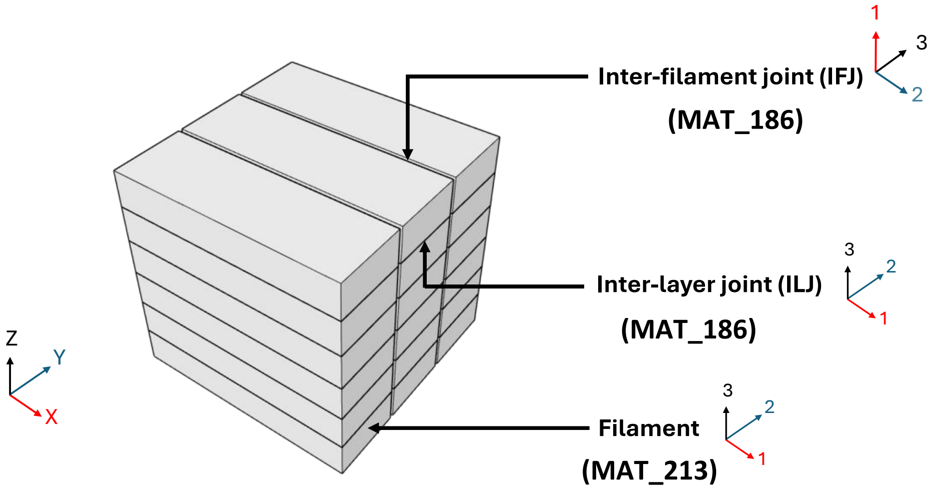




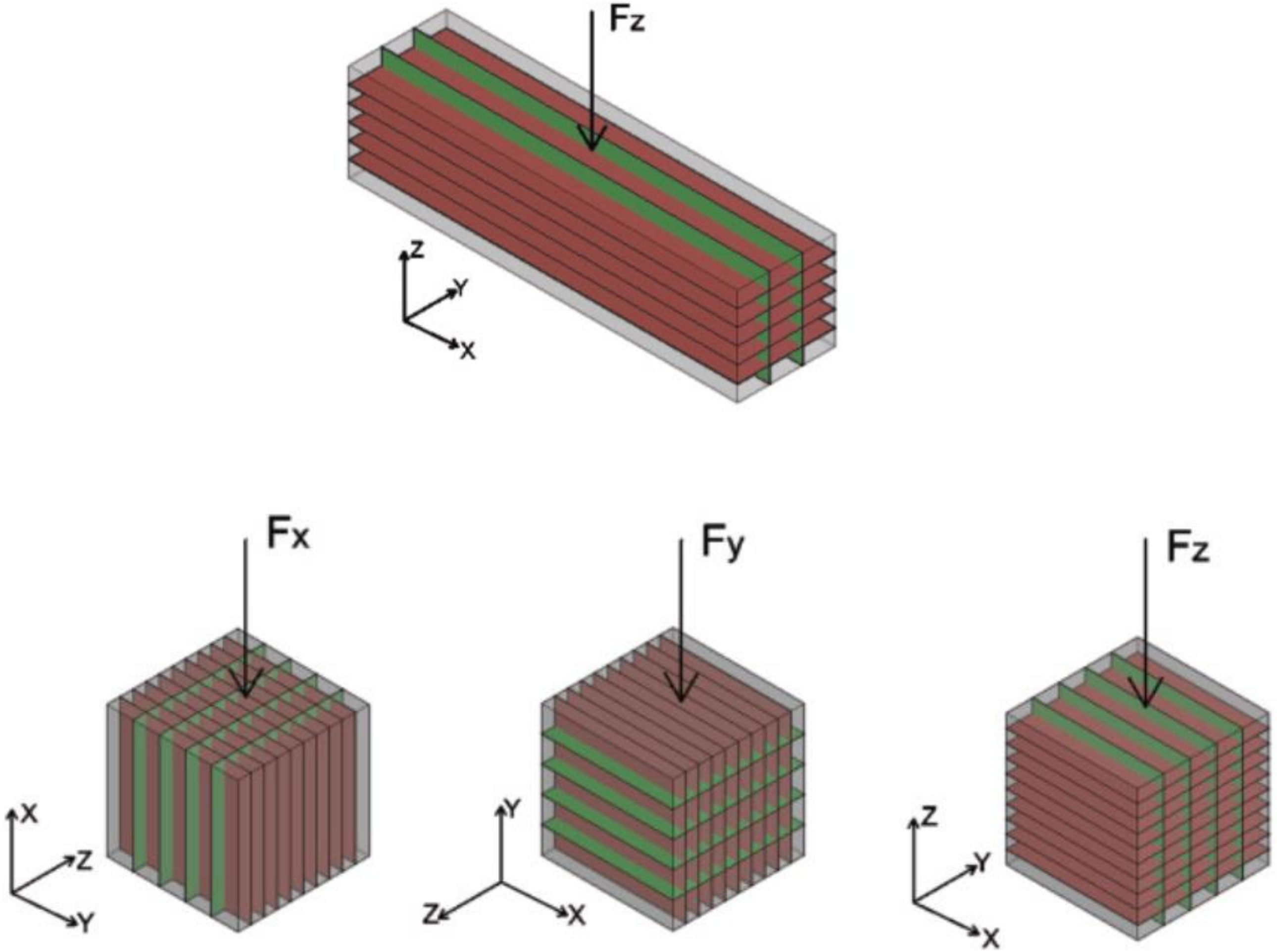
Numerical Modeling



Building block



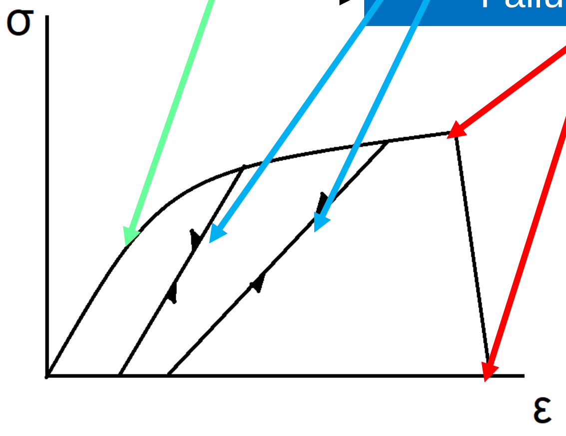
Representative FE Models



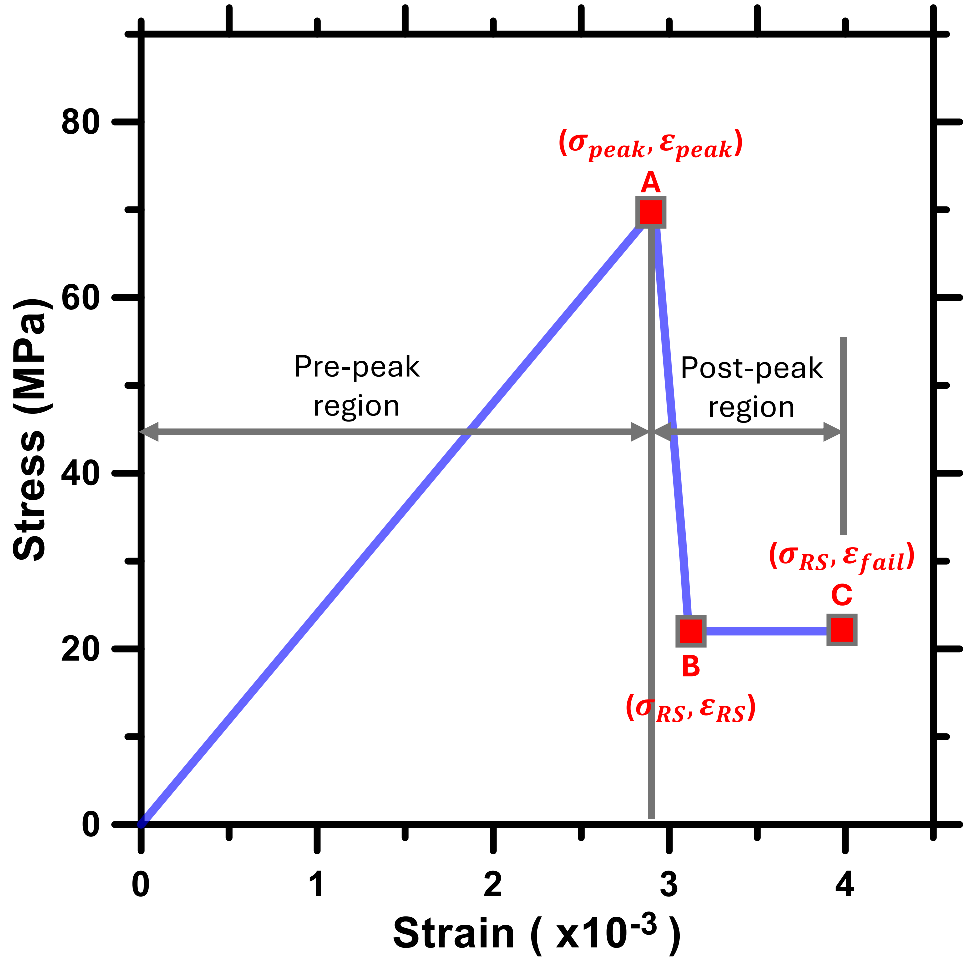
MAT-213

Composite Material Model

- Deformation → Tabulated Stress-Strain Curves with Orthotropic data
  Visco-elastic and Visco-plastic Behaviour
  (rate and temperature dependence)
- Damage → Uncoupled Damage
  Coupled Damage
- Failure → Tsai-Wu Failure Criterion (TWFC)
  Puck Failure Criterion (PFC)
  Generalized Tabulated Failure Criterion (GTFC)
  Point Cloud Failure Criterion (PCFC)



Using MAT-213 Model - Simplified



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MAT_213 Material Parameters

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Parameter	Remarks	Parameter Type	Value (L_{30})	Value (UB)
ρ	Mass density	-	2200 kg/m³	2536 kg/m³
E_1	Young's modulus in 1-direction	1-2 plane	24 GPa	40 GPa
E_2	Young's modulus in 2-direction	1-2 plane	24 GPa	40 GPa
E_3	Young's modulus in 3-direction	1-3 and 2-3 planes	24 GPa	40 GPa
ϑ_{12}	Poisson's ratio in 1-2 plane	1-2 plane	0.23	0.20
ϑ_{23}	Poisson's ratio in 2-3 plane	1-3 and 2-3 planes	0.23	0.20
ϑ_{31}	Poisson's ratio in 1-3 plane	1-3 and 2-3 planes	0.23	0.20
G_{12}	Shear modulus in 1-2 plane	1-2 plane	Estimated	Estimated
G_{23}	Shear modulus in 2-3 plane	1-3 and 2-3 planes	Estimated	Estimated
G_{31}	Shear modulus in 1-3 plane	1-3 and 2-3 planes	Estimated	Estimated
$(\sigma_1^{peak})^t$	Peak tensile stress in 1-direction	1-2 plane	2.50 MPa	3.67 MPa
$(\sigma_2^{peak})^t$	Peak tensile stress in 2-direction	1-2 plane	2.50 MPa	3.67 MPa
