Opportunities for Customization of Concrete Structures Using 3-D Printing Technology

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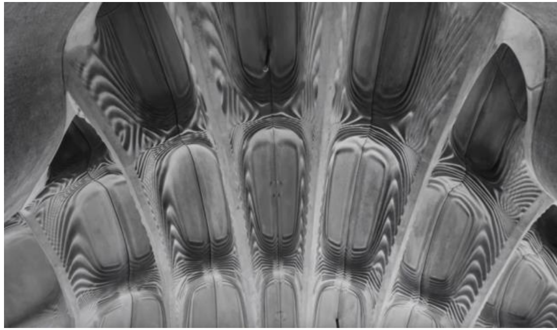
Opportunities with 3D Construction Printing

- Freedom of design
- Higher customization levels
- Automation of construction
  - Safer
  - Higher precision
  - Lower cost/higher productivity
  - Reduction of waste
  - Faster completion time

D. Asprone et al.,
CCR 2018



Digital Bldg. Tech. Group, ETH Zürich

T. Wangler et al., RILEM Technical Letters (2016)

3D construction opportunities – complex and unique structures

- Innovations in materials, engineering and design radically transform the way buildings are conceived
- These innovations open up possibilities to build more architecturally complex concrete structures
- These designs represent challenge to modes of production used in concrete construction of today
  - Complex structures often require custom formwork for each element produced
  - Expensive and unsustainable process

Digital Building Technologies Group, ETH Zürich

Present State of 3D Construction Printing

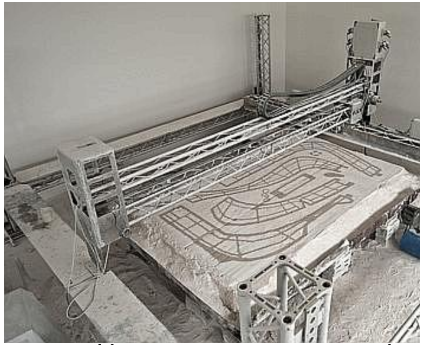
Several companies with “showcase-type” developments

- Contour Crafting-USA
- Smart Dynamic Casting
- Xtree-FR
- TotalKustom-USA
- WinSun-CN
- D-Shape-IT
- 3D Printhuset-DA

http://contourcrafting.com/building-construction/

http://www.totalkustom.com/

http://www.officeofthefuture.ae/#



http://foto.ilsole24ore.com/

Present State of 3D Construction Printing

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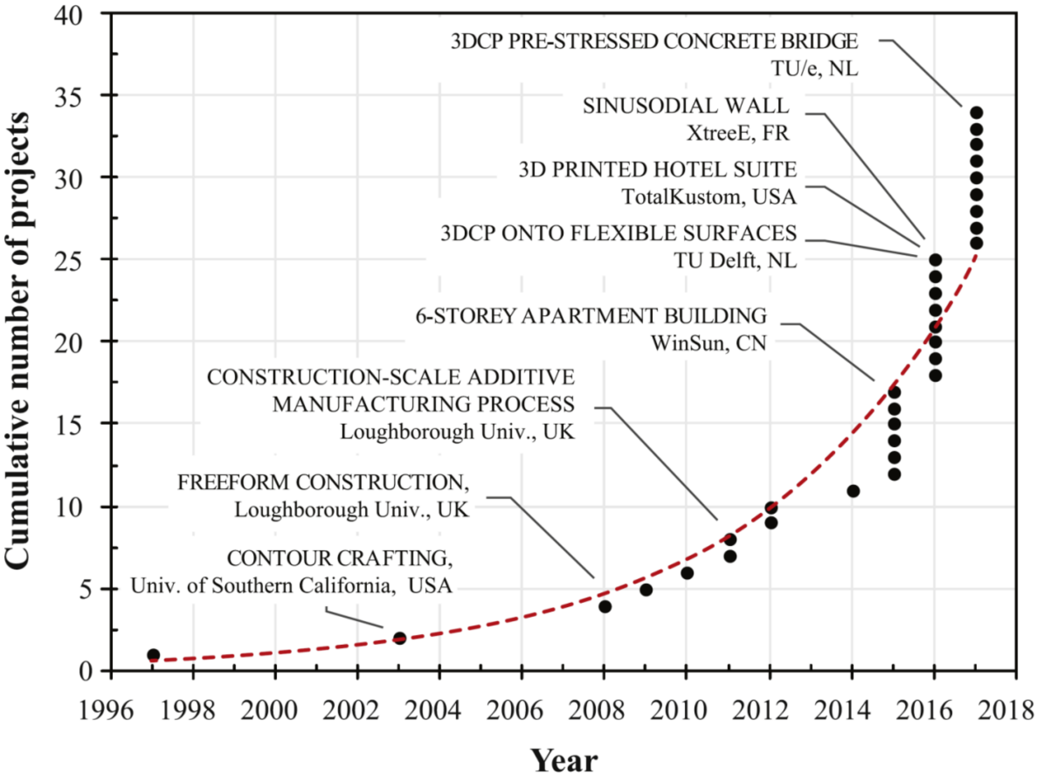


