3D Printed Structures: Vision and Opportunities

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What is 3D printing?

- It is a manufacturing process that fabricates 3D objects directly from a digital 3D model
- Also called digital fabrication or additive manufacturing (AM)
- 3D **CAD** model → converted into a **STL** (STereo Lithography) format → divided into multiple **2D layers** during (**slicing process**).
- **Cartesian coordinates** from the 2D layers + **printing parameters** (e.g. printhead speed, extrusion rate) → delivered to 3D printer in machine-readable language (e.g. **G-code**).
- In applications to concrete,
  - Methods based on extrusion (layered extrusion)
  - Methods based on selective binding
  - Methods based on robotic (adaptive) slip-forming (smart dynamic casting)

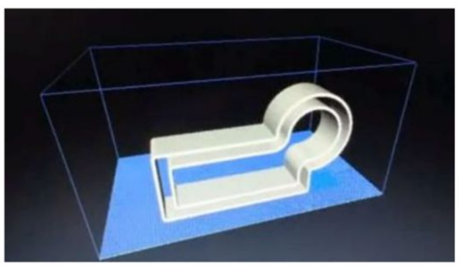
General steps in 3D printing

3D model of desired object → **Conversion to STL file** → **Generation of G-code via slicer program** → **3D printing**

Conversion to STL file: Model is represented as a series of 2d layers & design is converted into a file readable by the printer

Generation of G-code via slicer program: Tells the printer what to do

3D printing: Data file exported to printing machine. Material is processed by printer and layered according to the design



→

```
;layer 88, Z=8.79
G1 X145.31 Y41.195 F4800
M25; pause print
G1 Z8.79 F1000
G1 Z40 F1000; Height set to Z=40
G1 E0 F1800
G92 E0
```

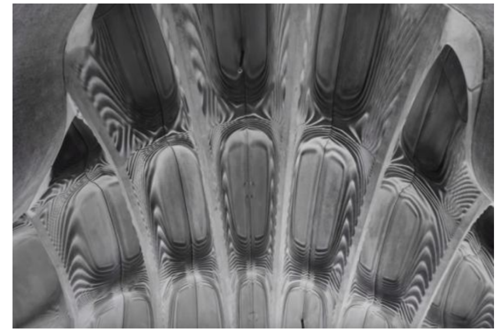
→

R. Ferron, UT Austin, ACI Convention, Fall 2018, Las Vegas, NV

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
  - Customization with no additional cost

D. Asprone et al., CCR (2018)



Digital Bldg. Tech. Group, ETH Zürich

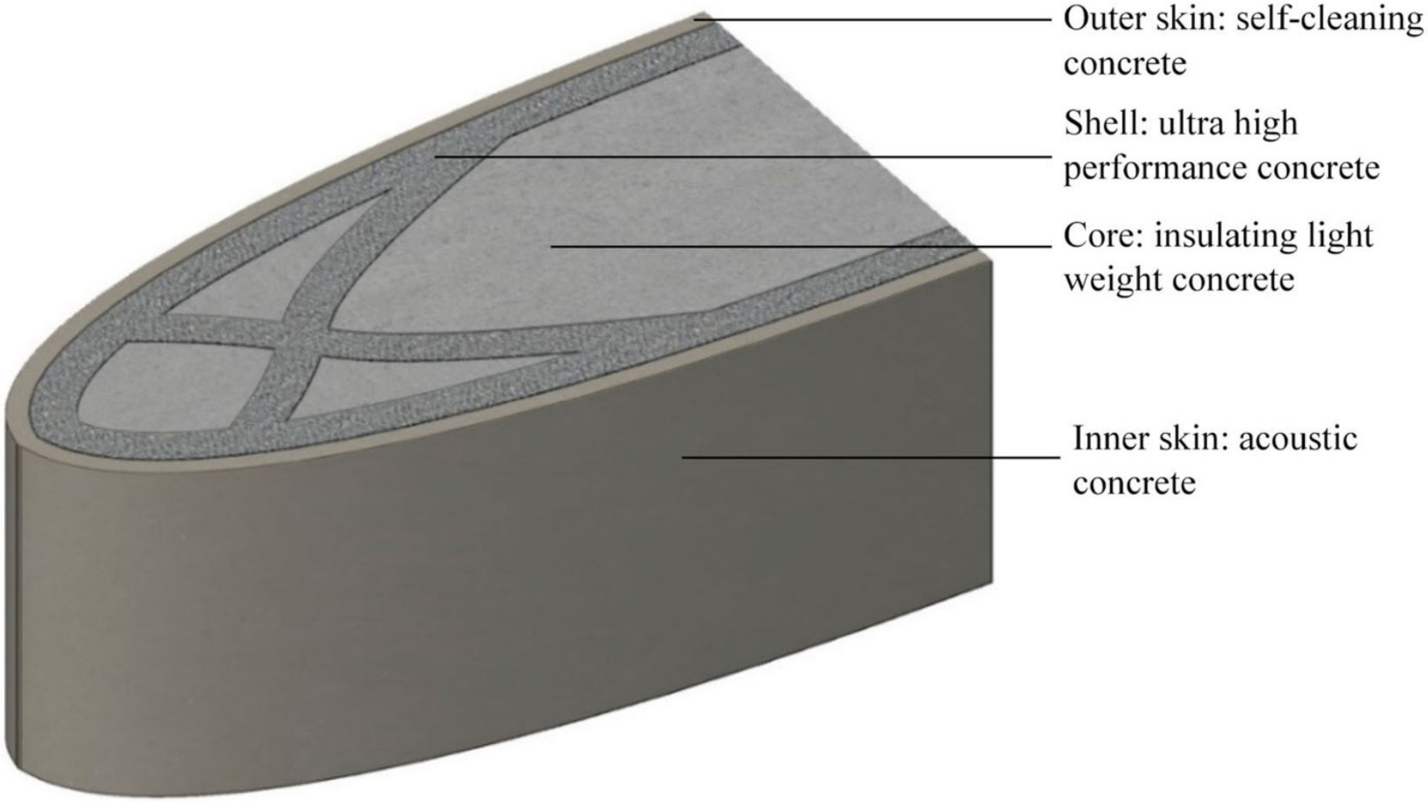
T. Wangler et al., RILEM Technical Letters (2016)

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

3D construction opportunities – complex and unique structures

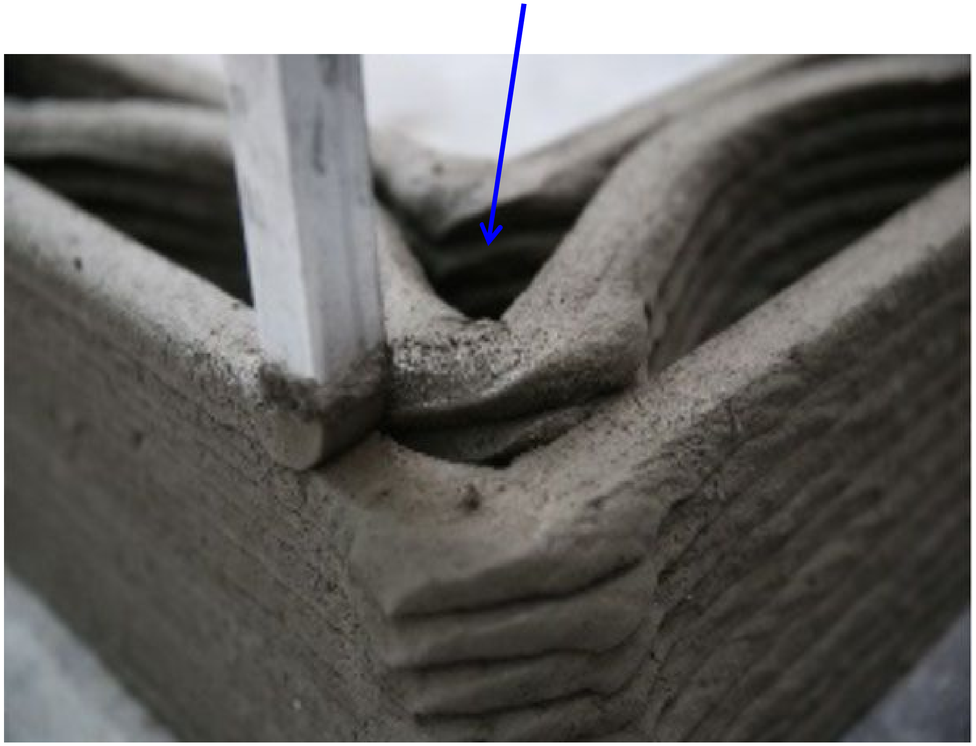


F. Boss et. al, VIRTUAL AND PHYSICAL PROTOTYPING, 2016 VOL. 11, NO. 3, 209–225

Extrusion methods

- Deposition of pre-mixed material at specified coordinates and at specified speed via a nozzle
- Contour Crafting, WinSun, Total Kustom, Apis Cor
- Concrete filaments (typical width 2 to 6 cm (0.8-2.4 in.) and a height of 1 to 4 cm (0.4-1.6 in.)
- Exterior layers often braced by interior "zig-zag" shaped connectors generating a "truss-like" structure

Printed outlines can be filled with concrete



http://www.winsun3d.com/Product/pro_inner/id/1

Extrusion methods

– Narrow filaments used to print semi-monolithic element (University of Loughborough)

Functional voids and customized, threaded rebar for post-tensioning

Lim, et al., (ISARC2011) (2011)

Example of element manufactured using fine filament ("endless loop") deposition method.

V. Mechtcherine, V. N. Nerella, *Beton- und Stahlbetonbau* 113 (2018),

Selective binding (binder jetting) method

- Single material (or mixture of several) placed on a platform (bed)
- Water (or cement paste) injected to, respectively, cement bed or aggregate bed at specified coordinates
- D-shape building process probably the most prominent example (selective binder activation)
- Offers greatest geometric freedom (suitable for creating opening, recesses, etc.)

