EGGSHELL

design and fabrication of non-standard, structural concrete columns using 3D printed thin-shell formwork

EGGSHELL

design and fabrication of non-standard, structural concrete columns using 3D printed thin-shell formwork

P5 Presentation
Sustainable Design Graduation
Delft University of Technology

Joris Burger
23.01.2019

Dr. ir. Christian Louter
Dr. ir. Serdar Asut
Dr. Ena Lloret-Fritschi

TUDelft

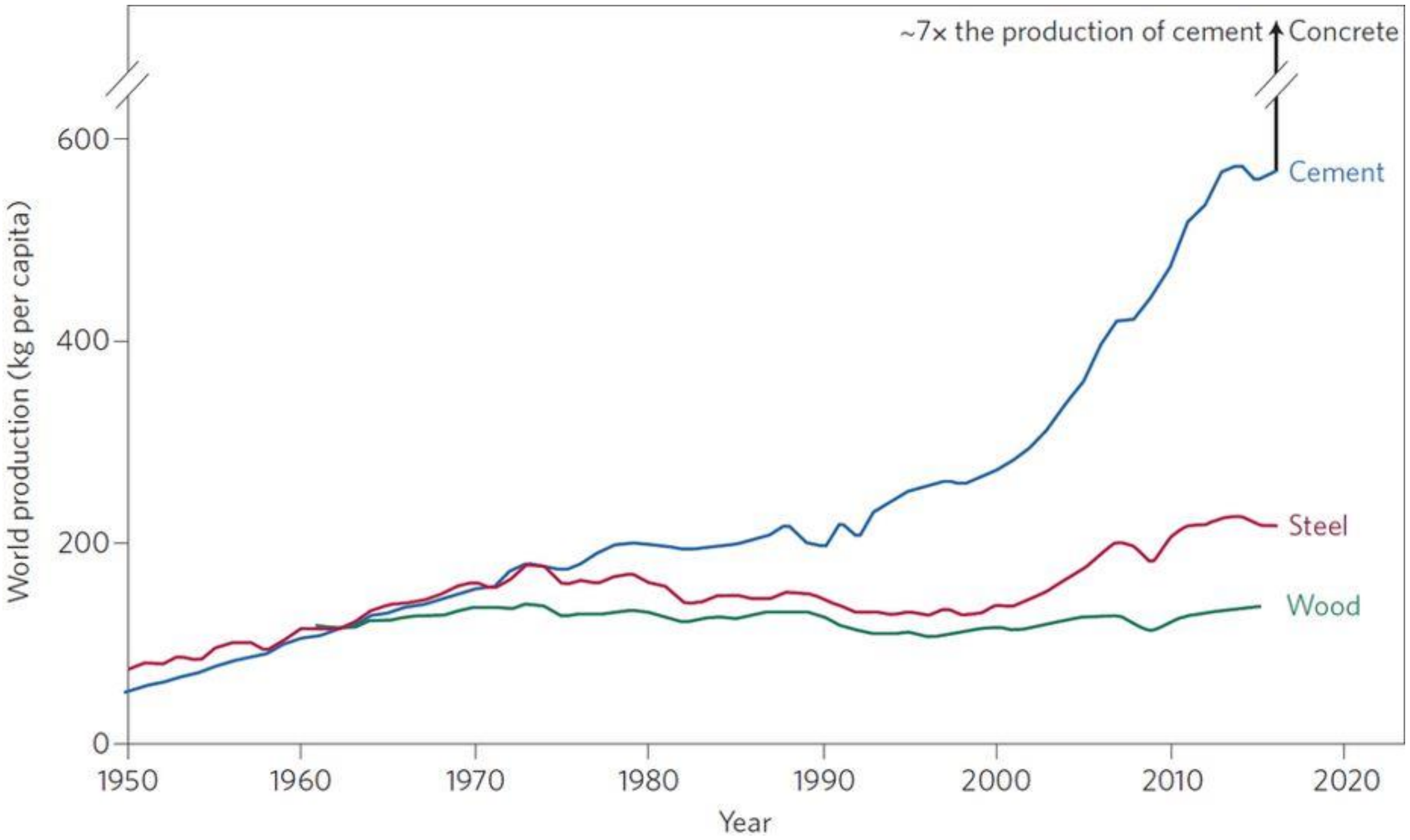
GRAMAZIO KOHLER RESEARCH

Content

1. INTRODUCTION

Introduction

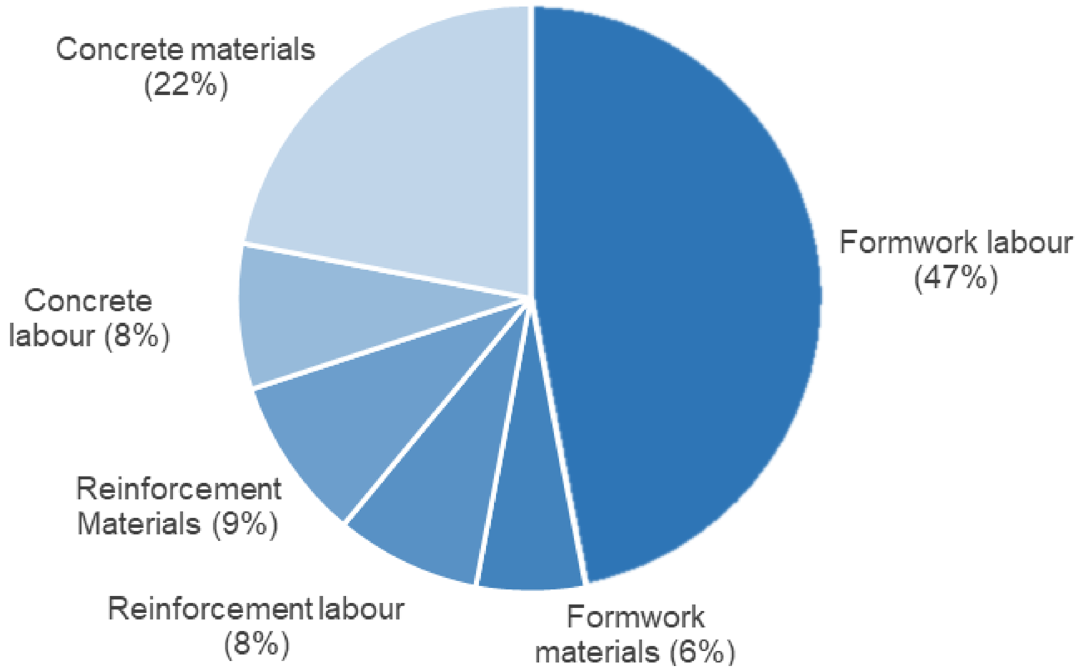
Production of various building materials



Paulo, Monteiro, Sabbie, Miller and Horvath (2017)

Introduction

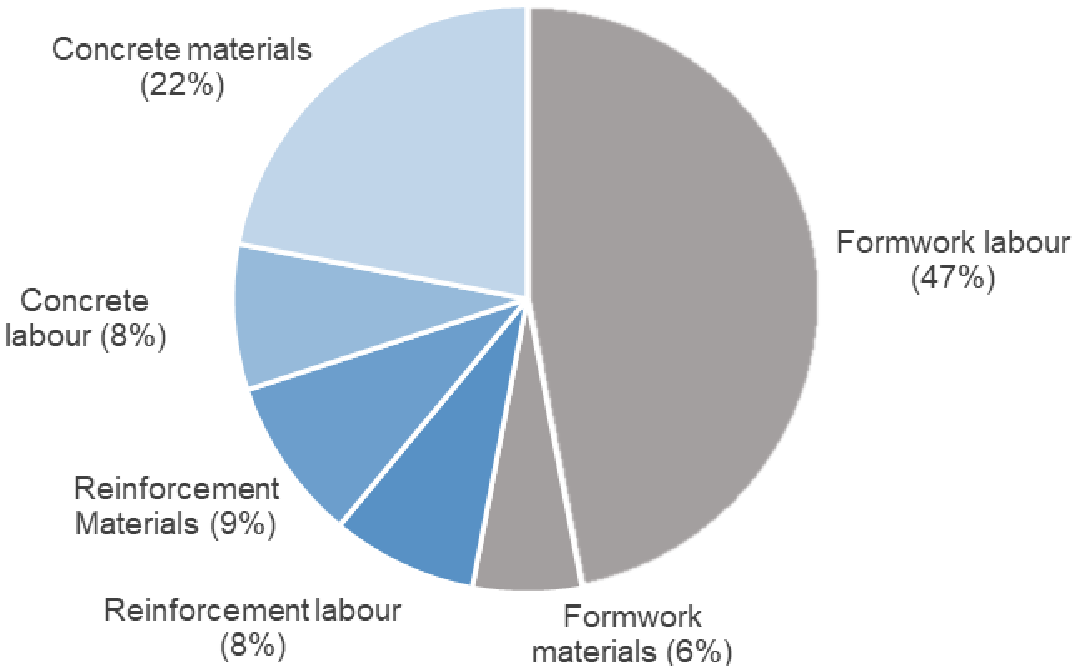
Cost distribution of a standard concrete element



