ICC LEARN LIVE

Innovation in 3D Printing

Mahmut Ekenel, Ph.D., P.E., FACI (ICC-ES)

Behrokh Khoshnevis, Ph.D. (Contour Crafting)

Babak Zareiyan, Ph.D. (Contour Crafting)

ICC EVALUATION SERVICE®

Mahmut Ekenel, Ph.D., P.E., FACI

Mahmut Ekenel, Ph.D., PE, FACI is a Senior Staff Engineer at ICC Evaluation Service with 15 years' experience. He received his MS in Civil Engineering from Southern Illinois University, and his PhD in Civil Engineering from Missouri S&T University, where he also worked as a Postdoctoral Researcher.

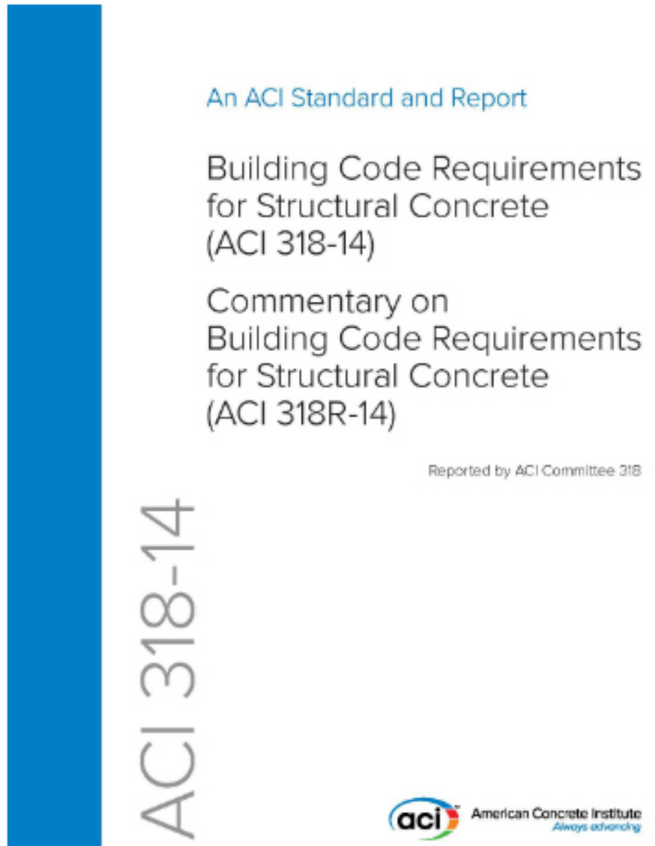
His research interests include fiber-reinforced composite strengthening of structures, fiber-reinforced concrete, concrete mixture optimization, and anchorage to concrete.

He is a registered Civil Engineer in California and Ohio.

The Building Codes

The *International Building Code* (IBC) is the predominant model building code in the U.S.A for new buildings. The IBC is used in all 50 states, Washington D.C., State Departments and all U.S. territories.

The Building Codes



The IBC addresses use of structural concrete in Chapter 19. The primary reference document in Chapter 19 of 2018 IBC is ACI 318-2014.

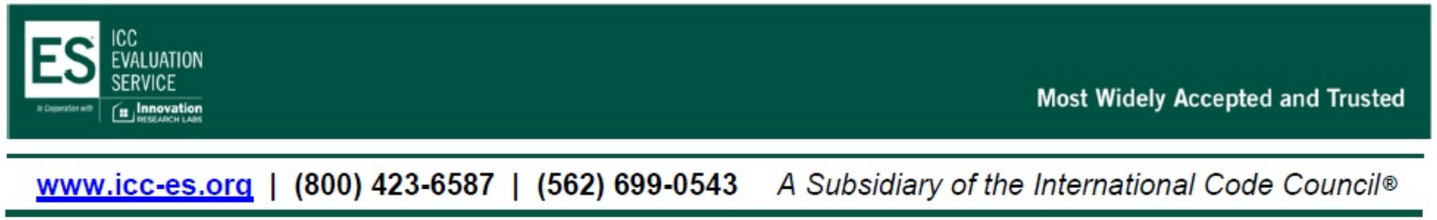
Building Code Compliance

104.11 Alternative materials, design and methods of construction and equipment. The provisions of this code are not intended to prevent the installation of any material or to prohibit any design or method of construction not specifically prescribed by this code, provided that any such alternative has been *approved*. An alternative material, design or method of construction shall be *approved* where the *building official* finds that the proposed design is satisfactory and complies with the intent of the provisions of this code, and that the material, method or work offered is, for the purpose intended, at least the equivalent of that prescribed in this code in quality, strength, effectiveness, *fire resistance*, durability and safety.

104.11.1 Research reports. Supporting data, where necessary to assist in the approval of materials or assemblies not specifically provided for in this code, shall consist of valid research reports from *approved* sources.

- IBC Section 104.11 allows alternative materials.
- IBC Section 104.11.1 allows research reports as a source of information on alternative materials.
- Research reports are primarily used by code officials and design professionals.

Building Code Compliance



ACCEPTANCE CRITERIA FOR 3D AUTOMATED CONSTRUCTION TECHNOLOGY FOR 3D CONCRETE WALLS

AC509

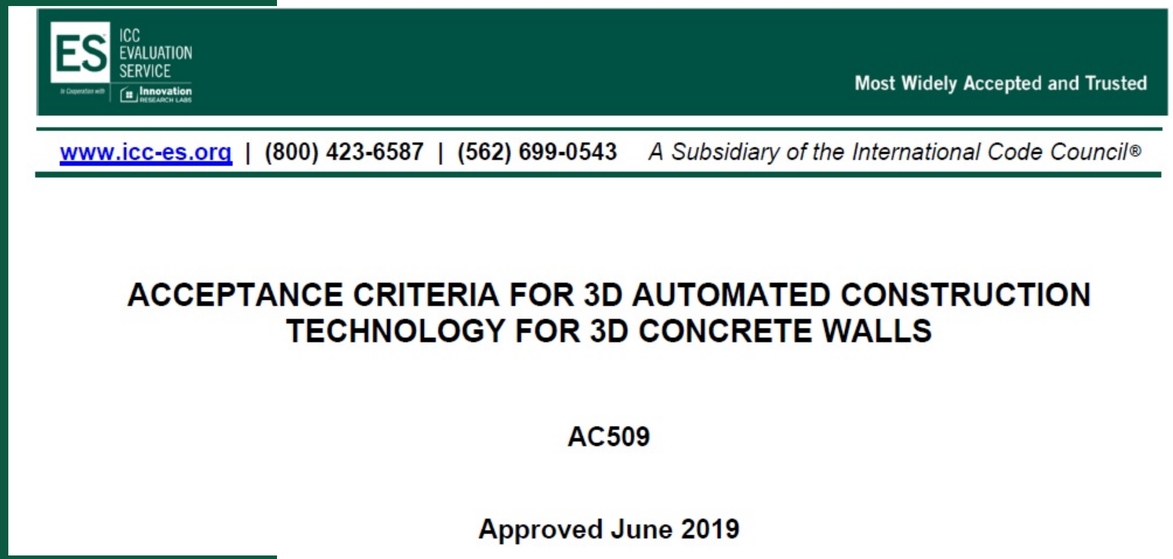
Approved June 2019

The ICC-ES Acceptance Criteria AC509 was published to provide the requirements to qualify use of 3D printed walls for compliance with the 2018 IBC.

Building Code Compliance

Evaluation Committee Public Meeting for new Acceptance Criteria

Building Code Compliance



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ACCEPTANCE CRITERIA FOR 3D AUTOMATED CONSTRUCTION TECHNOLOGY FOR 3D CONCRETE WALLS

AC509

Approved June 2019

ICC-ES AC509 addresses IBC objectives:

- Quality
- Strength
- Effectiveness
- Fire resistance
- Durability
- Structural safety

Building Code Compliance

Scope of AC509:

Interior and exterior 3D concrete walls, with or without structural steel reinforcing, used as bearing or non-load bearing walls, in one-story single-unit residential dwellings.

The 3D concrete walls used as the lateral-force-resisting system are limited to Seismic Design Categories (SDC) A and B only.

The foundation, roof, and their anchorage to the 3D concrete walls must comply with applicable sections of the IBC.

Building Code Compliance

Material Tests:

Compressive strength testing (ASTM C39 or C109).

Slump testing (ASTM C143 or C1611).

Min compressive strength of 2500 psi (17 Mpa).

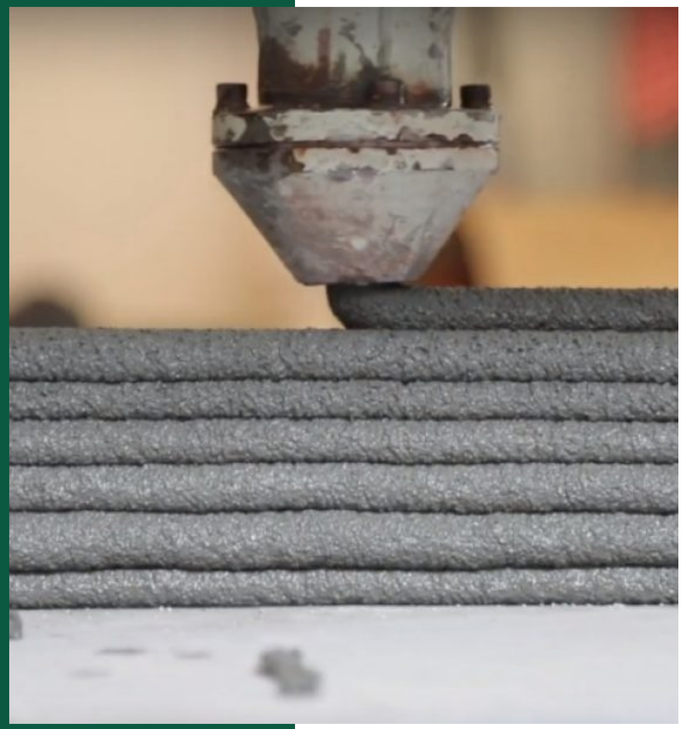
Both slump and min compr. strength to be reported for quality control purposes

Building Code Compliance

Durability Tests:

- Freezing and thawing (ASTM C666) with durability factor of 80 after 300 cycles.
- Shrinkage and volume change testing per ASTM C157.
- Fibers used in 3D concrete mix designs to comply with the ICC-ES Acceptance Criteria AC32, AC208, AC383, or AC470.

Building Code Compliance



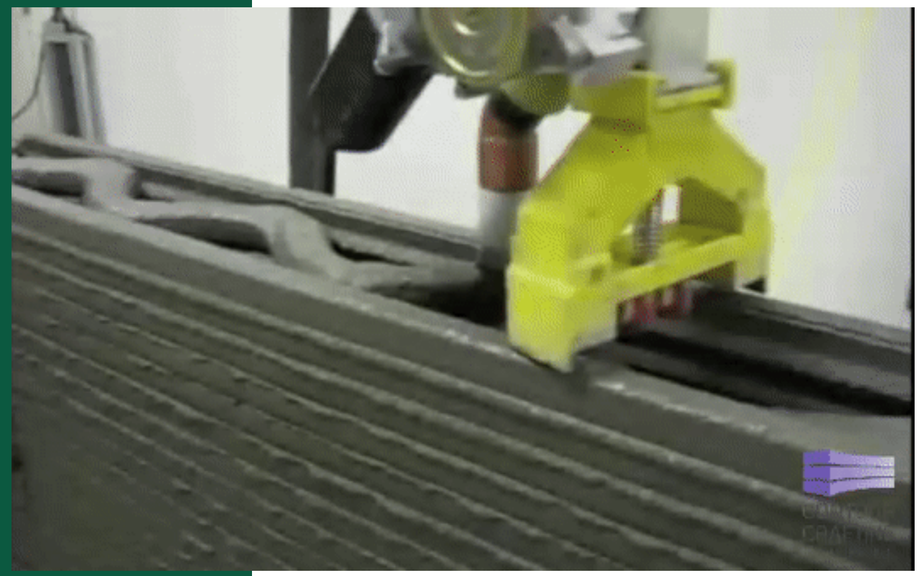
Min. and Max. Extrusion Time Interval

Intended to evaluate the effect of min and max time intervals on the bond between the extrusion layers.