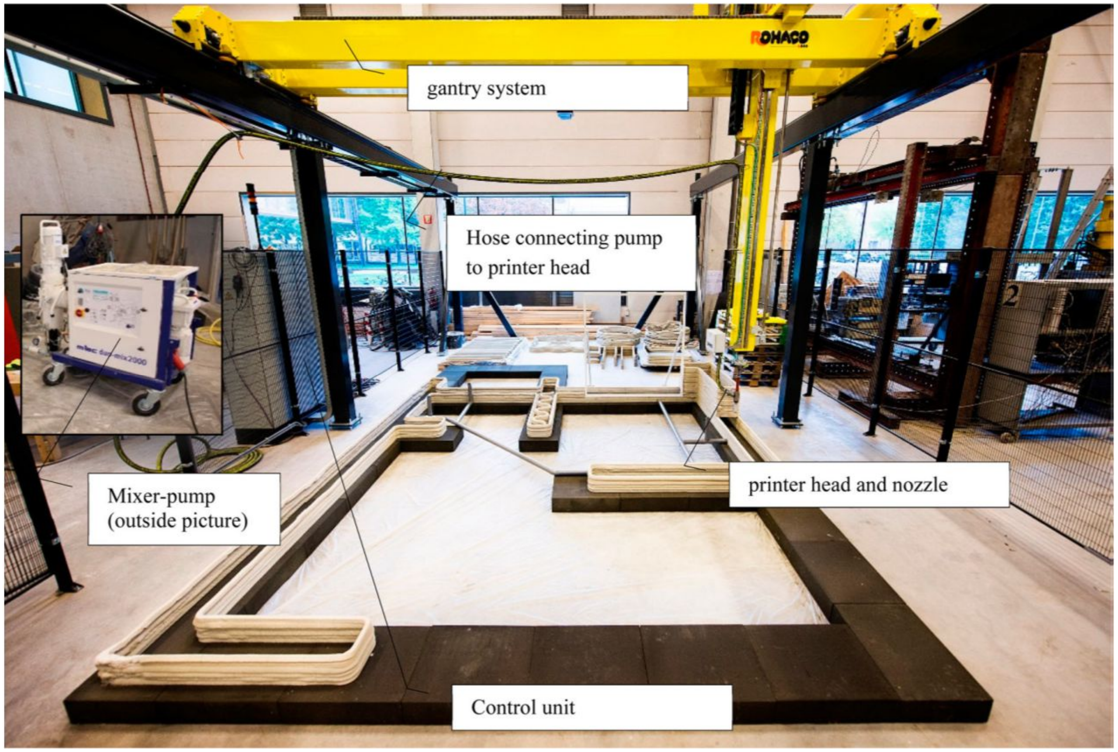
https://www.d-shape.com/wp-content/uploads/2018/02/Radiolaria-2.jpg

Adaptive slipforming methods

- Particularly suitable for production of columns and other components with relatively small cross sections
- Compared to traditional slipforming methods the formwork is much narrower and its geometry can be customized (computer controlled) during the slipforming process
- Example Smart Dynamic system (ETH Zurich)

E. Lloret et al. / Computer-Aided Design 60 (2015) 40–49

3D concrete printing systems-
gantry based system

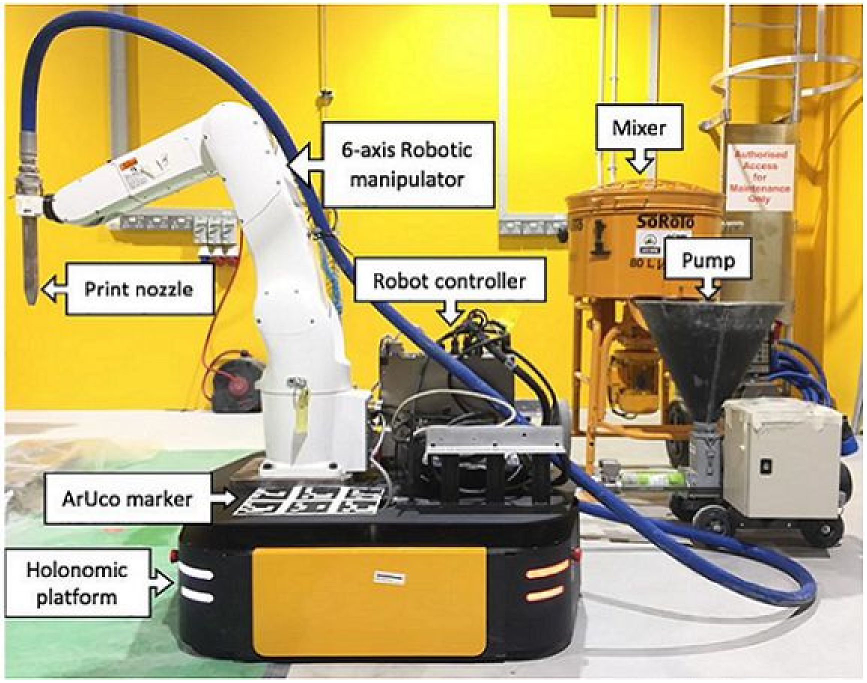


F. Boss et. al, VIRTUAL AND PHYSICAL PROTOTYPING, 2016 VOL. 11, NO. 3, 209–225

- Widely adopted
- Uses gantry to position print nozzle in XYZ Cartesian system of coordinates

3D printing Systems- robotic arm system

https://www.aniwaa.com/product/3d-printers/apis-cor-3d-printer/



https://3dprint.com/223728/mobile-robot-3d-print-construction/

- relatively new compared to the gantry systems
- provide additional roll, pitch and yaw controls to print nozzle,
- allow for smoother transition between print layers

List of extrusion–type 3D concrete printers available for sale – May 2019

PURDUE UNIVERSITY

Printer	Manufacturer	Max print size (m)	Printer Type	Price	Country
P1	BetAbram	1.6 x 8.2 x 2.5	Gantry	>$250,000	Slovenia
BOD2	COBOD	12 x 45 x 9	Gantry	>$250,000	Denmark
3D Constructor	MACHINES-3D	13 x 13 x 3.8	Robotic arm	$462,008	France
CyBeR 3Dp	CyBe Construction	2.75 x 2.75 x 2.75	Robotic arm	>$200,000	Netherlands
Vulcan II	ICON	2.6 x 8.5 x ∞	Gantry		USA
StroyBot 6.2	Total Kustom	10 x 15 x 6	Gantry		USA
BigDelta WASP 12m	WASP Crane	Ø 6.3 x 3	Delta system	$100,000 - $250,000	Italy

1 m = 3.28 ft

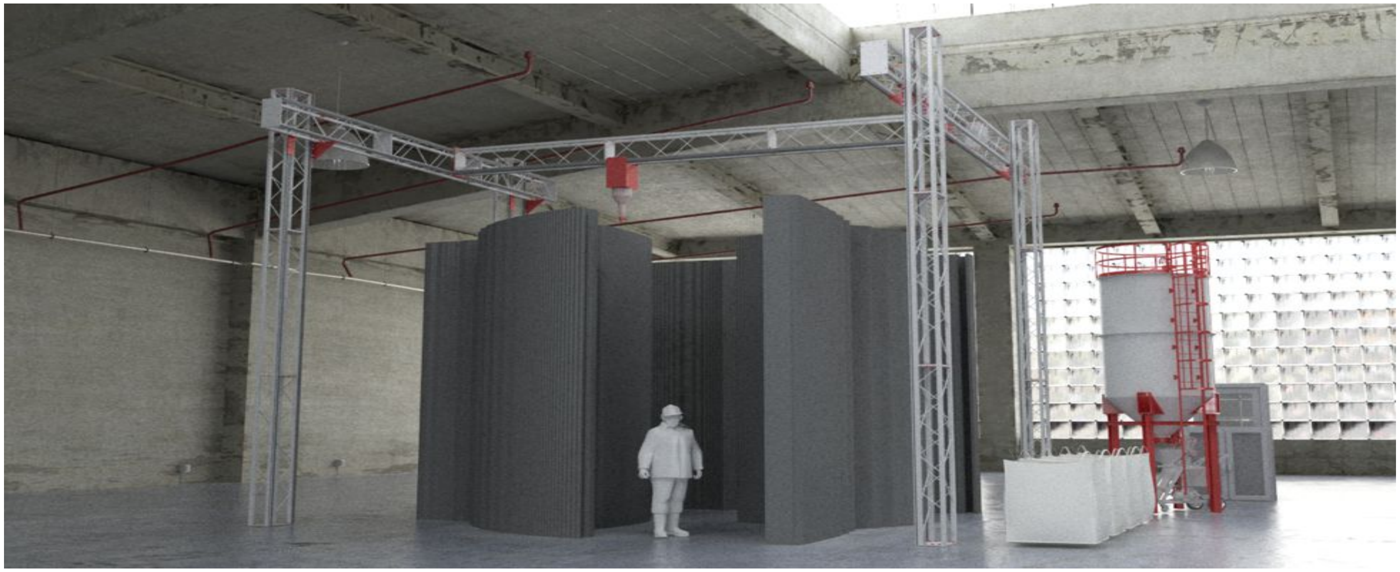
https://www.aniwaa.com/ Accessed May 2019

P1 printer

3D CONSTRUCTOR printer

https://www.aniwaa.com/

BOD 2 - a modular, gantry based 3D construction printer



https://cobod.com/bod2-specifications/

BOD 2 - a modular, gantry based 3D construction printer

Tangential rotation control

https://cobod.com/bod2-specifications/

CyBe RC 3Dp printer

https://www.3dnatives.com/en/3d-printed-house-companies-120220184/

PURDUE UNIVERSITY

ICON Vulcan II printer

Total Kustom Stroybot2 printer

https://www.aniwaa.com/

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WASP construction printer

https://www.aniwaa.com/

WASP BigDeltaWASP 12m

https://www.aniwaa.com/product/3d-printers/wasp-bigdeltawasp-12m/

D-Shape printer

PURDUE UNIVERSITY

https://www.3dnatives.com/en/3d-printed-house-companies-120220184/

3D concrete printer in operation. No-slump concrete leaves the nozzle as a relatively stiff continuous filament

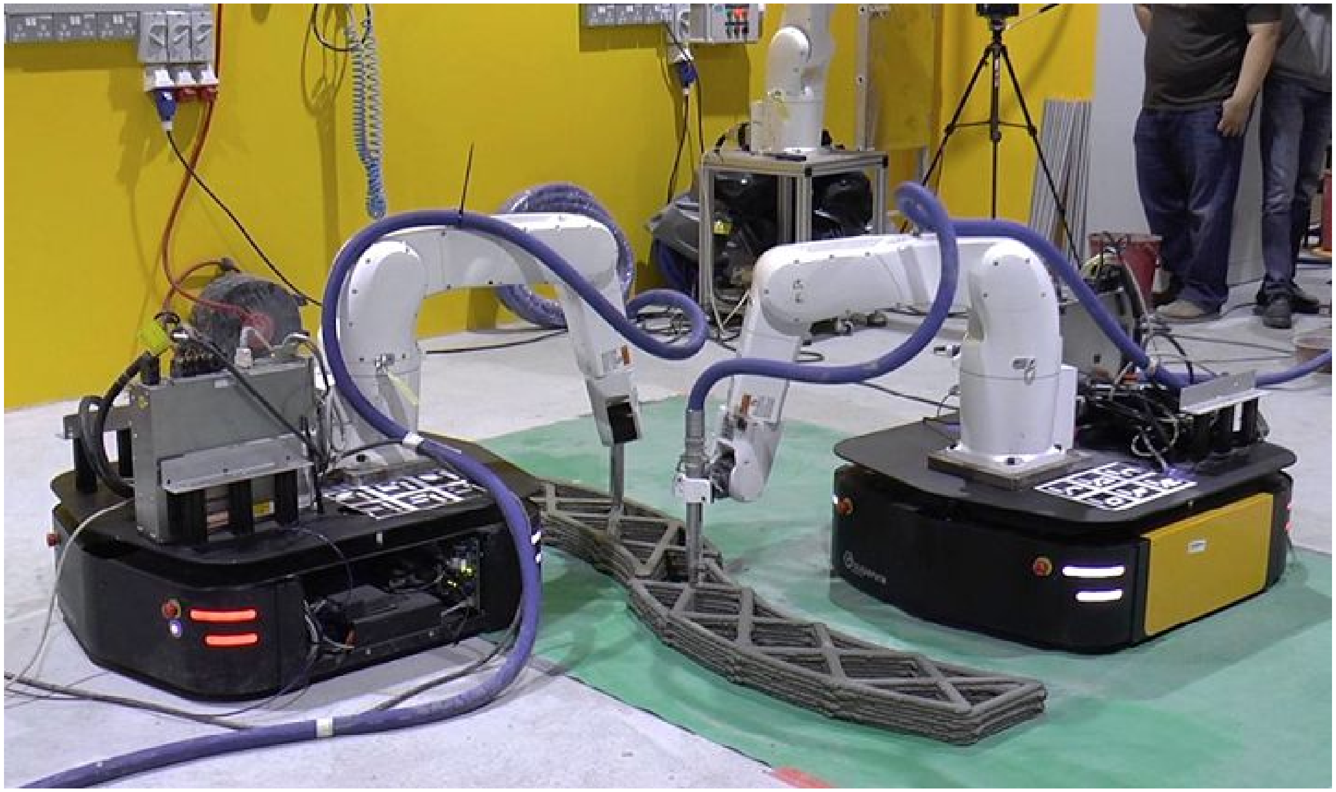
Twisting of filament.

