Digital image correlation enabled buildability determination of 3D printed concrete elements

Avinaya Tripathi

Graduate Student, School of Sustainable Engineering and the Built Environment
Arizona State University

Sooraj Nair

Senior Researcher, Gypsum Panel Laboratory

USG corporation

Narayanan Neithalath

School of Sustainable Engineering and the Built Environment
Arizona State University
Narayanan.Neithalath@asu.edu
http://neithalath.engineering.asu.edu; http://3dconcrete.asu.edu

Presented at The Spring ACI convention, San Francisco, April 2023

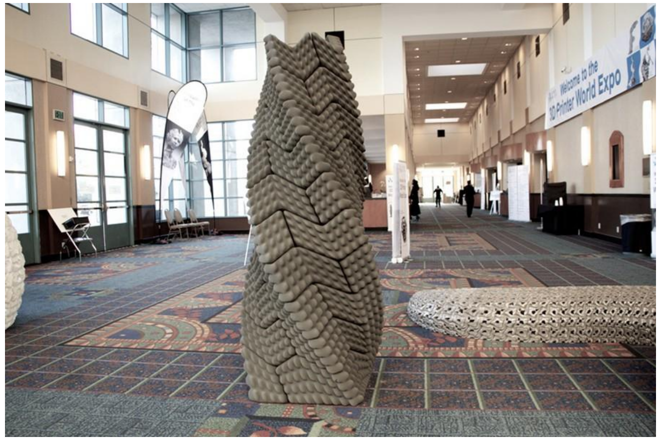
3D CONCRETE

Arizona State University

Concrete 3D Printing

Presented at The Spring ACI convention, San Francisco, April 2023

Concrete 3D Printing



Presented at The Spring ACI convention, San Francisco, April 2023

LITERATURE

Arizona State University

INTRODUCTION

BI-LINEARITY

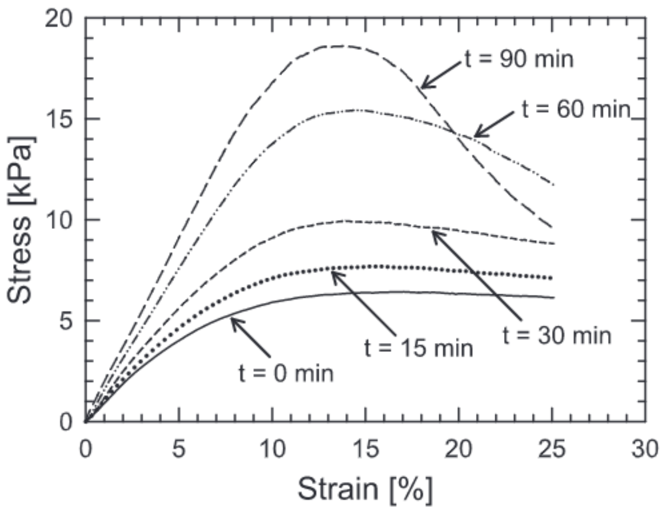
METHOD

RESULTS

DIGITAL IMAGE CORRELATION

SUMMARY

- Additive manufacturing for concrete, especially layer-wise construction, getting traction.
- Nobel field, requires development of proper understanding and characterization.
- Printability (extrudability and buildability) important.
- Different theoretical model for predicting buildability exist.
- Model based on mechanical response consider concrete in fresh state to be elastic strain softening material.
- Theoretical prediction deviated from experimental results, especially as we move more towards the end of open time.
- Strain at yield suggested that the behavior is not truly elastic.
- **Should there be some elastic response?**
- Casted sample, in fresh state, tested under uniaxial compression.



Average stress-strain relations for concrete (extracted from R.J.M. Wolfs et al., 2018)