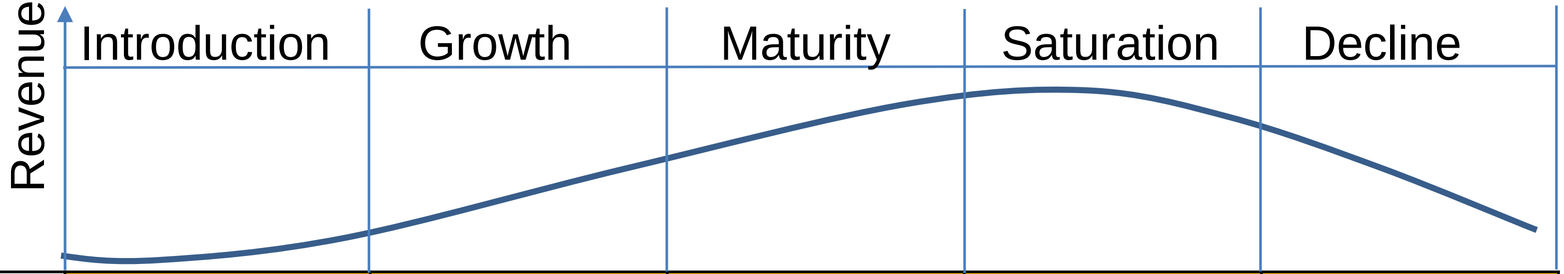
R.A. Buswell et al. *Cement and Concrete Research 112 (2018) 37–49*

Interest in future development of 3D printing

Recent investments in start-ups and own developments

Slide adopted from H. Lund-Nielse, 3D Printhuset, A/S

Stages of Product (Sector) Life Cycle



Audience	Innovators	Early Adopters	Early Majority	Late Majority	Laggards
Market	Small	Expanding	High	Peaked	Contracting
Price	Very High	High	High	Medium	Low
Sales	Low	Expanding	High	Flattening	Moderate
Competition	Low	Increasing	Moderate	High	Moderate
Business Focus	Awareness	Growth	Market Share	Consumer Retention	Transition

Present State of 3D Construction Printing

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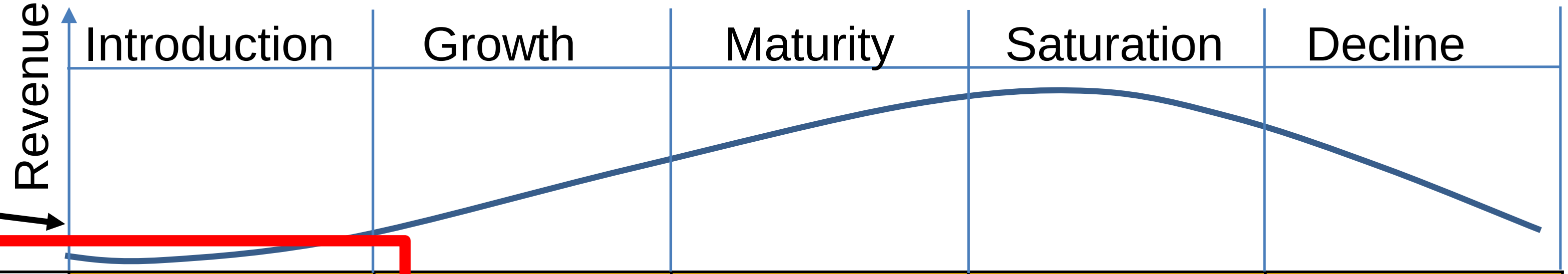
Now Early
Exploration



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Present State of 3D Construction Printing

Myth

Reality

Apis Cor did **not** print the house in 24 hrs and the house did not cost $10,000

- it took from Oct. 2016 to Feb. 2017
- The total cost was much higher

WinSun did not 3D print all of the Office of the future in Dubai

- **not** the “architecturally interesting “ parts
- and **not** in Dubai but in China

Slide adopted from H. Lund-Nielse, 3D Printhuset, A/S

Present State of 3D Construction Printing

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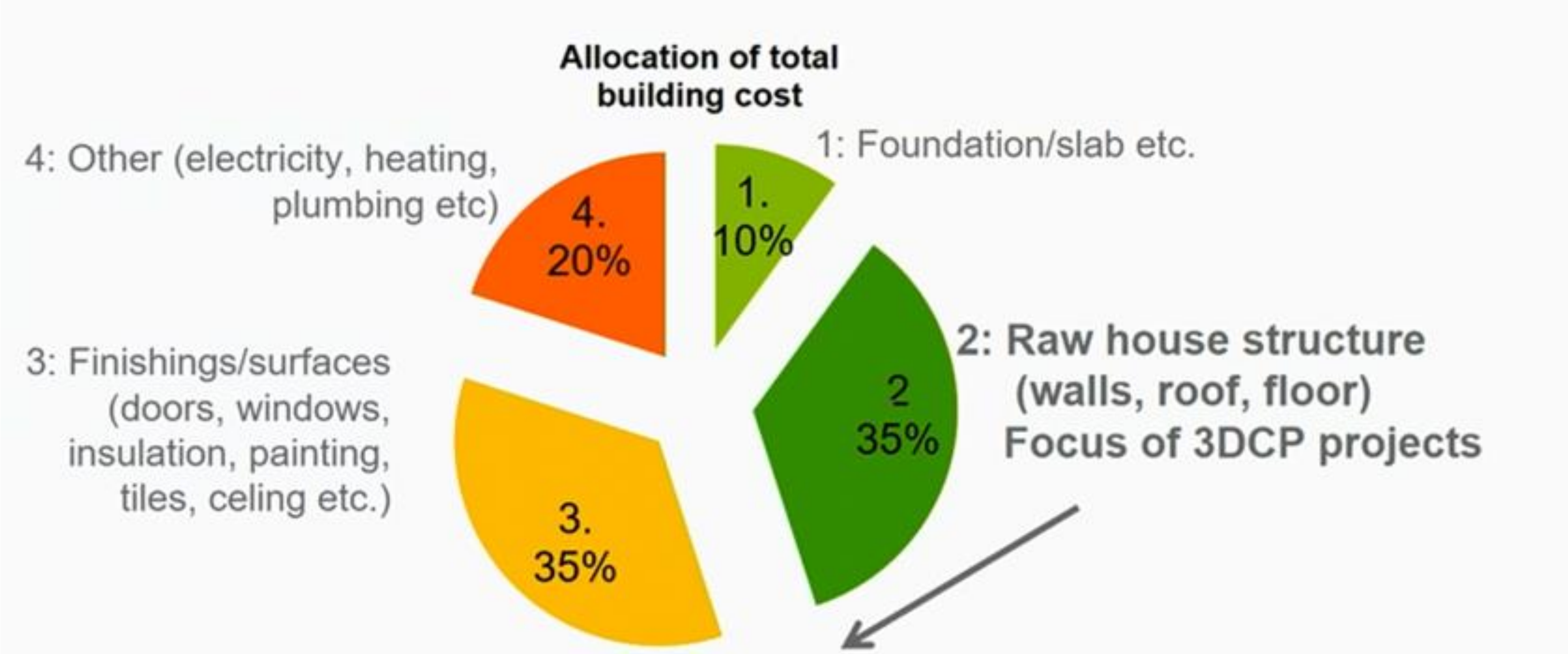