F. Boss et. al, VIRTUAL AND PHYSICAL PROTOTYPING, 2016 VOL. 11, NO. 3, 209–225

3D printing Systems - Limitations

- Lack of scalability
  - Both, gantry-based and robotic arm systems require elaborate (and massive) external framework to control the single print nozzle
  - Limited efficiency of the printer (print space dominated by the single nozzle)

3D printing Systems- Two-robots printing system

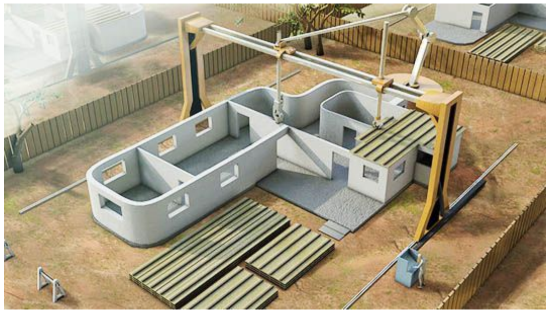


X. Zhang et al. Automation in Construction 95 (2018) 98–106

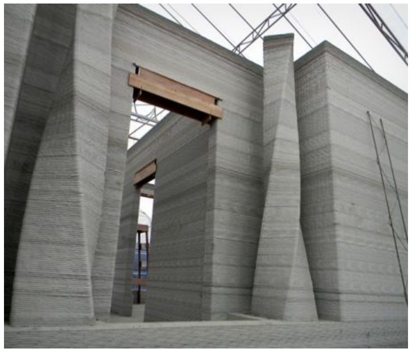
Present State of 3D Construction Printing

Several companies with “showcase-type” developments

- 3D Printhuset (COBOD)-DK
- Contour Crafting-USA
- Smart Dynamic Casting-CH
- Xtree-FR
- Apis Cor -RU
- Total Kustom-USA
- WinSun-CN
- D-Shape-IT
- WASP-IT
- ICON-USA
- CyBe-NL

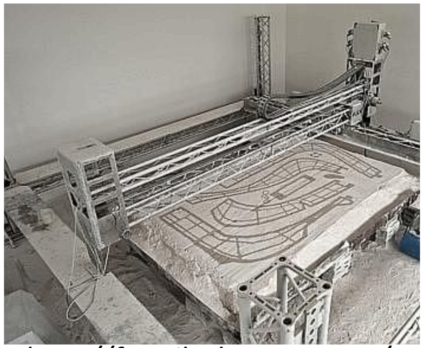


http://contourcrafting.com/building-construction/



http://www.totalkustom.com/

http://www.officeofthefuture.ae/#



http://foto.ilsole24ore.com/

Present State of 3D Construction Printing

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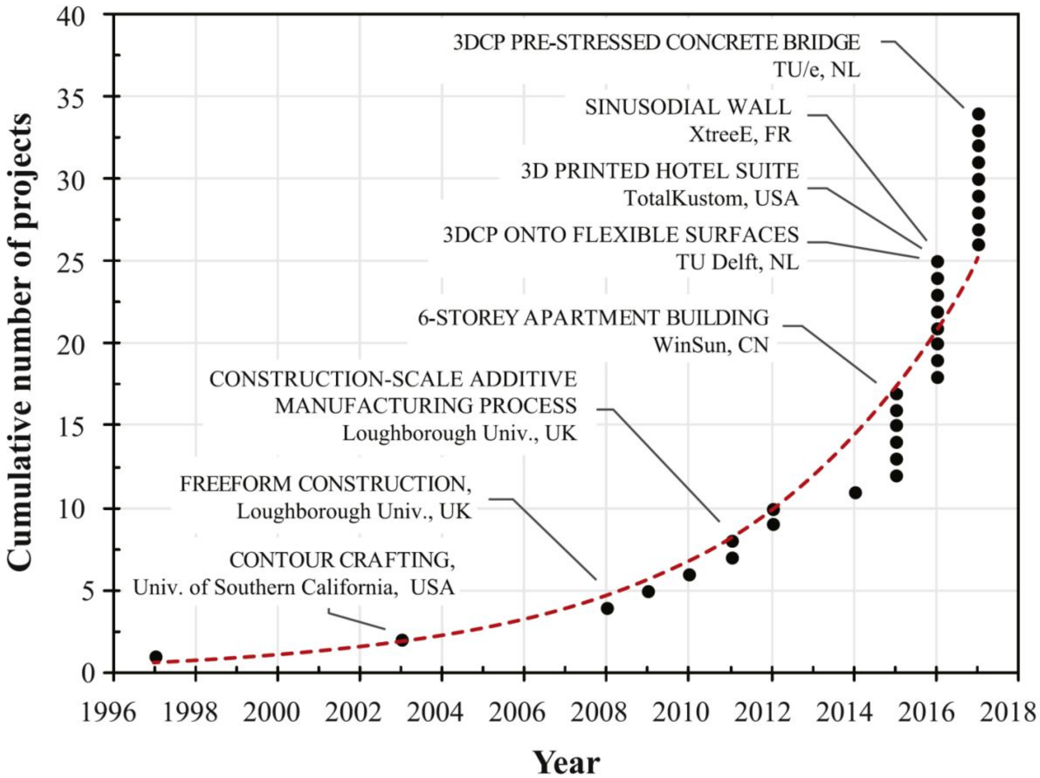


R.A. Buswell et al. Cement and Concrete Research 112 (2018) 37–49

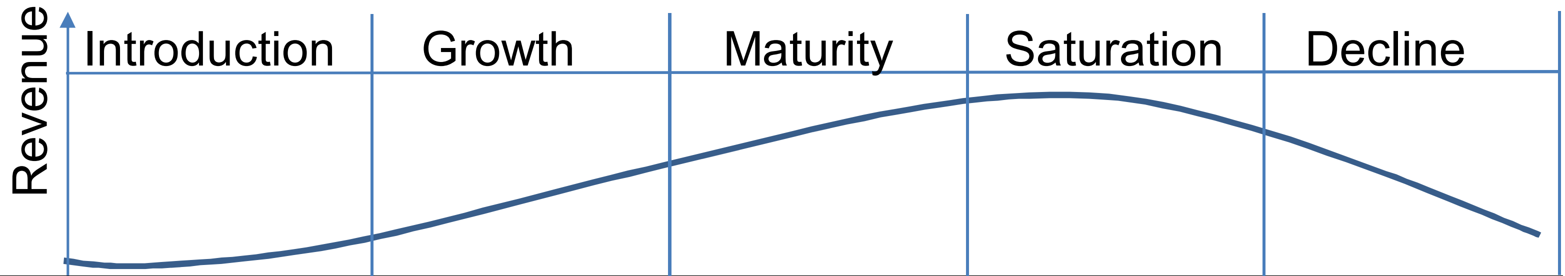
Interest in future development of 3D printing

Recent investments in start-ups and own developments

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

Stages of Product (Sector) Life Cycle

PURDUE UNIVERSITY



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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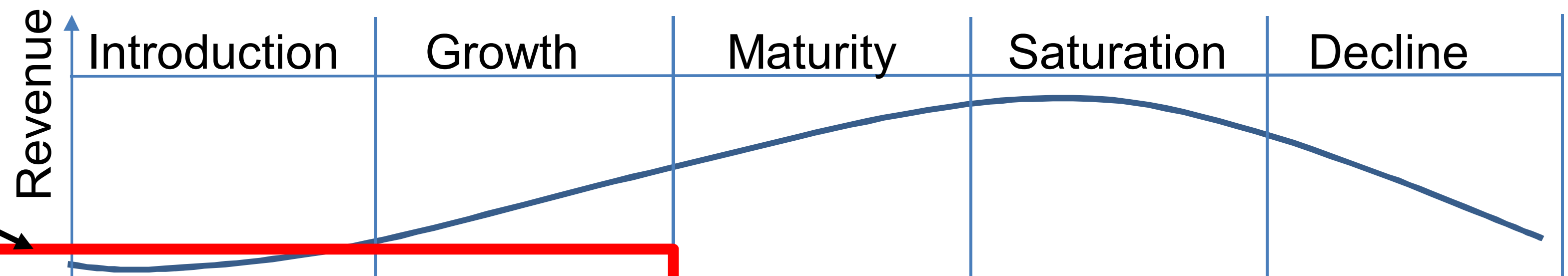
Now Early Exploration /Adoption



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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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- The 3D printed house produced by Winsun in in Shanghai, China.
- Printed parts shipped to Dubai and assembled
- Reported to have reduced labor costs by 50 to 80 percent and construction waste by 30 to 60 percent

https://all3dp.com/1/3d-printed-house-homes-buildings-3d-printing-construction/

Present State of 3D Construction Printing

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a) 2-story house in China by HuaShang Tengda (b) Office building in Dubai by WinSun,

(c) 5-story building in Suzhou, China, by Winsun, (d) Hotel suite interior in the Philippines, by Total Kustom, (e) Villa in Suzhou by WinSun, (f) Castle in Minnesota, USA, by Total Kustom, (g) series of 10 houses in Suzhou, by WinSun.