INTRODUCTION

BI-LINEARITY

METHOD

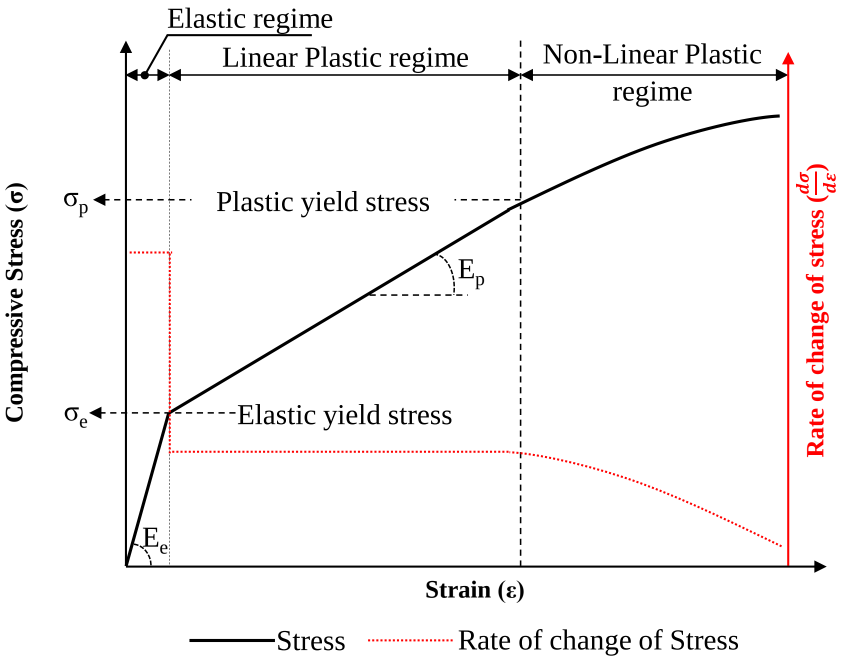
RESULTS

DIGITAL IMAGE CORRELATION

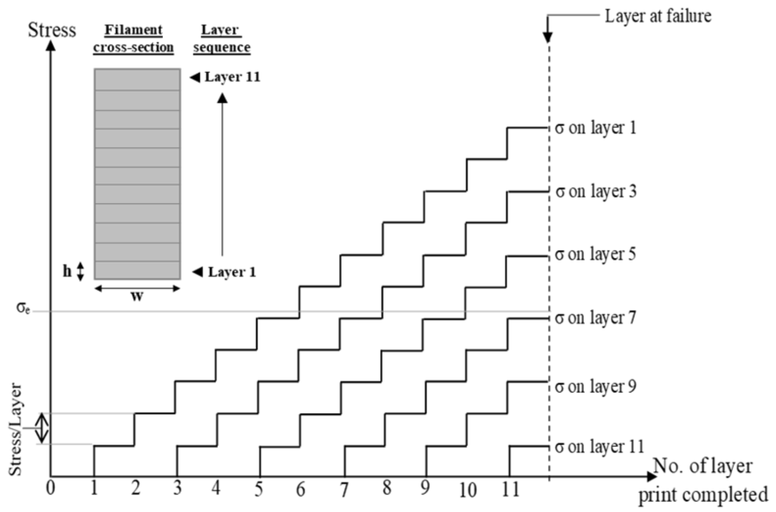
SUMMARY

BI-LINEAR STRESS-STRAIN RESPONSE

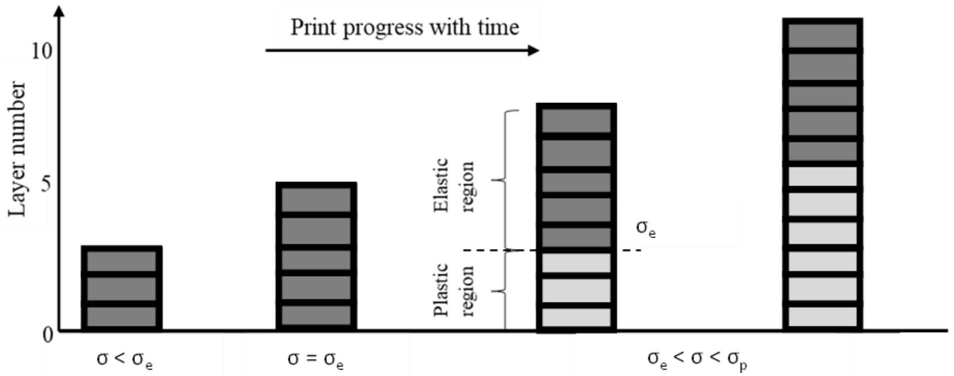
Arizona State University



Typical bi-linear stress-strain response of fresh mortars under compression showing elastic and plastic regimes. Also shown the elastic yield stress (σ_e), initial plastic yield stress (σ_p), elastic modulus (E_e), and initial plastic modulus (E_p)



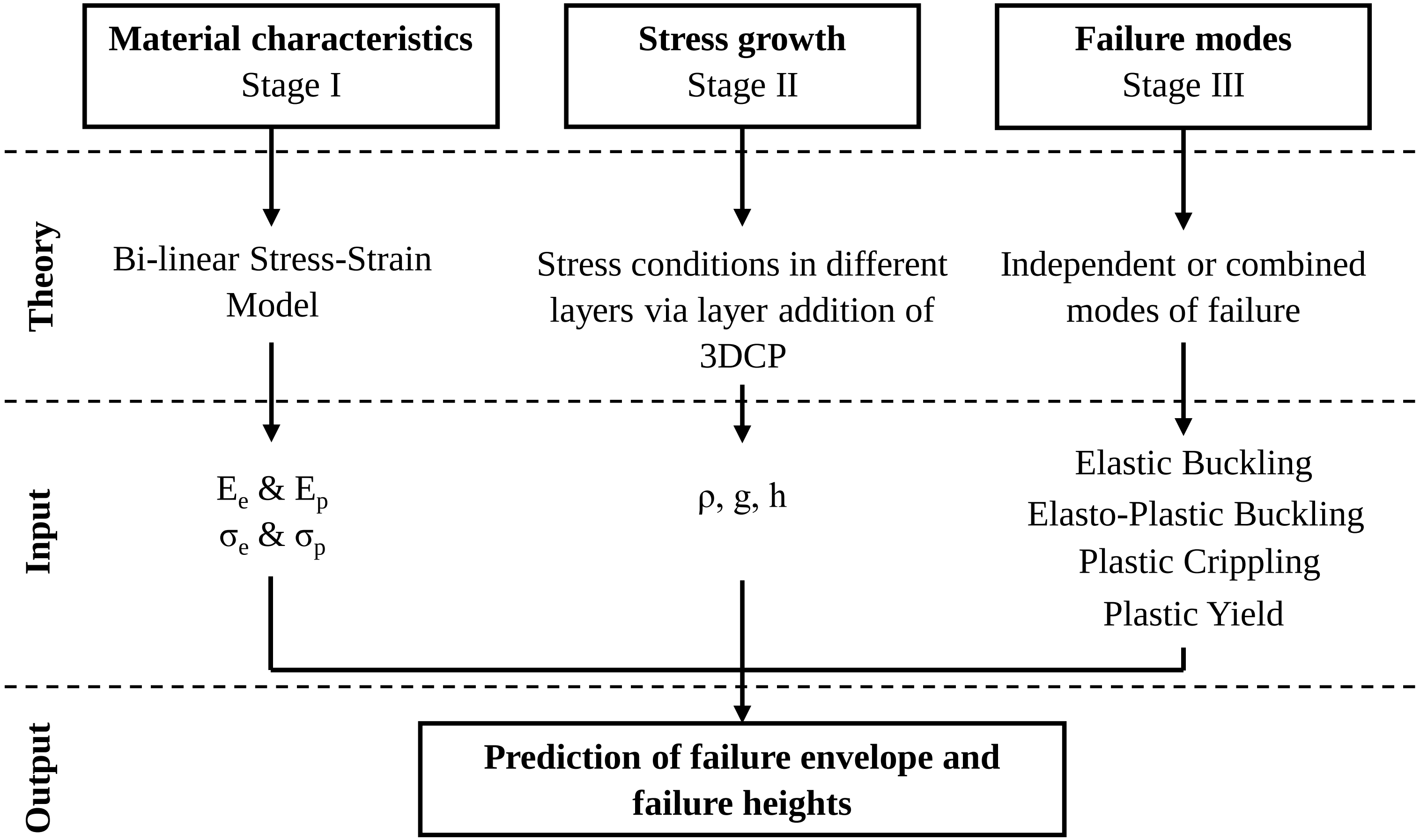
Schematic showing the stress growth in different layers with subsequent layer deposition.



Schematic showing the layers experiencing stresses lower than the elastic yield stress (dark) and greater than the elastic yield stress (light); σ is the stress on the bottommost layer of the print.