Lab (2007)

Introduction

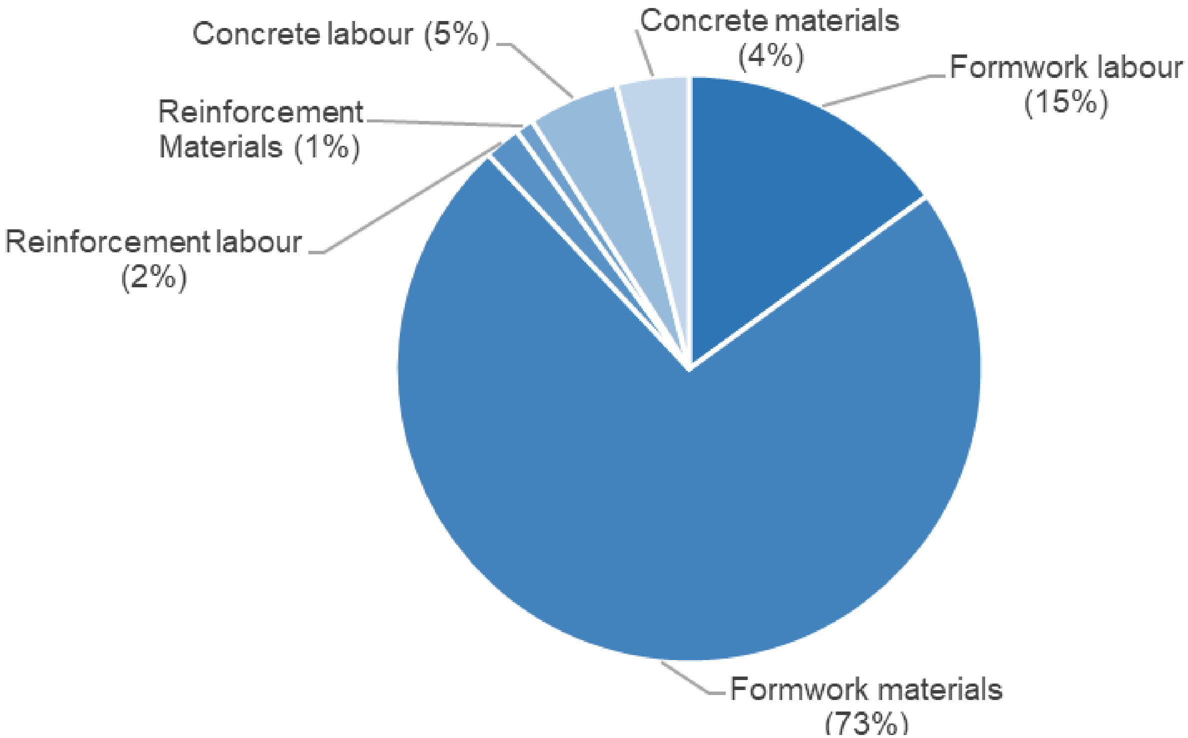
Cost distribution of a standard concrete element