F. Boss et. al, VIRTUAL AND PHYSICAL PROTOTYPING, 2016 VOL. 11, NO. 3, 209–225

Present State of 3D Construction Printing

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The "Building on Demand" (BOD) is a small 3D printed office building of less than 50 square meters located in Copenhagen's Nordhavn.

https://cobod.com/the-bod/#iLightbox[ddfa26b16352f739cb1]/8

Present State of 3D Construction Printing

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- Icon's "Vulcan" prototype in Austin, TX
- The first 3D-printed house in the U.S. permitted under local building codes.

https://www.citylab.com/design/2019/02/architecture-construction-3d-printing-technology-netherlands/582334/

Present State of 3D Construction Printing

3D Printed Pedestrian Bridge in Madrid (micro reinforced concrete)

six segments produced by the D-shape process (selective binder activation method) and held together by posttensioned reinforcement.

https://all3dp.com/3d-printed-pedestrian-bridge/

Present State of 3D Construction Printing

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- Prototype 3D printed hause in Nantes, France (2018)
- Constructed in a collaborative effort involving the University of Nantes, the city council and a construction company

- Area: 1022 square ft. (4 bedrooms plus central living area
- Priming time: 54 hrs
- Cost: ~239,000 (about 20% less than traditionally constructed house)
- Occupied by 5 people (2 adults and 3 children)

https://www.bbc.com/news/technology-44709534

Present State of 3D Construction Printing

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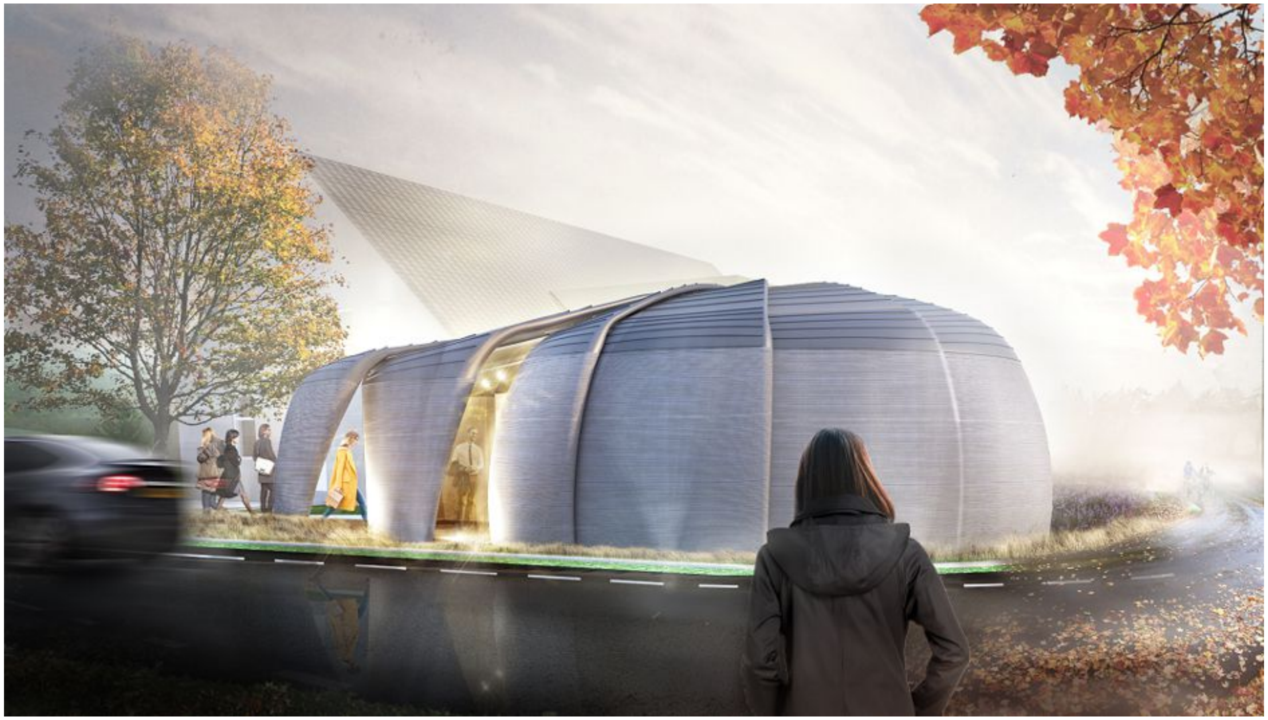
https://www.bbc.com/news/technology-44709534

https://www.3dnatives.com/en/3d-printed-house-companies-120220184/

Present State of 3D Construction Printing



A rendering of De Vergaderfabriek ("the Meeting Factory"); scaled-down version was constructed in the village of Teugen in the Netherlands.

https://www.citylab.com/design/2019/02/architecture-construction-3d-printing-technology-netherlands/582334/

Present State of 3D Construction Printing

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Curved wall section of the "Meeting Factory"

https://3dprint.com/242575/cybe-construction-3d-printing-small-meeting-structure-in-amsterdam-several-follow-eindhoven/

Present State of 3D Construction Printing

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The 512 square feet 3D printed barracks hut (B-Hut), Construction Engineering Research Laboratory (CERL) , ERDC, US Army, Champaign, IL

ERDC established a Cooperative Research and Development Agreement with Caterpillar Inc. to explore commercialization of the technology, with the potential application for disaster relief operations and conventional construction.

https://www.erdc.usace.army.mil/Media/News-Stories/Article/1281737/3-d-printing-a-building/

Present State of 3D Construction Printing

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A rendering of houses for 3D printed village.

- The printing will be done on site and is to begin in summer 2019
- Estimated print time - roughly 24 hours per house

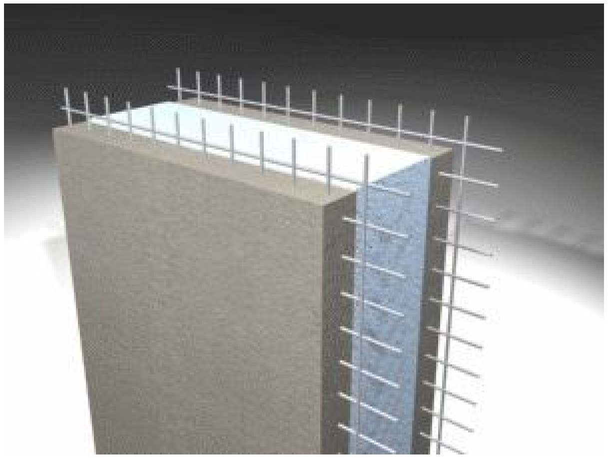
The New York Times – May 7, 2019

3D printed village

- Joint project of Fuseproject, New Story (a nonprofit) and ICON (a construction technologies company)
- Expected to build 50 houses for a community of farmers and weavers in Latin America (the exact location is not being disclosed until the construction phase).

Present State of 3D Construction Printing

- In January 2019, two companies announced a 3D-printed homebuilding system called We Print Houses, which they intend to license to builders and contractors around the U.S.
- Based on spraying concrete on the SCIT panels (a structural concrete-insulated panels- permitted under the building code)
- Promise 7-14 days print time



https://www.sipcrete.com/gallery/

Present State of 3D Construction Printing

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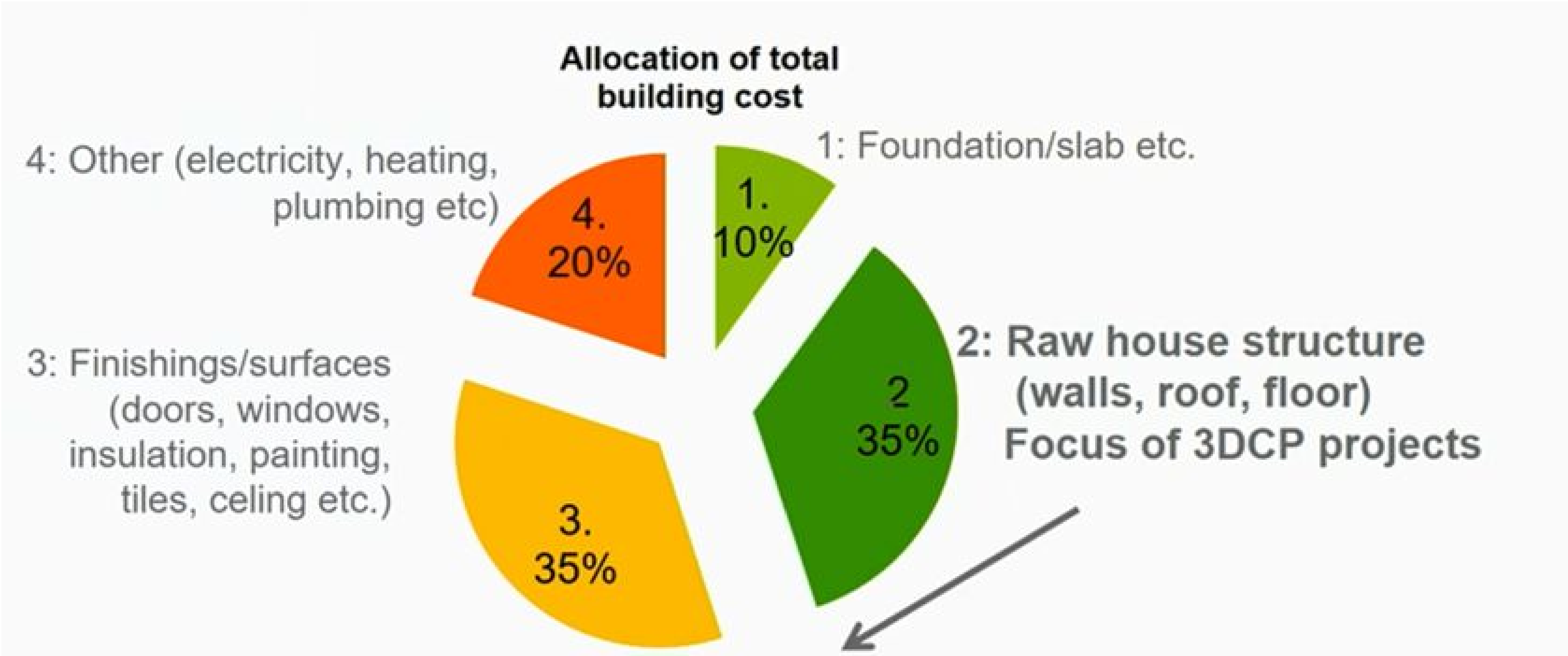
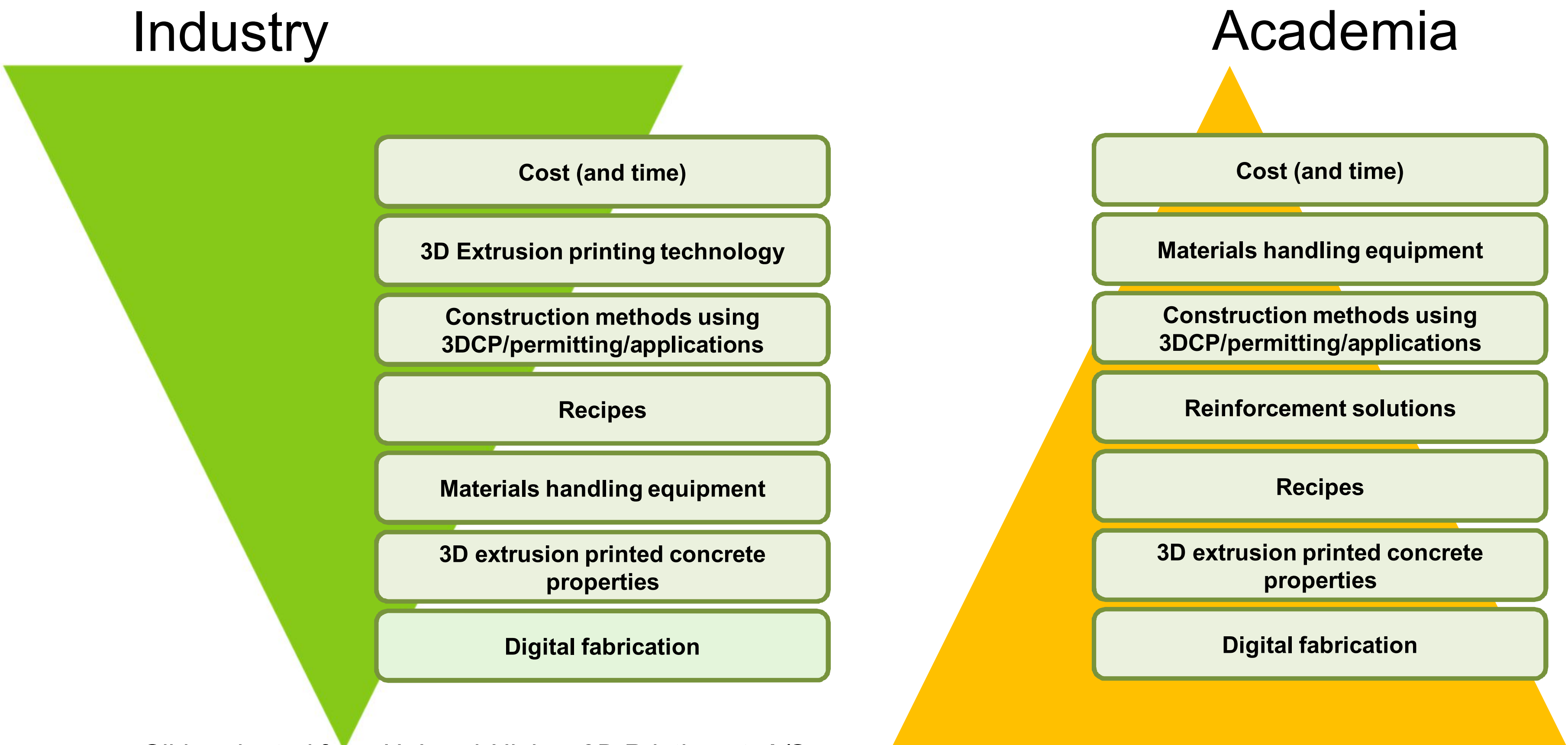