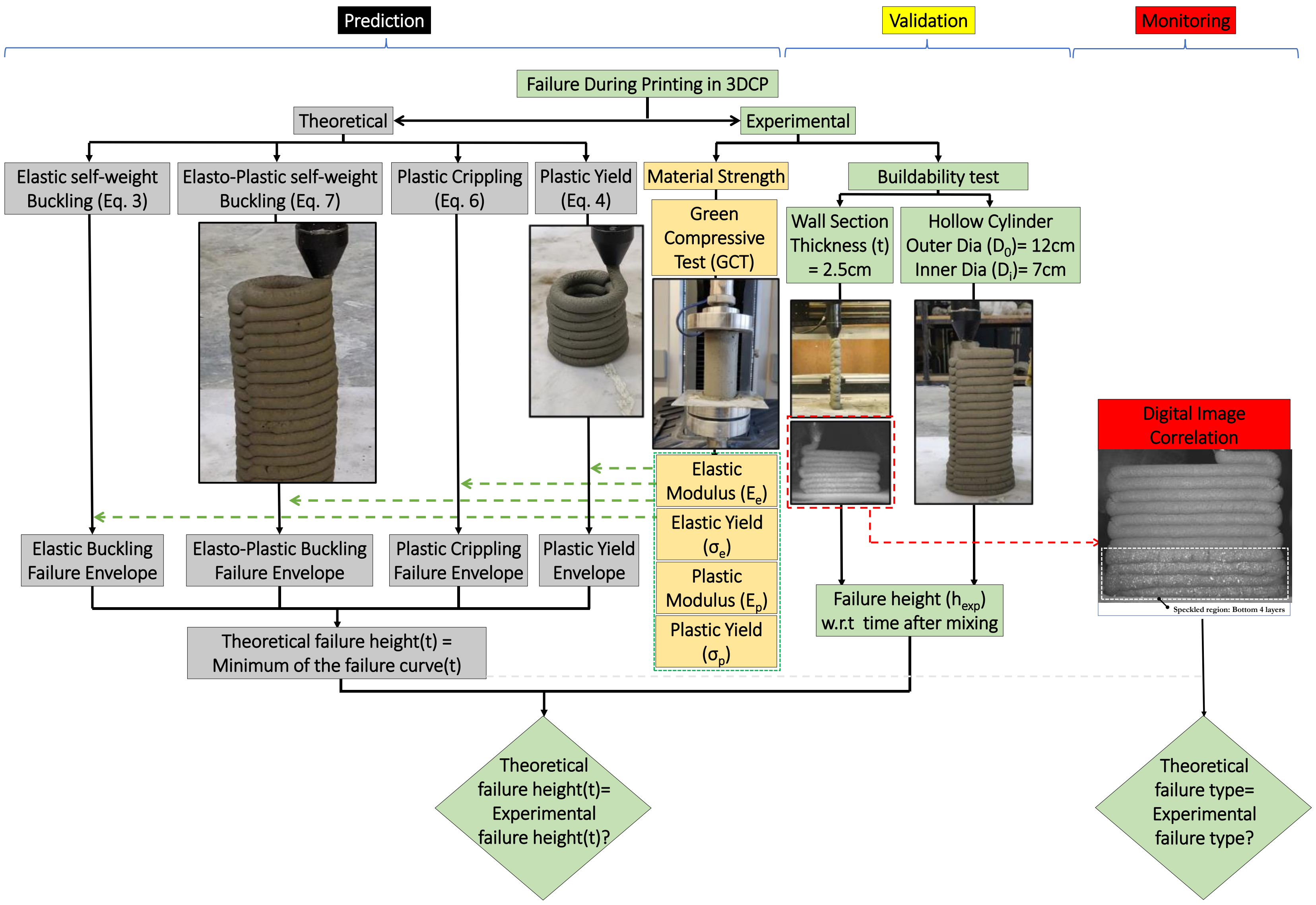
Presented at The Spring ACI convention, San Francisco, April 2023

THEORETICAL ASSESSMENT



Flow diagram showing the stages in the theoretical assessment model for buildability, using a bi-linear stress-strain criterion and stress growth in layers during printing.

OVERALL FLOW



Overall approach for buildability prediction and its experimental verification.

INTRODUCTION

BI-LINEARITY

METHOD

RESULTS

DIGITAL IMAGE CORRELATION

SUMMARY

TEST MIXTURES

Arizona State University

Mortar mixture proportion used in the study.

Mixture ID	Mass fraction of ingredients*					Water-to-binder ratio (w/b) by mass	SP[3] to powder ratio (SP%) by mass	Particle volume fraction in the paste phase
	OPC[1]	Limestone (L; d_{50}=1.5μm)	Fly Ash (F)	Sand (M)	LWA[2]			
$L_{30\text{-}M}$	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 bracket represent proportion in kg/m^3								