Flexural bond tests in accordance with of ASTM E518 at both min. and max. extrusion time intervals between layers.

Tested flexural bond strengths at min. and max. extrusion time intervals be statistically equal.

Building Code Compliance



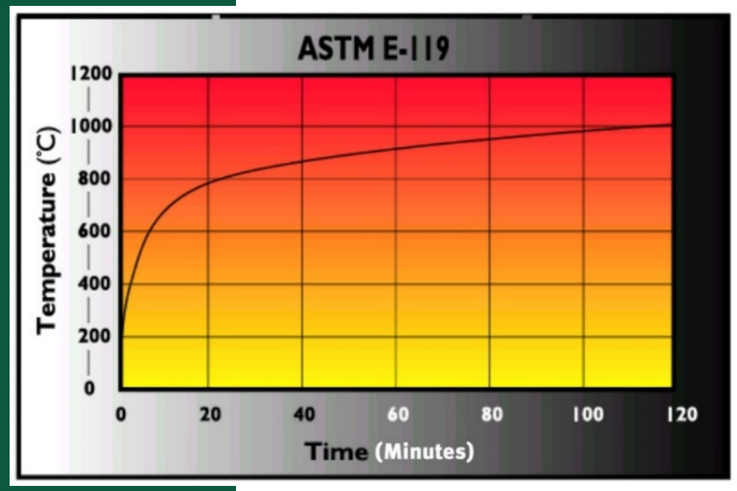
Structural Performance:

Wall Axial Compression Test

Wall Flexure Test

Wall Static In-Plane Shear Test

Building Code Compliance



Other Building Code Tests:

- Fire resistance testing when recognition is sought for fire-resistance-rated wall assemblies per ASTM E119 or UL 263.

- Interior wall finish test per ASTM E84 when recognition is sought for use as an interior wall finish.

Building Code Compliance

3D automated construction technology shall be labeled and maintained under an approved inspections program, performed twice annually.

3D concrete mixture design shall be labeled and manufactured under an approved inspections program, performed annually.

IBC objectives:

- Quality
- Strength
- Effectiveness
- Fire resistance
- Durability
- Structural safety

Building Code Compliance

Summary:

- IBC is the predominant building code in the USA.
- IBC Section 104.11 allows alternative materials, design and methods provided that any such alternative has been approved.
- ICC-ES AC509 was developed for 3D printed concrete walls that satisfies the requirements of the IBC.
- The resulting research report issued in accordance with AC509 demonstrates the code compliance and is primarily used by code officials and structural engineers.

Next:

1. History of 3D printing
2. Environmental impact of 3D printing
3. Future of 3D printing

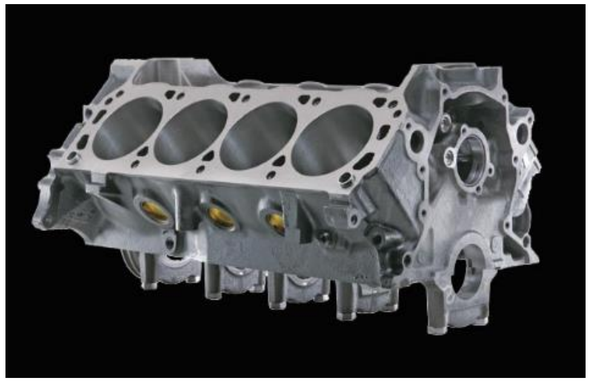
Behrokh Khoshnevis, Ph.D.

Behrokh “Berok” Khoshnevis is the President and CEO of Contour Crafting Corporation (CC Corp), the Louise L. Dunn Distinguished Professor of Engineering and the Director of the Center for Rapid Automated Fabrication Technologies (CRAFT) at the University of Southern California. He is active in robotics, and mechatronics related research and development projects that include the development of several novel Additive Manufacturing (3D Printing) processes such as Contour Crafting construction-scale 3D printing, SIS, which is licensed to HP, for fabrication of polymeric and metallic parts, and SSS for fabrication of high temperature alloys, ceramics and composites, as well as development of mechatronics systems for biomedical applications (e.g., digital dental prostheses fabrication, robotics for orthodontics, rehabilitation engineering, and tactile sensing devices), autonomous mobile and modular robots for fabrication and assembly on Earth, in space and on other planets, and specialized innovative equipment for oil and gas as well as renewable energy industries.

He has numerous inventions and over 100 US and international patents as well as nearly 200 refereed technical publications. He is a member of the National Academy of Engineering, a Fellow of the National Academy of Inventors, a Fellow the American Association for Advancement of Science.

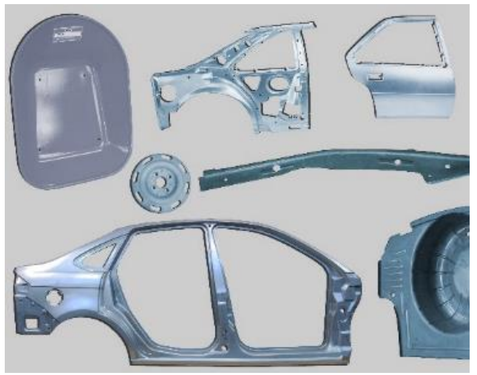
CONTOUR CRAFTING CORPORATION

Fabrication methods



Subtractive

Additive

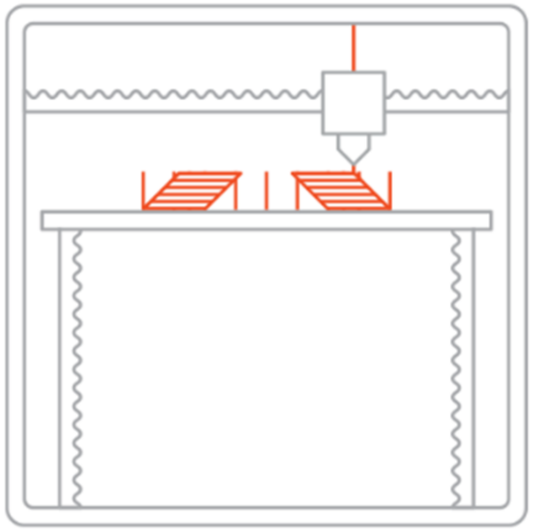


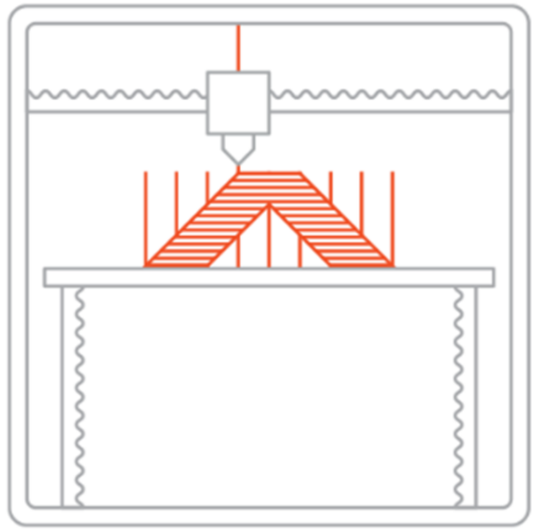
Formative

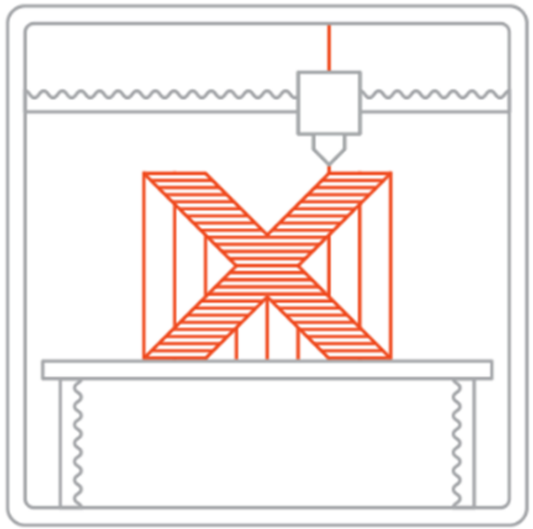
Additive Manufacturing; 3D Printing

Principle:

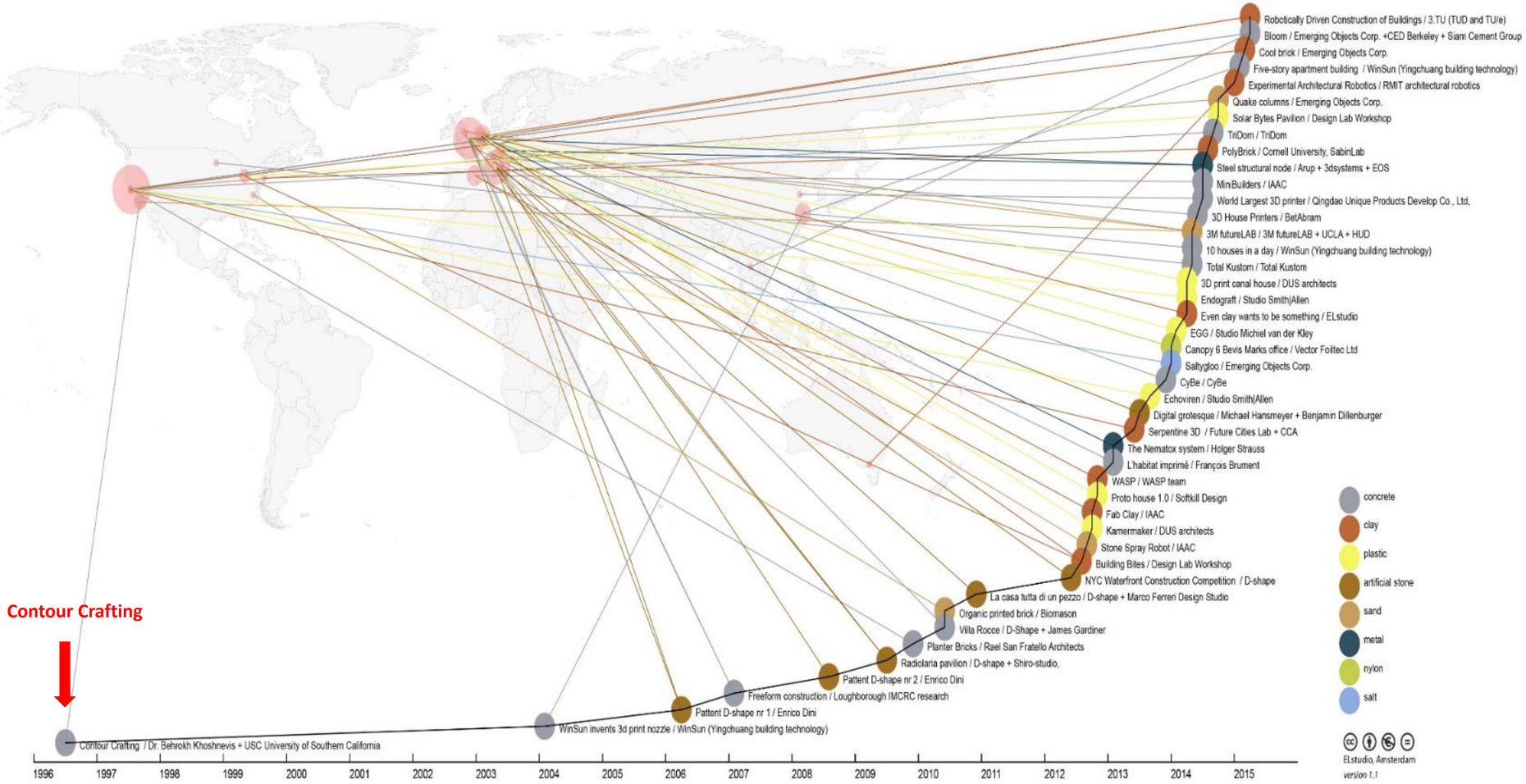
Add 2D layers of material one at a time to build the solid 3D part.