Some items still not addresses (reinforcement, roof)

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

The general focus areas



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

Some of the missing pieces………

- Compliance with the building codes
- Development of the process for optimization of the ink (cementitious material)
- 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

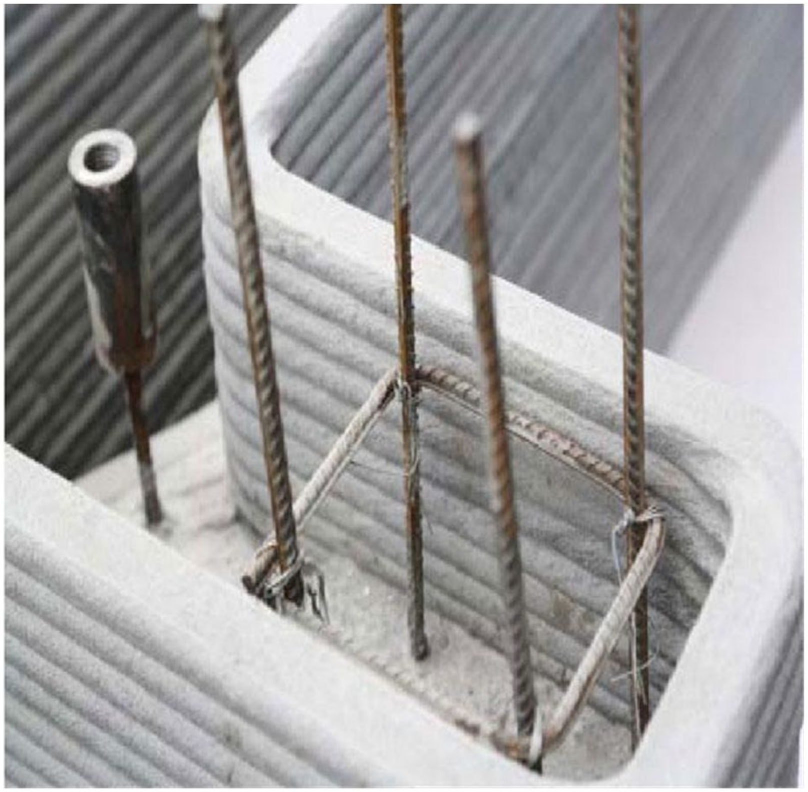
Printable cementitious materials

- Competing requirements
  - **Pumpability** (concrete needs to be flowable and have low plastic viscosity and yield stress) vs. **Buildability** (concrete should be much less flowable and have much higher yield stress and plastic viscosity)
  - **Rate of printing (***slow* enough for layers achieve adequate "green" strength but *fast* enough to achieve proper bond between layers and to make the process economically viable)

Printable cementitious materials

- Optimization of concrete properties
  - Understanding of the influence of constituent materials and process parameters on the following material properties
    - Slump and consistency retention
    - Pumpability
    - Extrudability and buildability
    - Setting time and temperature development
    - Compressive, tensile and flexural strengths in directions perpendicular and parallel to interfaces