Lab (2007)

Introduction

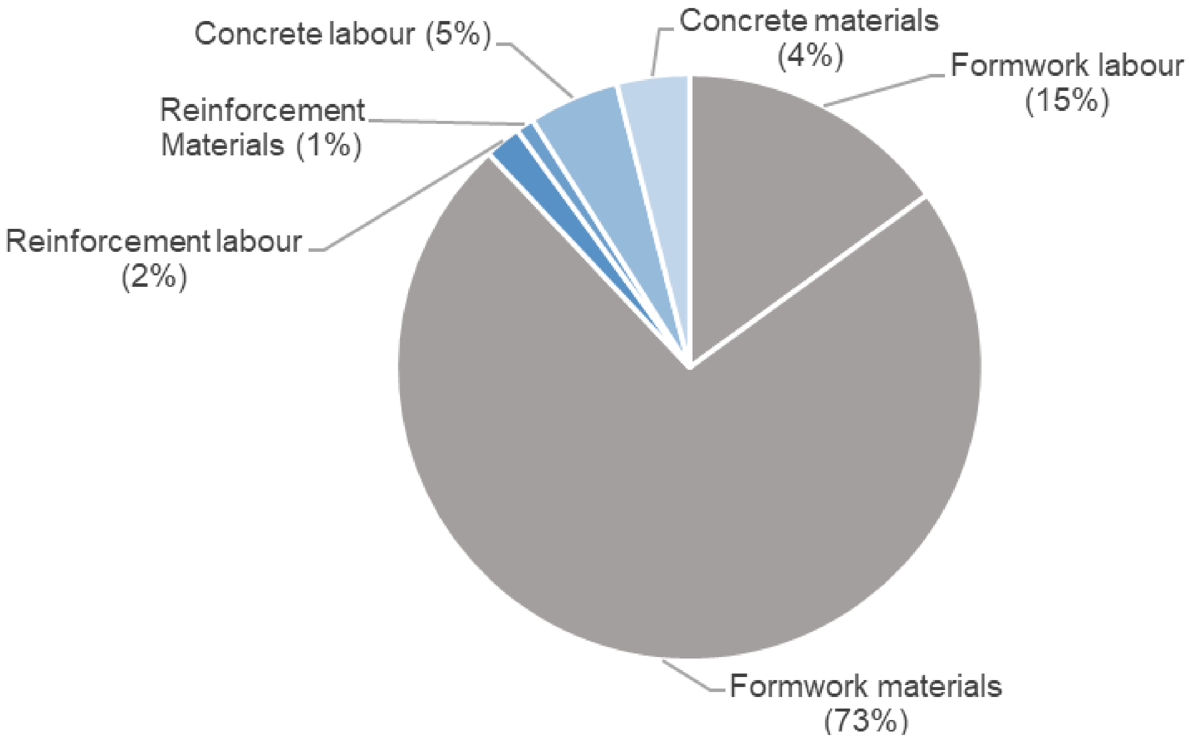
Cost distribution of a non-standard concrete element



Schipper and Grünewald (2014)

Introduction

Cost distribution of a non-standard concrete element



Schipper and Grünewald (2014)

Introduction

Rolex Learning Center, Lausanne – SANAA (2011)

Source: Lausanne Tourisme, n.d. photograph, viewed 20 January 2019, <https://www.lausanne-tourisme.ch/en/P10671/the-rolex-learning-center>.

