3D CONCRETE

Arizona State University

An analysis of buildability of sustainable 3D printed concretes and failure curves towards buildability prediction

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Concrete 3D Printing

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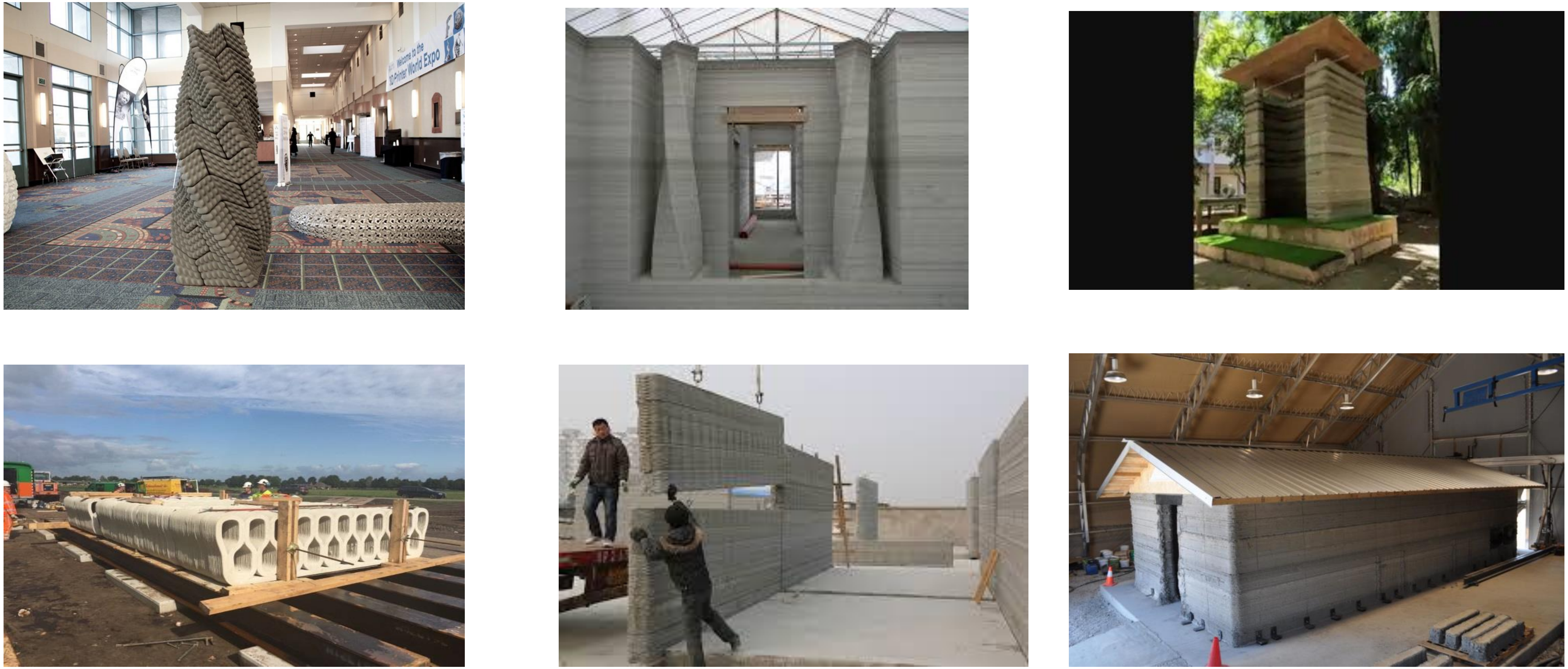
Concrete 3D Printing



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Concrete 3D Printing

Printable cement-based materials

- 3D printing by layered extrusion
- Concrete soft enough to be extruded and to intermix with the previous layer
- Support its own weight and the weight of the superimposed layer
  - "Finite" waiting time between layers
  - Yield stress change from layer to structure
  - Rate of build up
  - Operation time

Layer-wise extrusion and stacking

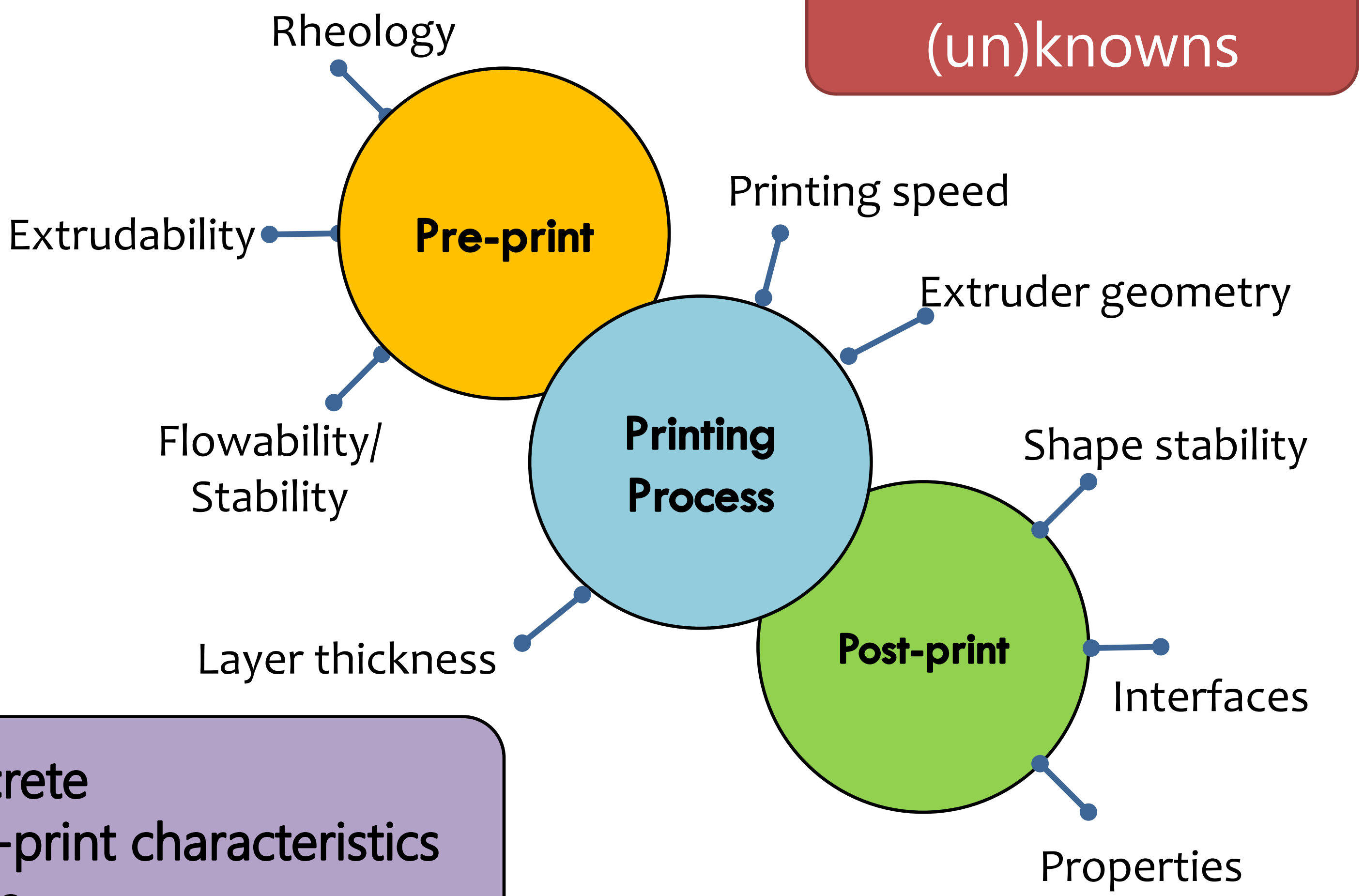

TU Eindhoven (2018)


Siam Research and Innovation Company (2018)

Printable cement-based materials

Known
(un)knowns

- Material selection
- Proportioning
- Mixing and Extrusion



Pre-print
Rheology
Extrudability
Flowability/ Stability

Printing Process
Printing speed
Extruder geometry
Layer thickness

Post-print
Shape stability
Interfaces
Properties

> Guidelines for 3DP of concrete
> Prediction of post-print behavior from pre-print characteristics
> Reliable scalable models