Reinforcement

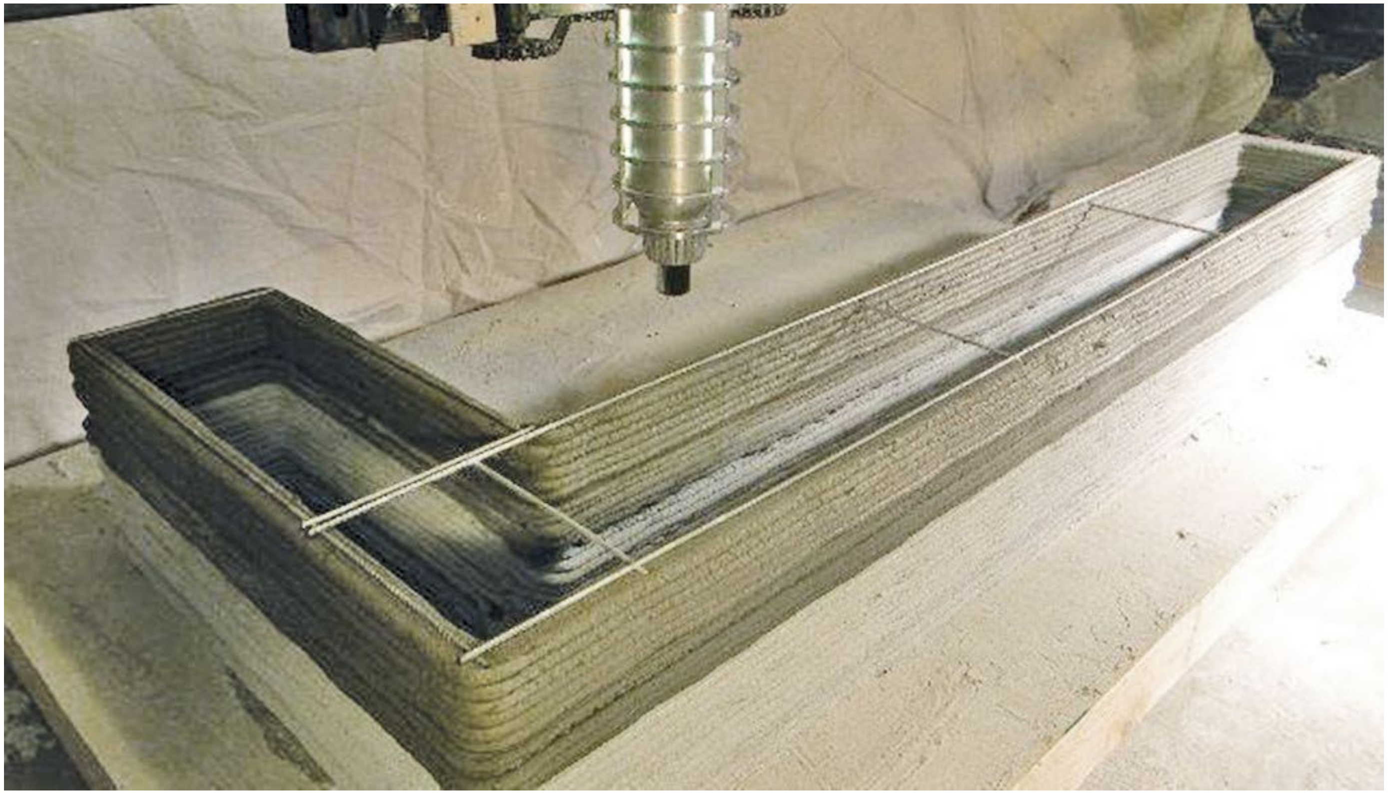


https://3dprint.com/38144/3d-printed-apartment-building/

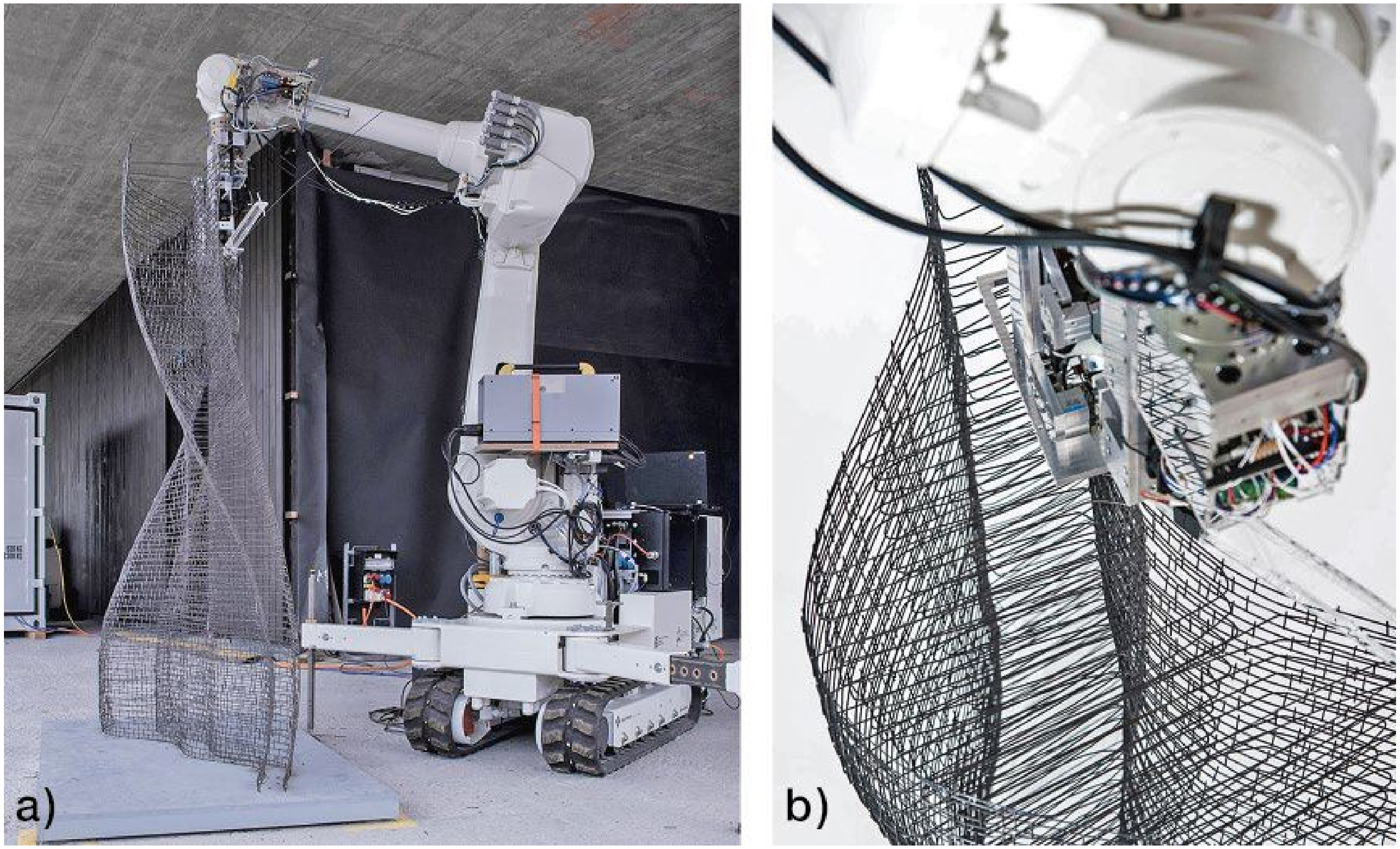
- Integration of conventional steel reinforcement in cavities of printed elements

Reinforcement

- Placement of the horizontal conventional steel reinforcement between the layers of printed concrete



V. Mechtcherine, V. N. Nerella, *Beton- und Stahlbetonbau* 113 (2018),



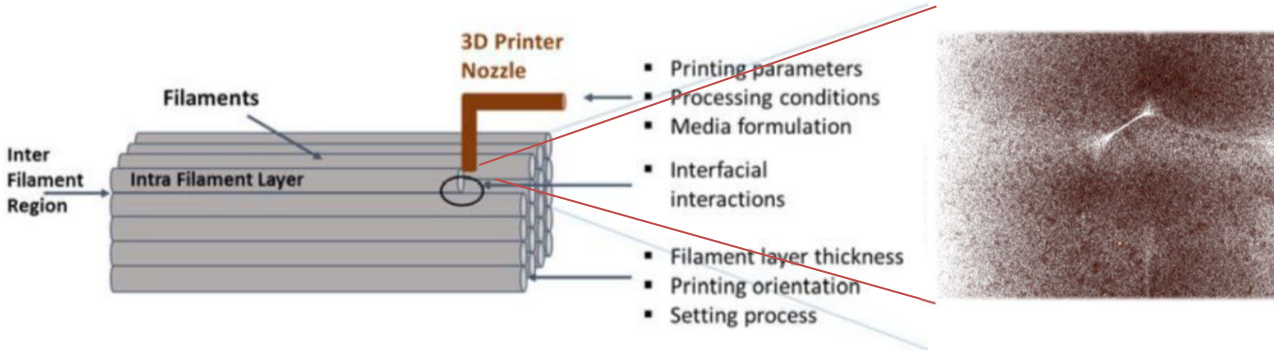
a) Robot-assembled (by pulling, bending, cutting and welding of a wire) reinforcement for a double curved wall, b) detail view of the “printhead”. Source: ETH Zurich

V. Mechtcherine, V. N. Nerella*, Beton- und Stahlbetonbau* 113 (2018),

- Forked nozzle developed by HuaShang Tengda Ltd.
- Simultaneous deposition of concrete on both sides of the rebars

V. Mechtcherine, V. N. Nerella, *Beton- und Stahlbetonbau* 113 (2018),

Role of interfaces

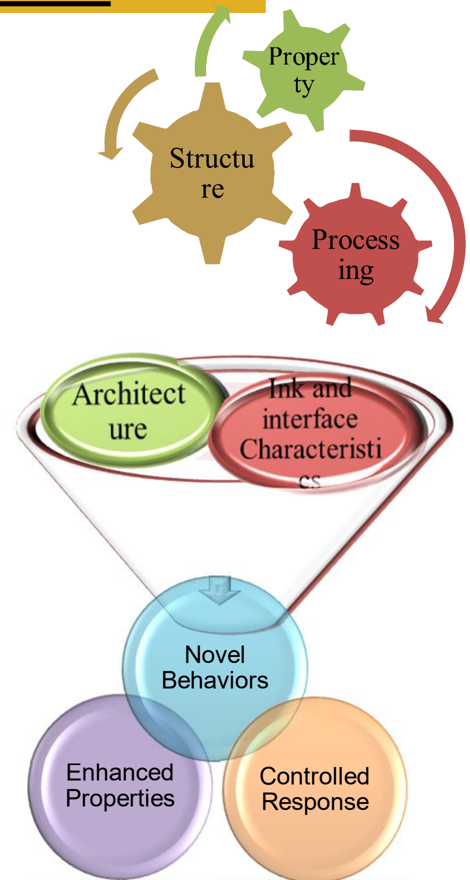


http://www.renca.org/

- 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

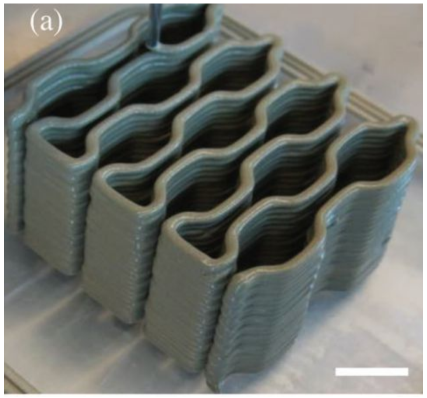
The appeal of 3D printing in Cementitious Materials– Control of Architecture, Microstructure, and Mechanical Response

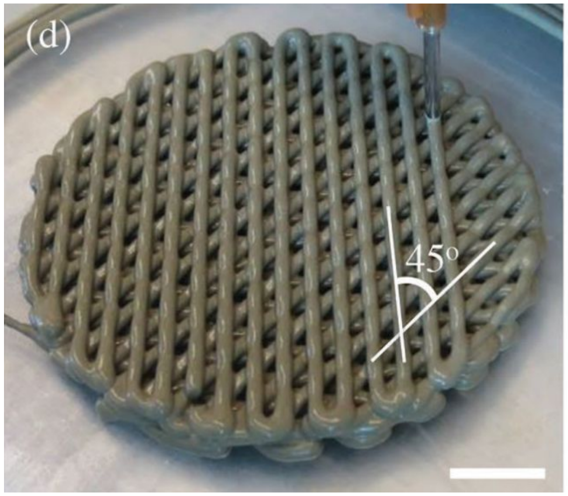
- Facilitates exploration of the intertwined relationships between: Processing-Structure-Property-Performance
- Allows for creation novel designs to achieve enhanced performance characteristics in printed elements (architectured cement based materials)
- Creates possibility of combining the effects of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

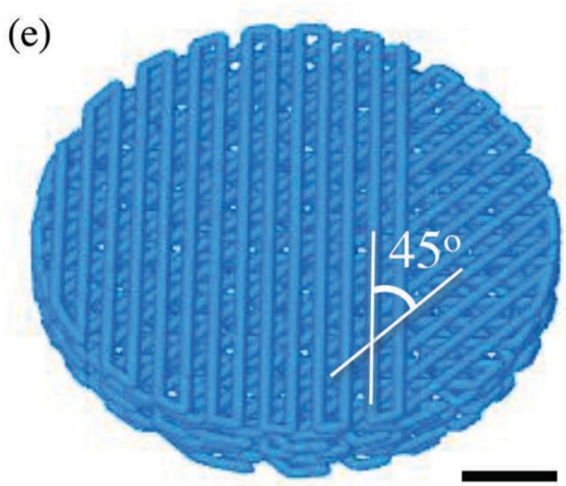


Presence of "weak interfaces" enhances performance of architectured cement-based materials:

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



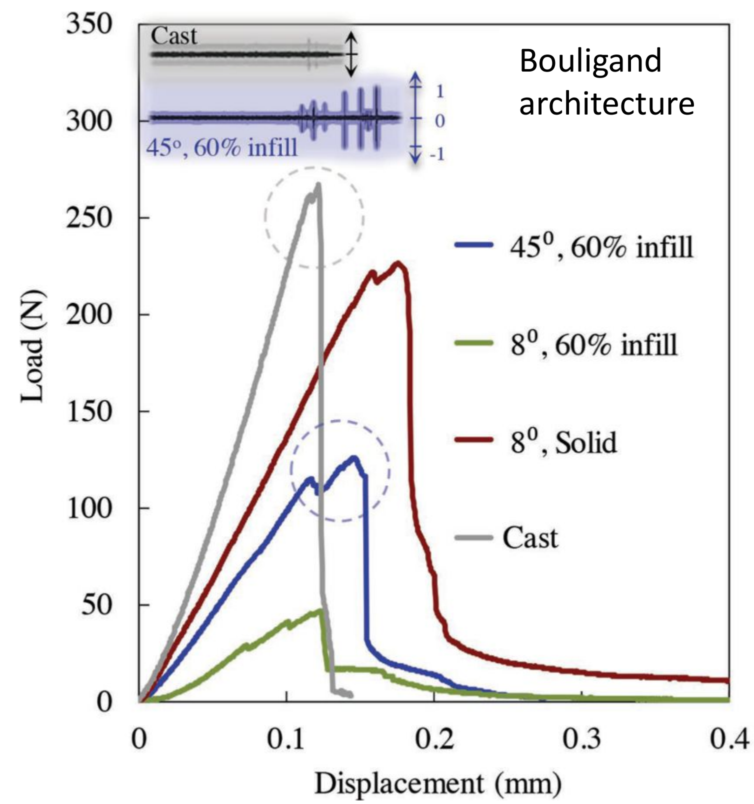




Moini et. al., *Adv. Mater. 2018*

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

- Combined effects of <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)