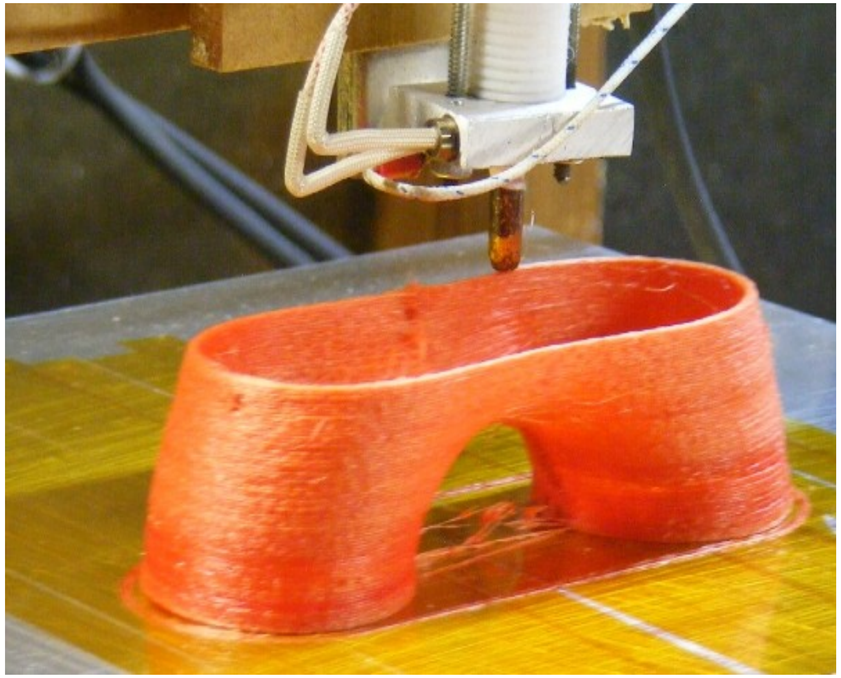
History chart of large-scale 3D printing



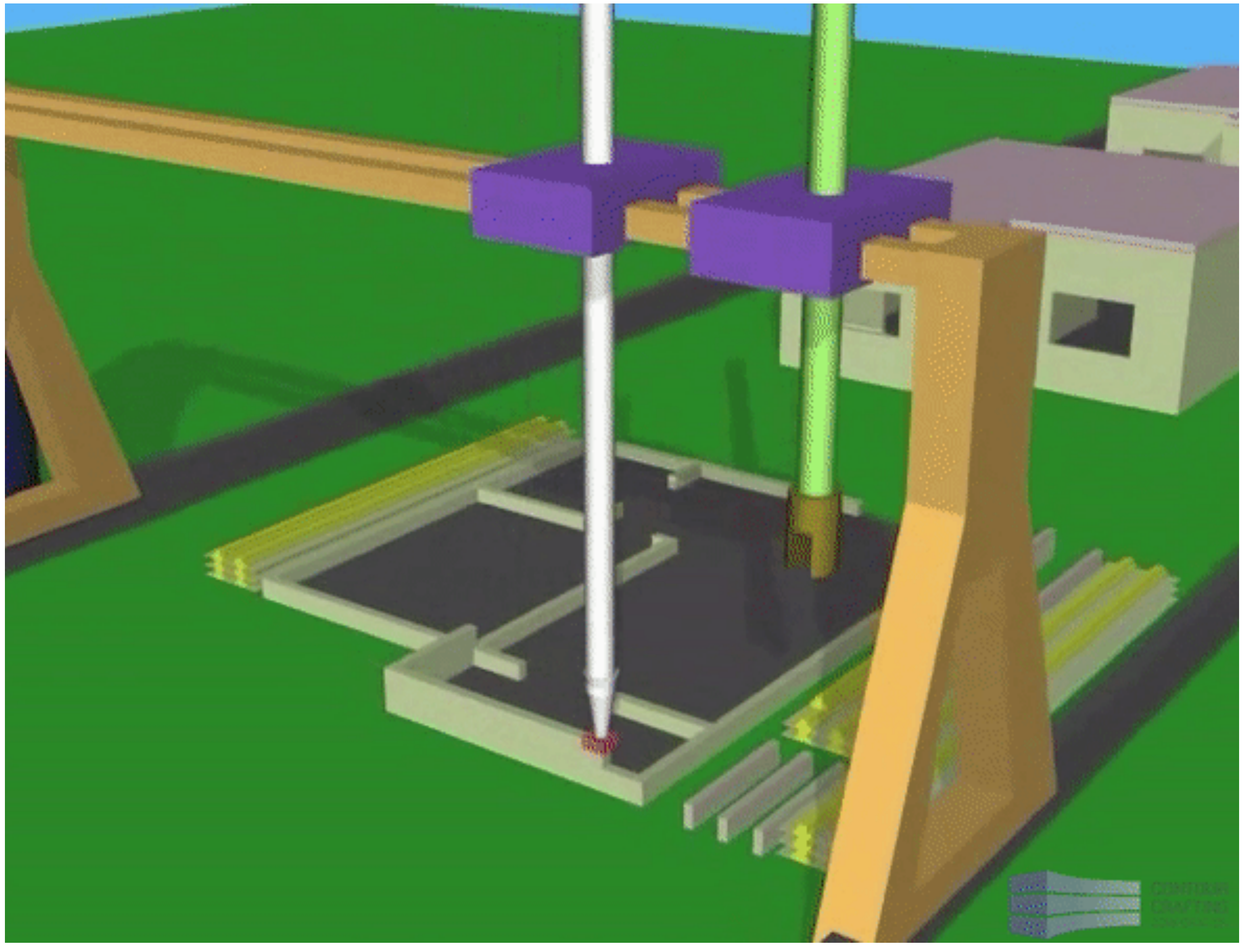
Published by: *Elstudio Amstrdam*, 2016

Realizations in 1994

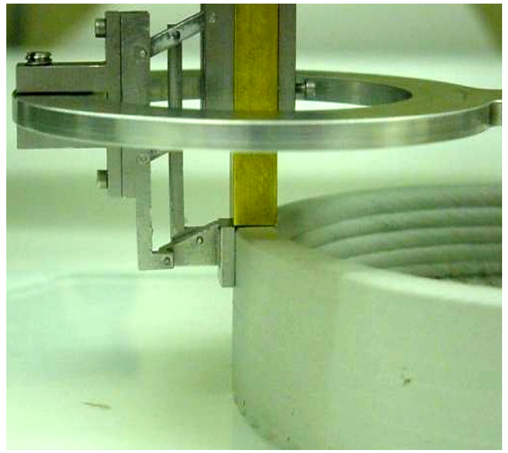
- 3D printing builds layer by layer
- We have been 3D printing for several millennia in construction

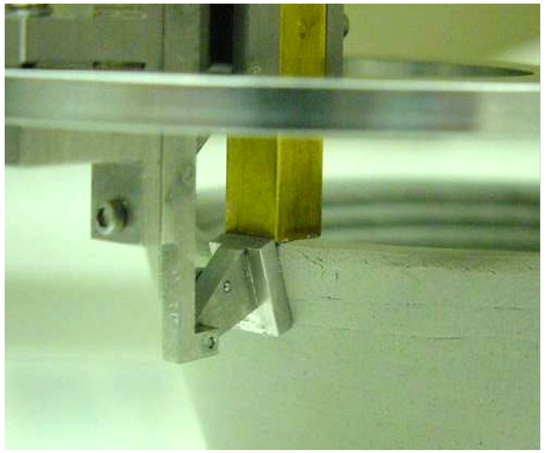


The vision of automated building construction is born

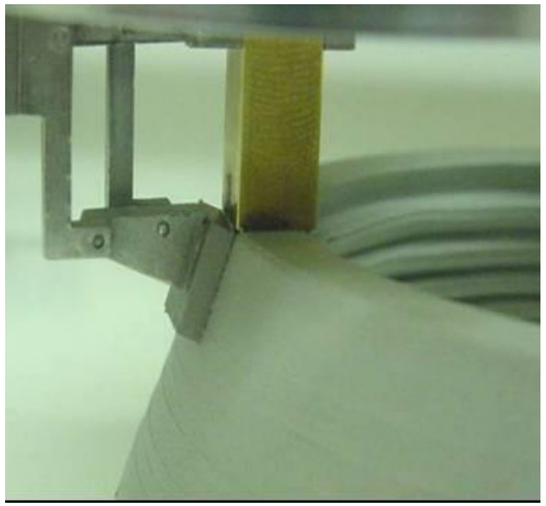


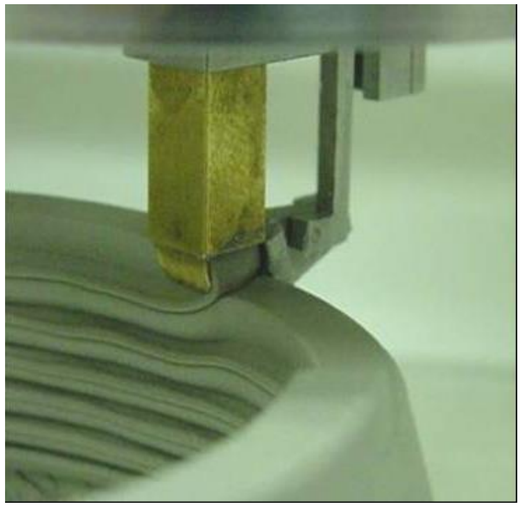
Invention of Contour Crafting



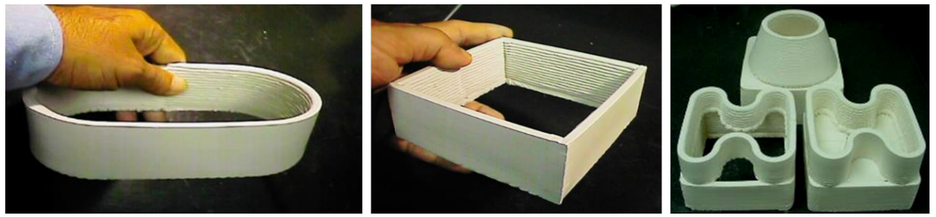


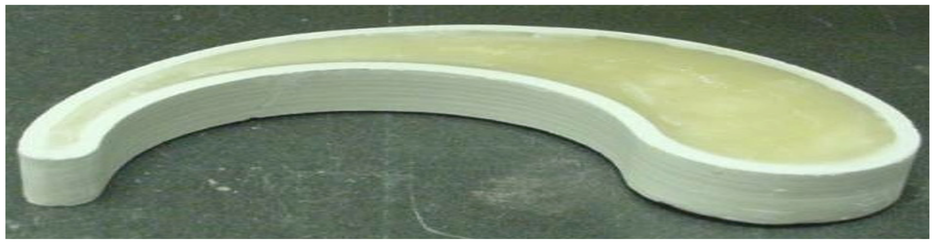
CC is an extrusion based a layered fabrication technology that builds objects with successive “thick” layers as it smooths out external surfaces.