$(\sigma_3^{peak})^t$	Peak tensile stress in 3-direction	1-3 and 2-3 planes	2.50 MPa	3.67 MPa
$(\sigma_{RS})_1^t$	Tensile residual strength in 1-direction	1-2 plane	0 MPa	0 MPa
$(\sigma_{RS})_2^t$	Tensile residual strength in 2-direction	1-2 plane	0 MPa	0 MPa
$(\sigma_{RS})_3^t$	Tensile residual strength in 3-direction	1-3 and 2-3 planes	0 MPa	0 MPa
$(\sigma_1^{peak})^c$	Peak compressive stress in 1-direction	1-2 plane	70 MPa	102 MPa
$(\sigma_2^{peak})^c$	Peak compressive stress in 2-direction	1-2 plane	70 MPa	102 MPa
$(\sigma_3^{peak})^c$	Peak compressive stress in 3-direction	1-3 and 2-3 planes	70 MPa	102 MPa
$(\sigma_{RS})_1^c$	Compressive residual strength in 1-direction	1-2 plane	0 MPa	0 MPa
$(\sigma_{RS})_2^c$	Compressive residual strength in 2-direction	1-2 plane	0 MPa	0 MPa
$(\sigma_{RS})_3^c$	Compressive residual strength in 3-direction	1-3 and 2-3 planes	0 MPa	0 MPa
τ_{12}^{peak}	Peak shear stress in 1-2 plane	1-2 plane	Estimated	Estimated
τ_{23}^{peak}	Peak shear stress in 2-3 plane	1-3 and 2-3 planes	Estimated	Estimated
τ_{13}^{peak}	Peak shear stress in 1-3 plane	1-3 and 2-3 planes	Estimated	Estimated
$(\tau_{12})_{RS}$	Shear residual strength in 1-2 plane	1-2 plane	0 MPa	0 MPa
$(\tau_{23})_{RS}$	Shear residual strength in 2-3 plane	1-3 and 2-3 planes	0 MPa	0 MPa
$(\tau_{13})_{RS}$	Shear residual strength in 1-3 plane	1-3 and 2-3 planes	0 MPa	0 MPa

Parameter list for MAT_213 obtained from experiment or estimated from experimental results, used for the concrete filament

- Filament assumed isotropic.
- Shear stress assumed to be correlated to tensile stress.
- Shear modulus calculated from E and ϑ.
- ε_{12P}^{eq} and ε_{123P}^{eq} control the highest strength achievable in compression.