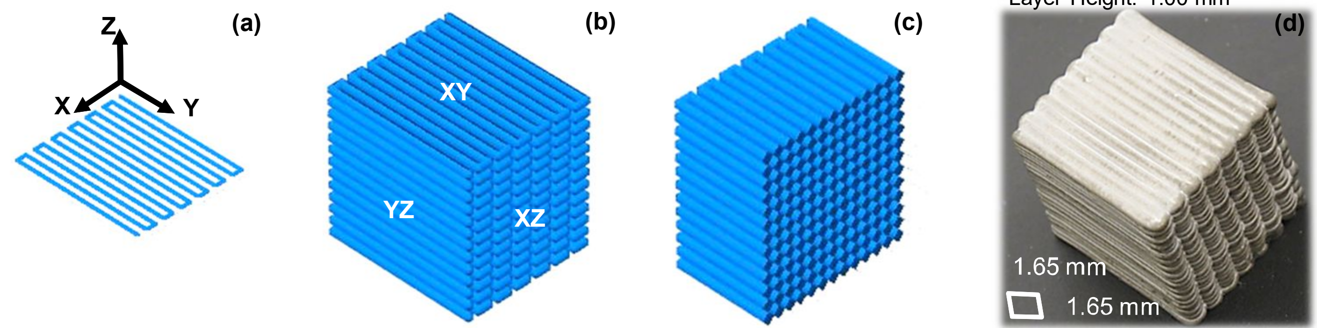


Moini et. al., Adv. Mater. 2018

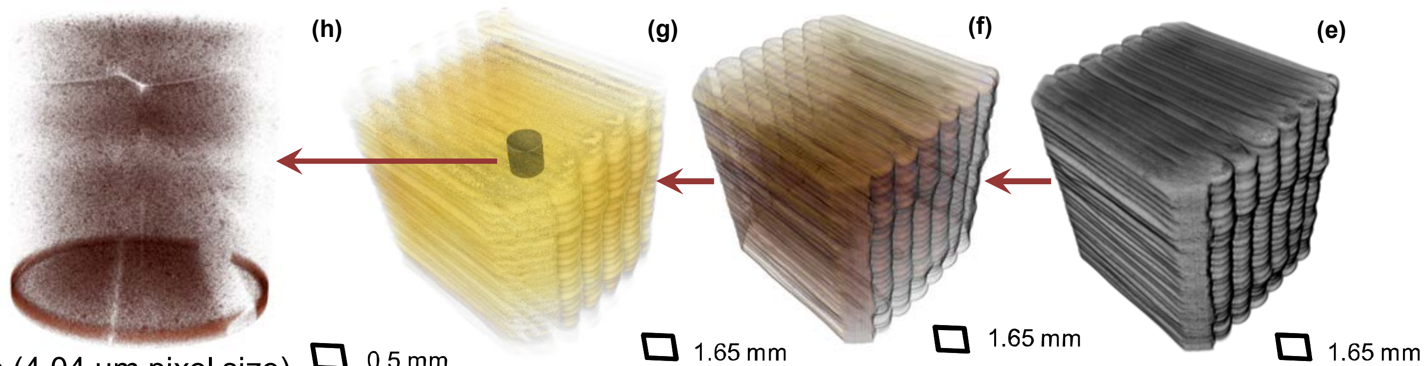
Characterization of the Interfaces:
Differences between “Core” vs. “Interfacial Regions (IRs)” of the filaments

Design of elements with lamellar (layered) architecture:

Nozzle Dia.: 1.36 mm
Layer Height: 1.00 mm



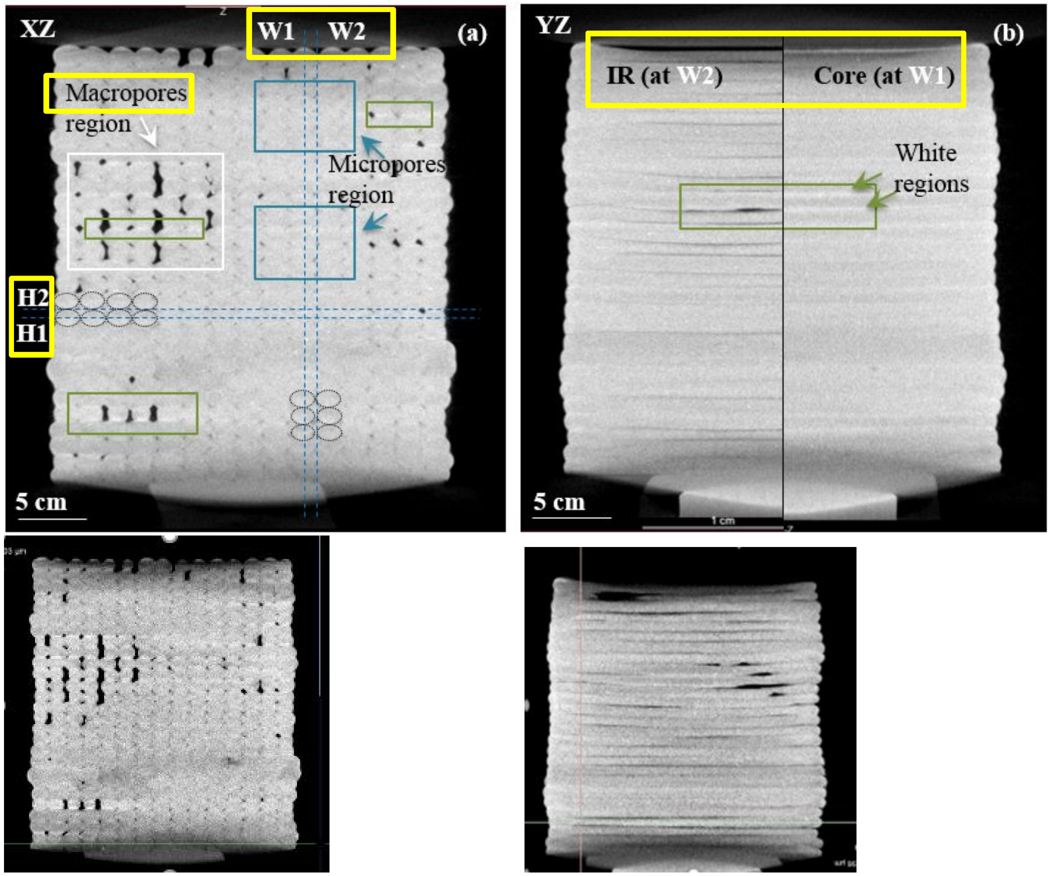
Micro-CT characterization at 2 magnifications (0.4X and 4X scans) – study of the processing-induced heterogeneities



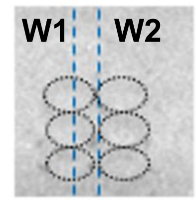
4X scan (4.04 μm pixel size)

0.4X scan (32.26 μm pixel size)

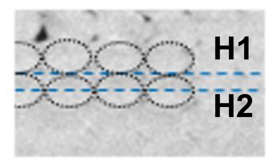
Microstructural Features: Macro- and Micro-Pores at IRs – 0.4X Scan

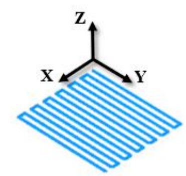


- Macro-Pores at vertical planes

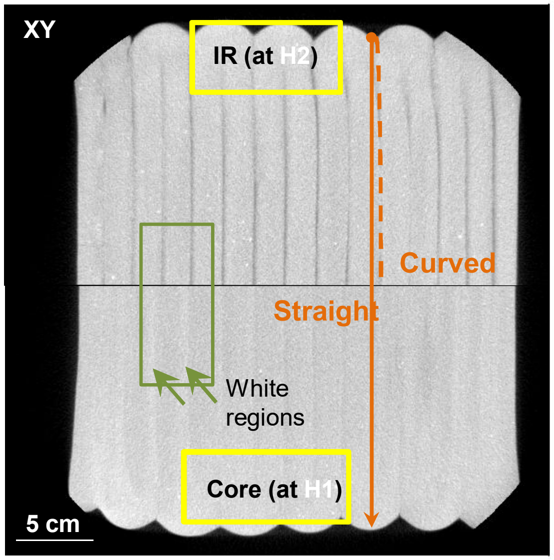


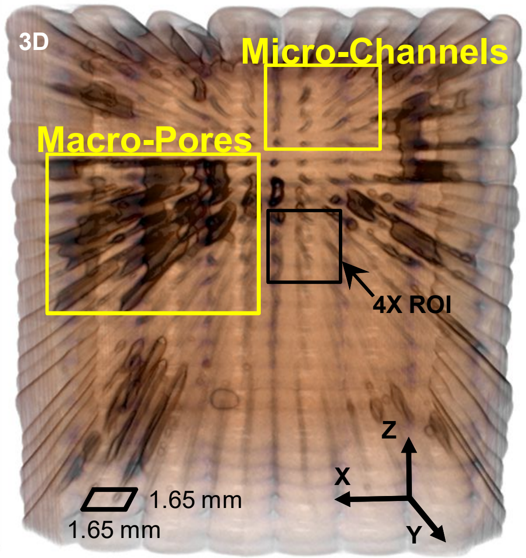
- Micro-Pores at vertical and horizontal planes



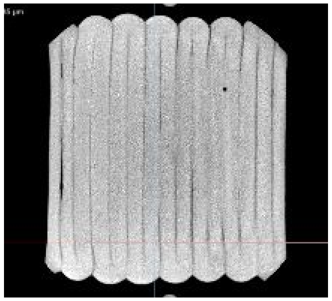


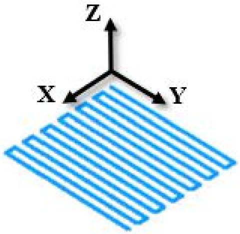
Microstructural Features: Core vs. IRs – 0.4X scan





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





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

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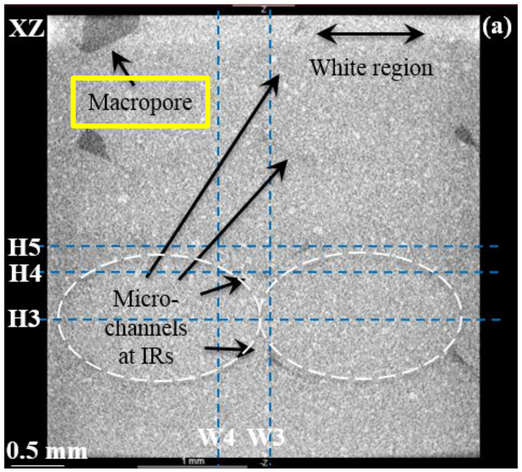
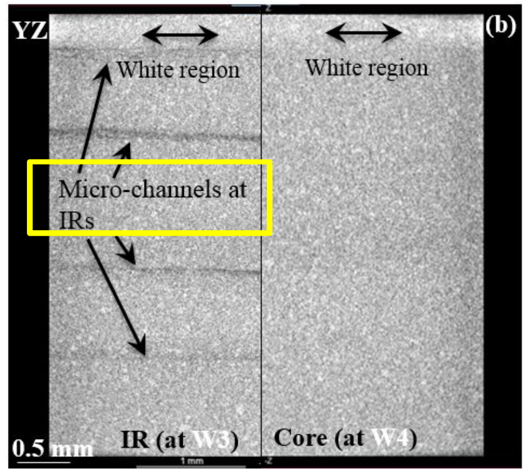
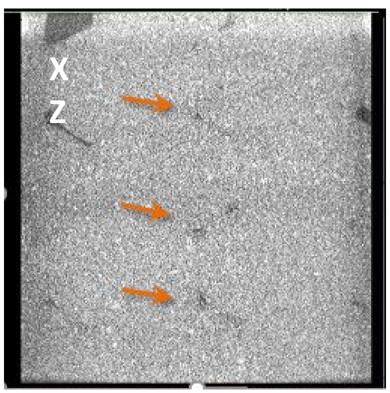
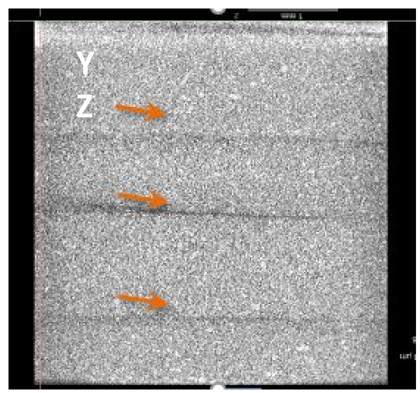
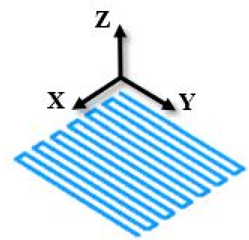