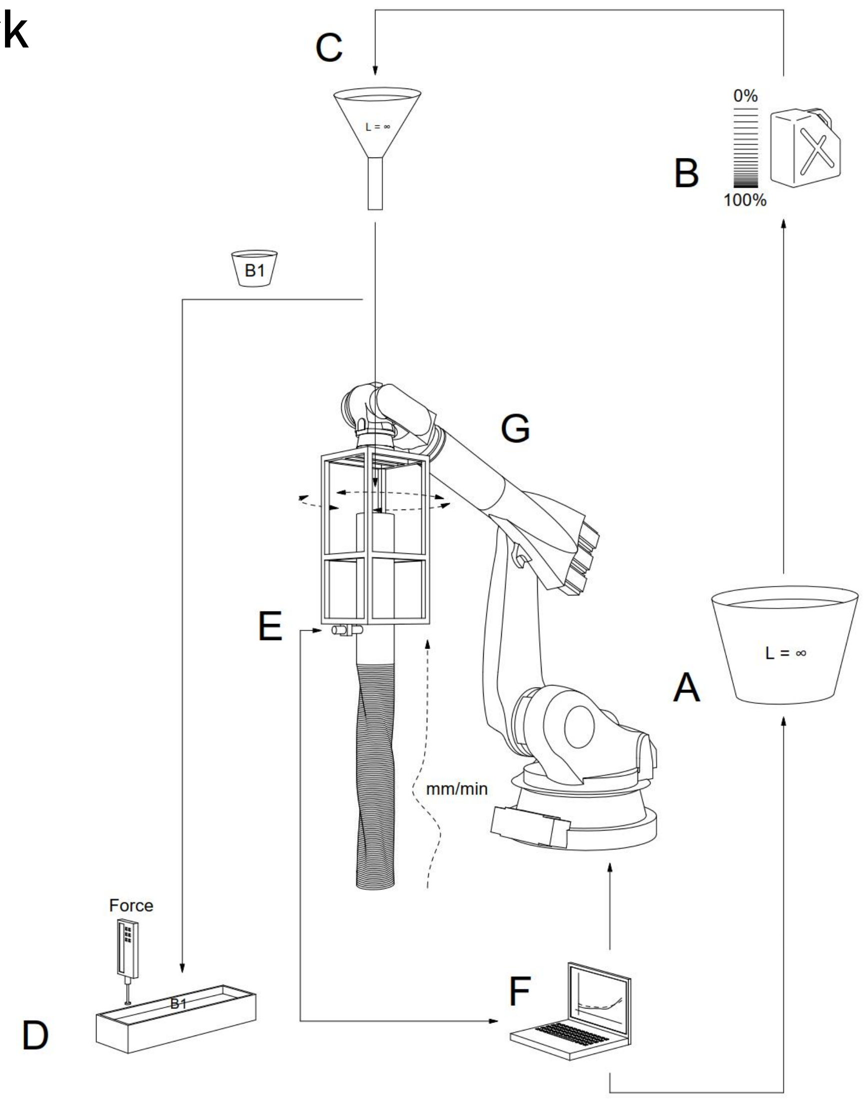
Introduction

Construction of the Rolex Learning Center

Weilandt, Grohmann, Bollinger, and Wagner (2009)