Some items still not addresses (reinforcement, roof)

Slide curtesy of H. Lund-Nielse, 3D Printhuset, A/S

The general focus areas

Industry

- Cost (and time)
- 3D Extrusion printing technology
- Construction methods using 3DCP/permitting/applications
- Recipes
- Materials handling equipment
- 3D extrusion printed concrete properties
- Digital fabrication

Academia

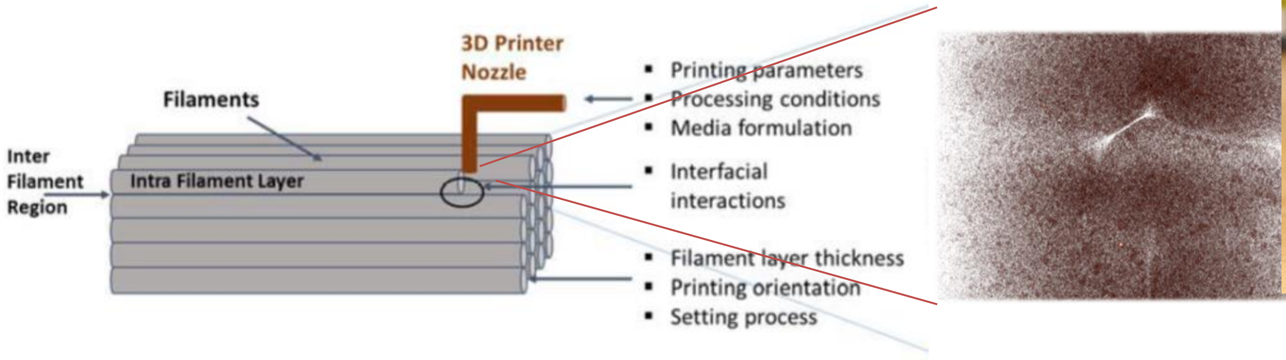
- Cost (and time)
- Materials handling equipment
- Construction methods using 3DCP/permitting/applications
- Reinforcement solutions
- Recipes
- 3D extrusion printed concrete properties
- Digital fabrication

Slide adopted from H. Lund-Nielse, 3D Printhuset, A/S

Some of the missing pieces………

- Compliance with the building codes
- Issue of reinforcement, multiple floors, roofs
- Printed solutions for overhangs
- Adaptation of recipes to changing weather conditions, print size and print speed
- Durability
- Role of interfaces

Role of interfaces

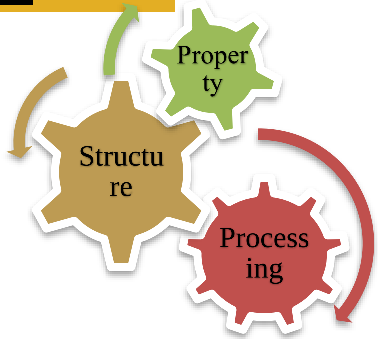


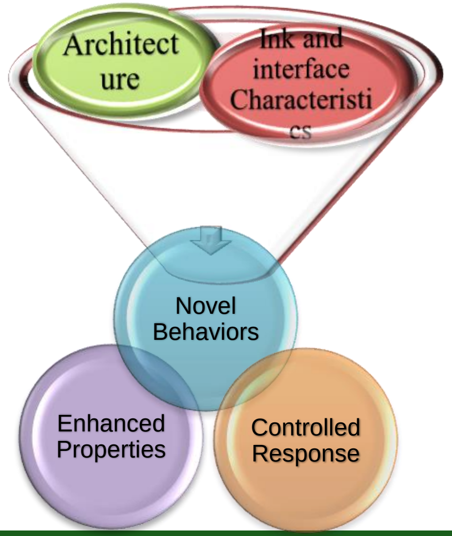
http://www.renca.org/

- The processing-induced heterogeneities and interfaces represent a challenge in elements created using Direct-Ink-Writing (DIW) elements
- Interfacial regions of filaments differ from core regions
- Linking microstructural architecture with properties requires spatial information

The Appeal of DIW in Cementitious Materials– Control of <u>Architecture,</u> <u>Microstructure</u>, and <u>Mechanical Response</u>