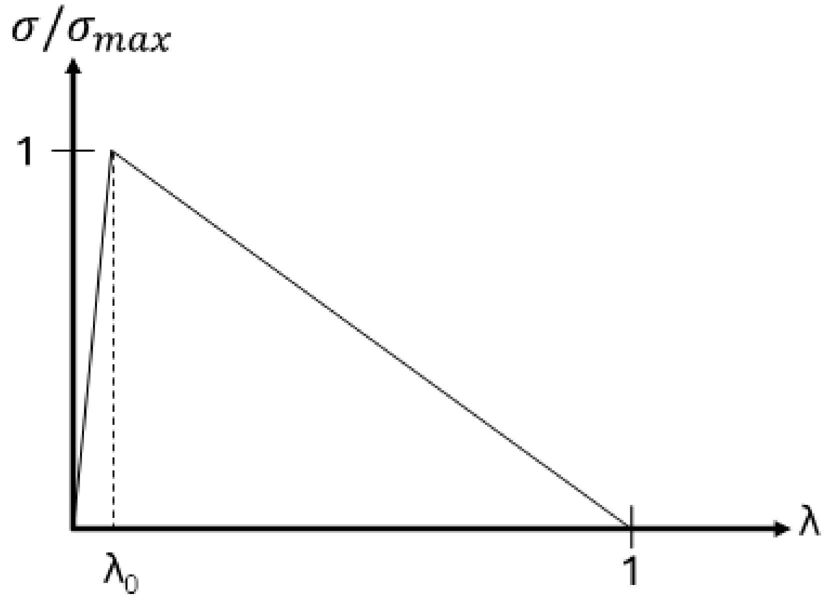
Parameter	Remarks	Parameter Type	Value
ε_{12P}^{eq}	Equivalent failure strain in 1-2 plane	1-2 plane	Calibrated
ε_{123P}^{eq}	Equivalent failure strain in 13 and 23 planes	1-3 and 2-3 planes	Calibrated

Calibrated parameter list for MAT_213, used for the concrete filament

MAT_186 Material Parameters

Parameter	Remarks	Value
σ^t	Peak tensile stress	Calibrated
σ^s	Peak shear stress	Estimated
G_{IC}	Fracture toughness in Mode-I	Calibrated
G_{IIC}	Fracture toughness in Mode-II	Calibrated

Parameter list for MAT_186, used for the interfaces



Normalized traction-separation curve for MAT_186, used for the interfaces

λ_0 = 0.002 for Mode-I and λ_0 = 0.25 for Mode-II → Consistent with literatures

- λ_0 kept consistent with literature used values.
- σ^s taken 0.55 times σ^t, which is again consistent with literature.
- The σ^t for inter-layer interface assumed to be higher than the that for the inter-filament interface.

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Compression Test Model

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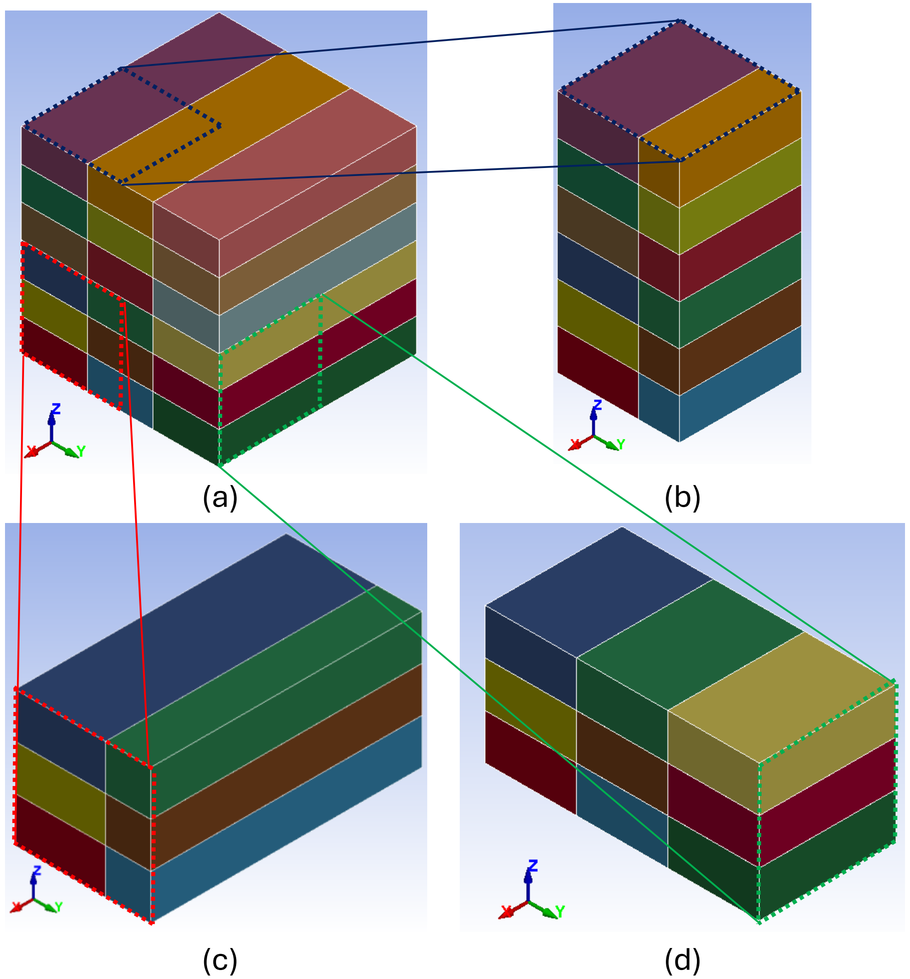
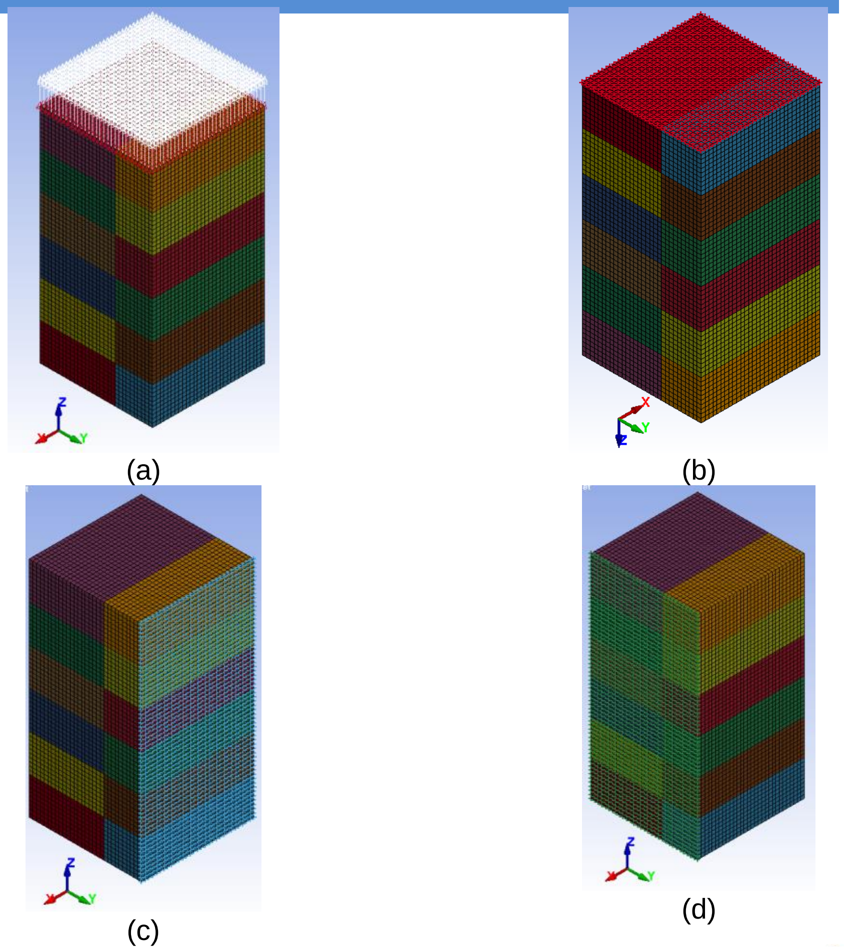
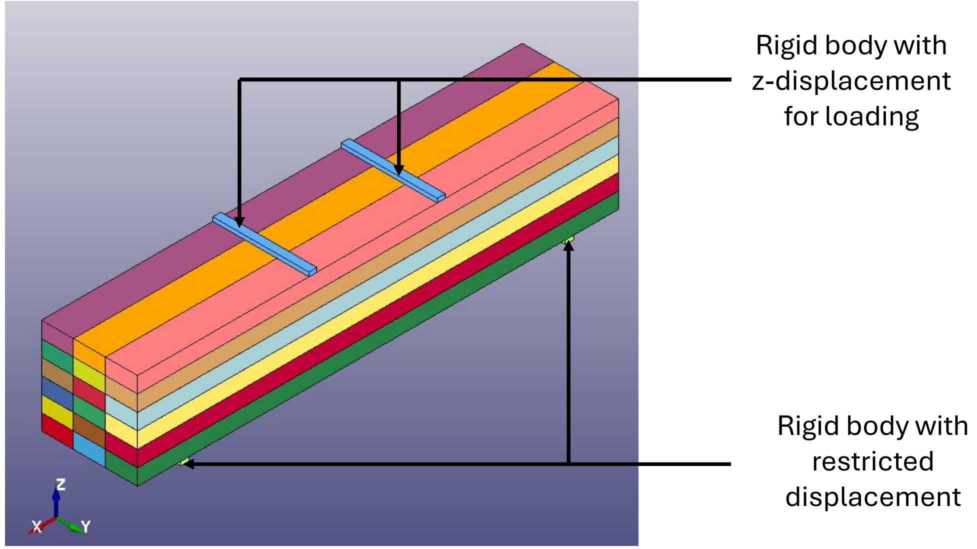