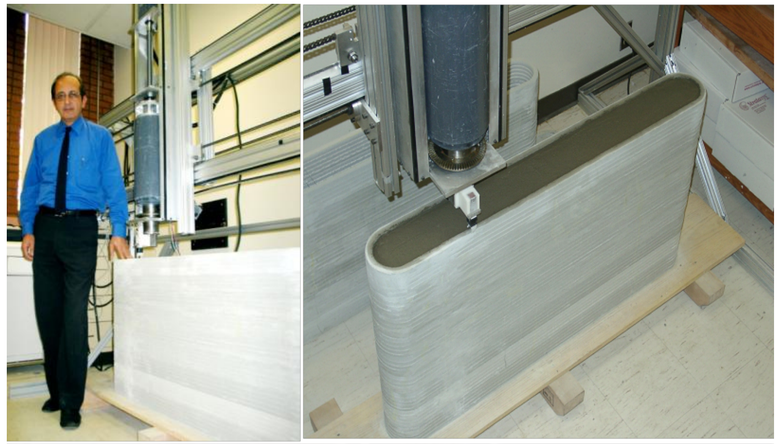


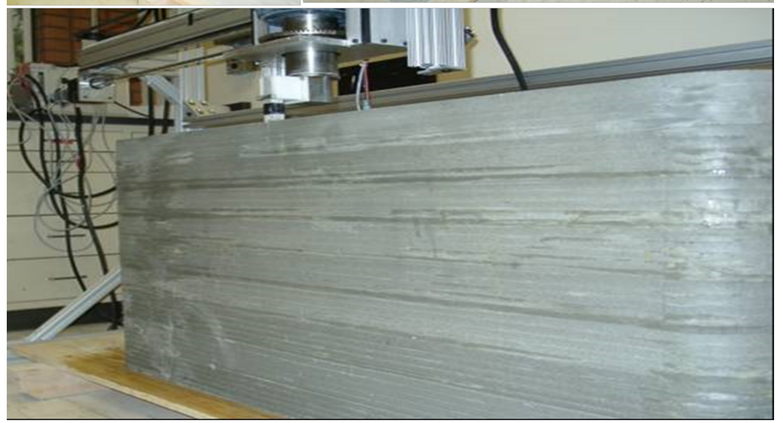


Small-scale ceramic to large scale concrete parts

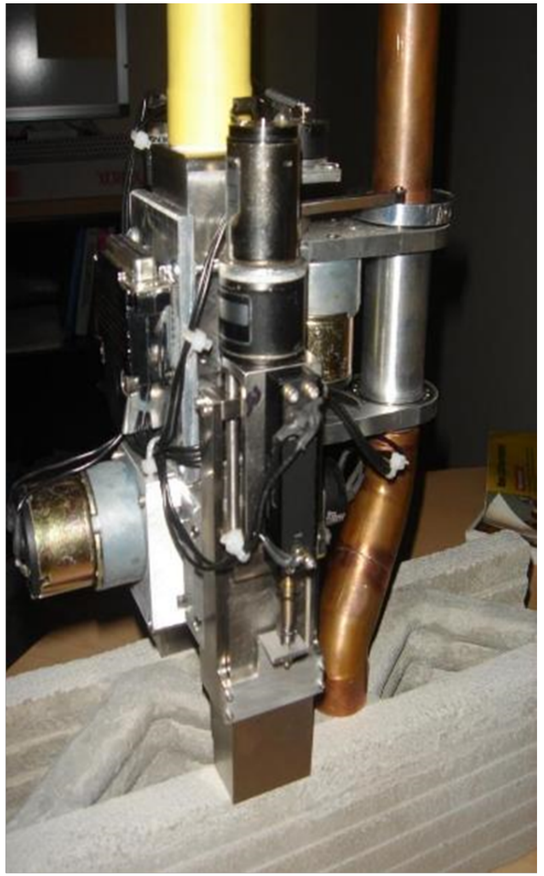




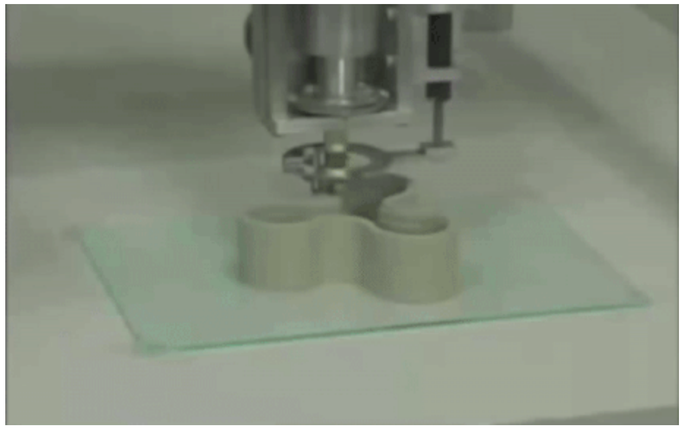


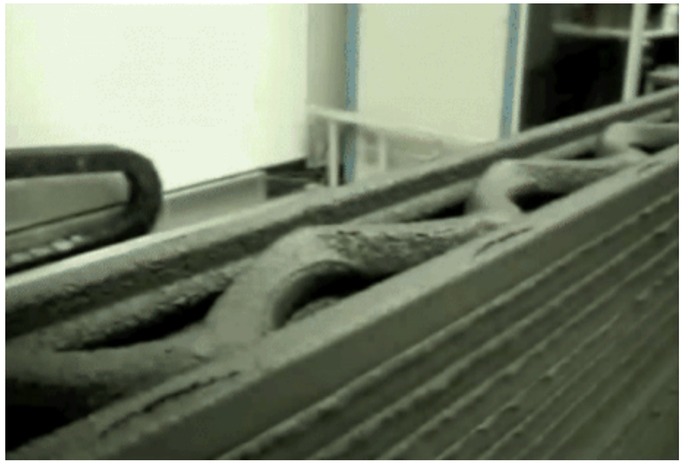


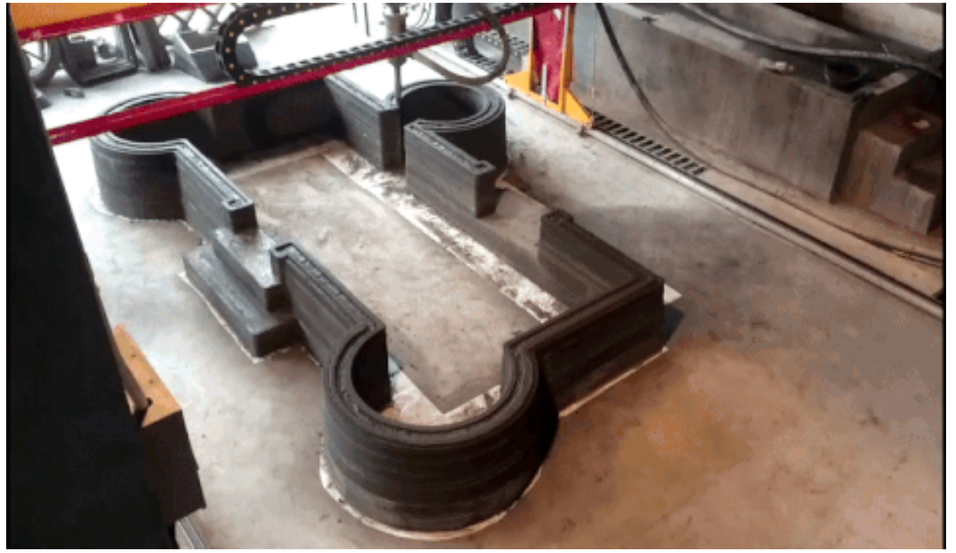
CC Technology and its concrete structures