[1] Ordinary Portland Cement
[2] Light-weight Aggregates
[3] Superplasticizer

INTRODUCTION

BI-LINEARITY

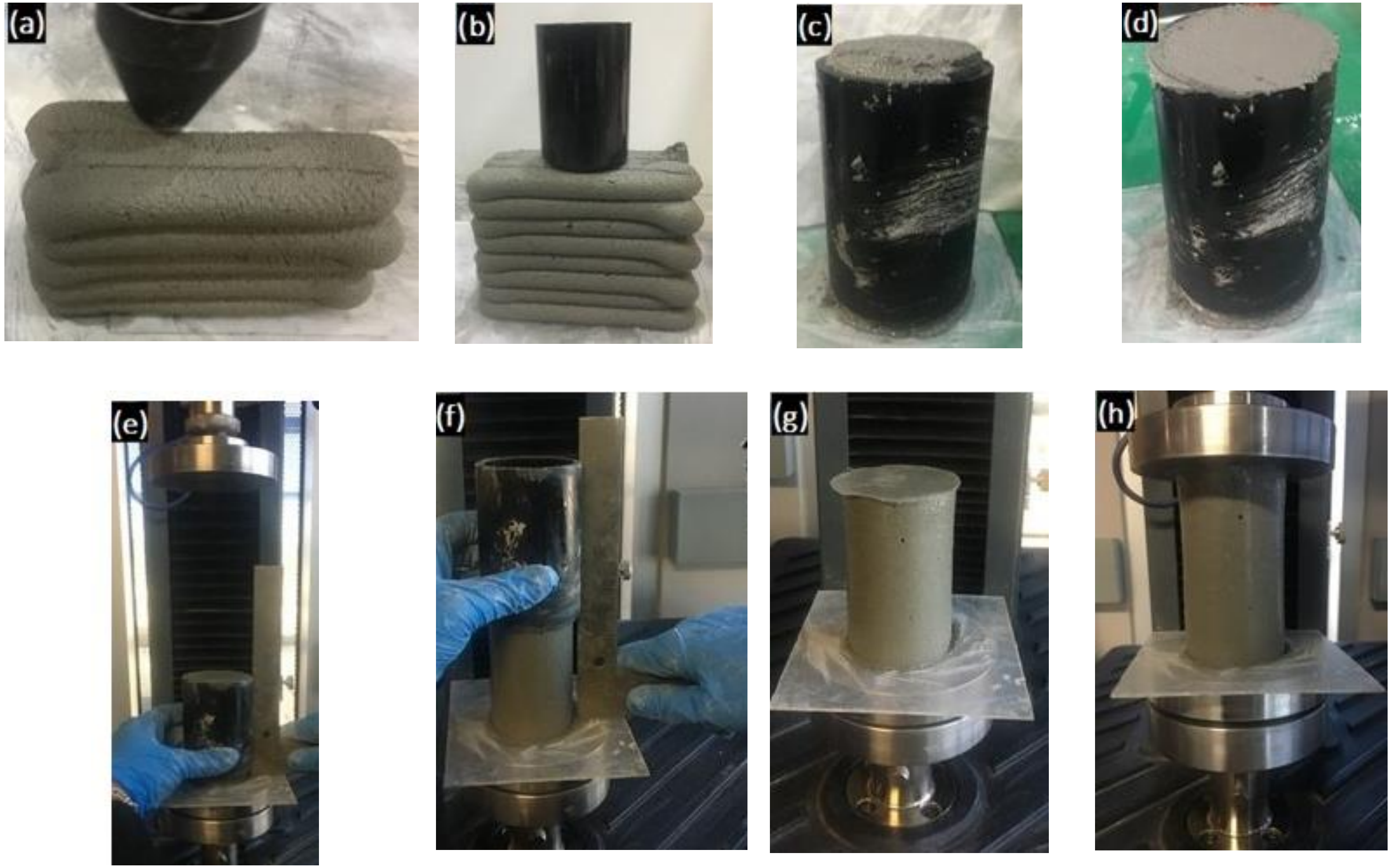
METHOD

RESULTS

DIGITAL IMAGE CORRELATION

SUMMARY

MECHANICAL CHARACTERIZATION



Sample extraction process for green compression testing, to obtain material parameters based on bi-linear stress-strain response.