Fresh state concerns

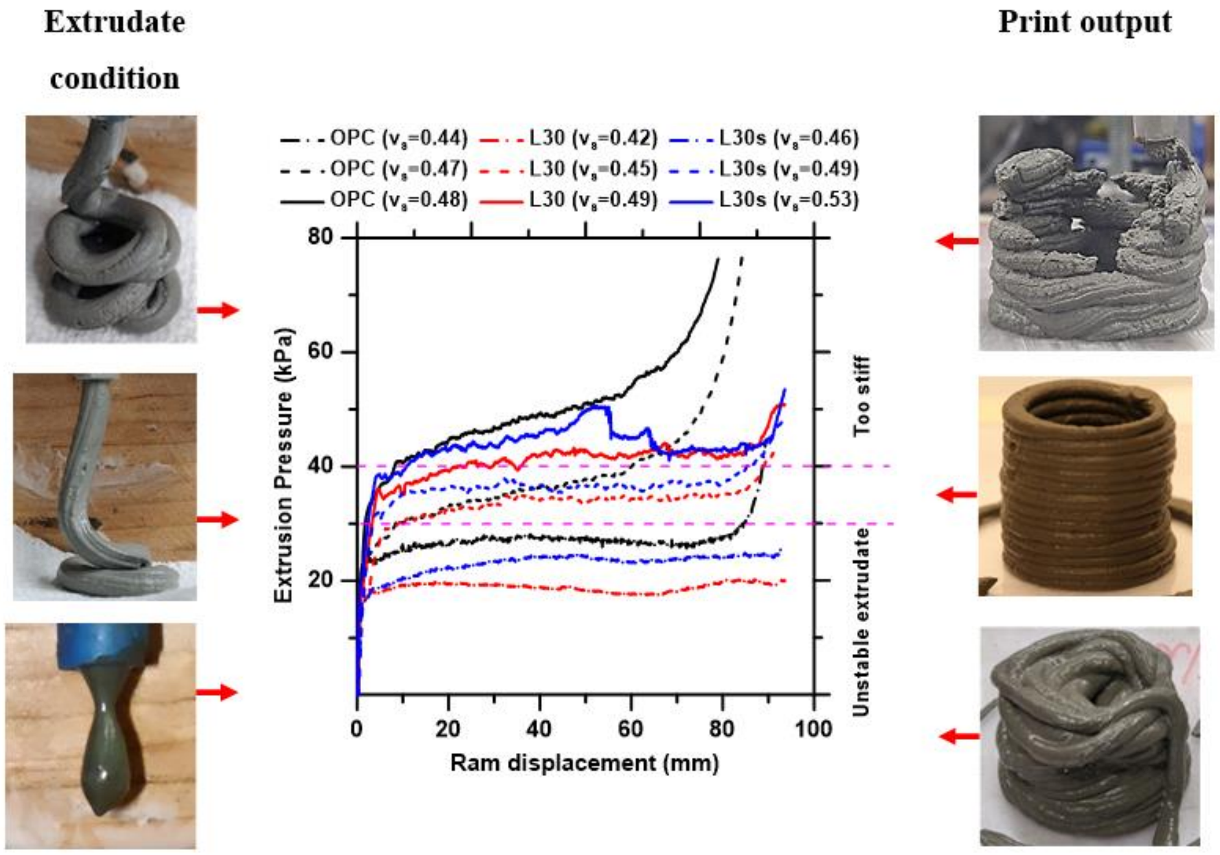
- Extrudability and Buildability (Printability)
- Open time - its influence on pumping and extrusion;
- Setting and layer cycle-time - its influence on vertical build rate;
- Deformation of material as successive layers are added;
- Rheology measurements - its importance to quality control

Extrudability and Buildability

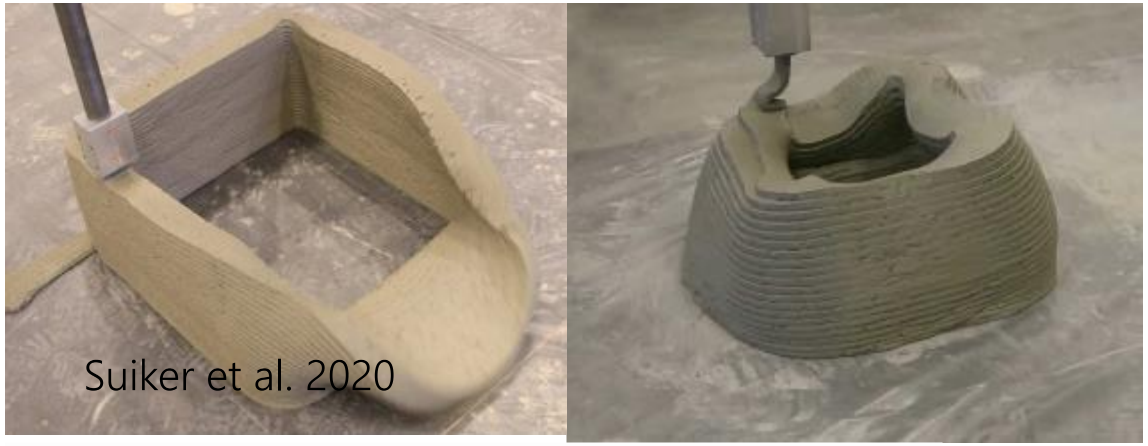
- Buildability is the ability to develop adequate strength at any given section of a print to overcome the overburden pressure exerted by the subsequent layers without excessive deformation or failure
- Height to which a given material can be printed without failure for a certain cross-section geometry
- Printability = Extrudability + Buildability
- Contrasting needs – moderate YS for extrudability; higher YS for buildability
- Requires time-dependent material behavior to be related to the imposed loads

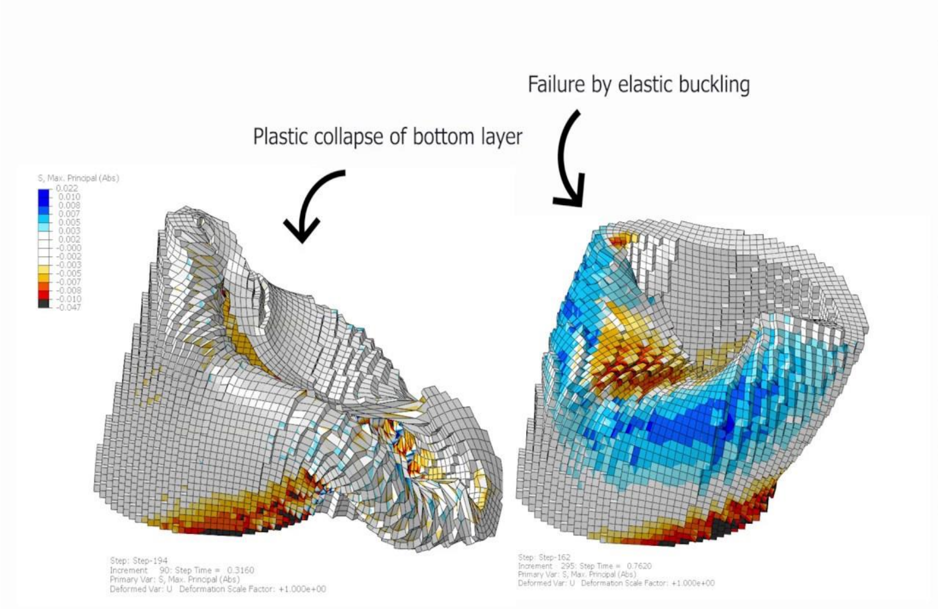
Extrudability

- Extrudability depends on the mixture and the extrusion process (system, velocity, pressure etc.)
- Pressure-displacement relationships as signatures of the materials-process combinations



Buildability of 3D printed systems


Suiker et al. 2020



https://www.food4rhino.com/en/app/concre3dlab

- Analytical model for buildability
  - Considering material property development, stepwise stress growth during printing, and failure modes
  - Verification using multiple print geometries
- Digital image correlation on fresh printed samples
  - Determining a failure initiation height, that is lower than the actual failure height
  - Predictive modes of failure through strain growth