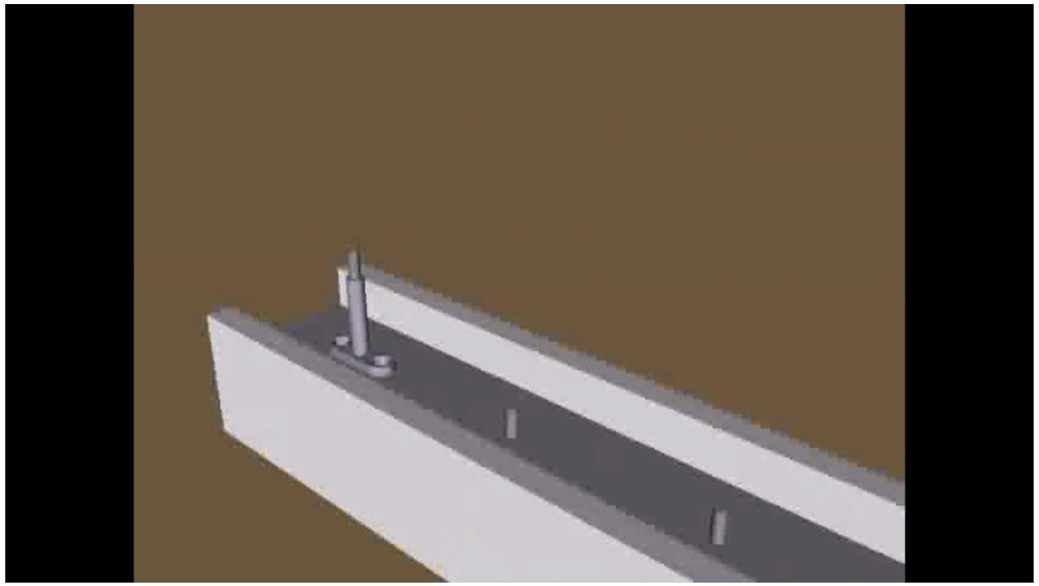
Many modes of fabrication

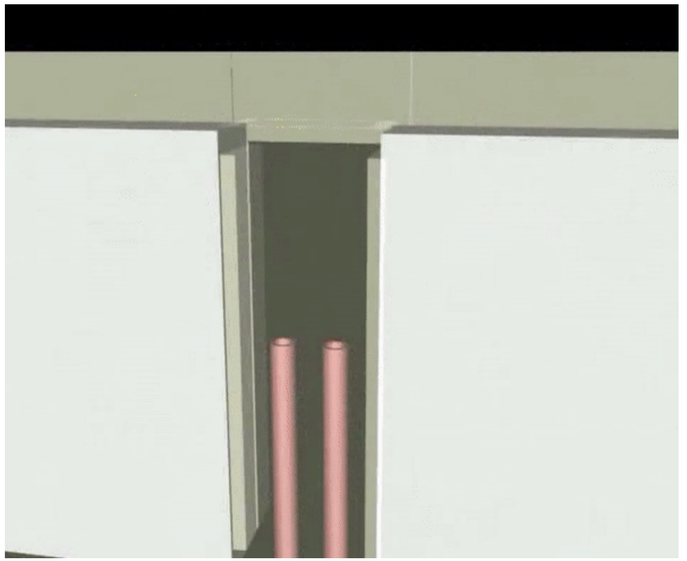




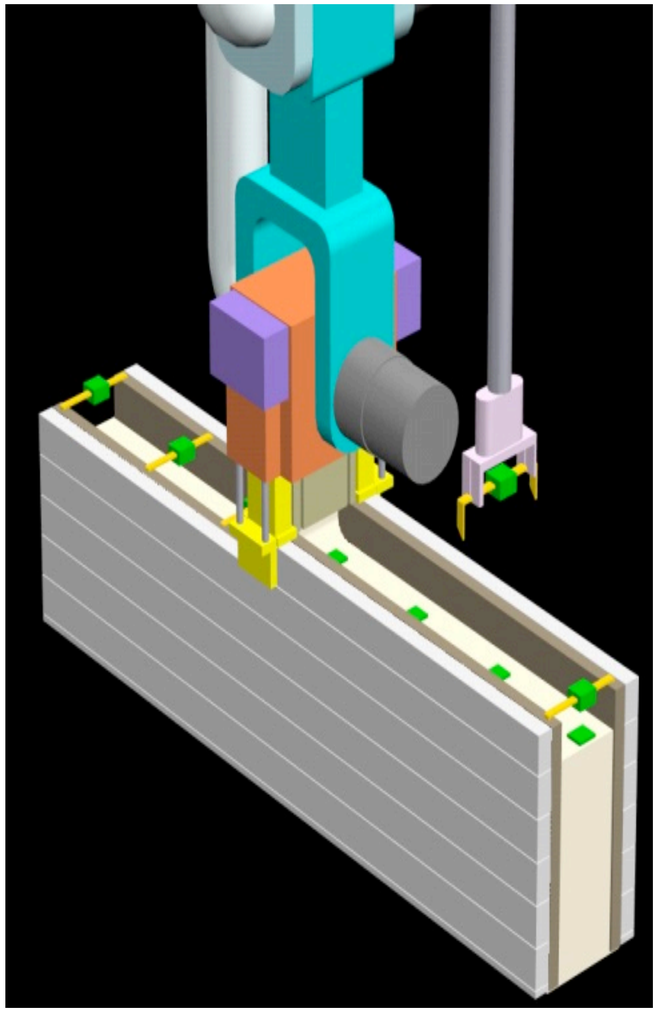


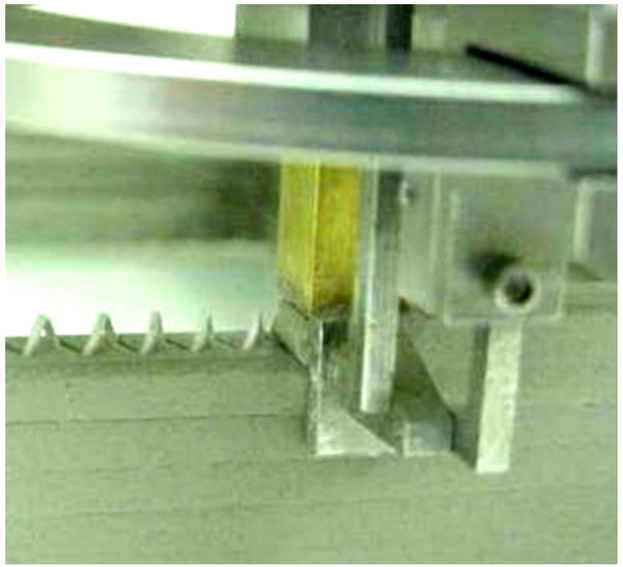
Concurrent object imbedding

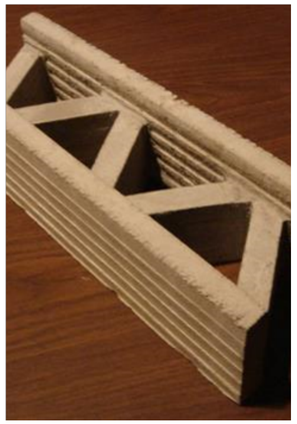




Numerous possibilities for innovation







PRESENT

Why construction needs a change

- Construction is the largest sector of almost all economies (~$6T/year in USA)
- Labor efficiency is alarmingly low
- Skilled workforce is vanishing
- Work quality is low
- Control of the construction site is insufficient and difficult
- Accident rate at construction sites is high (> 400,000 / year in US); 60,000 fatalities/year globally
- Waste and trims are high (3 To 7 tons per average home; 40% of all materials used worldwide are for construction).
- Low income housing and emergency shelters are critical
- All other products are fabricated automatically – construction is still largely a manual task

Application in Building Construction

Justifications

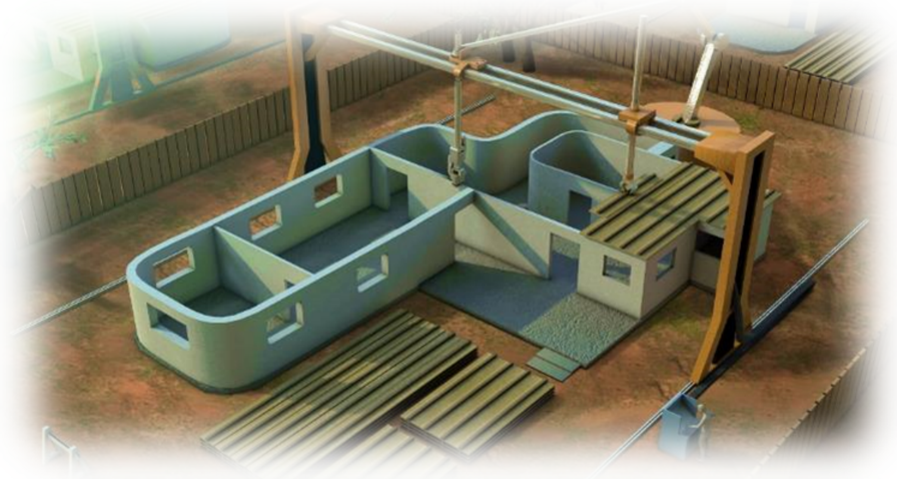
Residential:

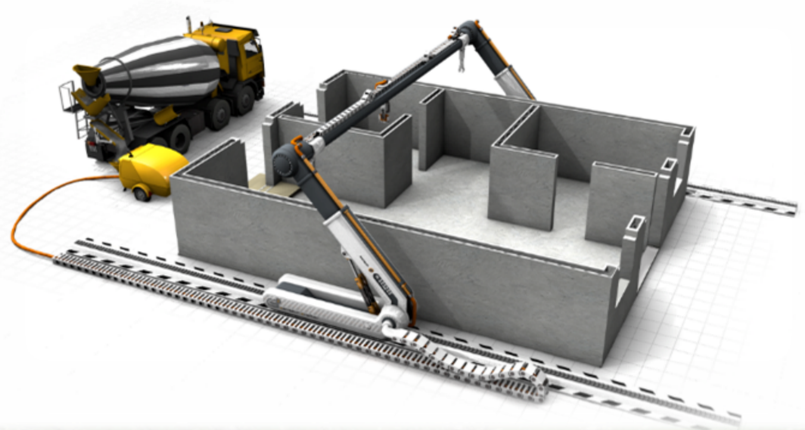
- Shortage of 800 million houses worldwide (UN statistics)
- Global markets are grossly under-served
    - Nearly 2 Billion people are homeless or live in slums
    - Annually 37 million people lose housing due to war and natural disasters

Commercial:

- Shortage of commercial and industrial buildings, especially in developing countries

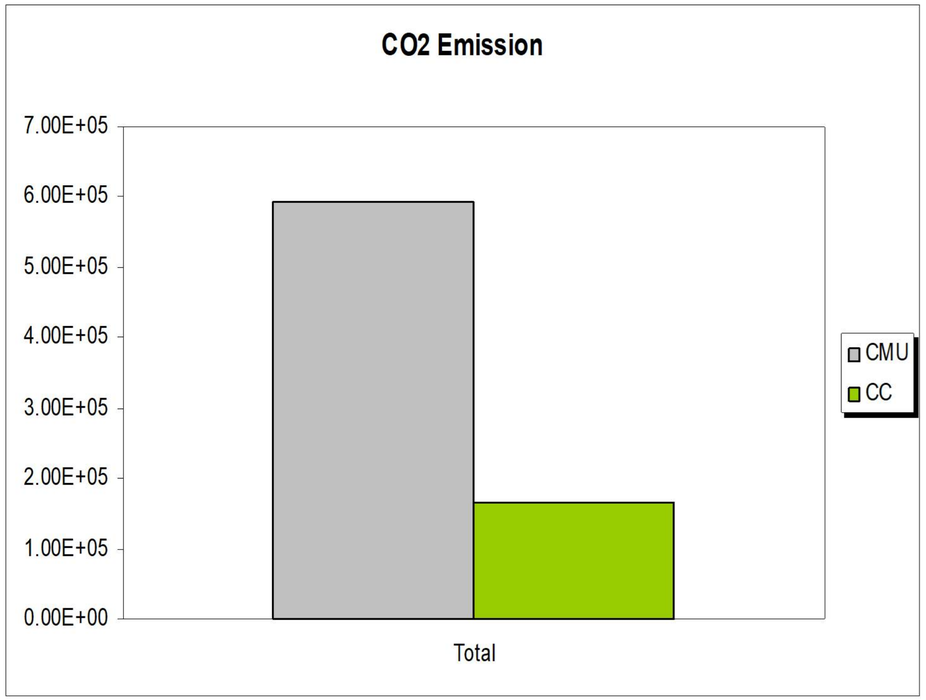
Building construction targets of CC Corp

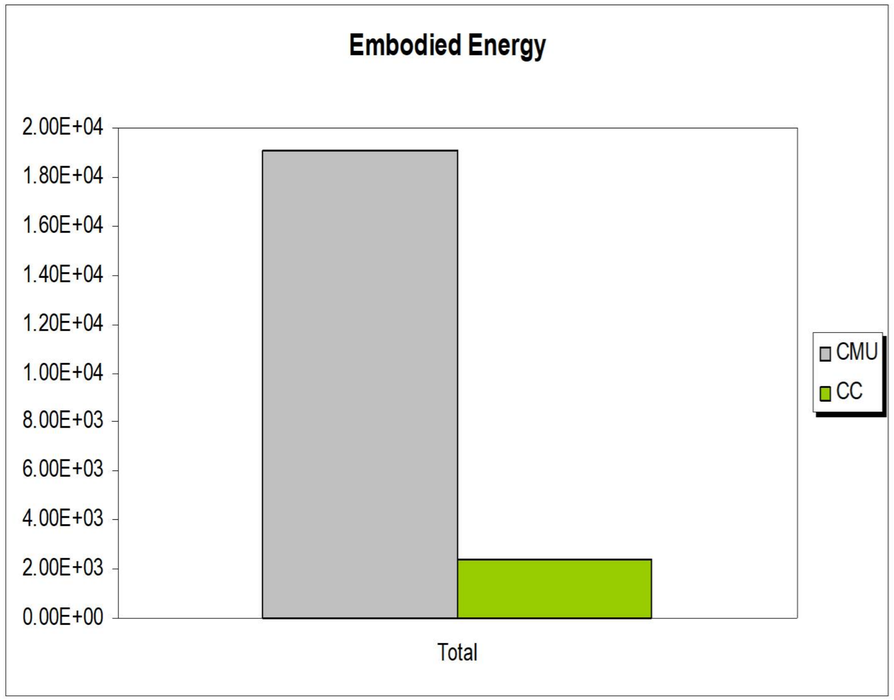




Environmental impact and Energy Usage

Comparison with Concrete Masonry Unit construction





FUTURE

Barriers against implementation in building sector

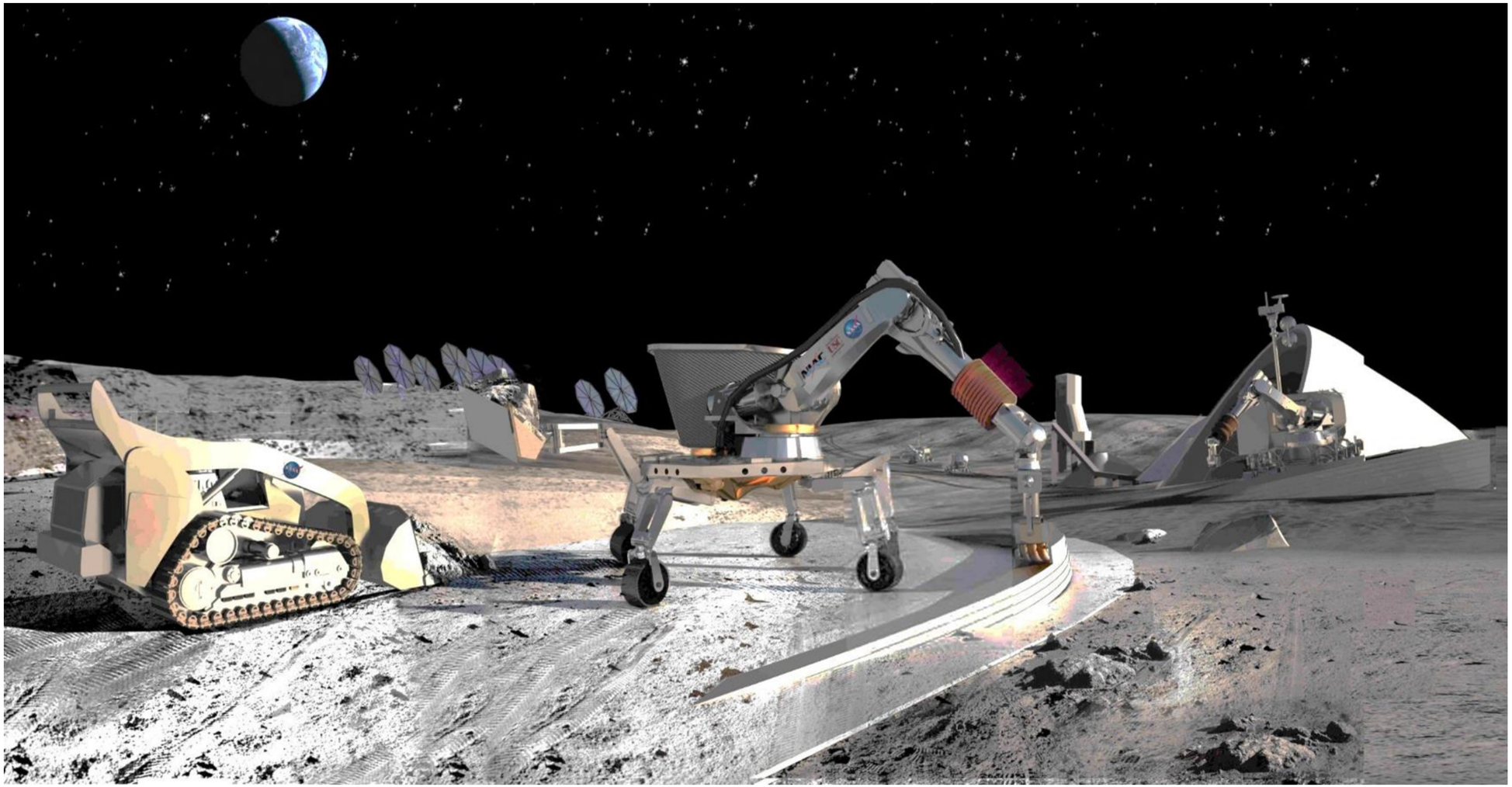
- Conservative industry
- Low profit margin
- Regulatory obstacles
- At best only the cost and time of building the shell is impacted
- Expensive material is used
- Major paradigm change requirement with respect to inspection
- Potential labor union opposition

