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

D. Asprone et al., CCR 2018

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
Present State of 3D Construction Printing

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

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Revenue
## Present State of 3D Construction Printing

### Transition Stages
- **Introduction**
- **Growth**
- **Maturity**
- **Saturation**
- **Decline**

### Audience Types
- Innovators
- Early Adopters
- Early Majority
- Late Majority
- Laggards

### Market Conditions
- Small
- Expanding
- High
- Peaked
- Contracting

### Price Levels
- Very High
- High
- High
- Medium
- Low

### Sales Trends
- Low
- Expanding
- High
- Flattening
- Moderate

### Competition Intensity
- Low
- Increasing
- Moderate
- High
- Moderate

### Business Focus
- Awareness
- Growth
- Market Share
- Consumer Retention
- Transition

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**ACI Spring Conference, March 24, 2019, Québec City, Canada**
Present State of 3D Construction Printing

**Myth**

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

**Reality**

*Slide adopted from H. Lund-Nielse, 3D Printhuset, A/S*
Present State of 3D Construction Printing

Some items still not addressed (reinforcement, roof)

*Slide courtesy 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
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 Architecture, Microstructure, and Mechanical Response

- Facilitates exploration of the intertwined relationships between: Processing-Structure-Property-Performance
- 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 architectures (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 architecture and interfacial porosity 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:

Micro-CT characterization at 2 magnifications (0.4X and 4X scans) – study of the processing-induced heterogeneities
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
- Heterogenous Interfacial Region (IR)
- Re-arrangement of filaments

XY

Core (at H1)
IR (at H2)
White regions
Curved
Straight

3D

Macro-Pores
Micro-Channels

4X ROI

5 cm

1.65 mm
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**
Randomly Distributed Pores

**3D-printed layered specimen**
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
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Thank you!

Questions?