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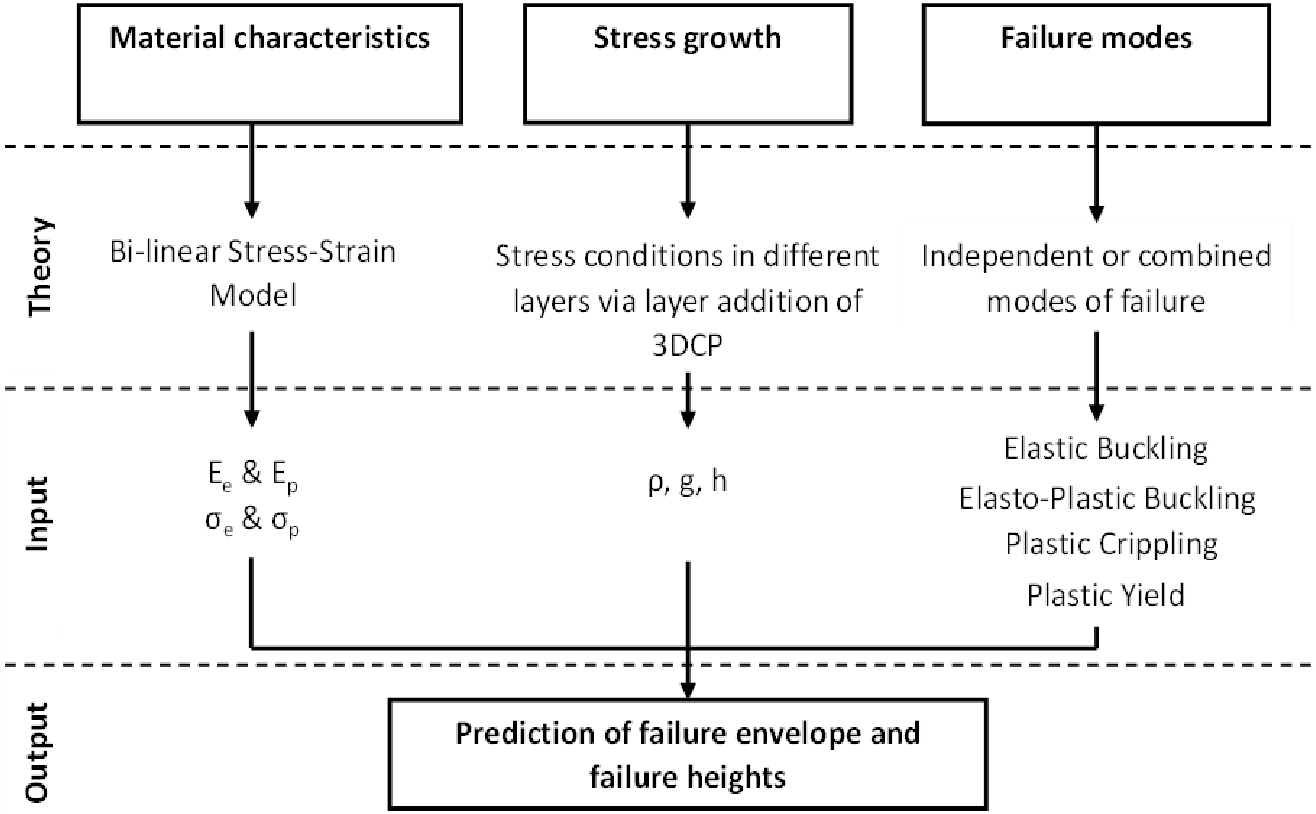
Formulating an analytical model



Material characteristics

Stress growth

Failure modes

Theory

Bi-linear Stress-Strain Model

Stress conditions in different layers via layer addition of 3DCP

Independent or combined modes of failure

Input

E_e & E_p

σ_e & σ_p

ρ, g, h

Elastic Buckling

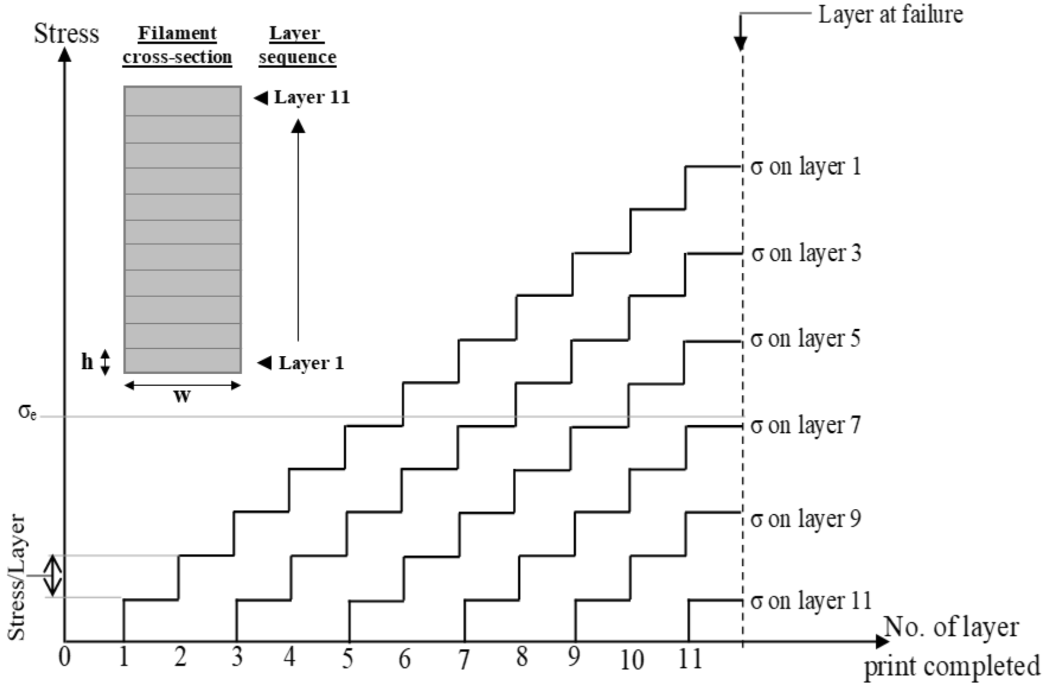
Elasto-Plastic Buckling

Plastic Crippling

Plastic Yield

Output

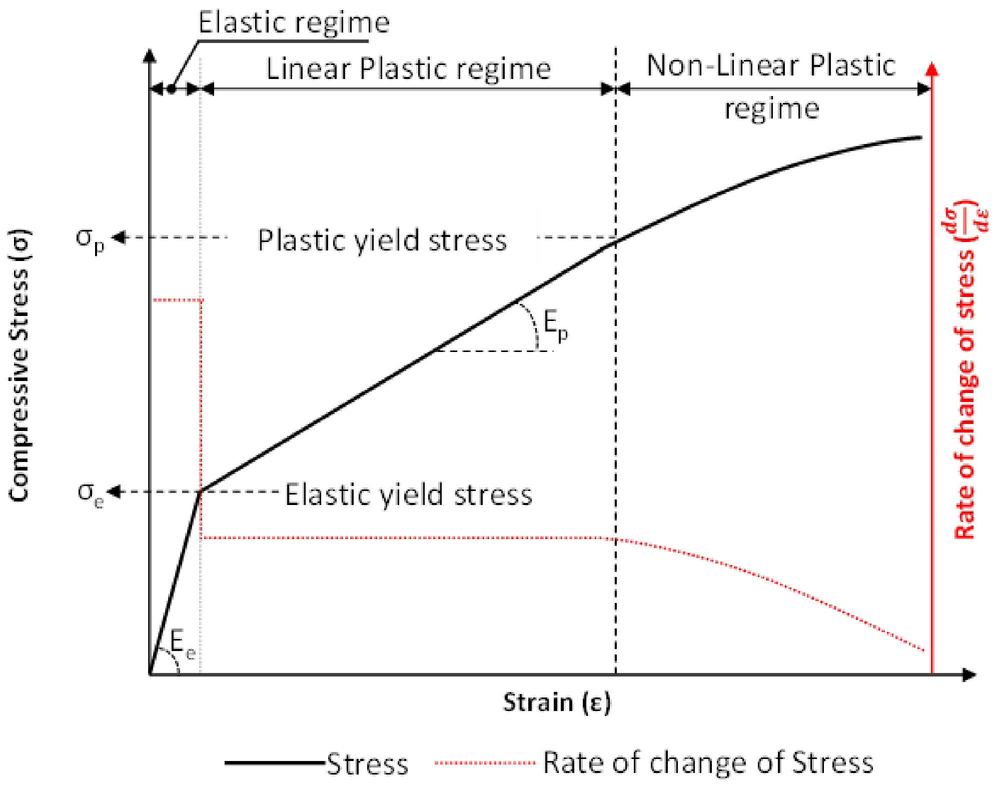
Prediction of failure envelope and failure heights