Infrastructure Construction

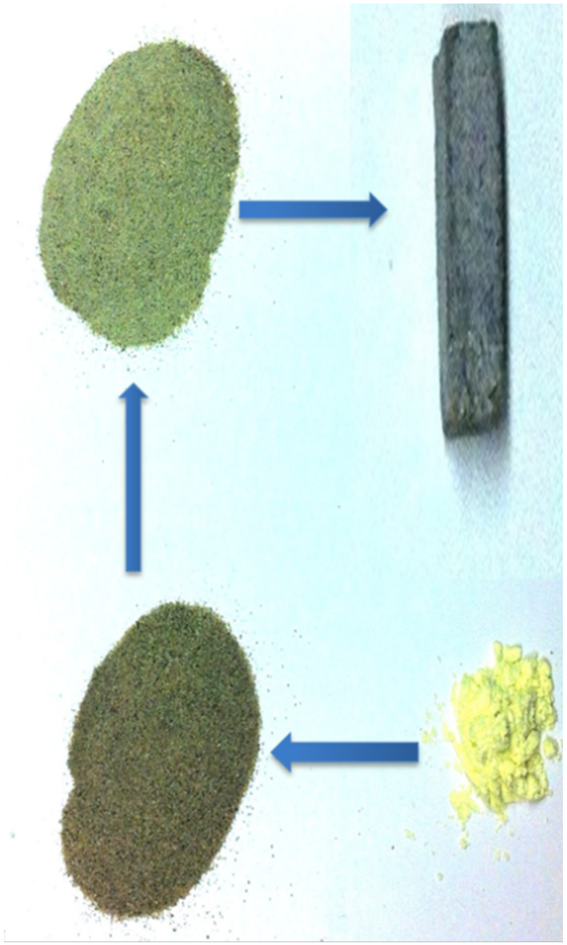
Space Applications

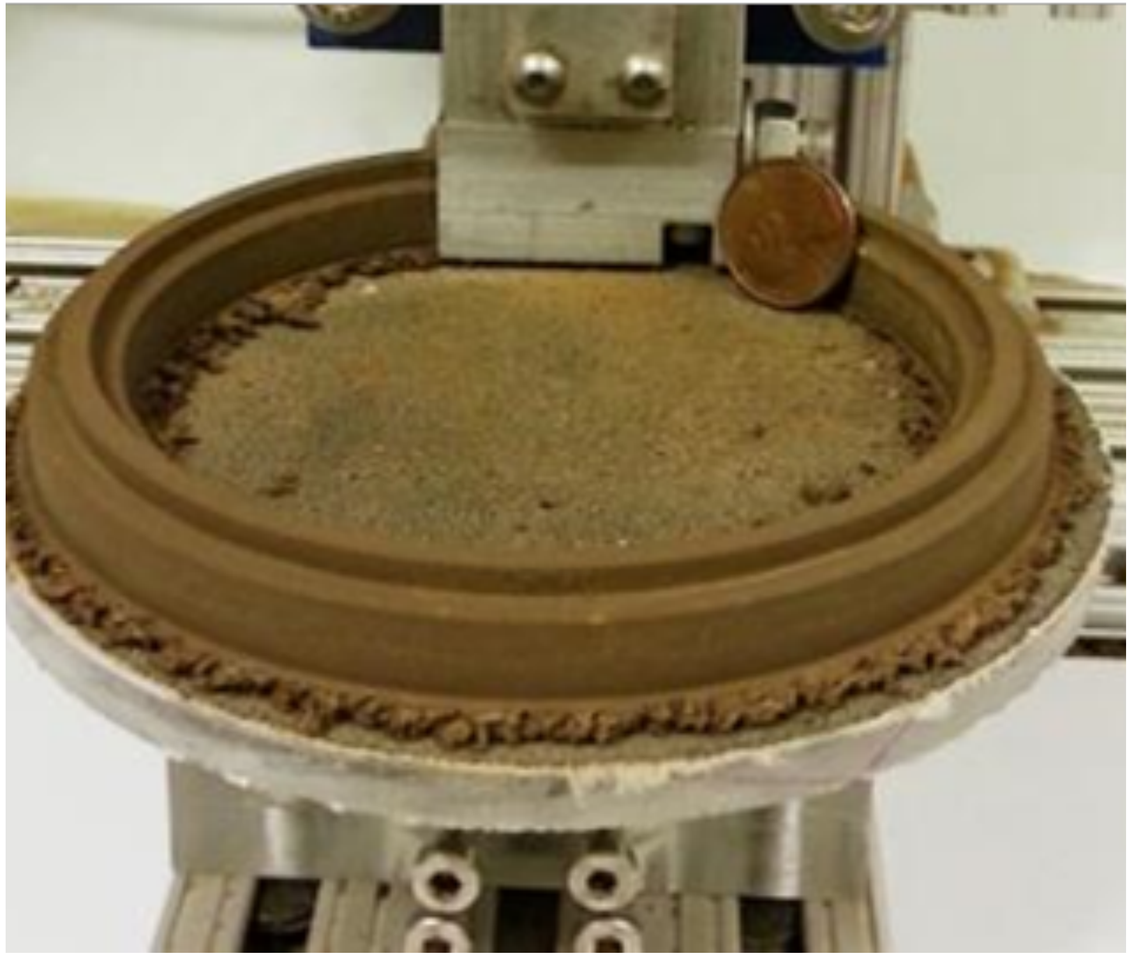
The next stage after our Earth-bound civilization is the Solar System Civilization – and it is beginning.

Planetary Construction by CC

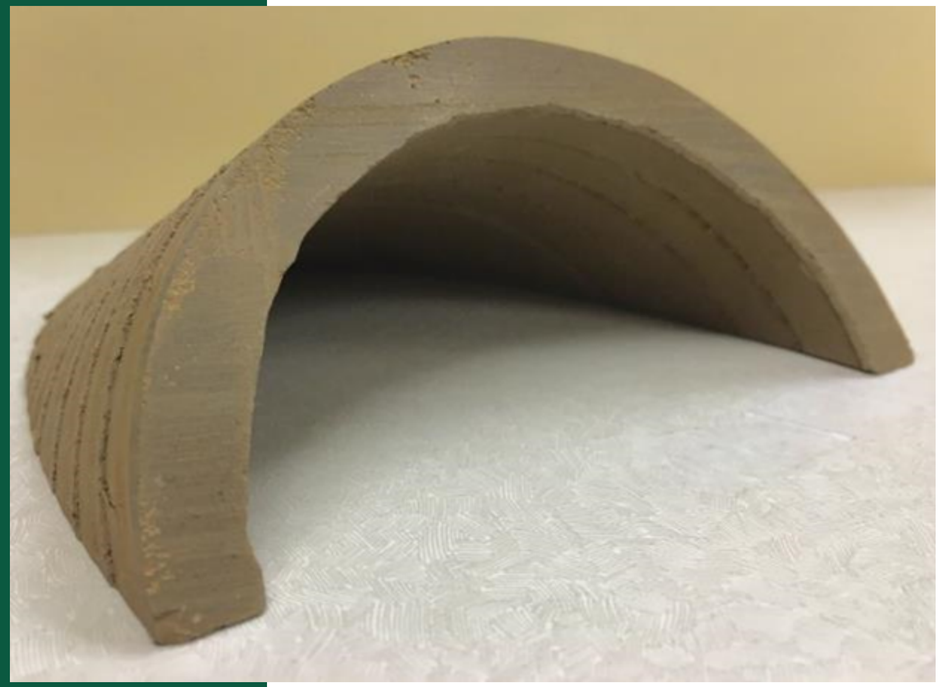


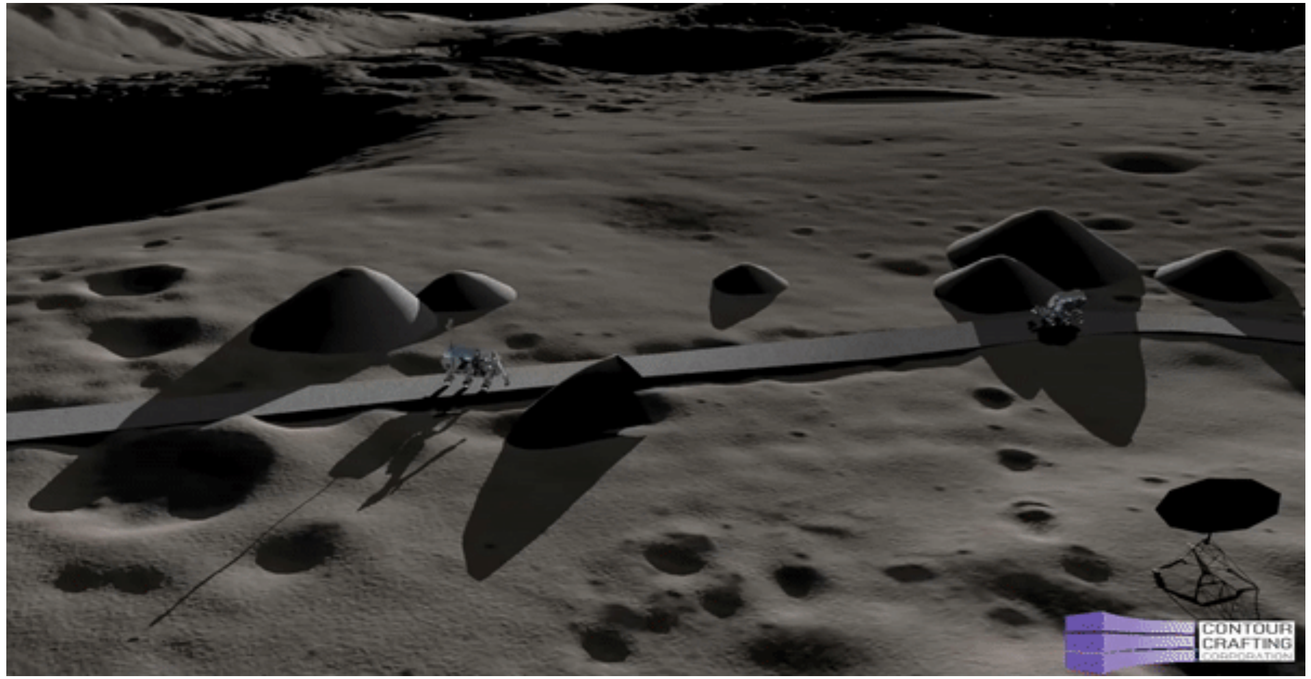
Sulfur concrete 3D printing





Planetary construction using in-situ material





Next:

Examples of Construction 3D Printing

Babak Zareiyan, Ph.D.