MECHANICAL CHARACTERIZATION

Arizona State University

INTRODUCTION

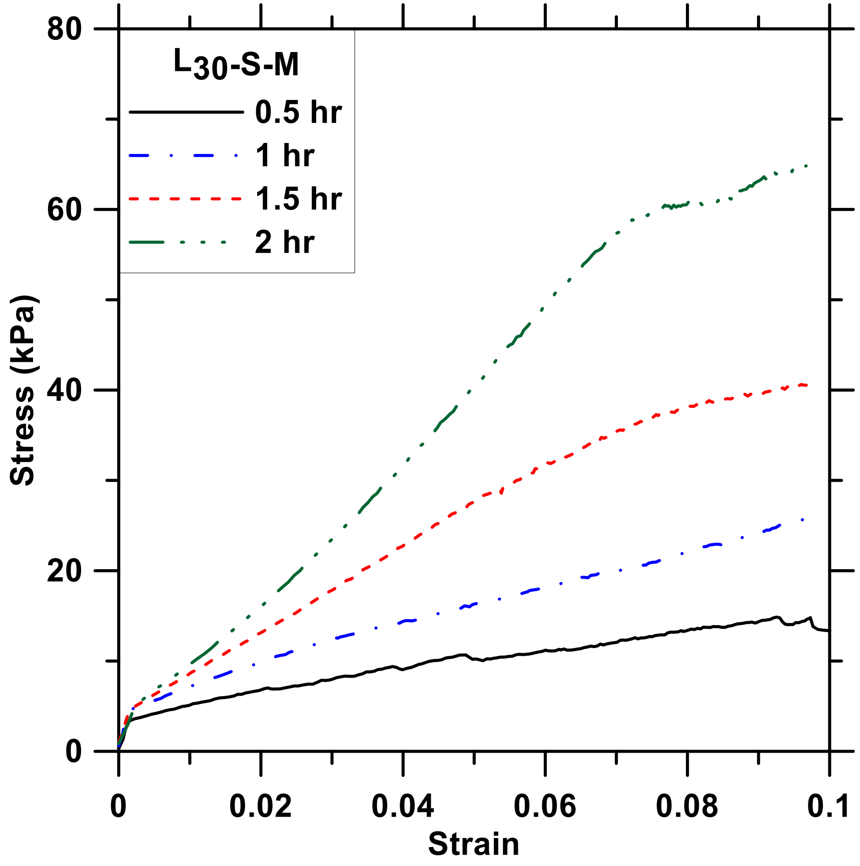
BI-LINEARITY

METHOD

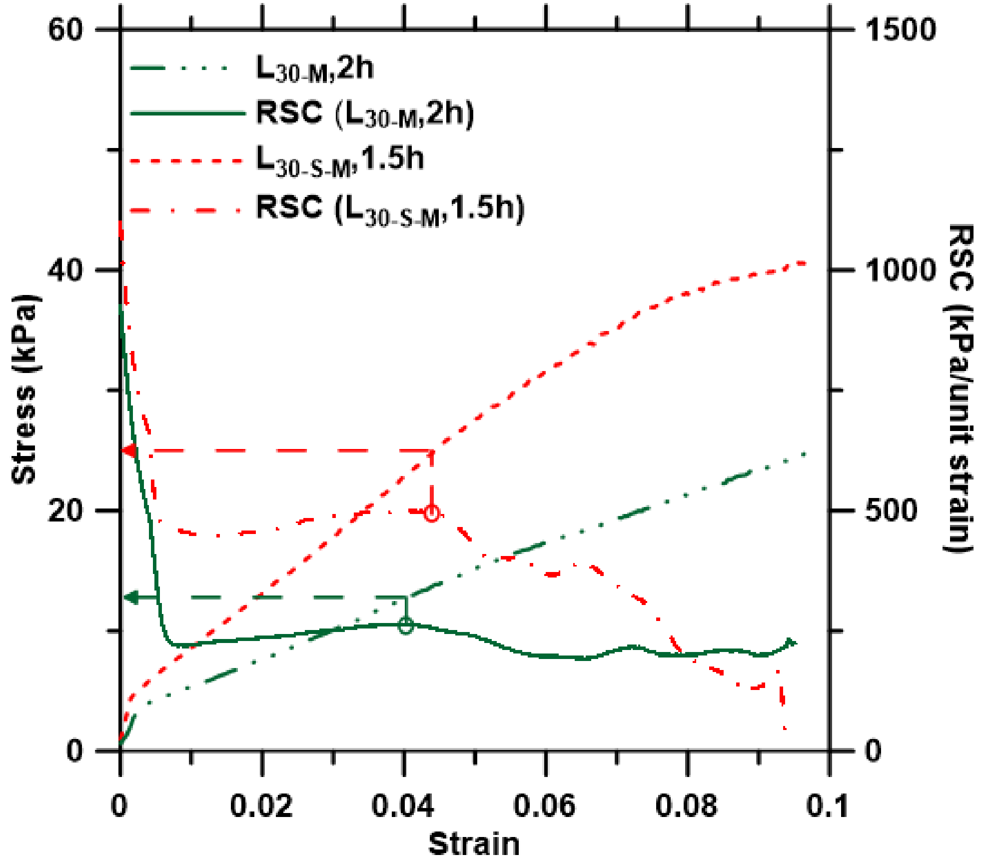
RESULTS

DIGITAL IMAGE CORRELATION

SUMMARY



Representative stress-strain response obtained from GCT.

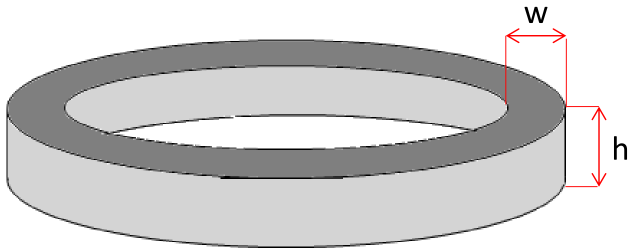


Representative diagram to show the use of rate of stress change (RSC) with strain to identify the plastic yield stress for mixtures..

EXPERIMENTAL VALIDATION

w: Layer width
h: Layer height

Length= 220mm
w= 25mm
h= 15mm



Outside Diameter= 120mm
Inside Diameter= 70mm
w= 25mm
h= 15mm

Figure 10: Cross-section used for print result validation.

EXPERIMENTAL VALIDATION

Arizona State University

INTRODUCTION

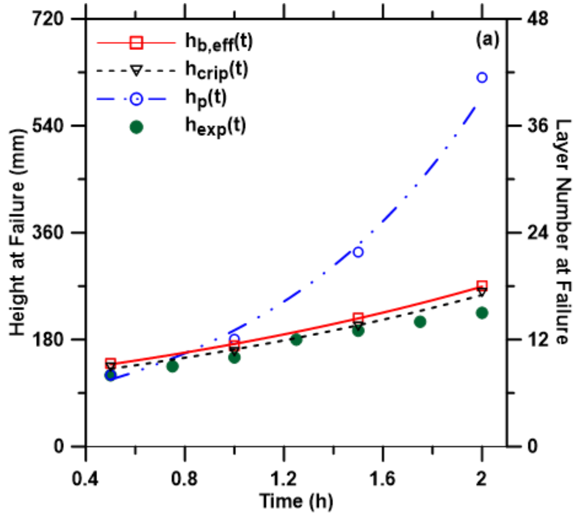
BI-LINEARITY

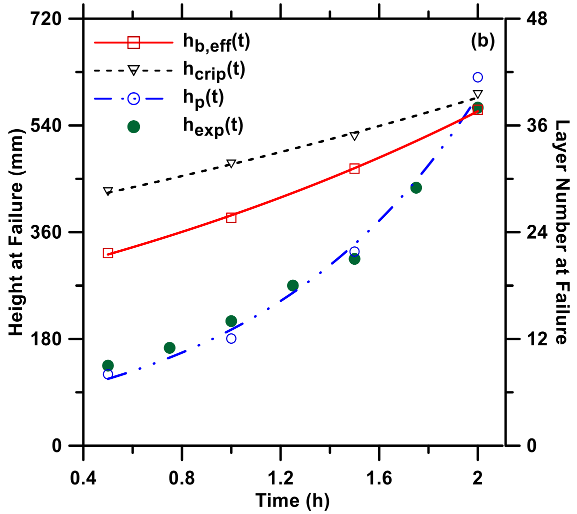
METHOD

RESULTS

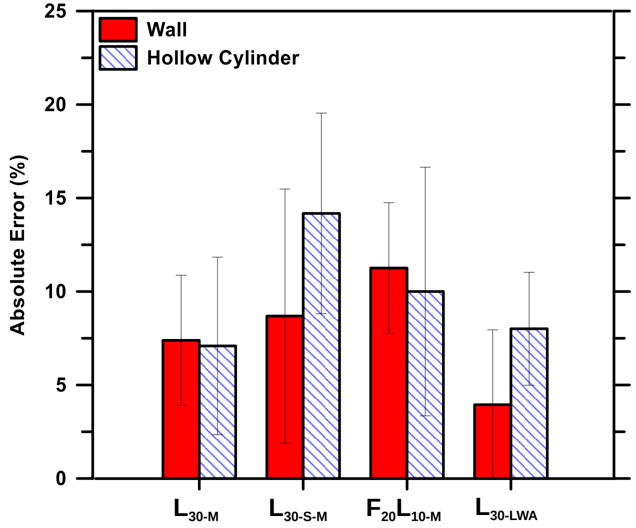
DIGITAL IMAGE CORRELATION

SUMMARY





Representative result for (a) wall print, and (b) hollow cylinder print; $h_{b,eff}(t)$ represents effective buckling height, $h_{crip}(t)$ represents crippling height, $h_p(t)$ represents plastic collapse height, and $h_{exp}(t)$ represents experimental failure height with respect to time.



Average absolute error in prediction w.r.t experimental results for all four mixtures. The error bars indicate the spread in the error between predictions and measurements for all times tested.