(a) The actual size compression cube model, and quarter symmetric FE model for compression in: (b) D3, (c) D1, and (d) D2 directions.

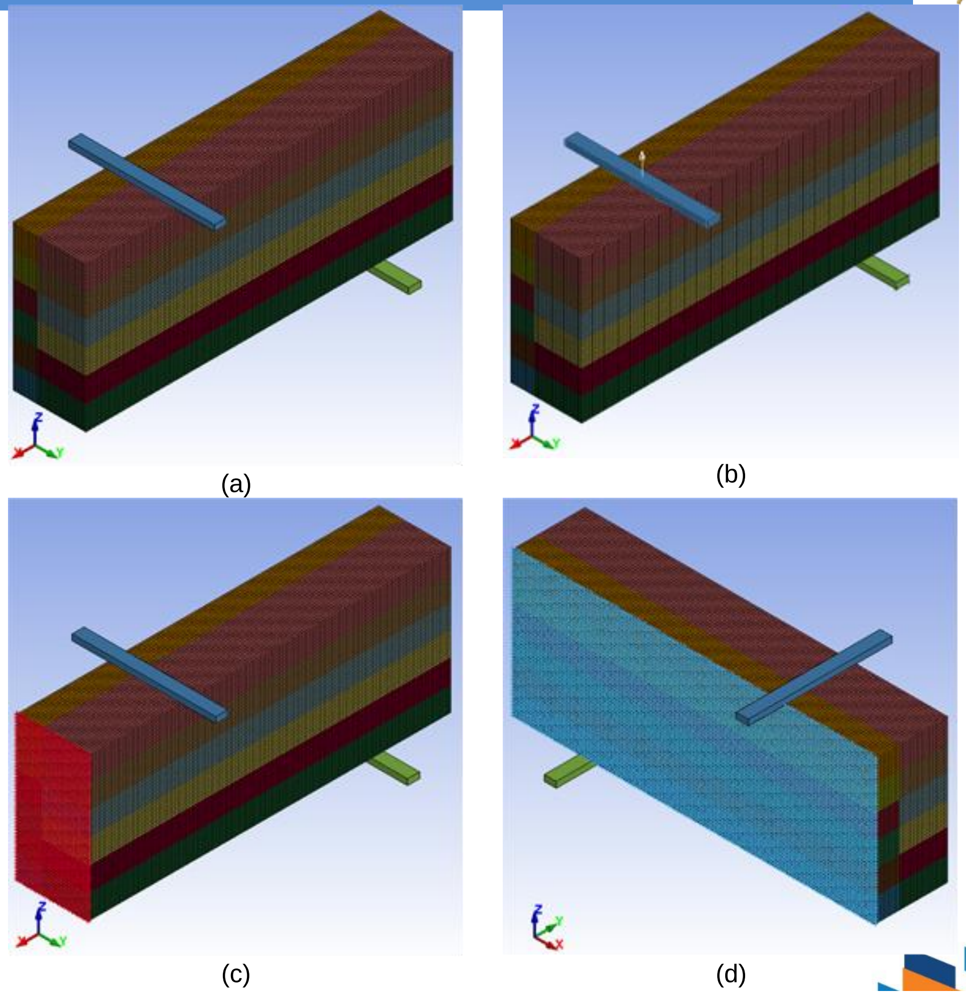


Boundary condition applied on cube element when being tested in D3, (a) nodal displacement on the surface with highest z-coordinate, (b) z-displacement restricted on the surface with lowest z-coordinate (note that the z co-ordinate has been flipped upside down for this figure), (c) y-displacement restricted along symmetry plane in y, and (d) x-displacement restricted along symmetry plane in x.

Flexure Test Model



Representative FE model setup, replicating actual test dimensions, for 4-point bending test (4PBT).



Representative (a) quarter symmetric model setup for flexure simulation, (b) rigid body movement imposed on loading and support plate, (c) nodal x-displacement and all rotation restrained for symmetry plane along x-axis, and (d) nodal y-displacement and all rotations restrained for symmetry plane along y-axis.

Calibrated Parameters

Material Model	Parameter	Direction/Plane	L_{30}	UB
MAT_213	Equivalent failure strain in 1-2 plane	-	0.0037	0.0035
	Equivalent failure strain in 1-3 and 2-3 plane	-	0.0037	0.0035
MAT_186	Traction Mode-I (MPa)	Inter-layer	2.500	3.670
		Inter-filament	0.750	2.200
	Traction Mode-II (MPa)	Inter-layer	1.375	2.019
		Inter-filament	0.413	1.210
	GIC (N/m)	Inter-layer	0.3000	0.4404
		Inter-filament	0.1125	0.1652
	GIIC (N/m)	Inter-layer	0.1650	0.2423
		Inter-filament	0.0620	0.0909