Stress growth in layers, with subsequent layer deposition

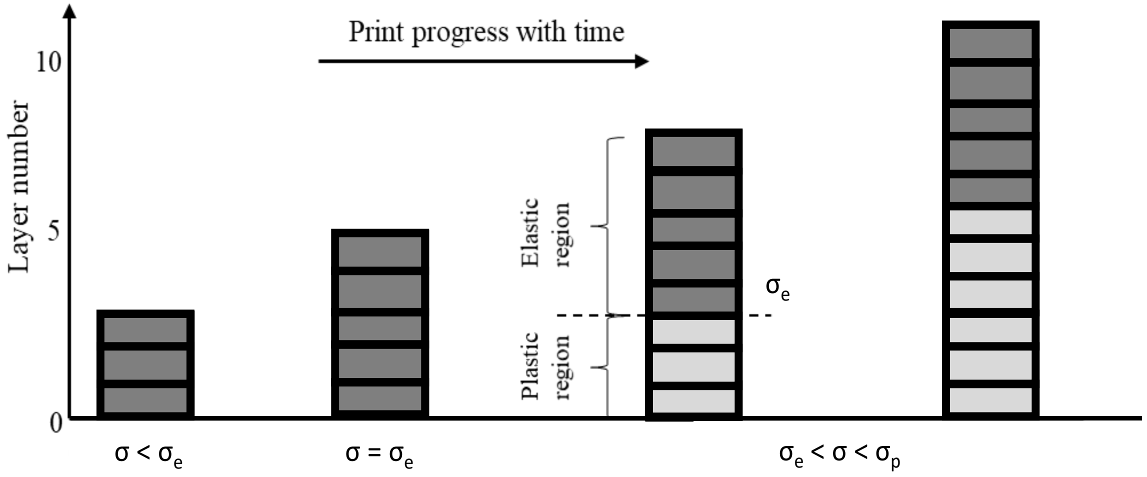
$$Stress\ per\ layer = \frac{Filament\ Weight}{Filament\ Area} = \frac{\rho V g}{A} = \frac{\rho(A \times h)g}{A} = \rho \times h \times g$$

Stress-strain response



- Slow loading rate (~1%/min)
- Elastic, and an initial plastic regime (result of low strain rates)
  - Common for soft materials – a function of network stress and fluid pressure
  - Elastic YS – axial loading of material already printed, through imposition of additional layers
  - Initial plastic YS – when stress in one or more bottom layers exceed the elastic YS
- Multiple soft layers subjected to incremental and differential loading during printing
- Accounts for change in rate of deformation (strain) of a considered layer under increasing loads

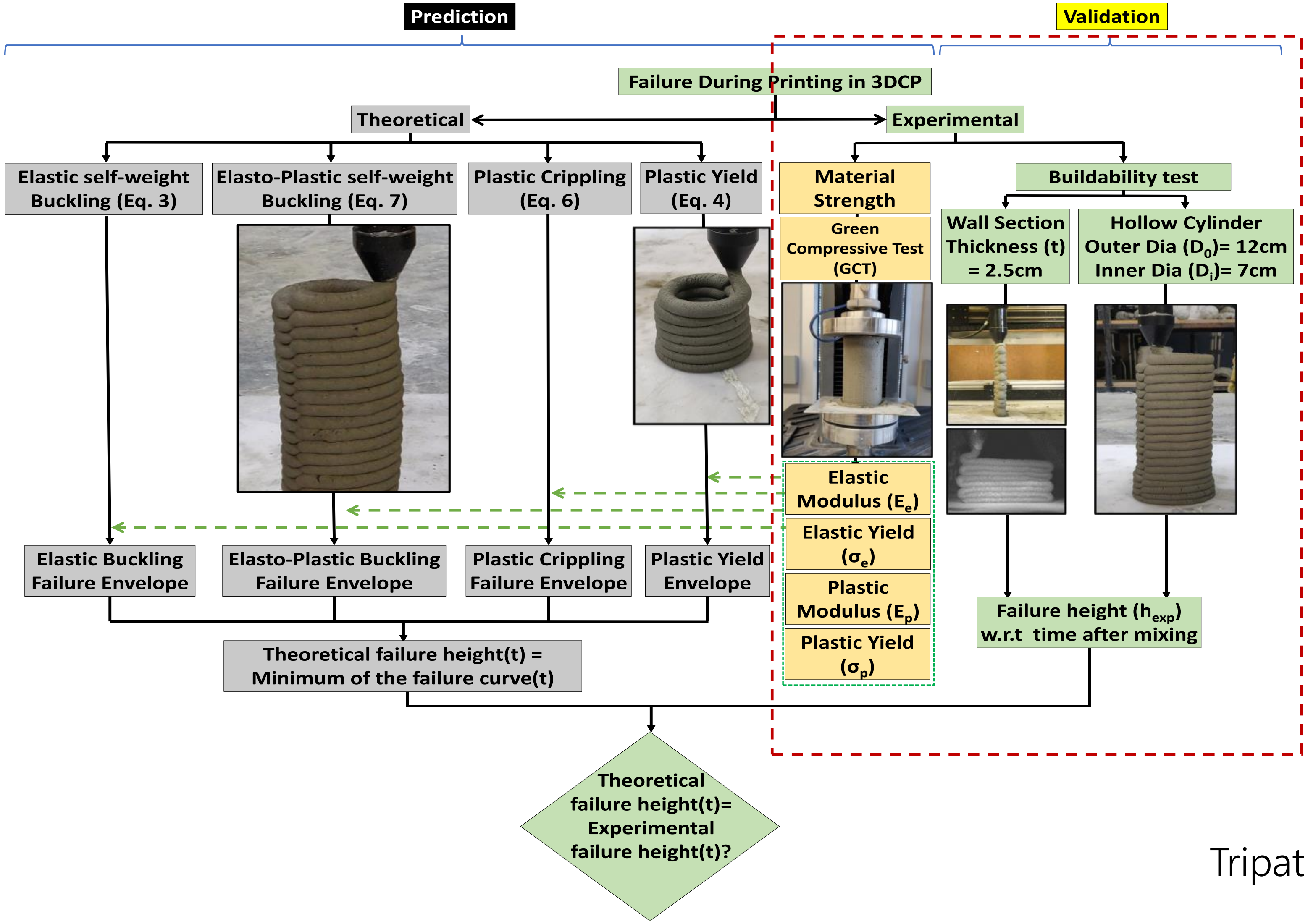
Stress growth



- Printing rate governs the rate of stress growth in each layer
- Staircase model of stress growth as a function of number of layers printed (or time)
  - Tread indicates the duration of printing a certain layer (i.e., time elapsed between layer n and n+1), and the rise denotes the incremental stress on layer n due to the deposition of the layer n+1

- Dark colored regions correspond to layers where stress < elastic YS
- With time, the composite printed specimen demonstrates variable stresses in different layers

Theoretical models



Prediction

Validation

Failure During Printing in 3DCP

Theoretical

Experimental

Elastic self-weight Buckling (Eq. 3)

Elasto-Plastic self-weight Buckling (Eq. 7)

Plastic Crippling (Eq. 6)

Plastic Yield (Eq. 4)

Material Strength

Green Compressive Test (GCT)

Buildability test

Wall Section Thickness (t) = 2.5cm

Hollow Cylinder Outer Dia (D_0)= 12cm Inner Dia (D_i)= 7cm

Elastic Modulus (E_e)

Elastic Yield (σ_e)

Plastic Modulus (E_p)

Plastic Yield (σ_p)

Elastic Buckling Failure Envelope

Elasto-Plastic Buckling Failure Envelope

Plastic Crippling Failure Envelope

Plastic Yield Envelope

Failure height (h_{exp}) w.r.t time after mixing

Theoretical failure height(t) = Minimum of the failure curve(t)

Theoretical failure height(t)= Experimental failure height(t)?

$$h_{b,el} = \left[7.8373 \frac{E_e I}{\rho g A}\right]^{\frac{1}{3}}$$

$$h_p = \frac{\sigma_p}{\rho g} + h_l$$

$$l_{crip} = \sqrt{\frac{\pi^2 E_p I}{4 \times \sigma_e A}}$$

$$h_{crip} = l_{crip} + h_e$$

$$h_{b,eff} = \left[7.8373 \frac{E_{eff} I}{\rho g A}\right]^{\frac{1}{3}}$$

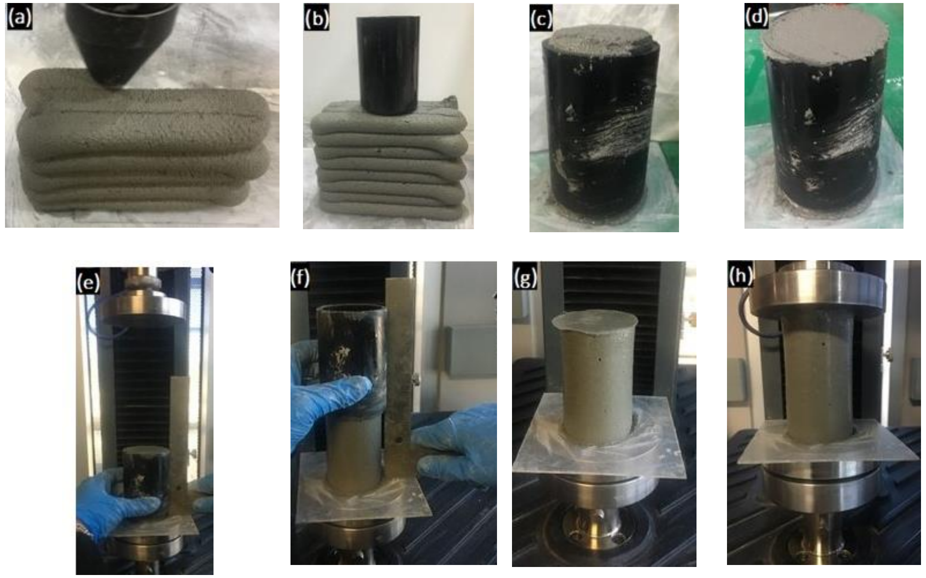
$$(h_e + h_{p,eff}) - \left[7.8373 \frac{E_e E_p I}{(h_e{}^2 E_p + h_{p,eff}{}^2 E_e)\rho g A}\right]$$