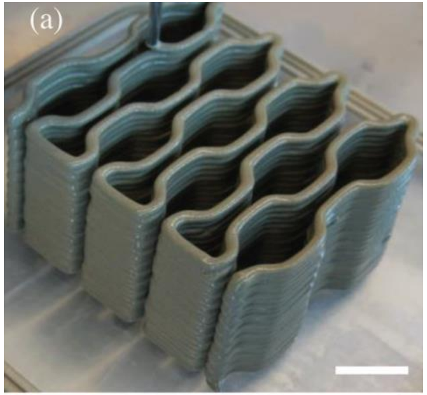
- Facilitates exploration of the intertwined relationships between: <u>Processing-Structure-Property-Performance</u>
- Allows for creation novel designs to achieve enhanced performance characteristics in printed elements (architectured cement based materials)
- Creates possibility of combining the effects of architectured microstructure and weak interfaces

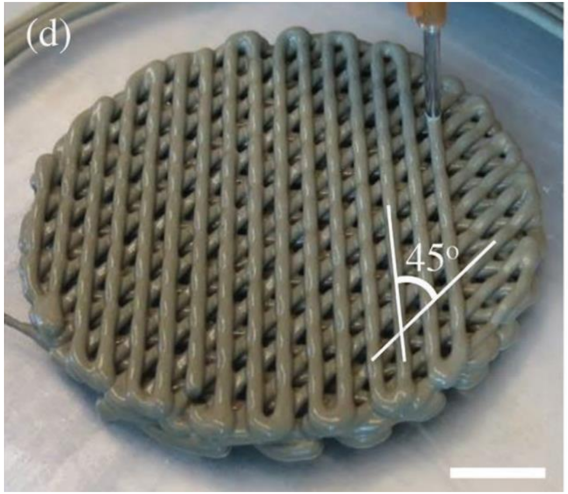


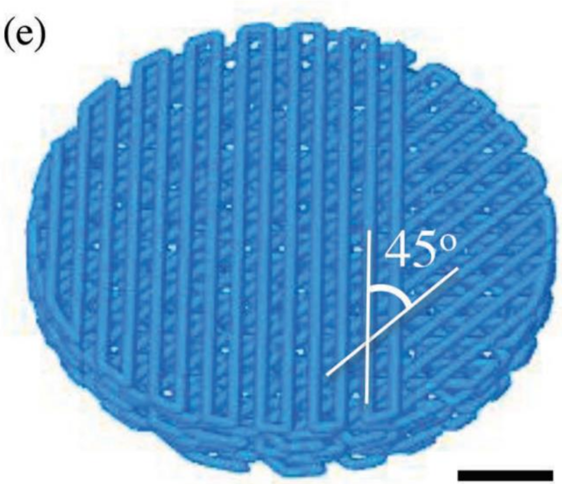


Presence of "weak interfaces" enhances performance of architectured cement-based materials:

- Used DIW to create several <u>architectures</u> (such as honeycomb (a) or Bouligand (d) and (e) to explore the structure-property relationship in 3D-printed hcp.



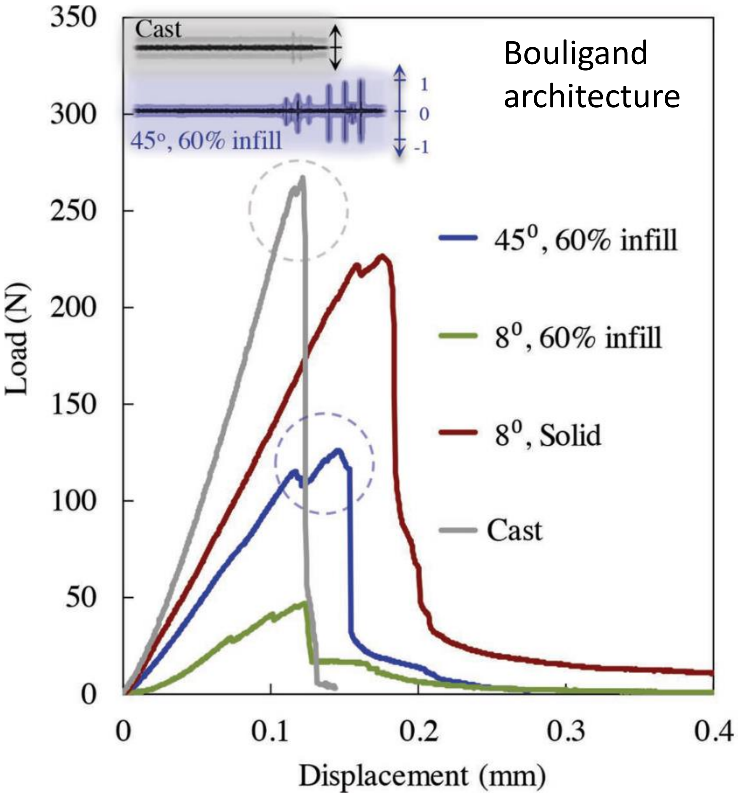




Moini et. al., *Adv. Mater. 2018*

Presence of “weak interfaces” enhances performance of architectured cement-based materials:

- Combined effects of <u>architecture</u> and <u>interfacial porosity </u>on mech. performance:
  - Promotion of unique damage mechanisms, such as spread of interfacial cracking and micro-cracking
  - Increased toughness
  - Increase of fracture resistance (quasi-brittle and flaw-tolerant behaviors in brittle hcp elements)