Calibrated parameters for the material cards

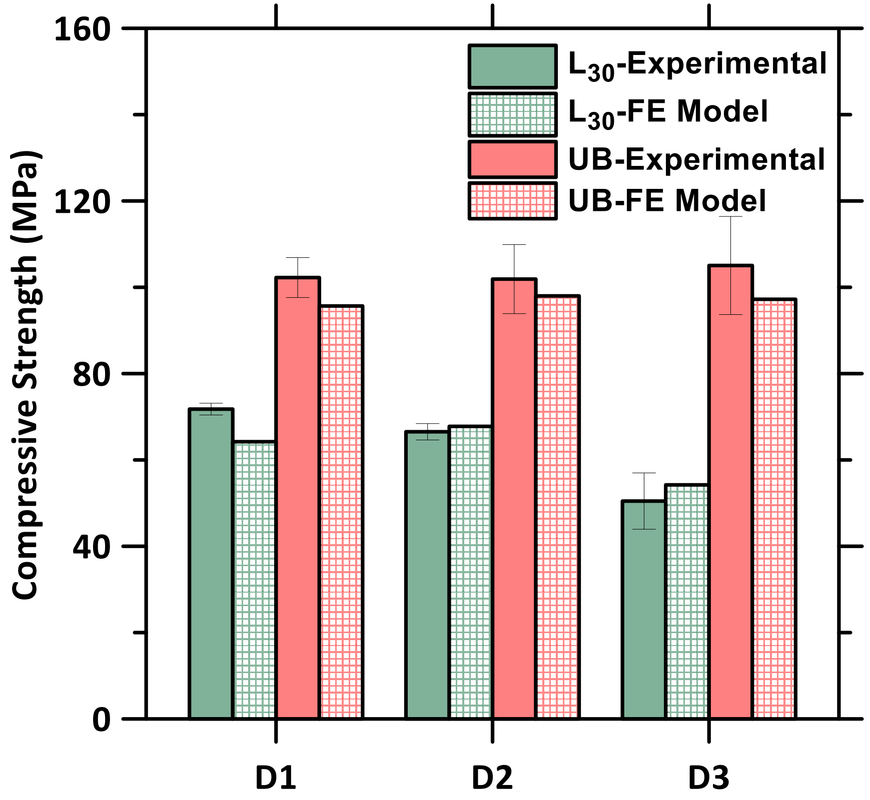
$$\frac{0.0037}{70} * 2.5$$

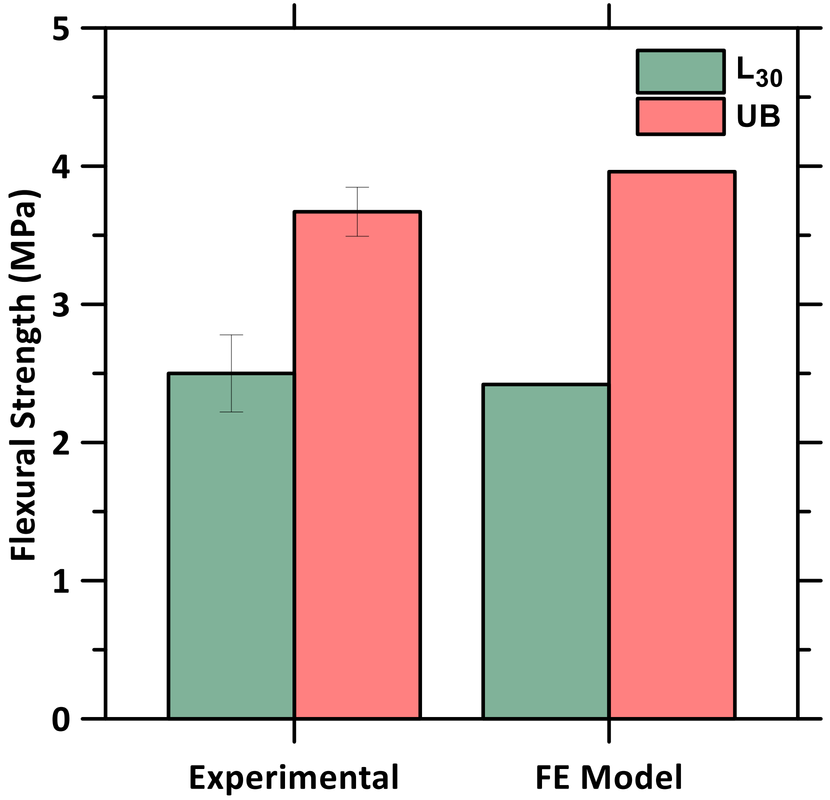
Parameter	L_{30}	UB
Equivalent failure strain for 1-2 plane	1.3214×10^{-4}	1.2593×10^{-4}