Babak Zareiyan is Senior Research and Development Engineer at Contour Crafting Corporation (CC Corp). He is a multidisciplinary Engineer and Researcher in the area of large-scale 3D Printing (3D Concrete Printing), development and application of new construction materials, sustainability and/or resiliency of the built environment.

During his Ph.D. program, he served as research assistant in Center for Rapid Automated Fabrication Technologies (CRAFT) at the University of Southern California. The focus of his research was utilization of 3D Printing in construction and development of new construction materials based on coupled statistical modeling and experimental characterization. He has several publications in the area of 3D Concrete Printing.

After graduation, he continued his research on different projects related to build environment and 3D Printing. He has also been invited as reviewer for five scientific journals.

CONTOUR CRAFTING CORPORATION

May 2017 start of CC Corp

Investment by Umdasch Group Ventures, Austria

CONTOUR
CRAFTING
CORPORATION

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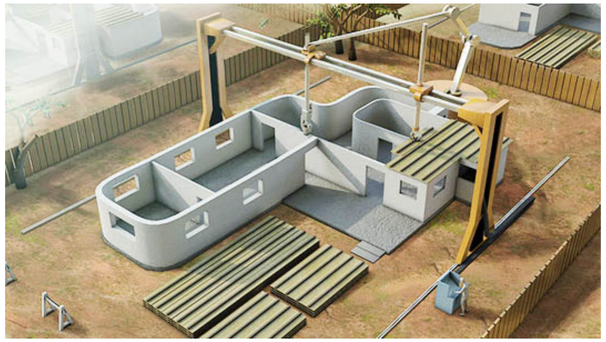


Contour Crafting Corporation (CC Corp)

www.ContourCrafting.com

Federal Government Award for Rapid Response Construction

Effective 25 JUL 2018, the Department of Defense has awarded Contour Crafting Corporation with a Rapid Innovation Fund contract in the do...

ICC-ES Evaluation Committee Meeting – First Major Regulatory Step Towards 3D...

On June 4th 2019, acceptance criteria AC509 (proposed new acceptance criteria for concrete walls built using construction-scale 3D printi...

Los Angeles County Development Authority (LACDA) Award

In an open competition, proposal solicitation (RFP NO. LACDA19-125) and selection process, the Los Angeles County Development Authority (...

#ICCLEARNLIVE

Examples of Construction 3D Printing

CC Corp – China Branch

Print location: Keqiao Expressway

Print, installation & painting time: 2 weeks

Examples of Construction 3D Printing

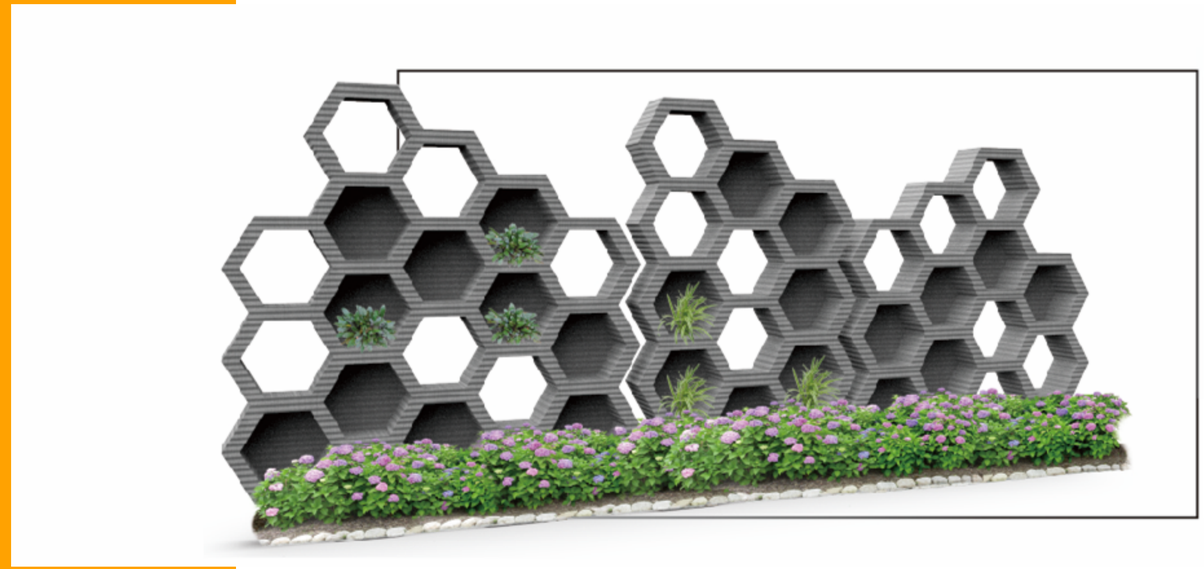
Templated solution

- High flexibility, customized according to project needs.
- Fast printing, high efficiency of on-site construction efficiency.
- Mass production can reduce the cost of design, modeling, printing, etc.
- High security, reduce the risk of personnel construction

Customization:

- background wall
- flower bed
- flowerpot
- bus stop
- homestay, etc.

Examples of Construction 3D Printing



Templated solution

- High flexibility, customized according to project needs.
- Fast printing, high efficiency of on-site construction efficiency.
- Mass production can reduce the cost of design, modeling, printing, etc.
- High security, reduce the risk of personnel construction

Customization:

- background wall
- flower bed
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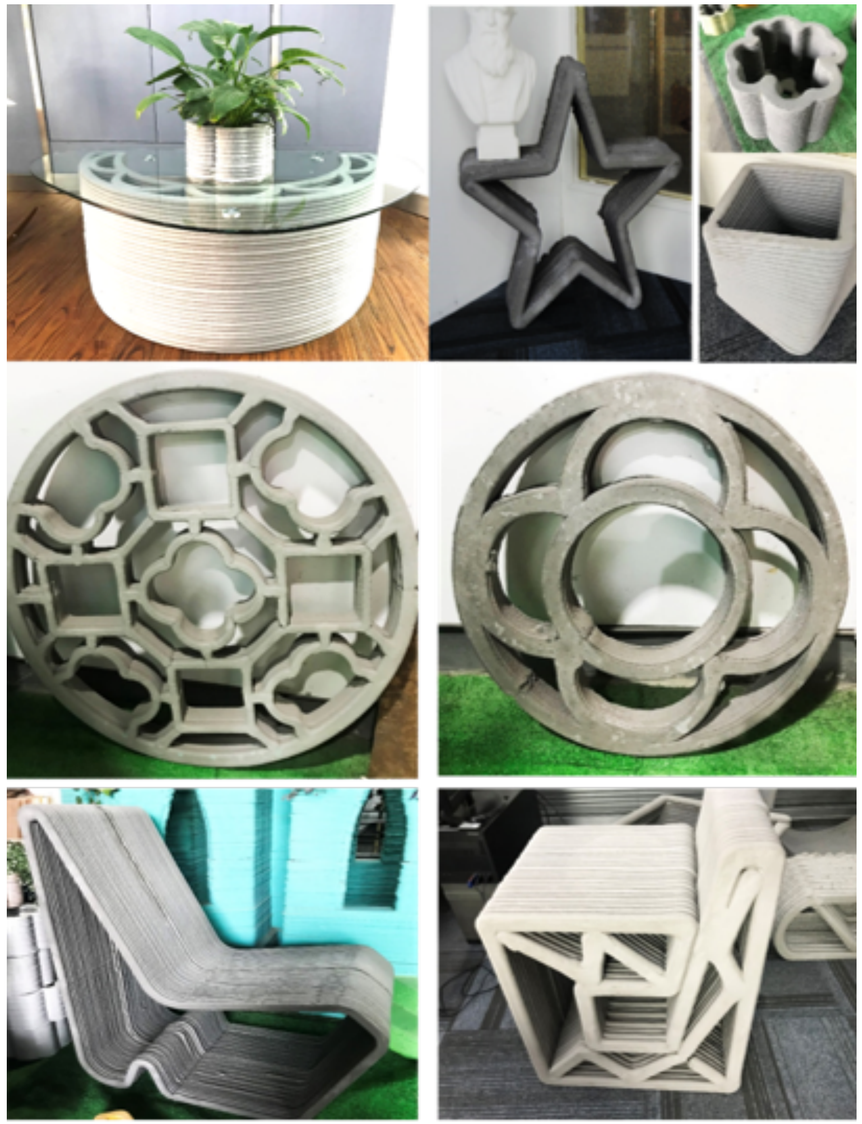
- bus stop
- homestay, etc.