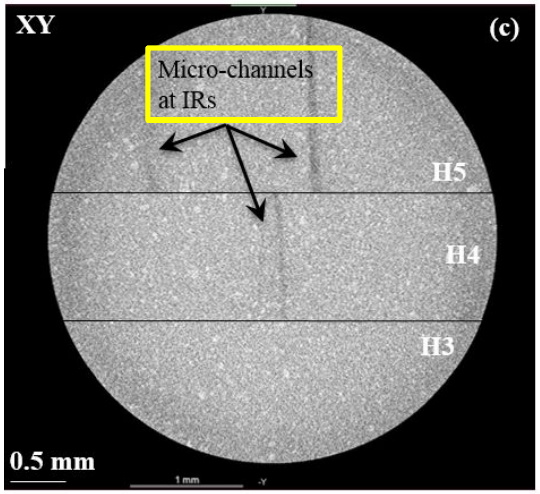
- White Regions accumulation of unhydrated grains near the pores
- Micro-Channels along filaments

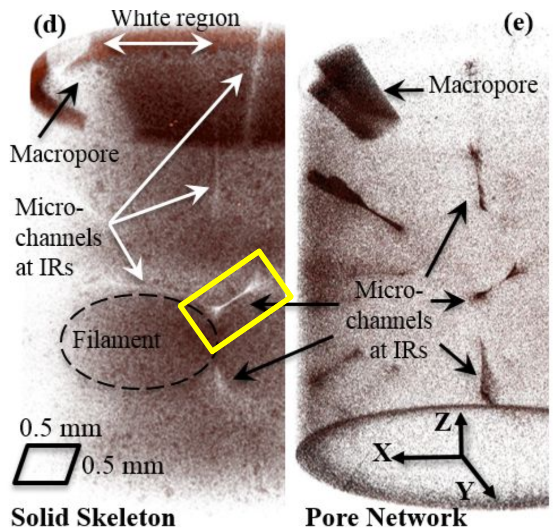


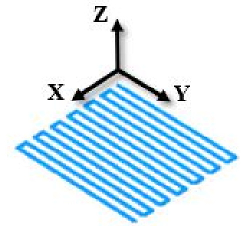




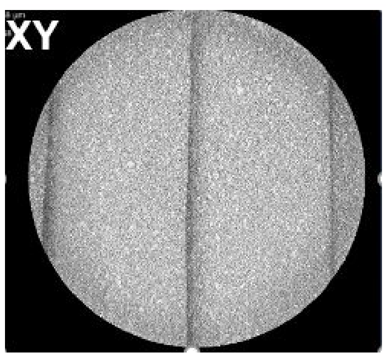
Microstructural Features: <u>Micro-Channels</u> and <u>Re-arrangement</u> – 4X Scan

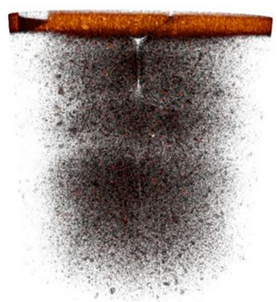


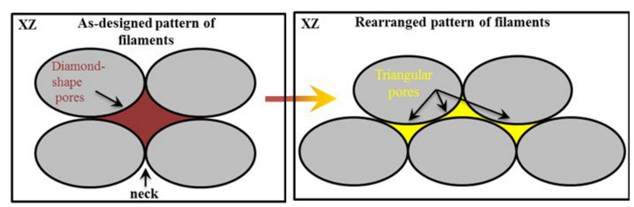




- <u>Filaments shift</u> formation of triangular micro-channels

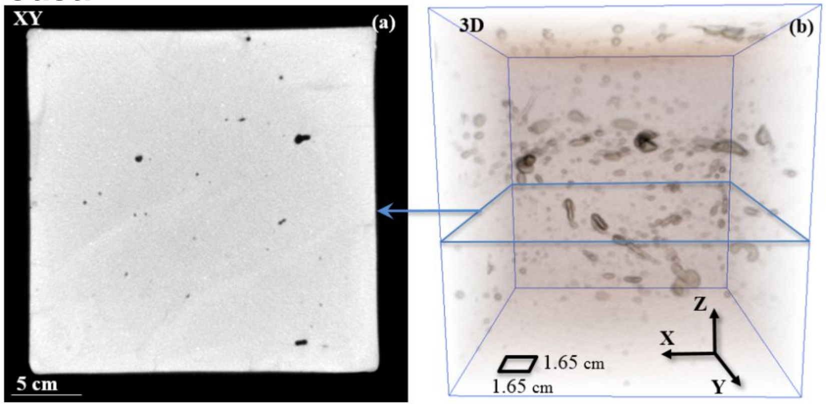






How about the cast specimen?

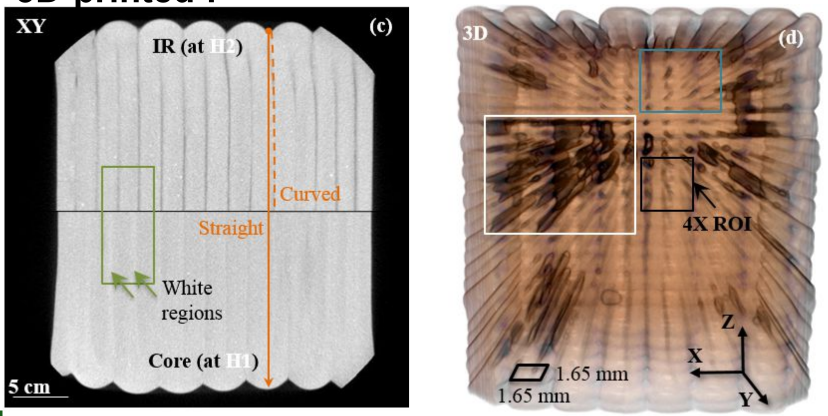
Cast:



- <u>Cast</u>

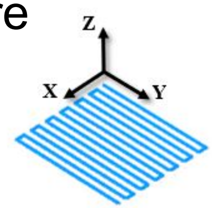
  Randomly Distributed Pores

3D-printed :

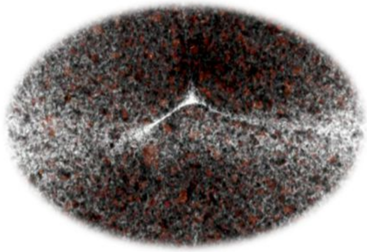


- <u>3D-printed layered specimen</u>

  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.

3D Printed Structures: Vision and Opportunities - Summary

- 3D printing of concrete – developing but promising technology
- Particularly useful for manufacturing geometrically complex components
- Real potential for reduced construction times, decreased power consumption, and reduced construction waste
  - Important due to global increase in urbanization and industrialization activities (issues with waste disposal, timelines of construction)
  - Prospect for optimization and flexibility in design
  - Consistency in quality
- May help to address the demand for fast-paced building construction in the developing countries (affordable housing, local and eco-friendly materials)
- Initially probably mostly used in residential construction

3D Printed Structures:
Vision and Opportunities - Summary

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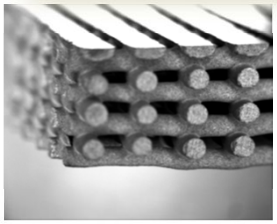
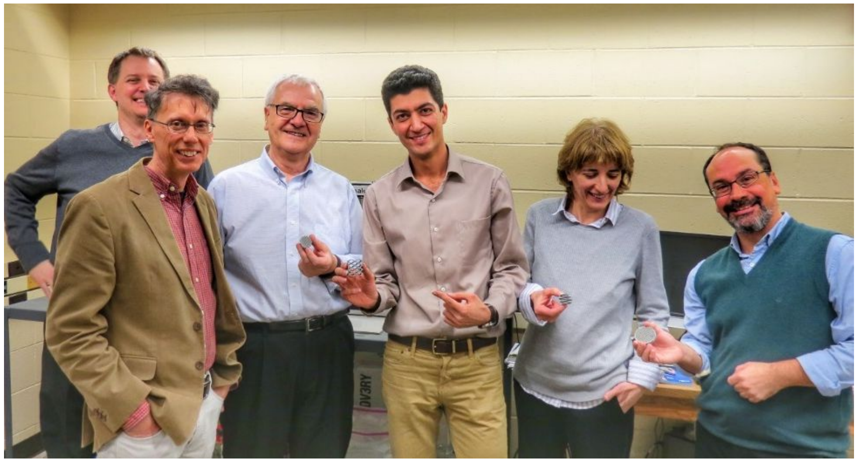
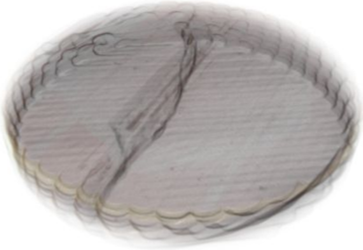
- Existing challenges
  - Initial capital investment quite high
  - Absence of skilled workforce
  - Lack of design, construction and quality control standards
  - Lack of methodology for optimized usage in construction sector
  - Integration with other components of the structure
  - Printable materials (material behavior)
  - Max. printing height/total object size
  - Robotic path generation
  - Large extrusion systems
  - Reinforcement
  - Durability

Acknowledgment

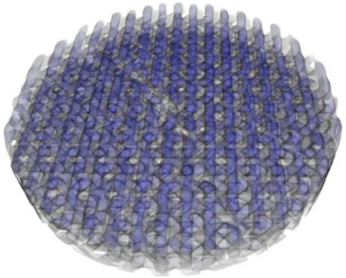


Support:
NSF CMMI 1562927
Purdue School of Civil Engineering
Purdue College of Engineering





Jeff Youngblood (Purdue), Joe Biernacki (Tenneesee Tech), Jan Olek (Purdue) M. Reza Moini (PhD student, Purdue), Florence Sanchez (Vanderbilt), Pablo Zavattieri (Purdue)



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Thank you!

Questions?