$$\frac{0.0035}{102} * 3.67$$

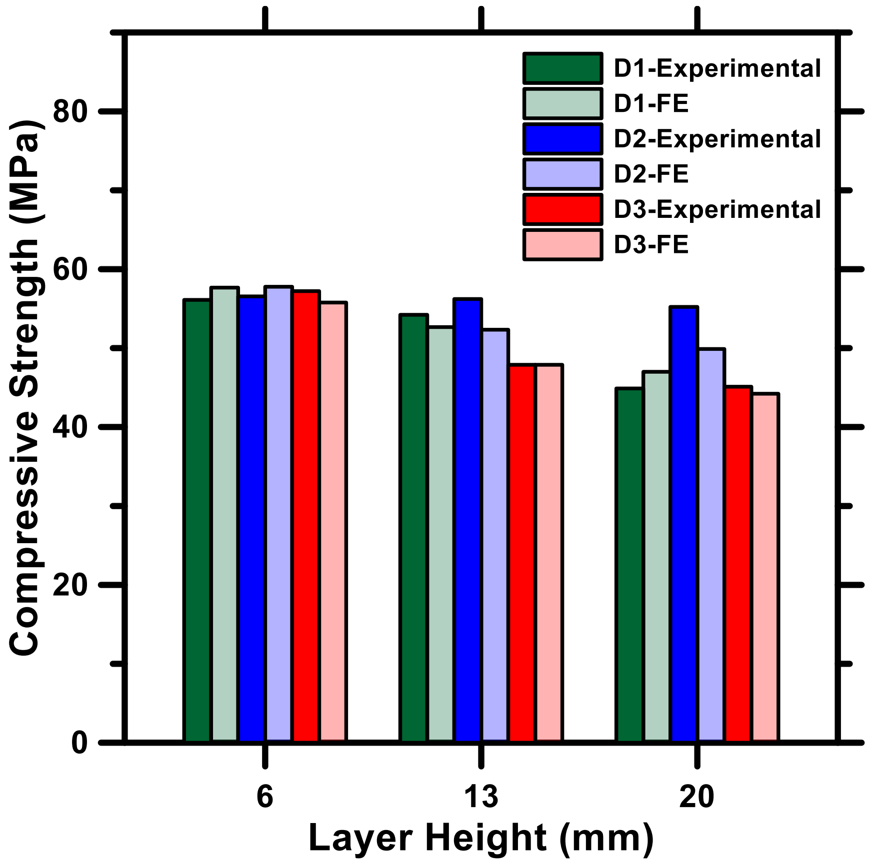
Change required for flexure model

Validation Test



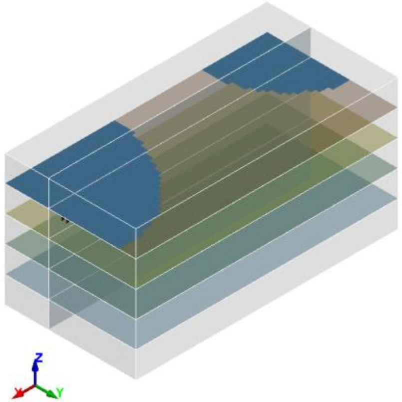
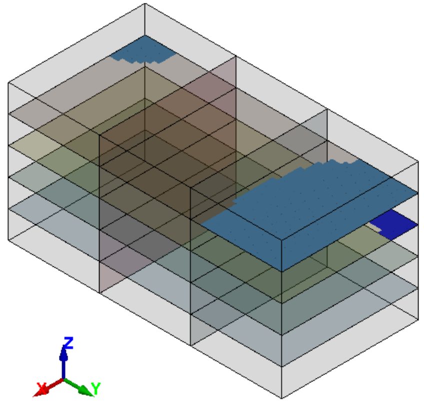
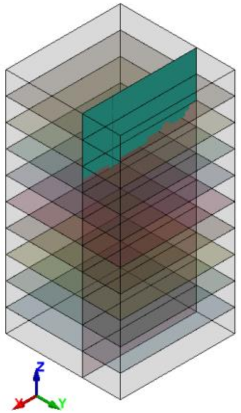
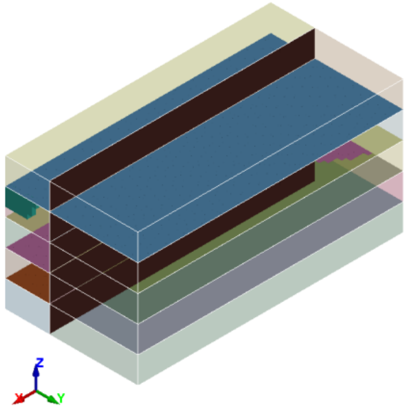
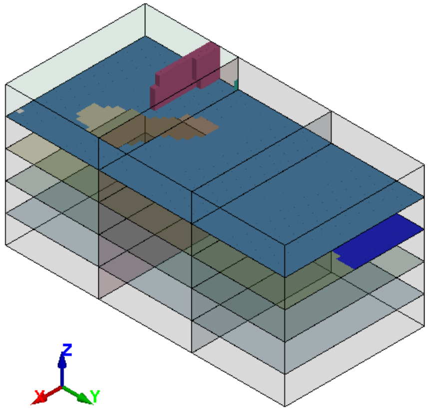
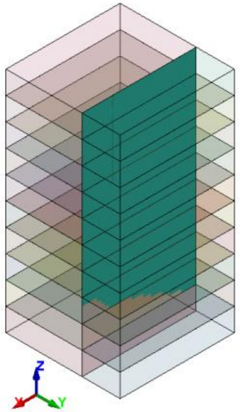


Validation Test



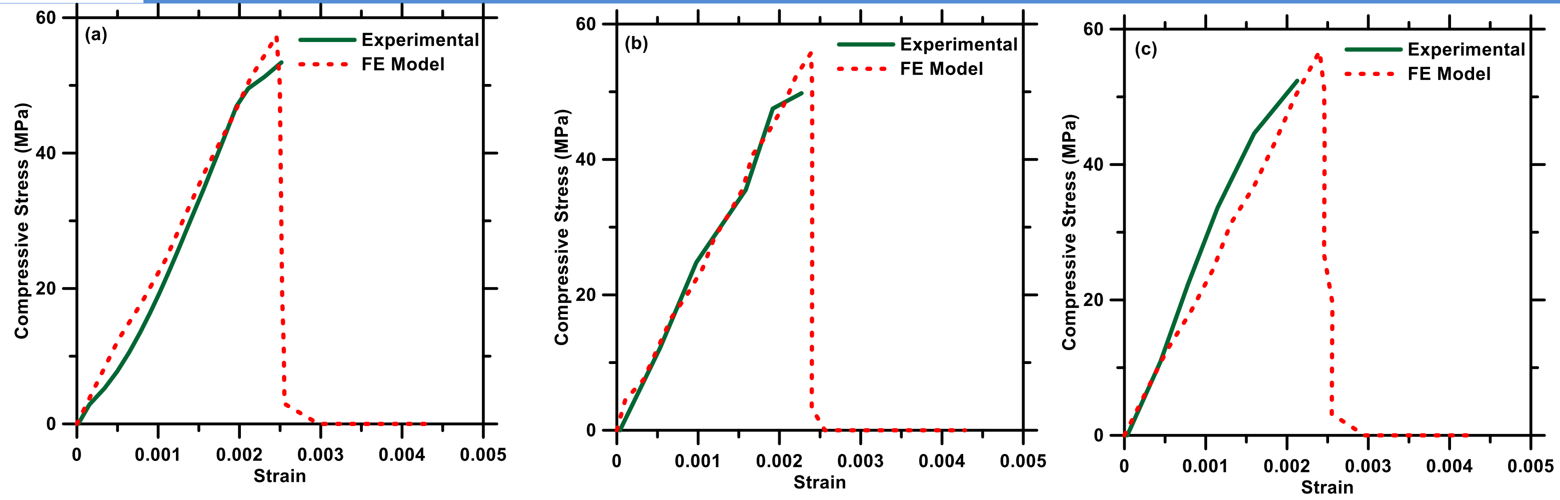
Compressive strength (Surehali et. al. 2023)

Validation Test

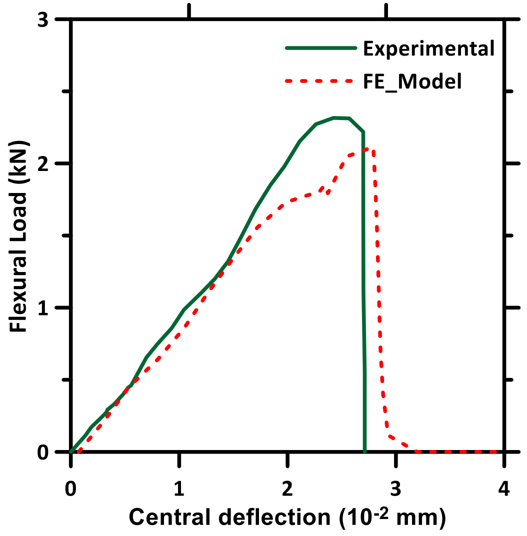
Load / Direction	D1	D2	D3
50% of Peak Load			
Peak Load			

Erosion for LH 6 mm model (Surehali et. al. 2023)