DIC SETUP

INTRODUCTION

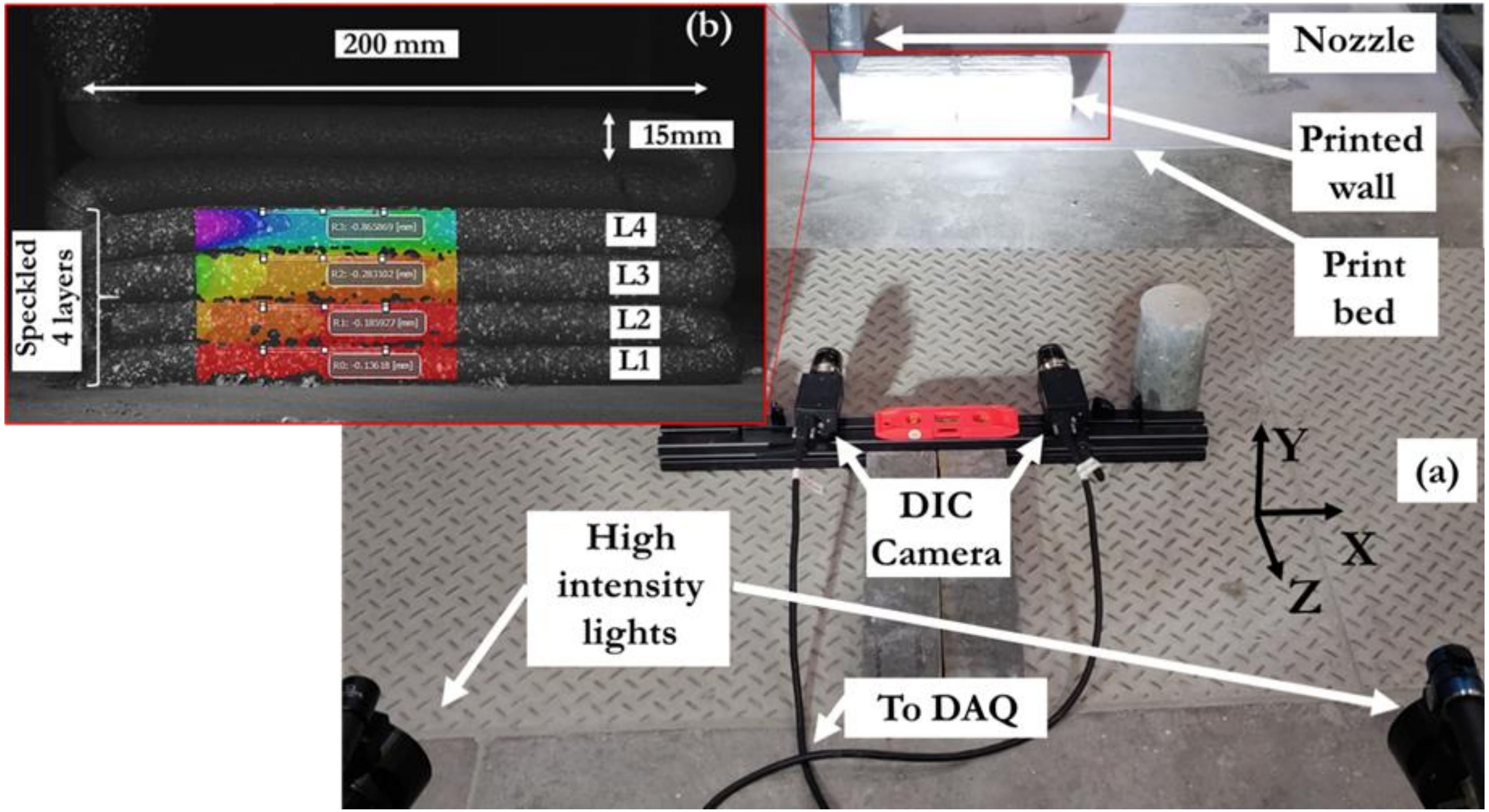
BI-LINEARITY

METHOD

RESULTS

DIGITAL IMAGE CORRELATION

SUMMARY



(a) The overall DIC setup showing the components, and (b) a DIC image showing the first four layers (L1 to L4) speckled and post-processed after calibration. 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