Tripathi et al., Cem. Concr. Compos. 2022

Experiments

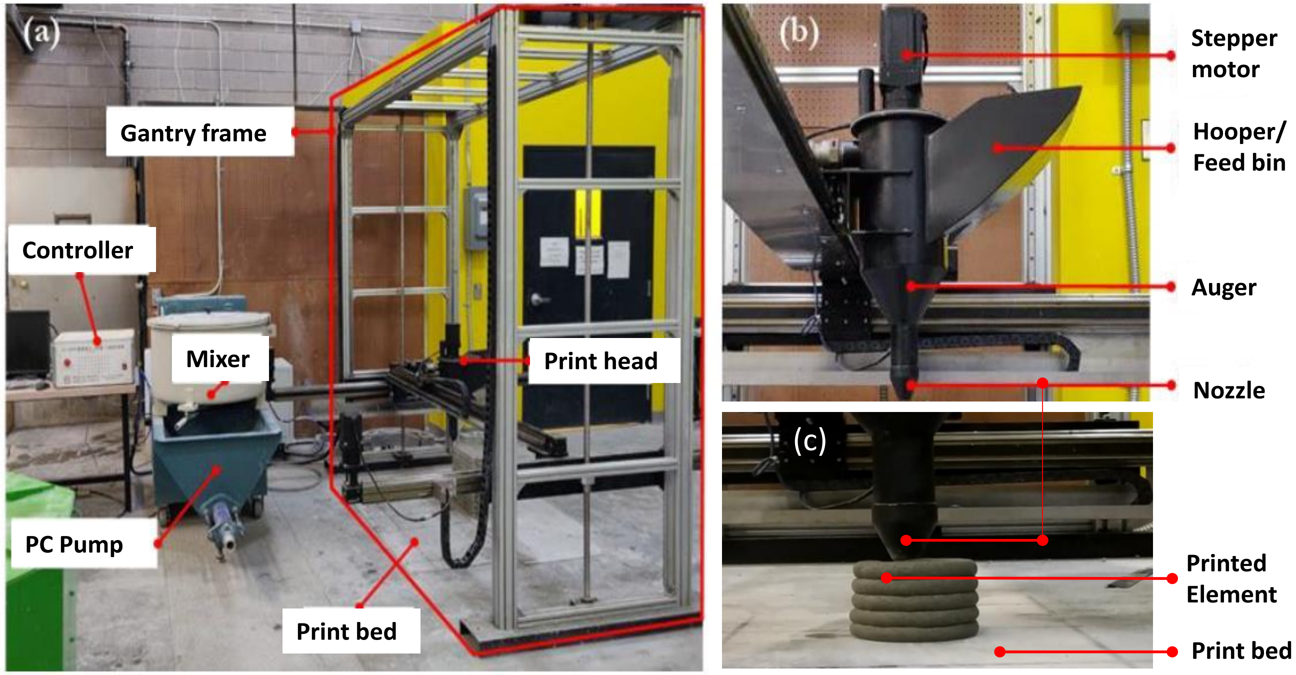
Mixture ID	Mass fraction of ingredients*					Water-to-binder ratio (w/b) by mass	SP to powder ratio (SP%) by mass	Particle volume fraction in the paste phase
	OPC	Limestone (L; d_{50}=1.5μm)	Fly Ash (F)	Sand (M)	LWA			
$L_{30\text{-}M}$	0.37 (638.30)	0.16 (273.56)	-	0.47 (808.51)	-	0.43	-	0.437
$L_{30\text{-}S\text{-}M}$	0.37 (688.52)	0.16 (295.08)	-	0.47 (872.13)	-	0.35	0.35	0.488
$F_{20}L_{10\text{-}M}$	0.36 (646.00)	0.05 (92.28)	0.10 (184.56)	0.49 (875.88)	-	0.37	-	0.491
$L_{30\text{-}LWA}$	0.49 (688.52)	0.21 (295.08)	-	-	0.30 (424.59)	0.35	0.25	0.488

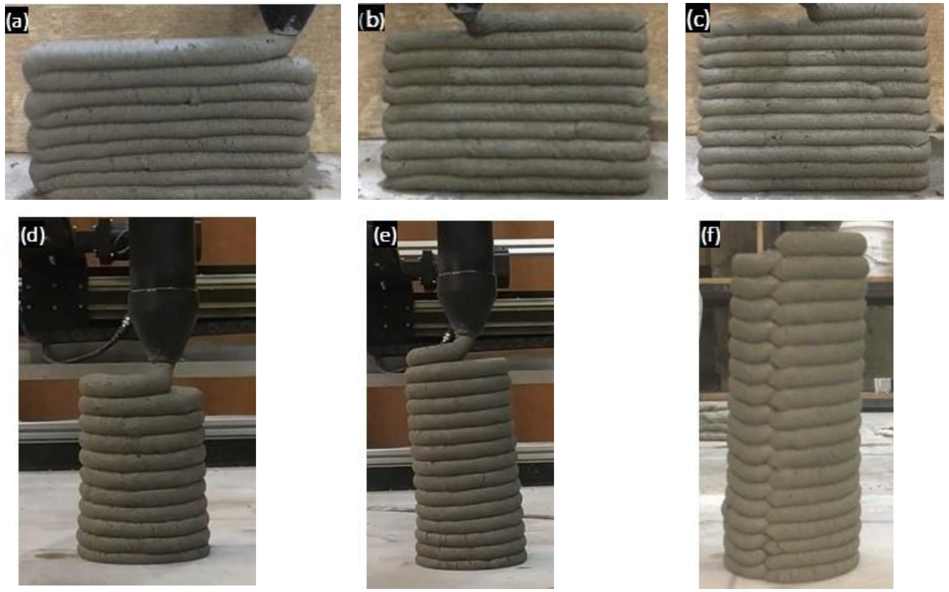
*Values in parenthesis represent the amounts of ingredients in kg/m^3



- Green compression test (stress-strain, at very low rates)
- Extract elastic and plastic stresses and moduli