Validation Test

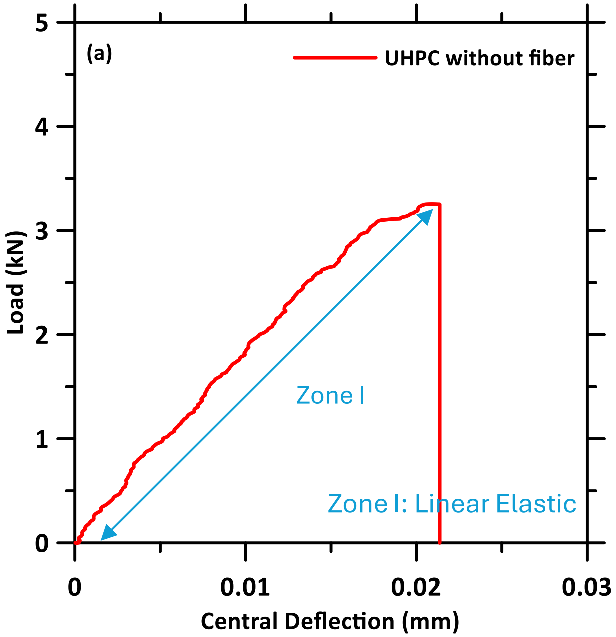


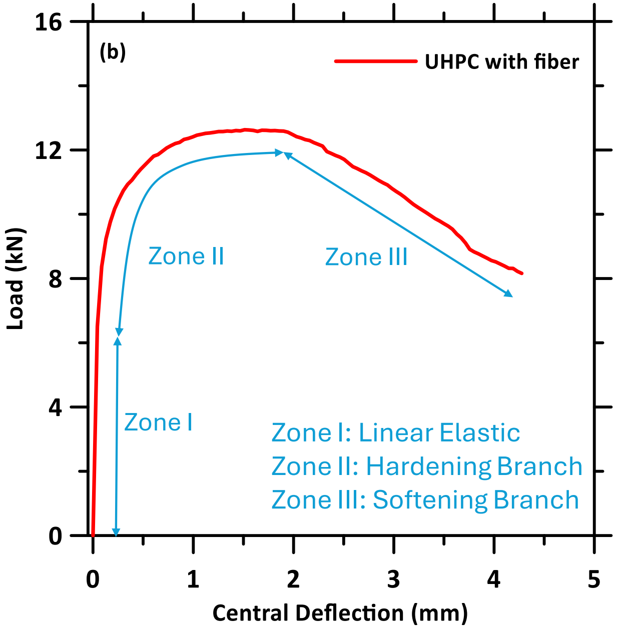
Representative compressive stress-strain curves for LH 6 mm (a) D1, (b) D2, and (c) D3 (Surehali et. al. 2023)



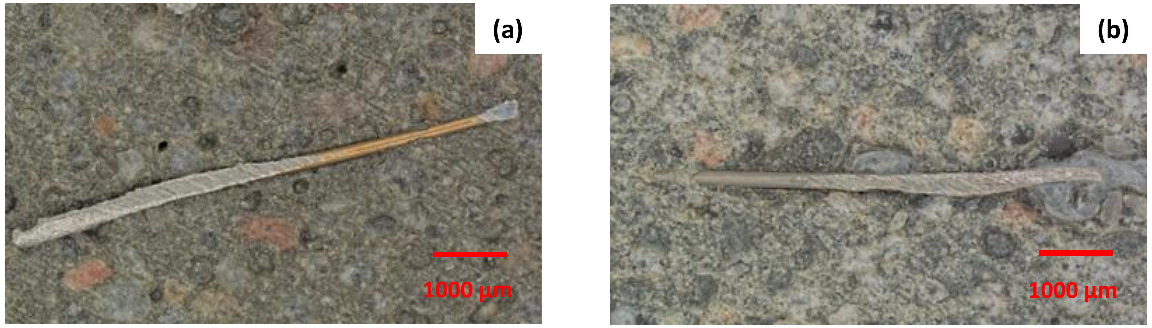
Representative flexural load vs central deflection curves for LH 10 mm (Nair et. al. 2021)

Orthotopic Material



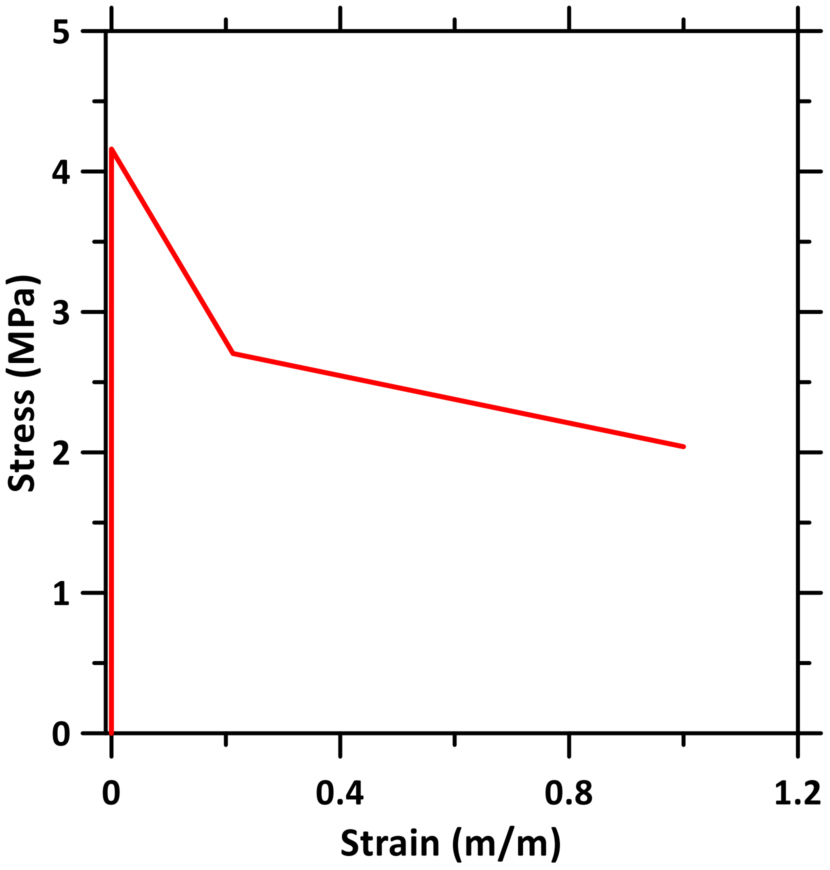


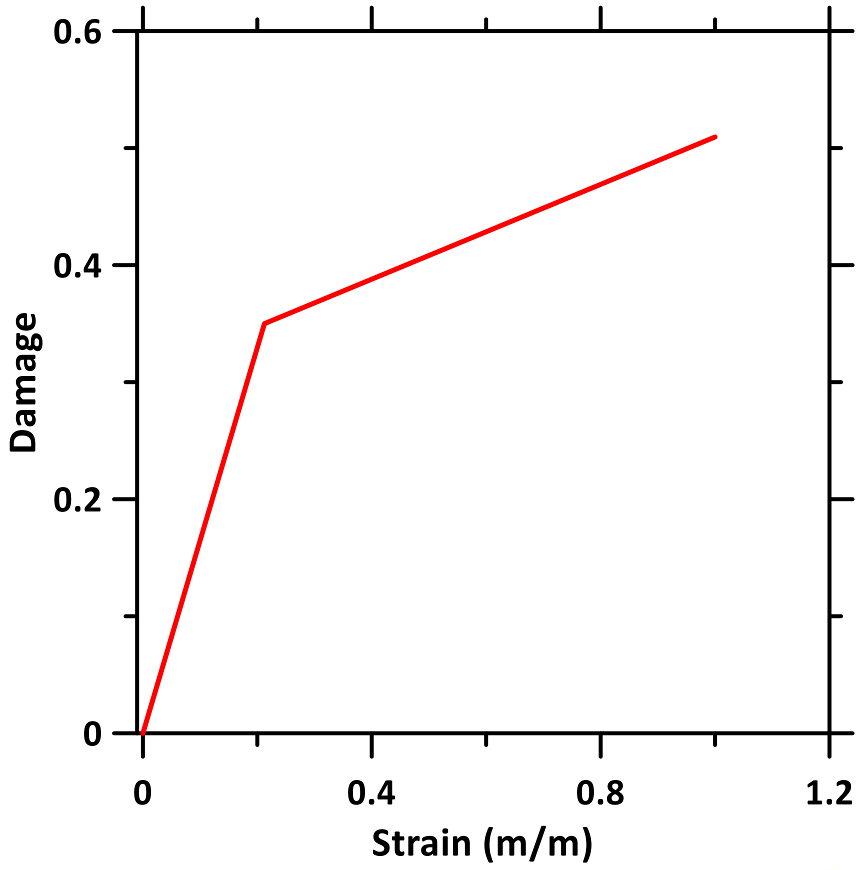
Print Direction



Representative section parallel to: (a) X-Z plane, and (b) X-Y plane for printed UB-SF$_{1.5\%}$