Examples of Construction 3D Printing

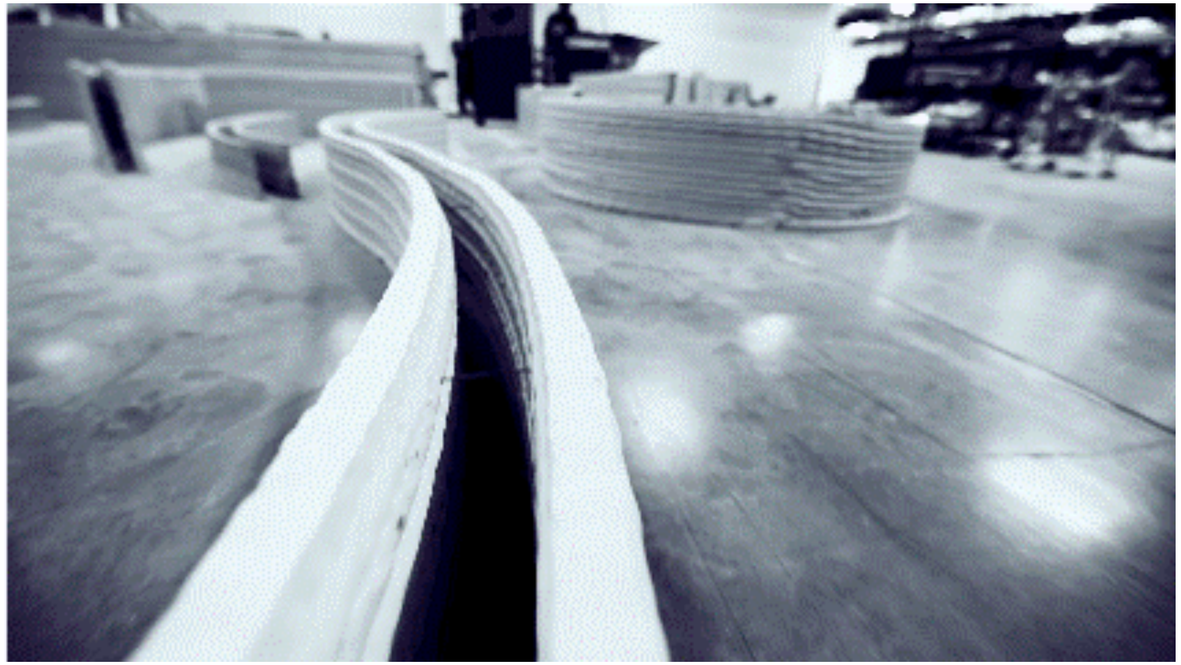
Hardscaping Elements

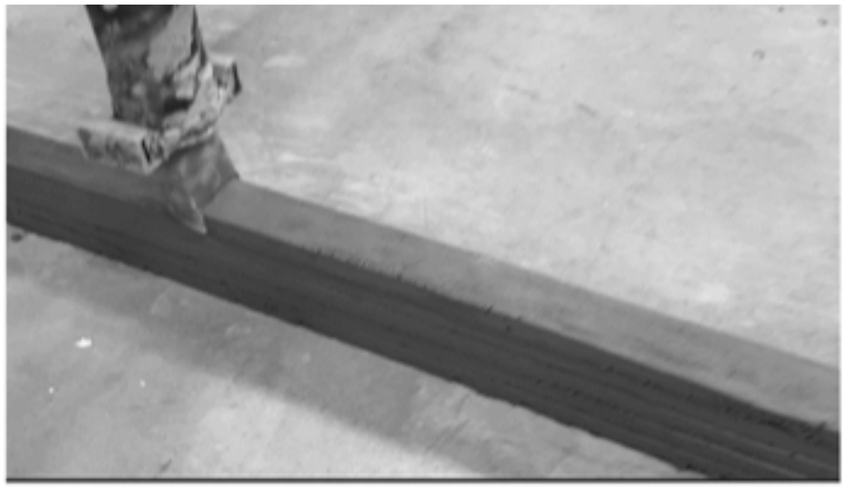


Mini-buildings

Examples of Construction 3D Printing

- 3D concrete
- Concrete core

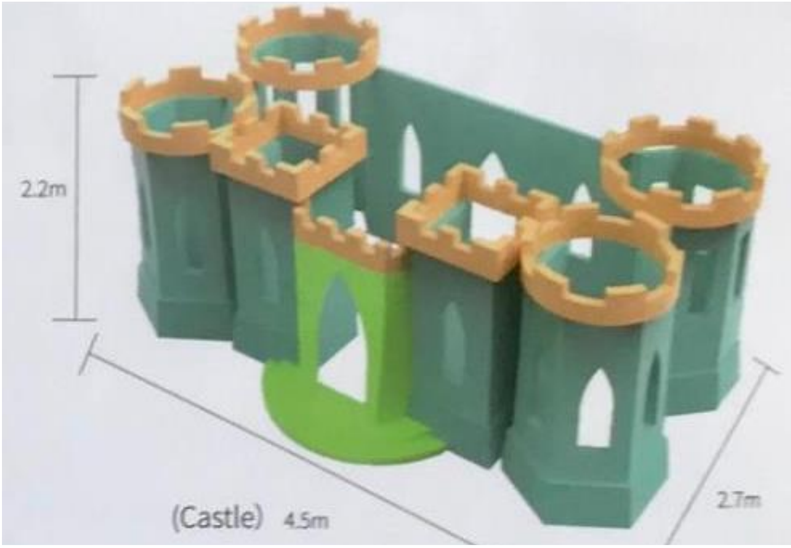




CC Corp – China Branch

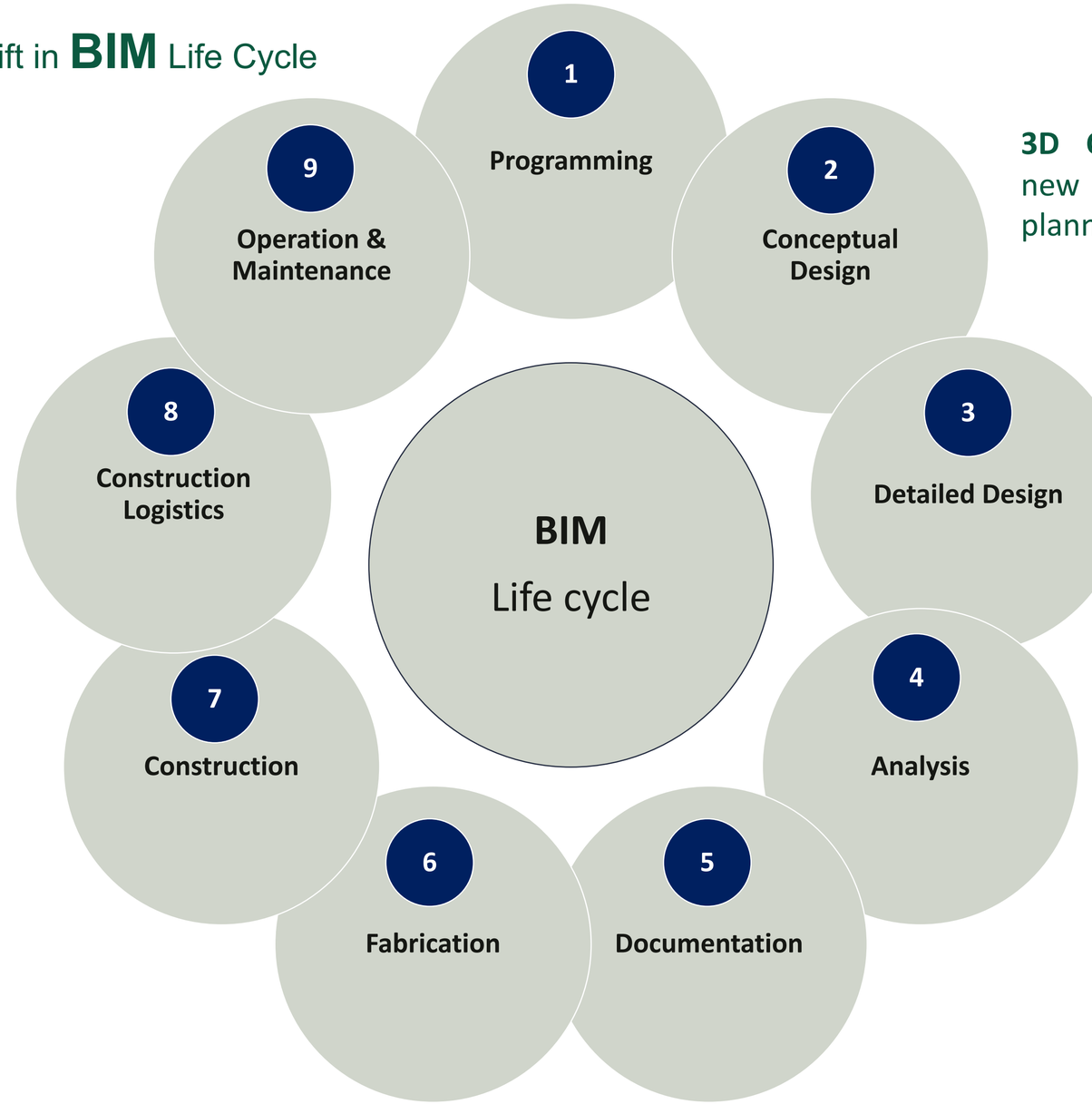
Print location: Architectural Printing Lab

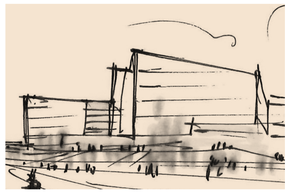
Project requirements: Rapid prototyping



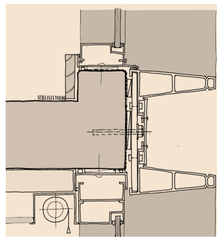
3D Printing

Paradigm shift in **BIM** Life Cycle





3D Construction printing brings new possibilities in design and planning process.



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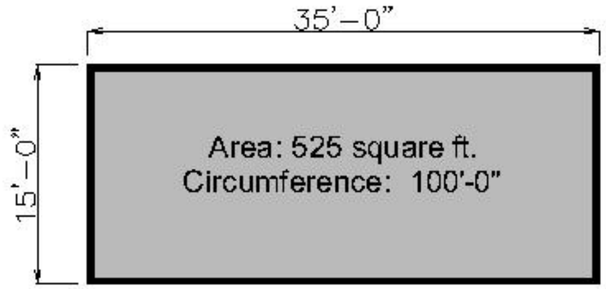
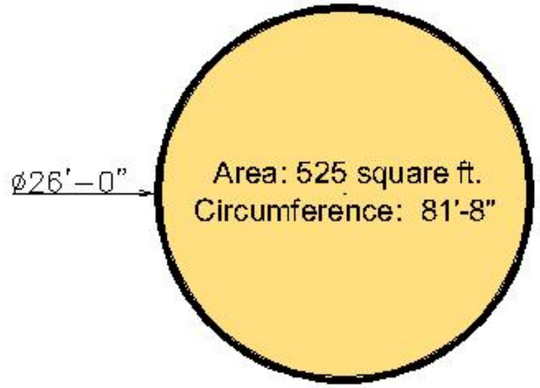
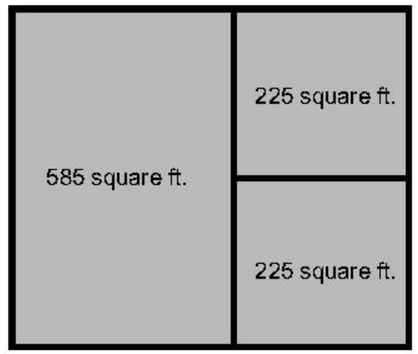
3D Printing

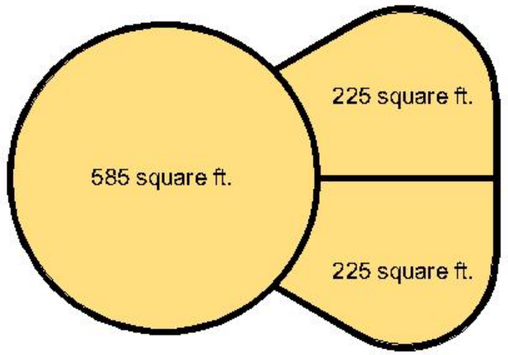
Sustainability and Material consumption



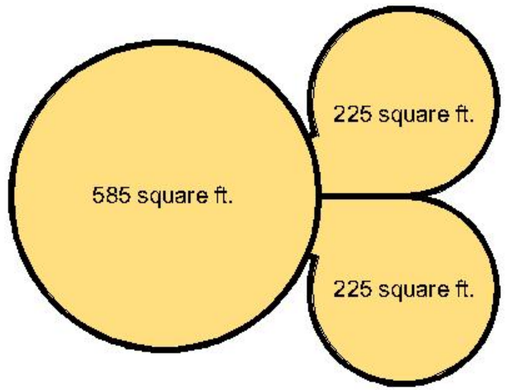




TOTAL WALL LENGTH: 186'-0"

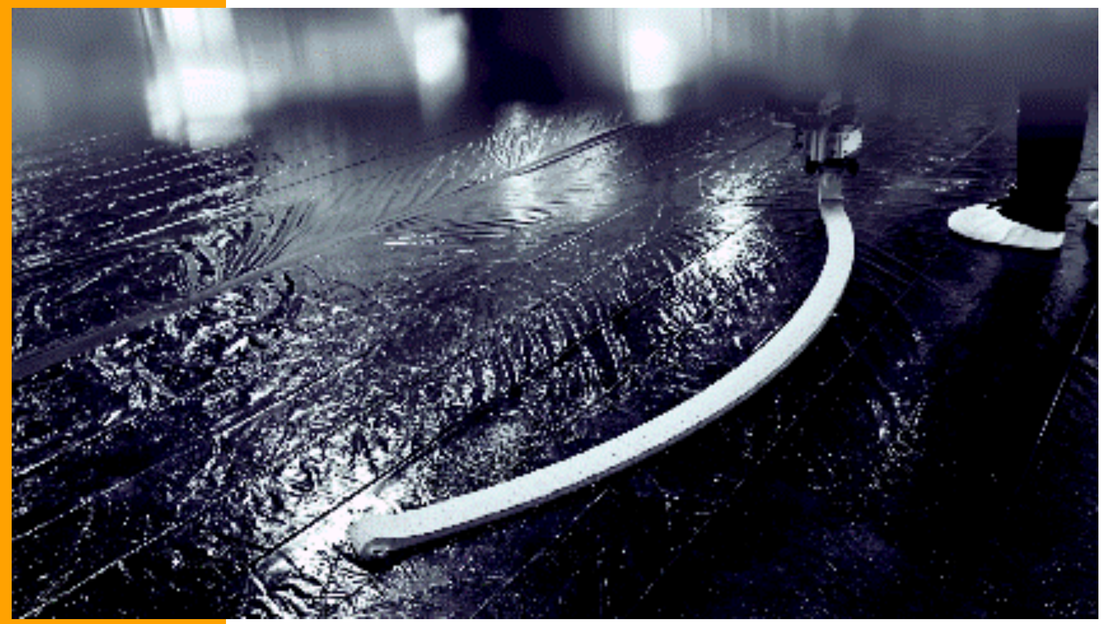


TOTAL WALL LENGTH: 166'-0"



TOTAL WALL LENGTH: 176'-0"

Mortar vs Concrete



Low-Income Housing Units

(Los Angeles, California)

QUESTIONS?

ICC LEARN LIVE

Thank you for participating!

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