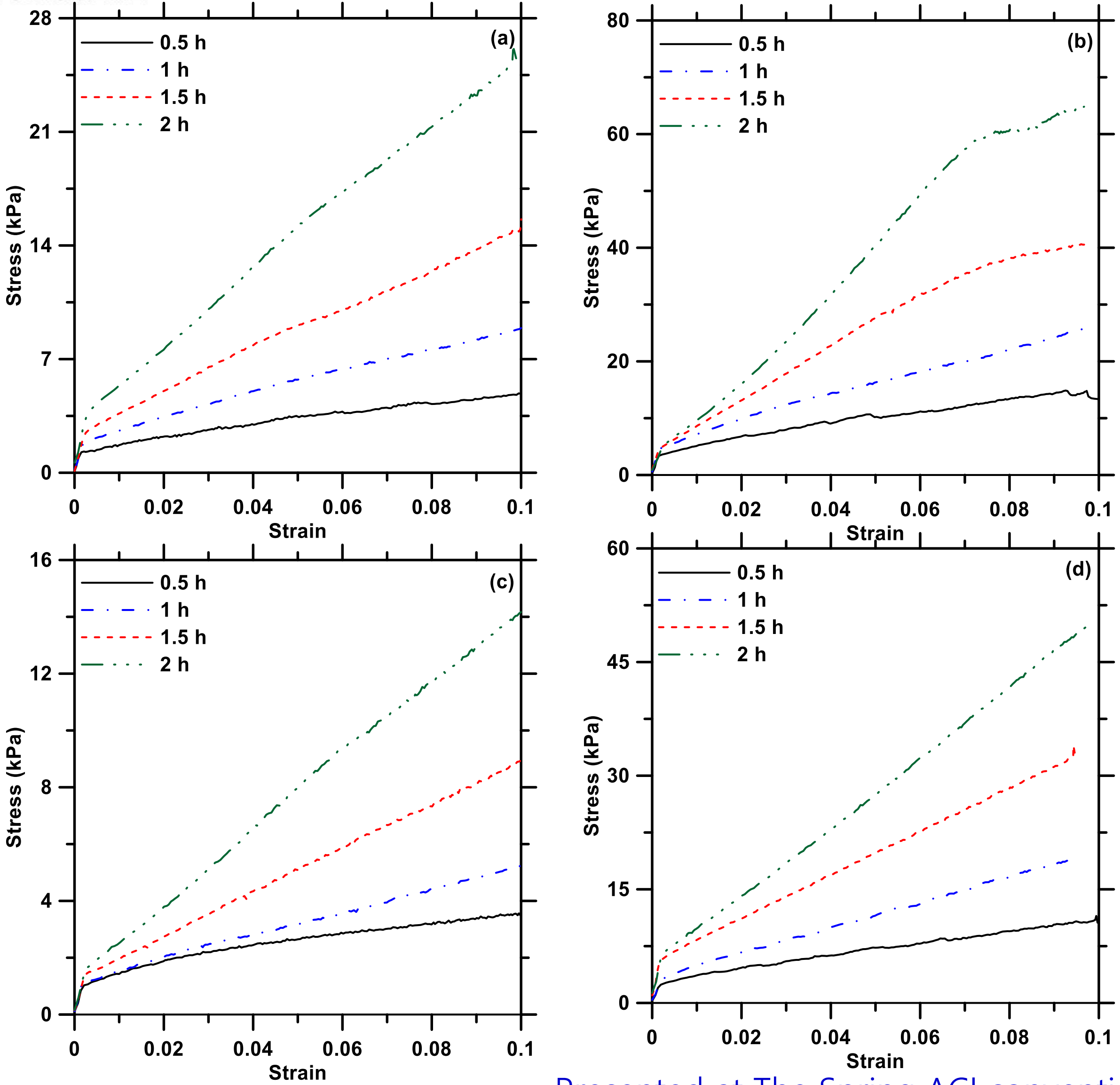
Experiments





- Print wall and hollow cylinder samples at different times
- Compare experimental height of failure to those predicted using different models of failure

Fresh state parameters



Mixture ID	Time (h)	Elastic		Plastic	
		Yield stress (kPa)	Modulus (MPa)	Yield stress (kPa)	Modulus (MPa)
$L_{30\text{-}M}$	0.5	1.21	0.99	2.28	0.056
	1.0	1.65	1.03	3.58	0.088
	1.5	2.56	1.14	6.74	0.14
	2.0	3.71	1.47	13.10	0.22
$L_{30\text{-}S\text{-}M}$	0.5	3.49	2.51	6.00	0.19
	1.0	4.54	3.68	9.70	0.30
	1.5	4.62	3.66	25.00	0.45
	2.0	4.94	2.36	48.10	0.60
$F_{20}L_{10\text{-}M}$	0.5	1.06	0.57	1.98	0.047
	1.0	1.06	0.69	2.20	0.055
	1.5	1.38	0.64	3.91	0.074
	2.0	1.61	0.68	6.57	0.12
$L_{30\text{-}LWA}$	0.5	2.49	1.49	4.10	0.14
	1.0	3.33	1.63	6.05	0.20
	1.5	5.77	3.60	16.70	0.30
	2.0	6.58	3.19	27.70	0.41

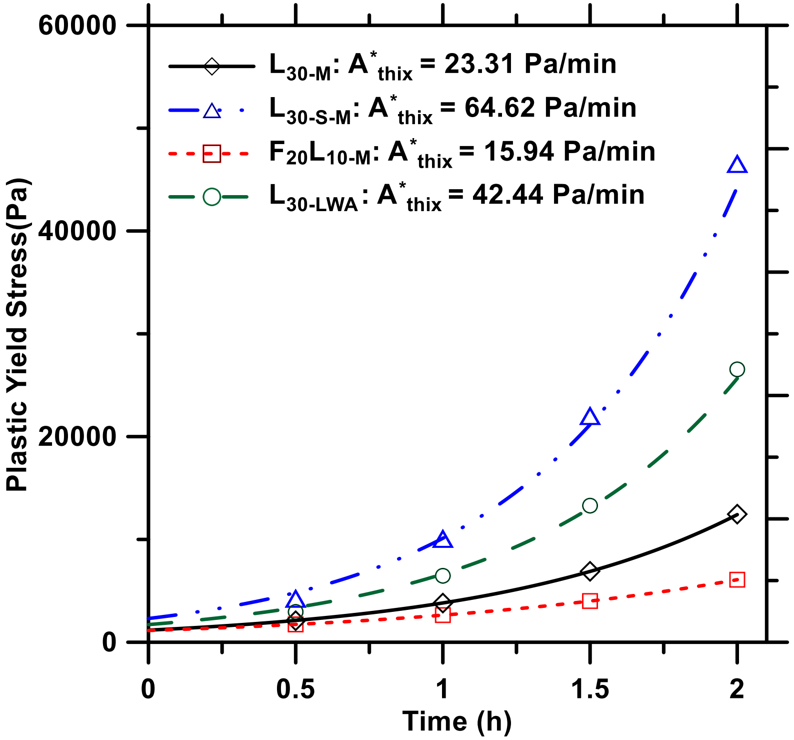
Yield stress growth

- The plastic yield stress obtained from GCT can be considered to be related to the shear yield stress of the deposited material (in a manner similar to how extrusional and shear yield stresses are related)

$$\sigma_p(t) = \alpha_{geom}.\tau_0(t)$$

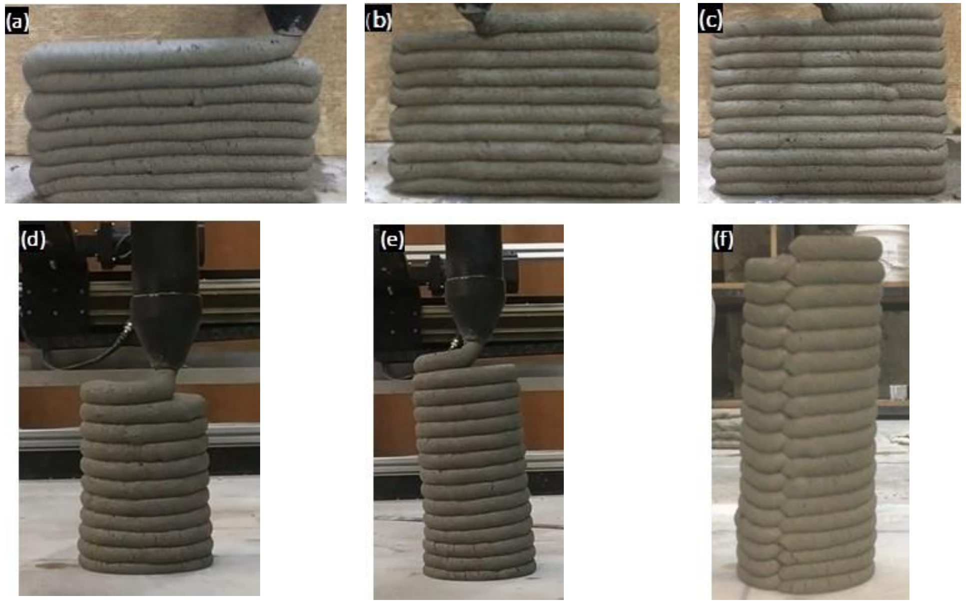
$$\sigma_p(t) = \alpha_{geom} A_{thix} t_c \left(e^{\frac{t}{t_c}} - 1\right) + \sigma_{p,0}$$

$$\sigma_0(t) = A^*_{thix} t_c \left(e^{\frac{t}{t_c}} - 1\right) + \sigma_{p,0}$$



$\sigma_{p,0}$ is hard to determine experimentally since testing cannot be started right away after mixing. Exponential fit was used for the GCT results at 0.5, 1, 1.5 and 2 h, and then extrapolated backwards to time $t = 0$ to obtain $\sigma_{p,0}$.