Flexible fabrication of formwork

Smart Dynamic Casting

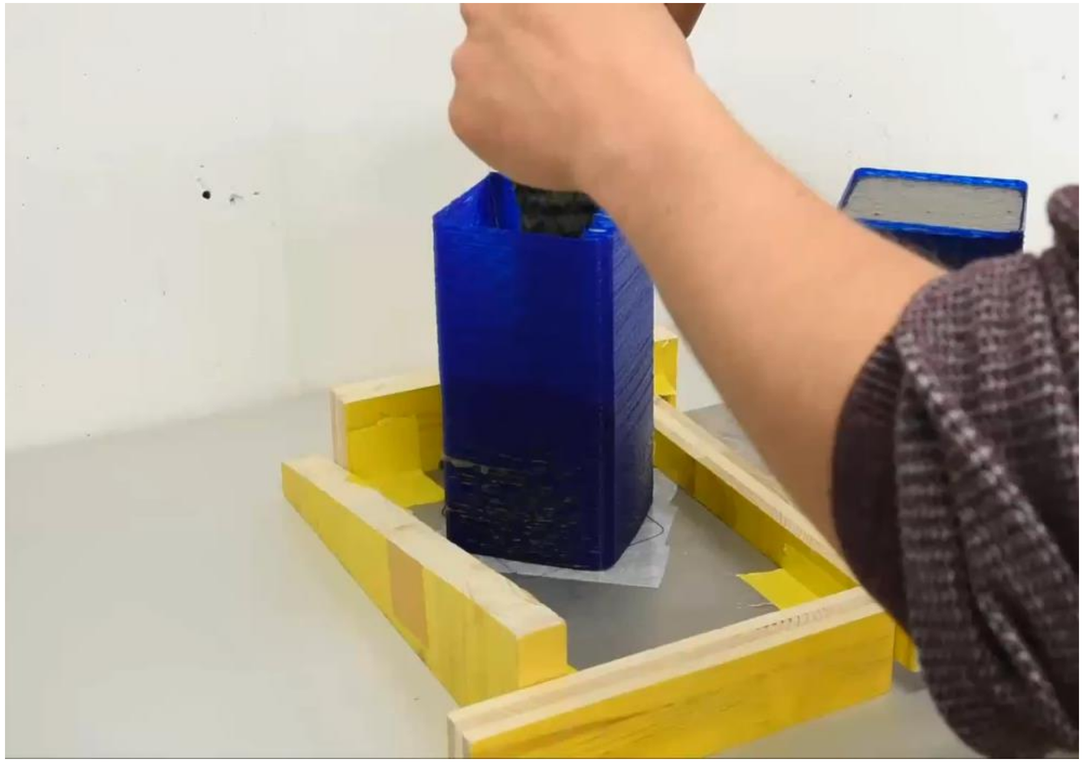


Lloret-Fritschi et al. (2015)