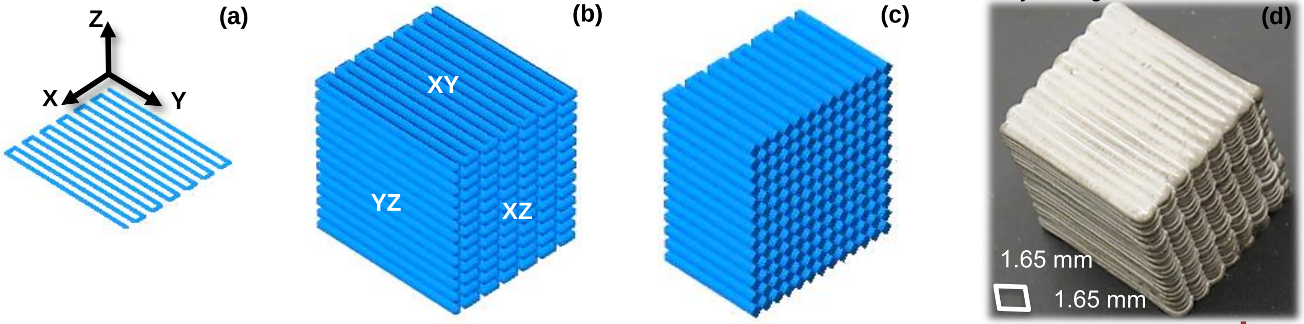


Moini et. al., Adv. Mater. 2018

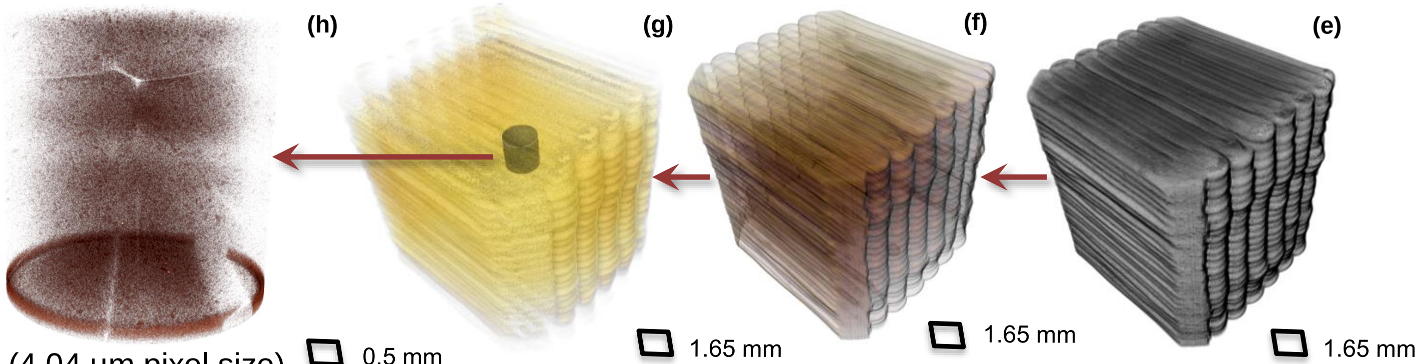
Characterization of the Interfaces:
Differences between “Core” vs. “Interfacial Regions (IRs)” of the filaments

Design of elements with lamellar (layered) architecture:

Nozzle Dia.: 1.36 mm
Layer Height: 1.00 mm



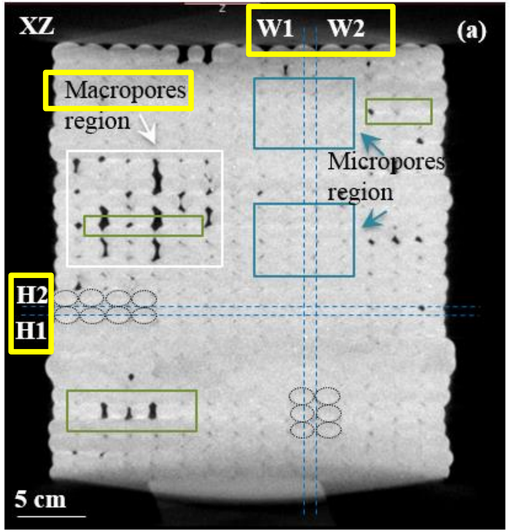
Micro-CT characterization at 2 magnifications (0.4X and 4X scans) – study of the processing-induced heterogeneities

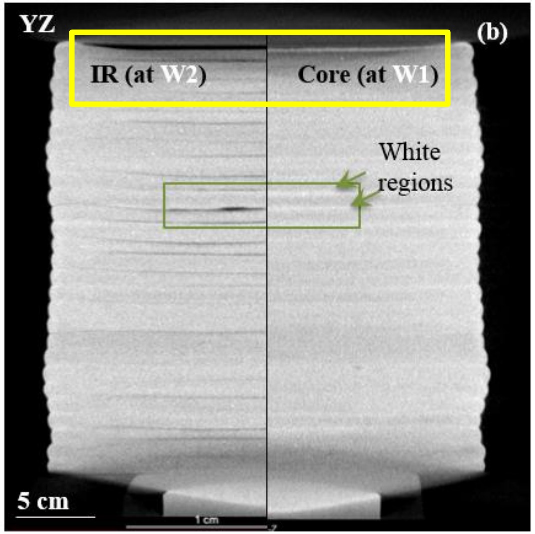


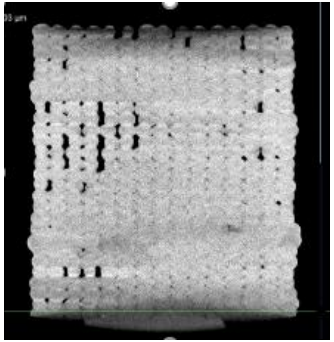
4X scan (4.04 µm pixel size)