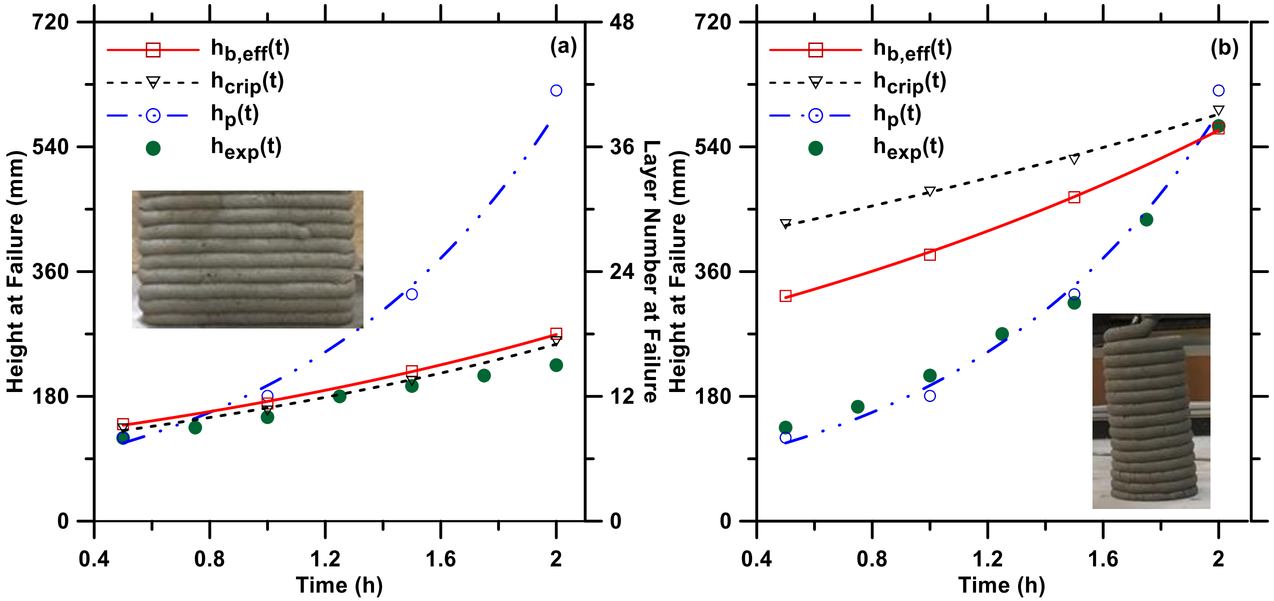
Model verification



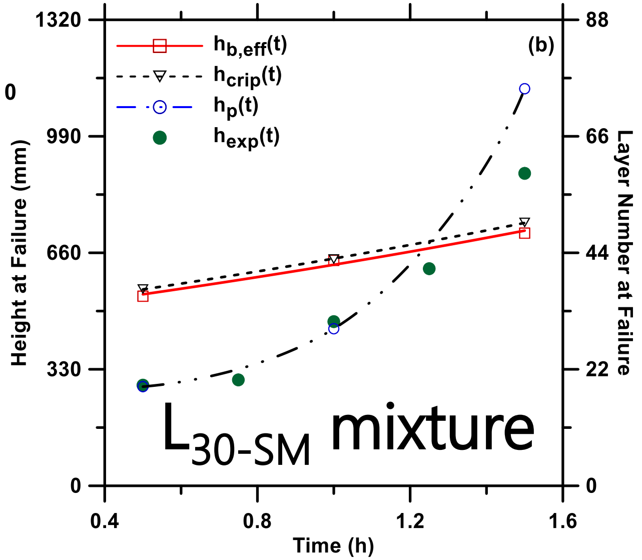
- Failure is defined when no more layers could be printed because of significant geometric deformation and/or collapse of the printed structure
- Wall and hollow cylindrical prints were made every 15 min until 2 h, while the theoretical failure curves are derived from GCT carried out at 30 min intervals until 2 h.

Buildability predictions

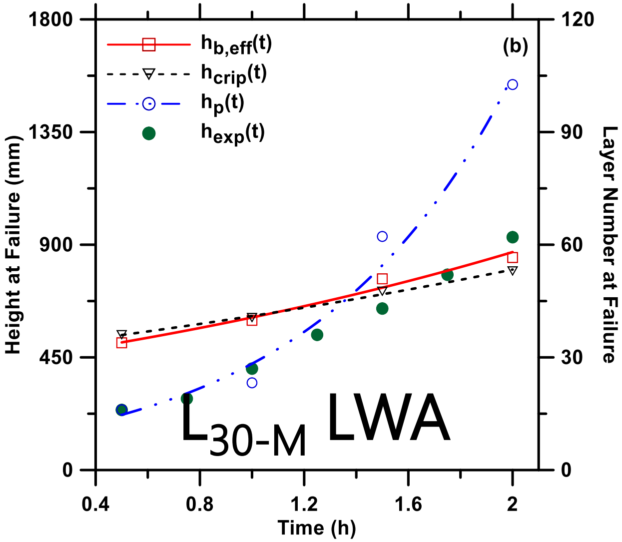
Visual inspections showed that, for the wall prints, out-of-plane movement caused the final failure.



$L_{30\text{-}M}$ mixture



$L_{30\text{-}SM}$ mixture



$L_{30\text{-}M}$ LWA

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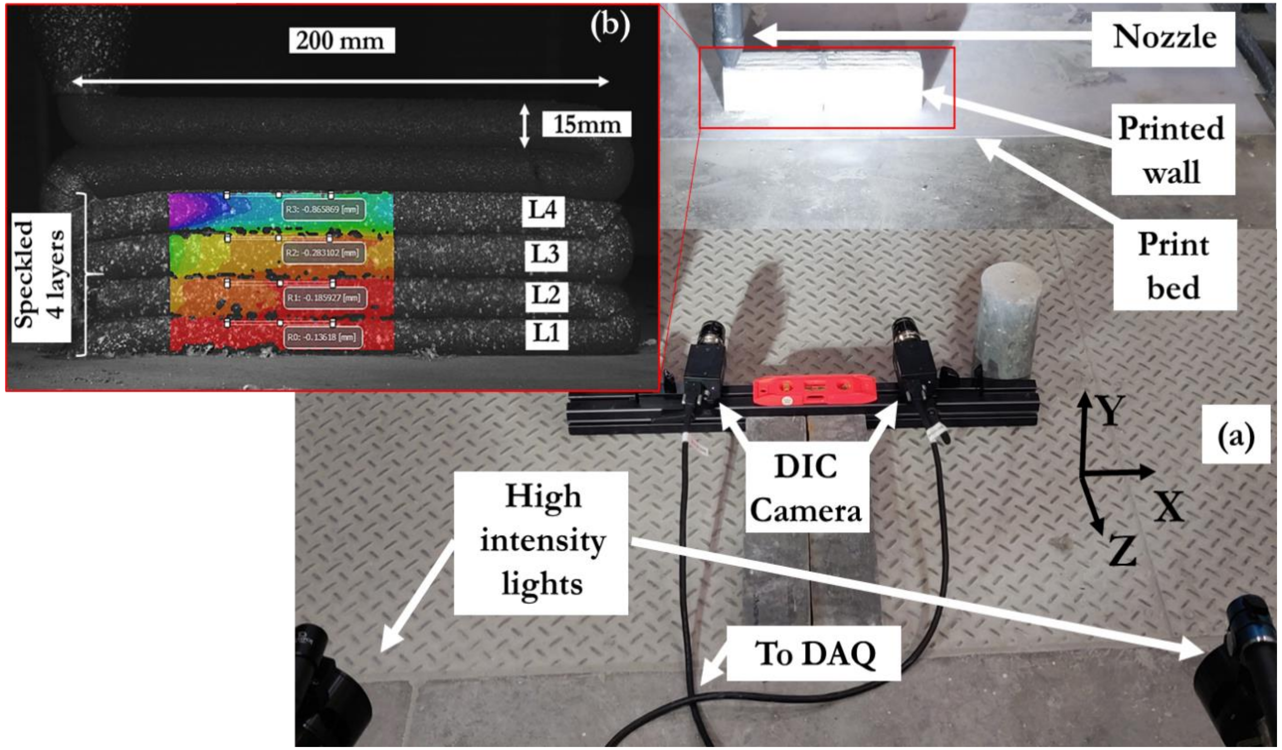
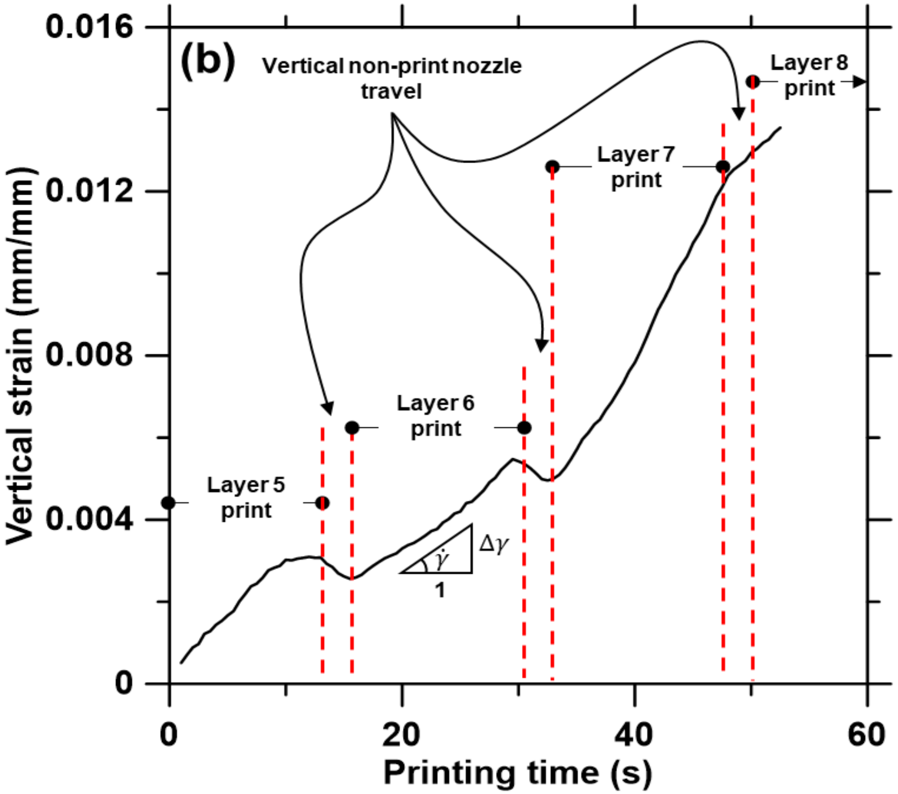
Digital image correlation