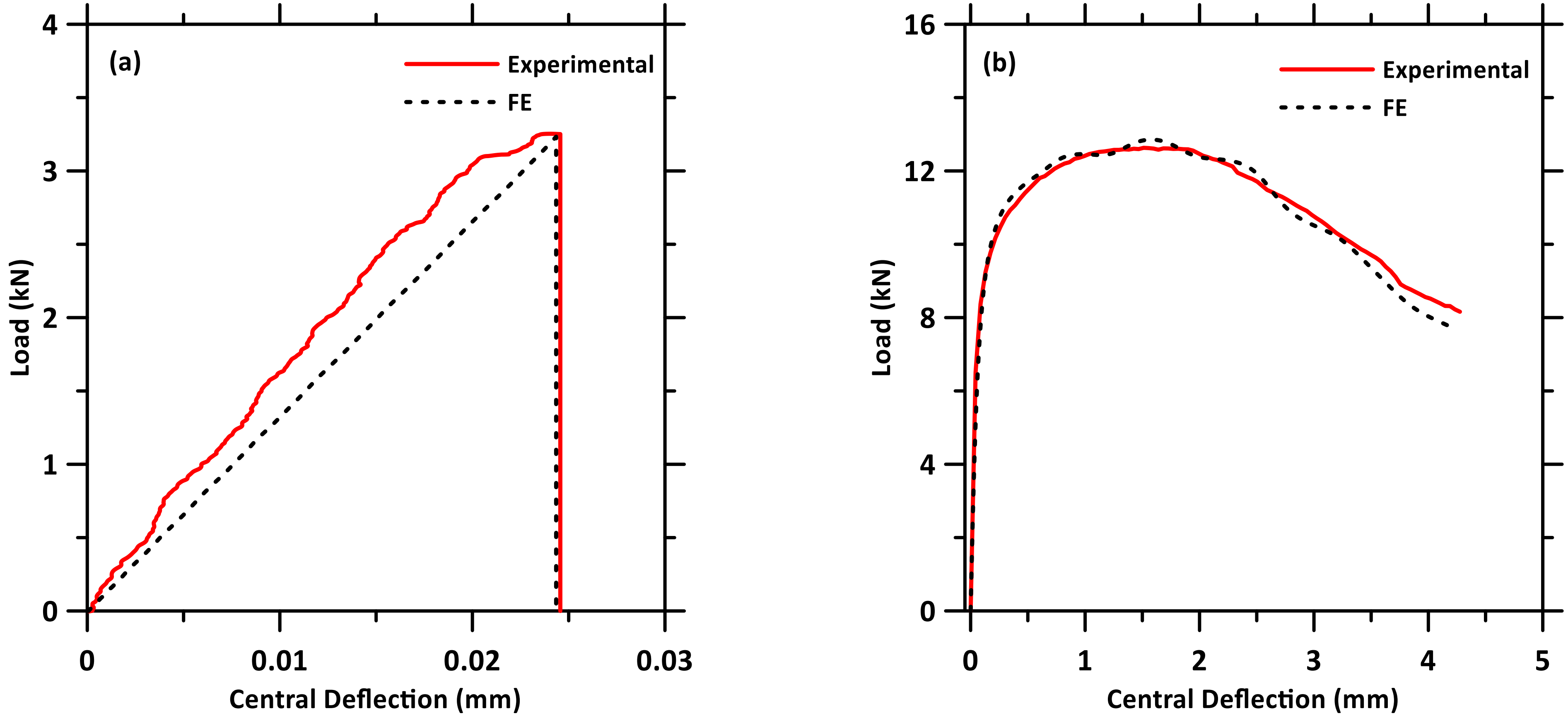
Orthotopic Material





The tensile response in x-direction (i.e., the print direction) and the corresponding damage

Orthotopic Material

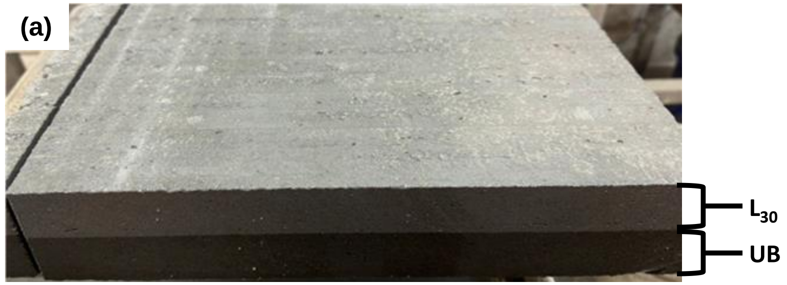


Flexural load vs central deflection curves

Future Scope

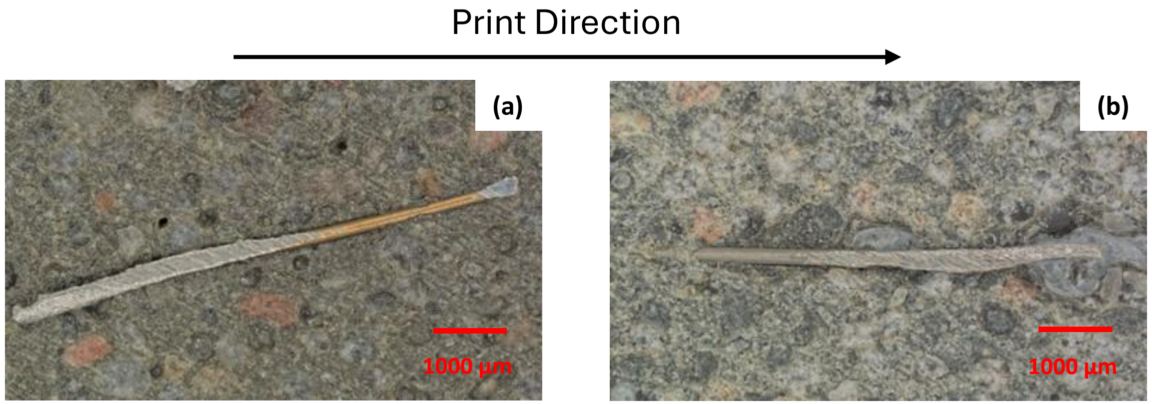
- Orthotropic Material

- Multi-Material Composite Sections



- Experimental Characterization of Interface*

- Fresh State Modeling



Representative section parallel to: (a) X-Z plane, and (b) X-Y plane for printed UB-$SF_{1.5\%}$

Narayanan.Neithalath@asu.edu

3D CONCRETE

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THANK YOU!

QUESTIONS?