DIC ANALYSIS

INTRODUCTION

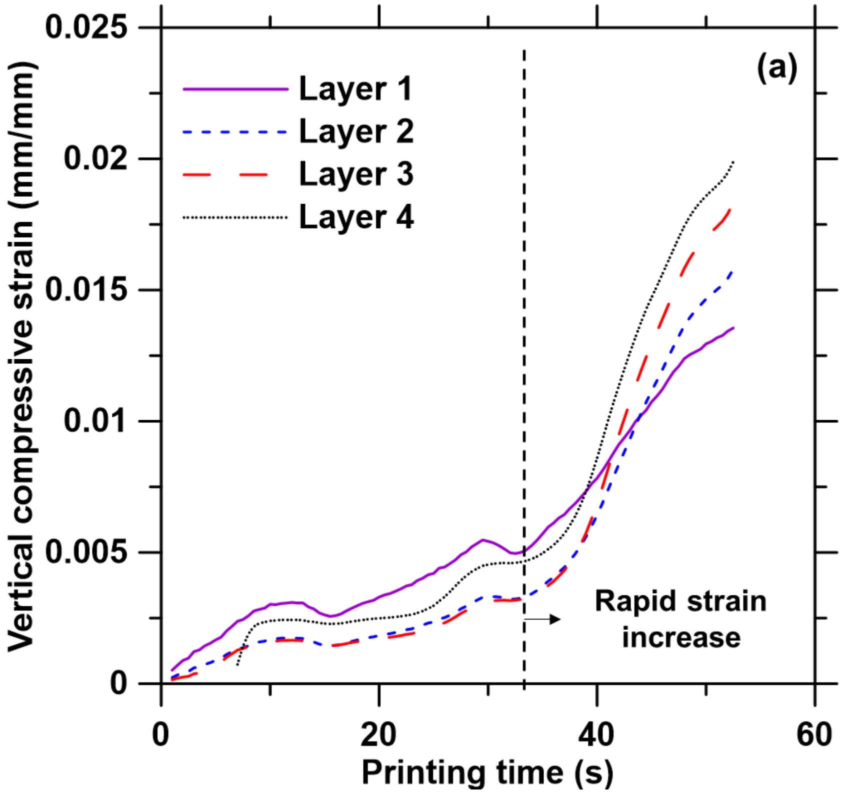
BI-LINEARITY

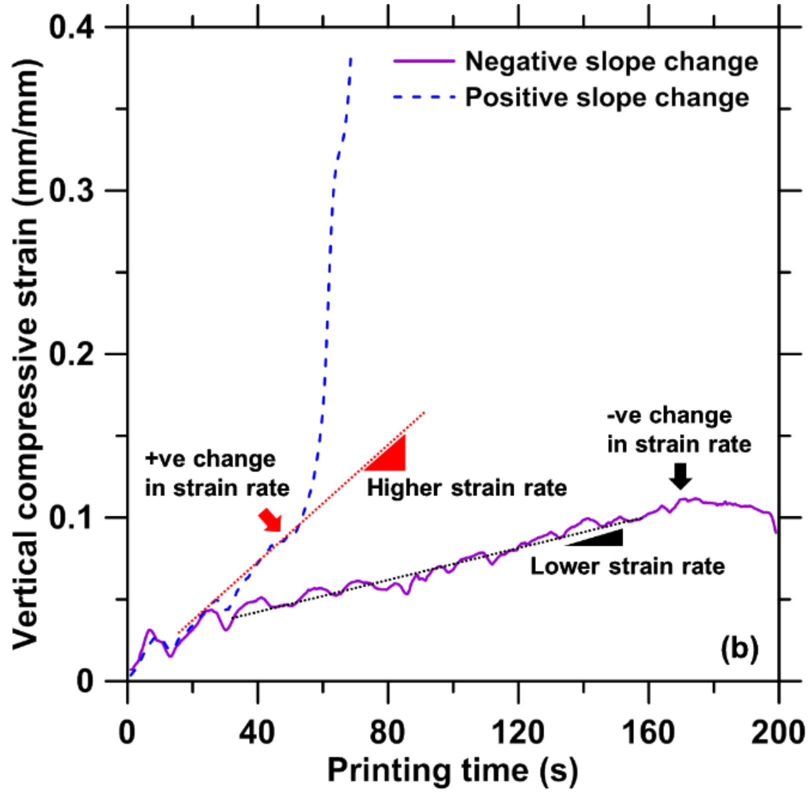
METHOD

RESULTS

DIGITAL IMAGE CORRELATION

SUMMARY





(a) Typical vertical strain profile for the speckled layers as a function of printing time for the superimposed layers (after 4 layers have been printed and speckled) showing the approximate time of rapid increase in strain, and (b) typical strain profiles characteristic to plastic collapse and buckling failure, based on the calculated changes in strain rate, and vertical compressive strain profiles extracted from layer 2.

DIC ANALYSIS

INTRODUCTION

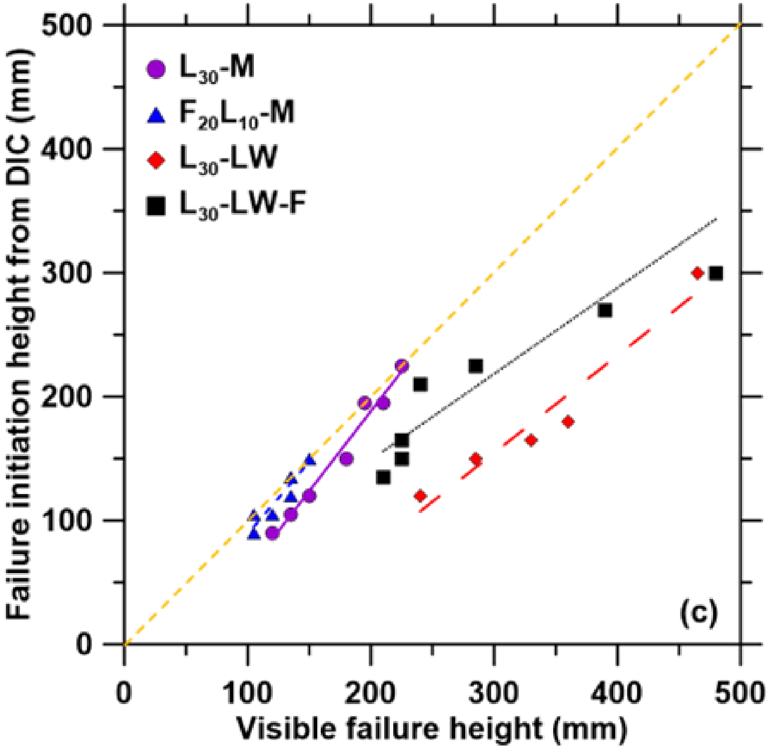
BI-LINEARITY

METHOD

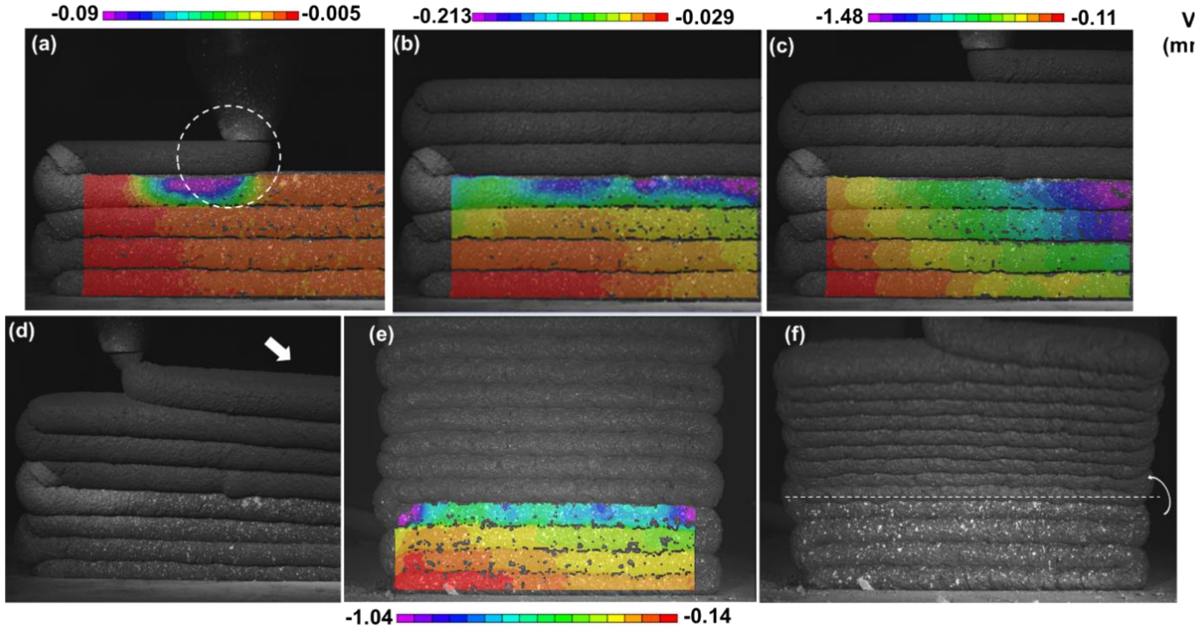
RESULTS

DIGITAL IMAGE CORRELATION

SUMMARY



The comparison of initiation and critical failure heights, observed using DIC and visible collapse, respectively.