Linear region elements placed near the top of each layer is used to calculate the average vertical displacement of the layers as the printing progresses.



Stepwise strain profile of layer 1 when layers 5, 6, 7, and 8 are printed, showing a linear increase followed by a dip/plateau corresponding to layer shifting

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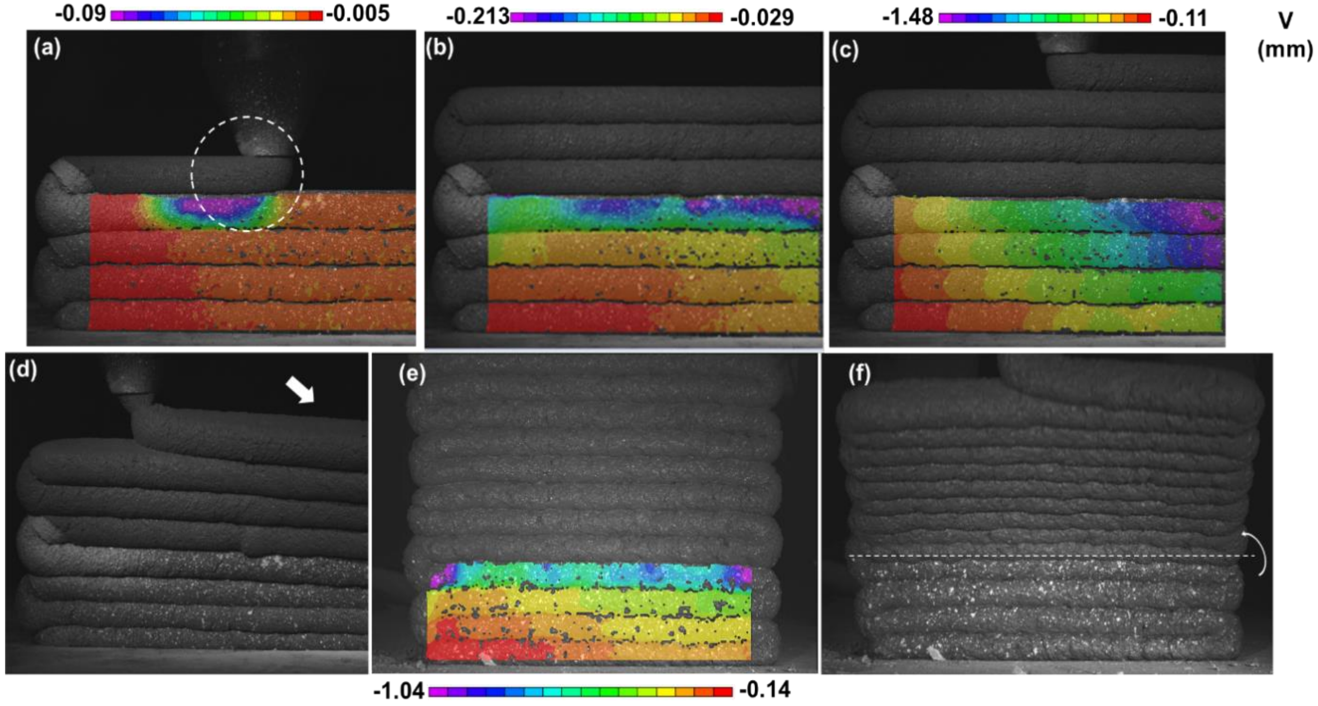
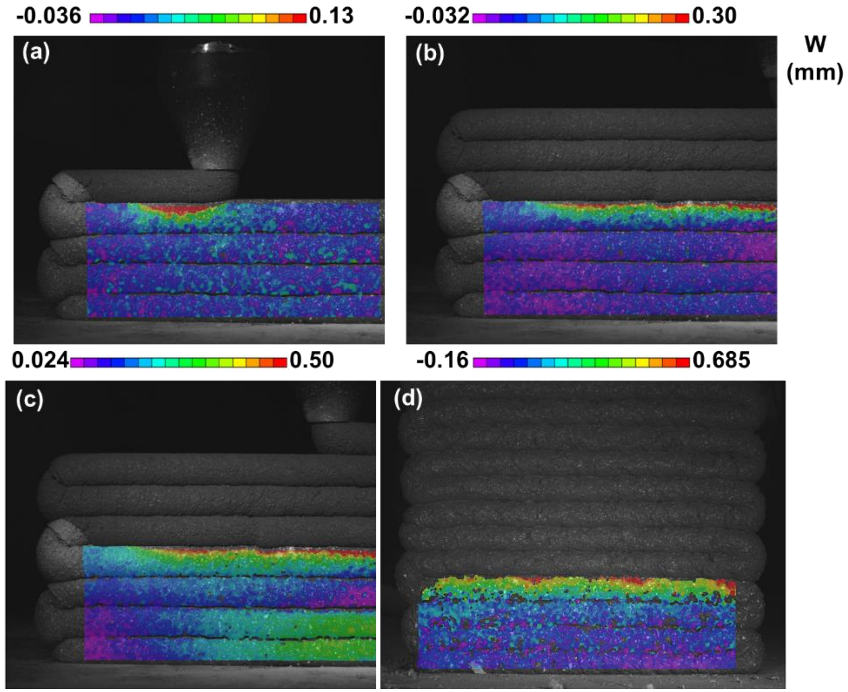
Displacement profiles

Vertical displacement



(a) during printing resumed after speckling, (b) 3 additional layers are printed, (c) significant increase in vertical displacement is detected before failure initiation, and (d) at critical failure when right end of the print fails under <u>plastic collapse</u>. Lightweight mortar: (e) right before failure with no specific localized displacement increase after a number of layers are printed, and (f) <u>crippling</u> near the interface of 5th and 6th layers

Out-of-plane displacement



Summary

- A model based on different potential failure modes for the buildability of 3D printed concrete at different times
- Elastic response at very small strains, encountered in practice due to the initial overburden of the next printed layer(s), captured.
- The slope of the stress-strain response started to drop at around 0.25% and the relatively linear behavior continued on until a strain of 2-5% depending on the material and the time after mixing, which is termed the initial plastic response
- Using the bi-linear response, the elastic and apparent/initial plastic yield stress and moduli of the material extracted at different times, which were subsequently used in the failure models (considering both material-based and stability-based failures) to determine the theoretical failure height.

Summary

- For geometries with lower I/A ratios (e.g., wall section), instability due to buckling/crippling dominated the failure.
- As the I/A ratio increased (e.g., hollow cylinders), material failure occurred due to the stress exceeding plastic yield stress in the lower filaments, even before the critical height for buckling/crippling failure was reached
- Failure curves considered both these approaches, ensuring the robustness of the model in predicting failure heights.
- The experiments showed that the wall prints failed predominantly in the buckling or crippling modes, and the corresponding failure curves satisfactorily predicted the failure heights
- If the initial elastic response were to be completely ignored and the predictions were made based solely on a single slope of the stress-strain curve until the plastic yield point the failure heights would have been significantly under-predicted for buckling collapse.

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