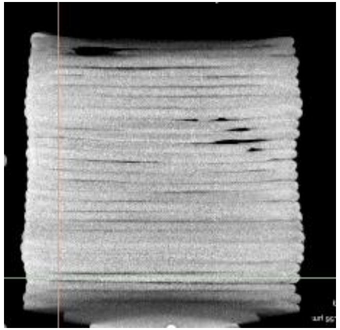
0.4X scan (32.26 µm pixel size)

Microstructural Features: Macro- and Micro-Pores at IRs – 0.4X Scan

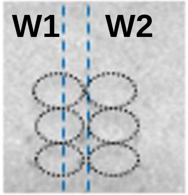




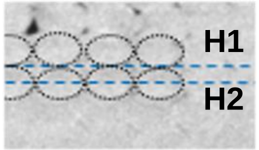


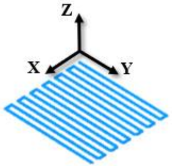


- Macro-Pores at vertical planes

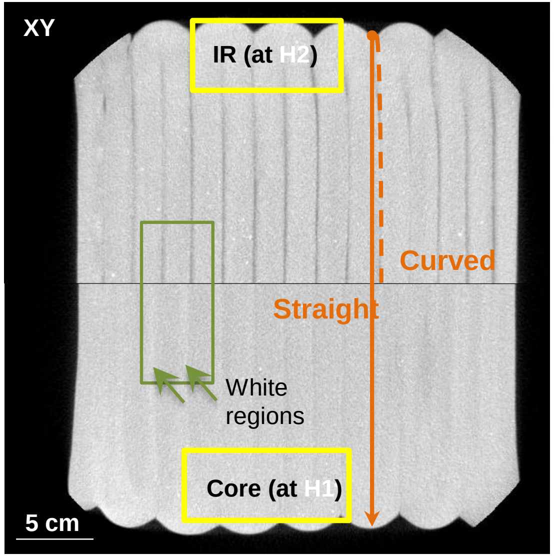


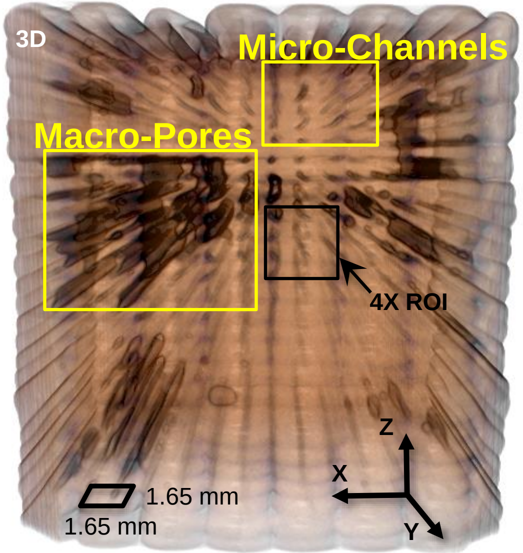
- Micro-Pores at vertical and horizontal planes



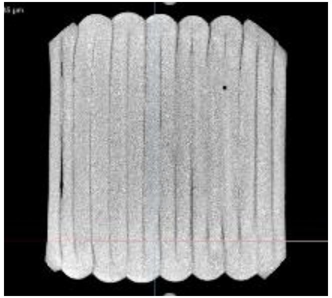


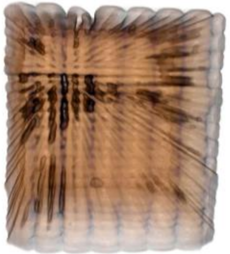
Microstructural Features: Core vs. IRs – 0.4X scan

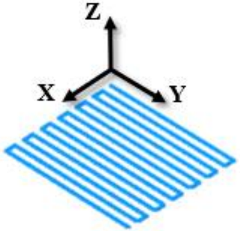




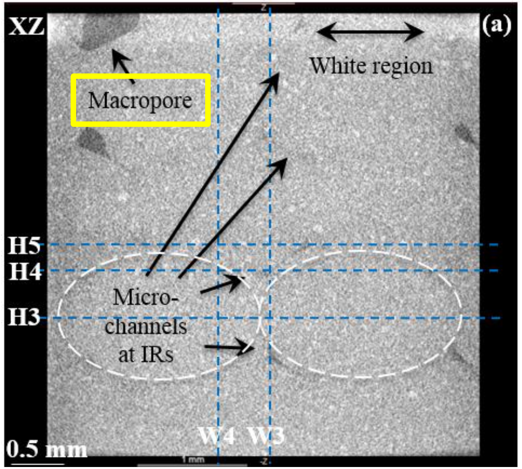
- ➢ Homogenous Core
- ➢ Heterog. Interfacial Region (IR)
- ➢ Re-arrangement of filaments