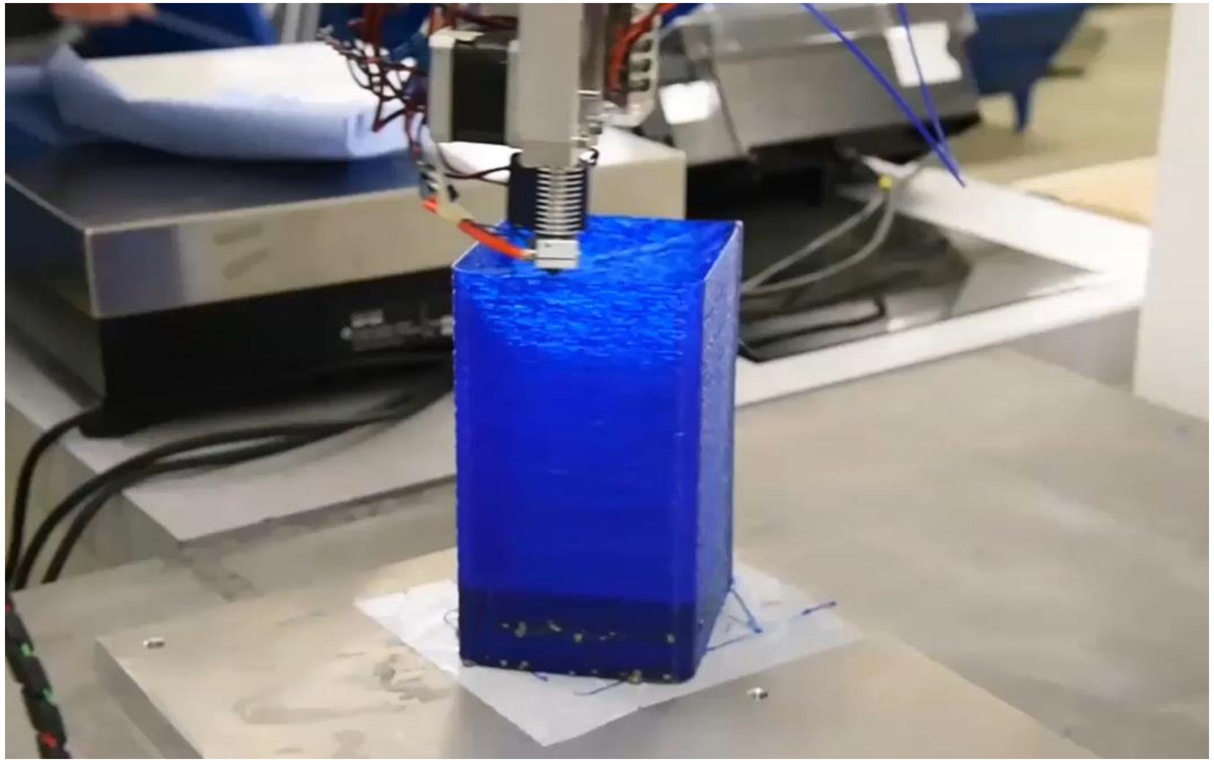
Flexible fabrication of formwork

Lloret-Fritschi et al. (2015)

Concept



Classic concrete filling process



Set-on-demand concrete filling process

Ulrich (2017)

Research question

Can 3D printed, thin-shell formwork be used to fabricate full-scale, non-standard, structural, concrete columns?

Experiments & Results

PHASE I
EXPLORATIONS

- Proof of concept

PHASE II
SCALE-UP

- Integration of reinforcement
- Large scale 3D printing
- Formwork pressure resistance
- Concrete temperature development

PHASE III
CASE-STUDY

- Design
- Detailling
- Fabrication

Experiments & Results

PHASE I
EXPLORATIONS

- Proof of concept

Phase I: Explorations

Branching column fabrication

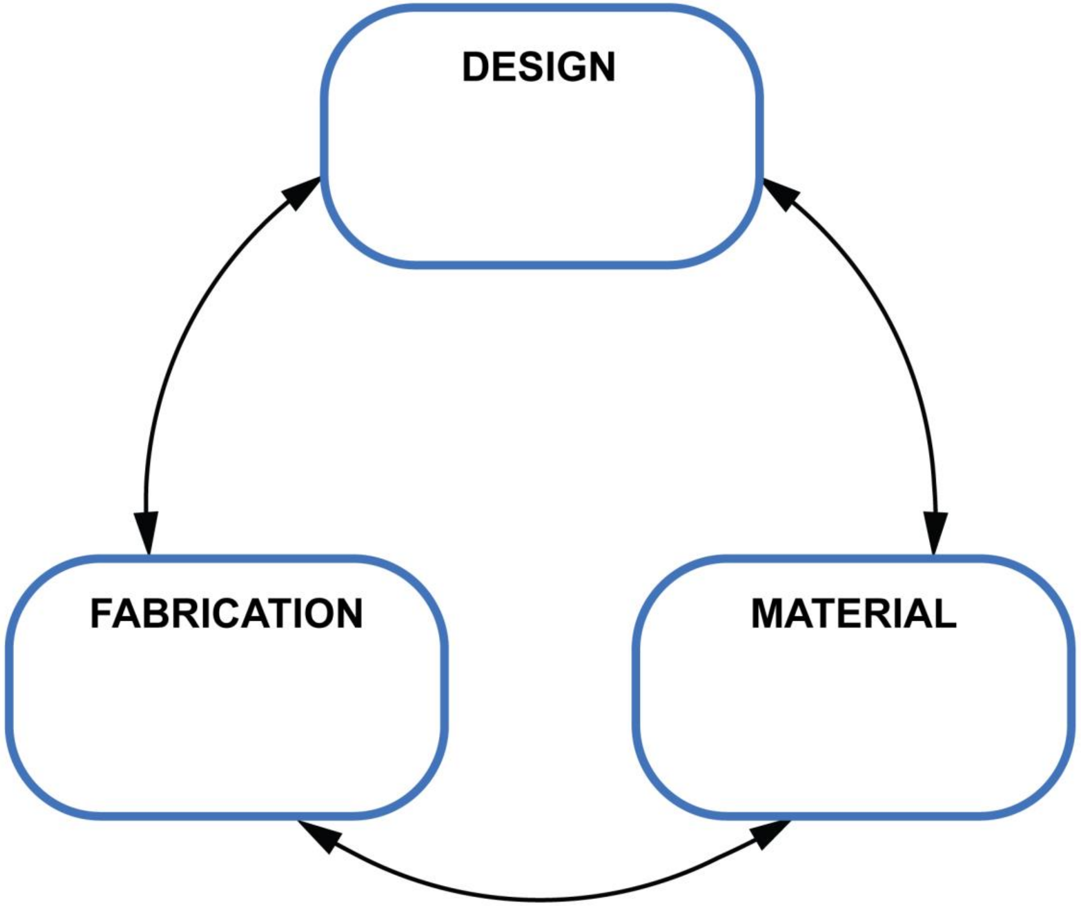
Height	1600mm
Layer height	1.2mm
Vertical build rate	4mm/min
Fabrication time	8 hours
Volume	100L