Different frames in the printing cases showing the vertical displacement (v; in mm) profiles and mode of failure. Figures show the state of L_{30}-M mortar: (a) during printing resumed after speckling, (b) after three additional layers are printed, (c) where significant increase in vertical displacement is detected before failure initiation, and (d) at critical failure when right end of the print fails under plastic collapse. Also shown is the state of L_{30}-LW mortar: (e) right before failure with no specific localized displacement increase after a number of layers are printed, and (f) crippling near the interface of 5^{th} and 6^{th} layers with the dotted line showing the axis of rotation, and the onset of out-of-plane failure of the wall. Please note the differences in the magnitude of displacements between the figures.

INTRODUCTION

BI-LINEARITY

METHOD

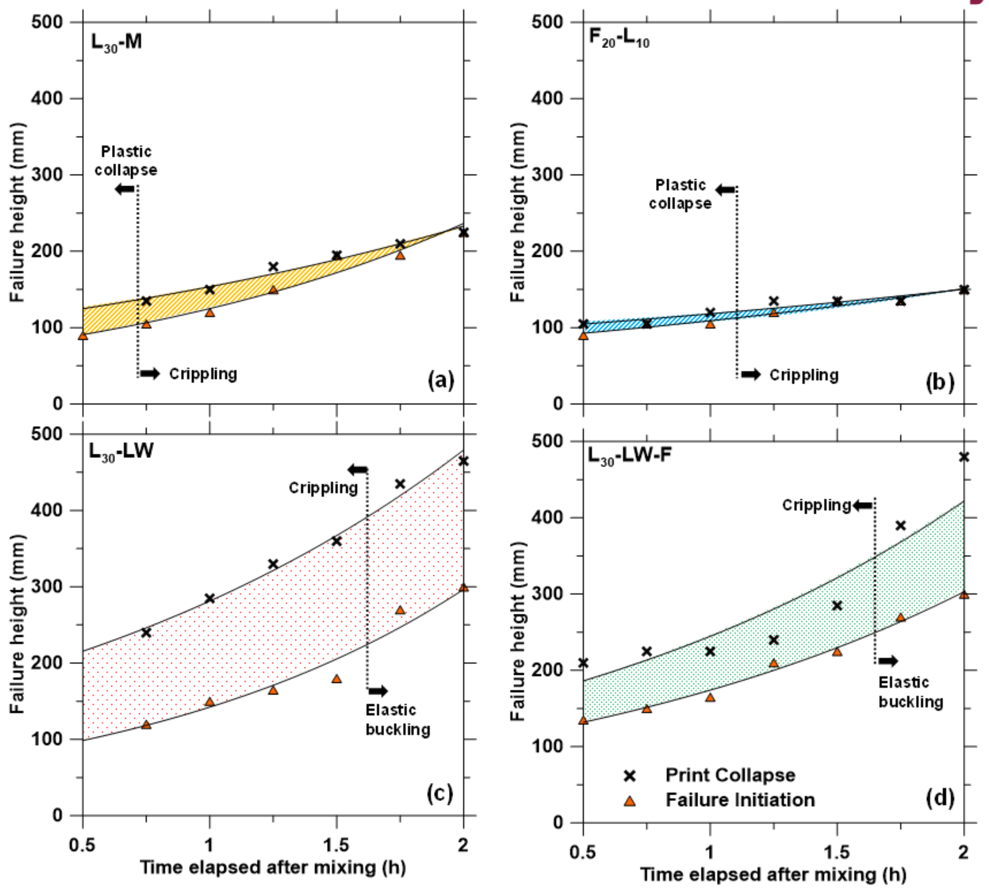
RESULTS

DIGITAL IMAGE CORRELATION

SUMMARY

SUMMARY

- Method to obtain bi-linear stress-strain response proposed.
- Theoretical prediction model based on bi-linear response proposed.
- Theoretical prediction showed good agreement with experimental results throughout the open time.
- Failure type predicted by the theoretical model was verified by DIC analysis.
- Possibility of preventing failure through development of in-line DIC analysis, through initiation height.



The observed initiation and visible failure heights, and the predicted failure types for: (a) L_{30}-M, (b) $F_{20}L_{10}$-M, (c) L_{30}-LW, and (d) L_{30}-LW-F mixtures. The vertical dotted lines indicate the demarcation between predicted failure mode based on green compressive strength tests on these mixtures. The solid lines are exponential fits to the initiation and failure heights extracted using DIC and the solid region indicates the print window between initial and visible failure heights.

Narayanan.Neithalath@asu.edu

3D CONCRETE

An NSF AccelNet Collaborative Effort

NSF

U.S. DEPARTMENT OF ENERGY

QUESTIONS?

EQUATIONS

Arizona State University

INTRODUCTION

BI-LINEARITY

METHOD

RESULTS

DIGITAL IMAGE CORRELATION

SUMMARY

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

$$h_e = \frac{\sigma_e}{\rho g}$$

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

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

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

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

$$E_{eff} = \frac{(h_e + h_{p,eff})^2 E_e E_p}{h_e^2 E_p + h_{p,eff}^2 E_e}$$

$$(h_e + h_{p,eff}) - \left[7.8373 \frac{E_e E_p I}{(h_e^2 E_p + h_{p,eff}^2 E_e)\rho g A}\right] = 0$$

Symbols used in the equations

- $h_{b,el}$: Elastic buckling failure height
- E_e : Elastic modulus
- I : Moment of inertia of cross-section
- ρ : Density of material
- g : Acceleration due to gravity
- A : Area of cross-section
- h_e : elastic yield height
- σ_e : Elastic yield stress
- h_{crip} : Crippling failure height
- l_{crip} : Height in plastic regime at crippling failure
- E_p : Initial Plastic modulus
- $h_{b,eff}$: Elasto-plastic buckling failure height
- E_{eff} : Effective modulus of the combined system
- $h_{p,eff}$: Height in plastic regime at elasto-plastic buckling failure