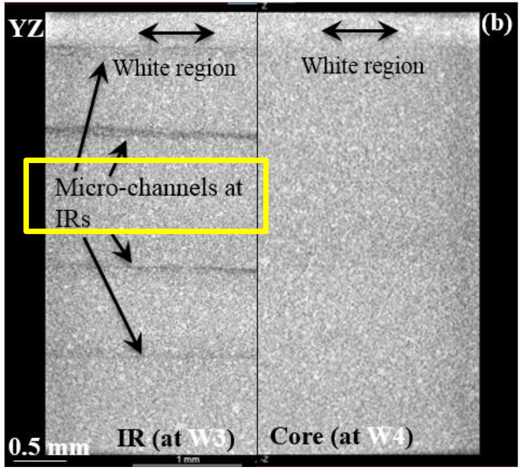




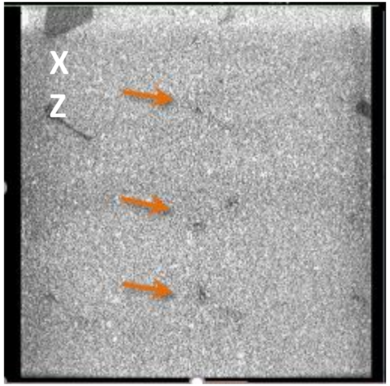


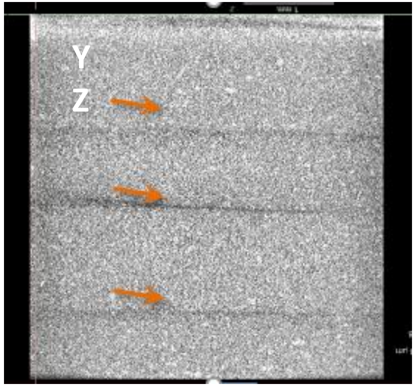
Microstructural Features:
Micro-Pores form Micro-Channels at IRs – 4X Scan

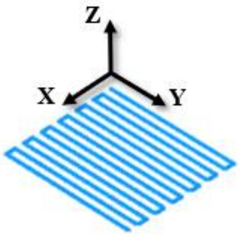




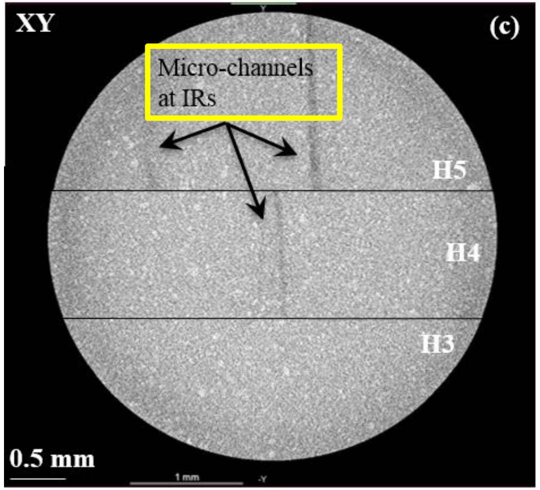
- White Regions accumulation of unhydrated grains near the pores
- Micro-Channels along filaments

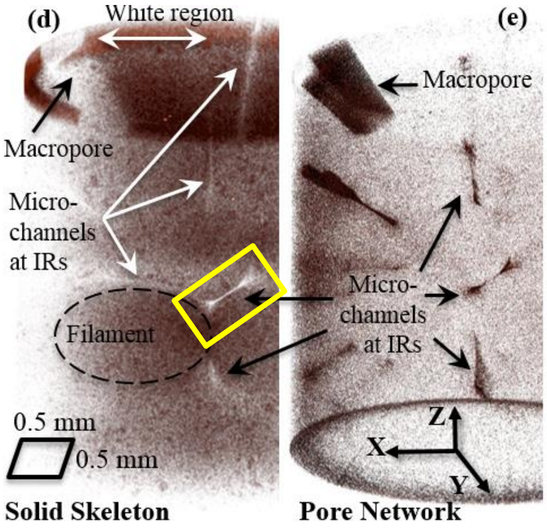


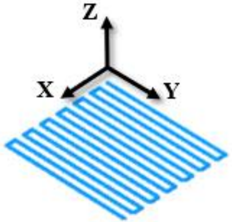




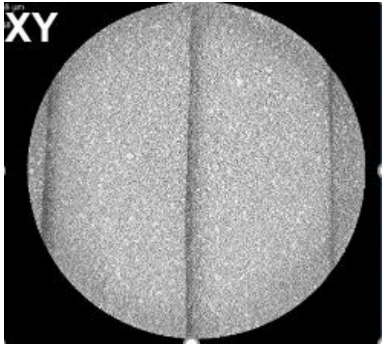
Microstructural Features: Micro-Channels and Re-arrangement – 4X Scan

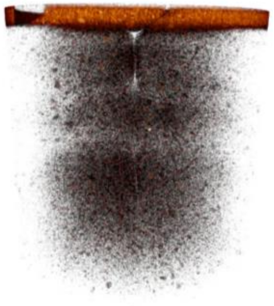


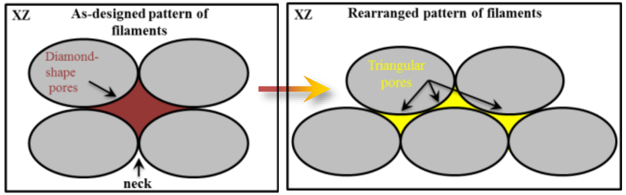




- Filaments shift formation of triangular micro-channels

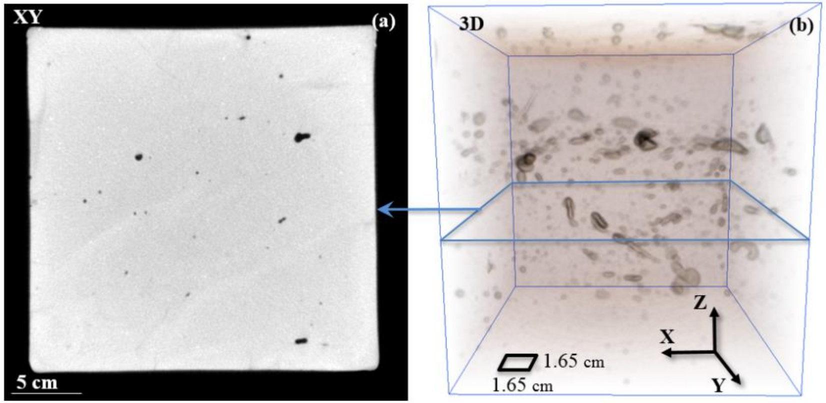




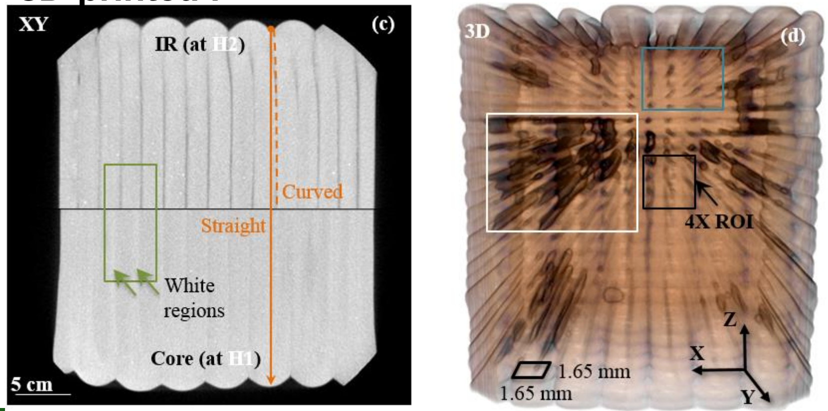


How about the cast specimen?

Cast:



3D-printed :

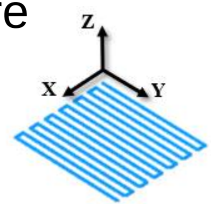


- <u>Cast</u>

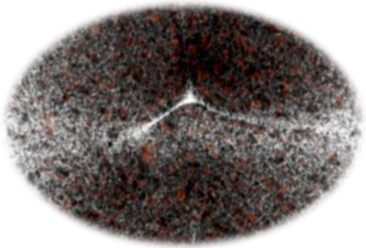
  Randomly Distributed Pores

- <u>3D-printed layered specimen</u>

  Patterned Pore Network



Summary of Micro-CT characterization of 3D-Printed hcp:



- Revealed 4 microstructural features in lamellar architecture:
  - ➢ macropores, and micropores at (IRs) in the form of micro-channels (smaller than 100 μm),
  - ➢ self-rearrangement of filaments from their designed (toolpath) position,
  - ➢ high accumulation of unhydrated cement particles near the macropores (white regions)
- Pore network follows the architectural pattern of materials
- Processing-induced **heterogeneities.** introduce anisotropic properties to 3D-printed cement-based materials.

Where do we go from here?

- Reinforced concrete is a composite material
  - achieving desired performance requires a complex assembly of various materials and involves a multitude of processing steps
  - The challenges require rethinking the material system and fabrication process
  - At the same time 3D technology offers unique to change current building paradigms
  - 3D fabrication with concrete will require intense collaboration of architects, materials scientists, roboticists, and structural engineers

Acknowledgment

Support:
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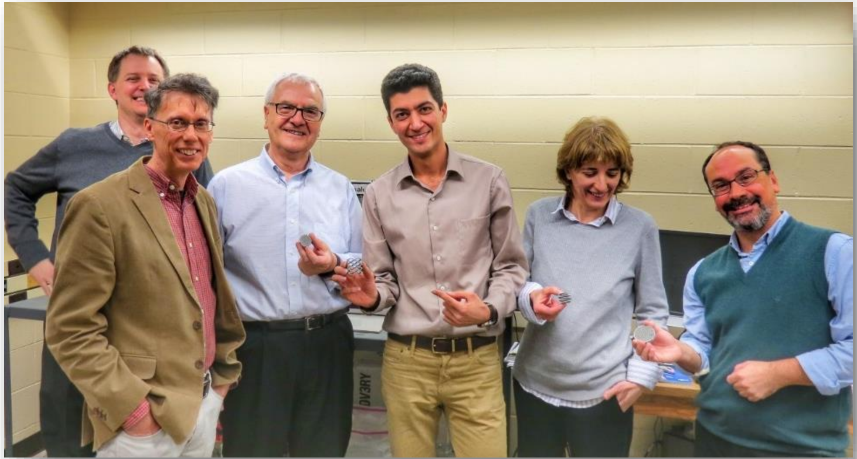
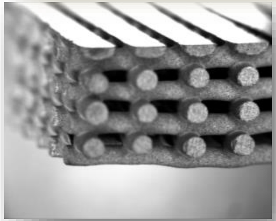
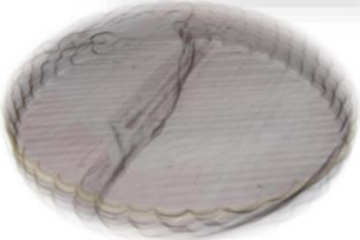
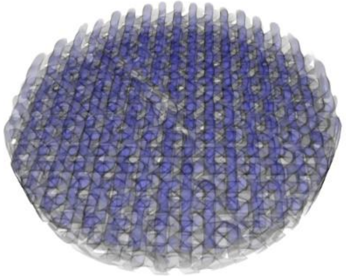
Purdue School of Civil Engineering
Purdue College of Engineering









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Thank you!

Questions?