Simultaneous fabrication

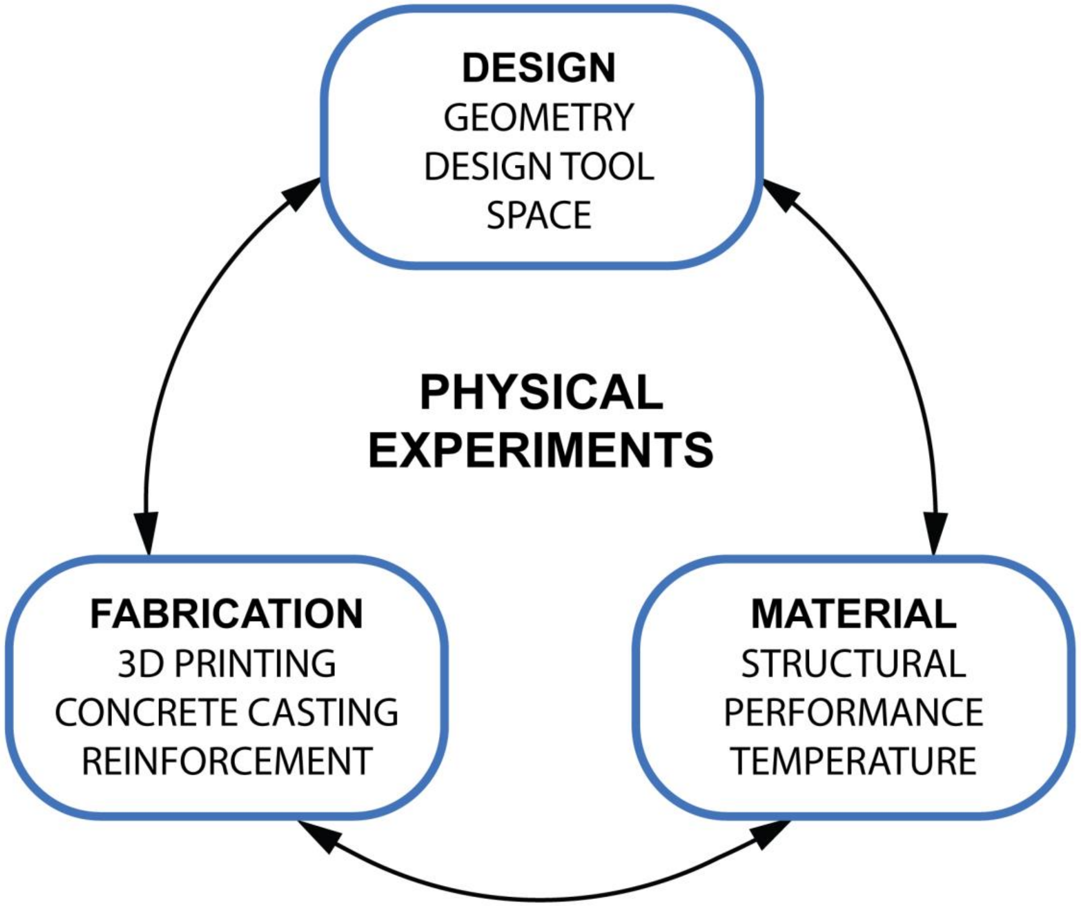
Phase I: Explorations

Formwork removal

Research methodology

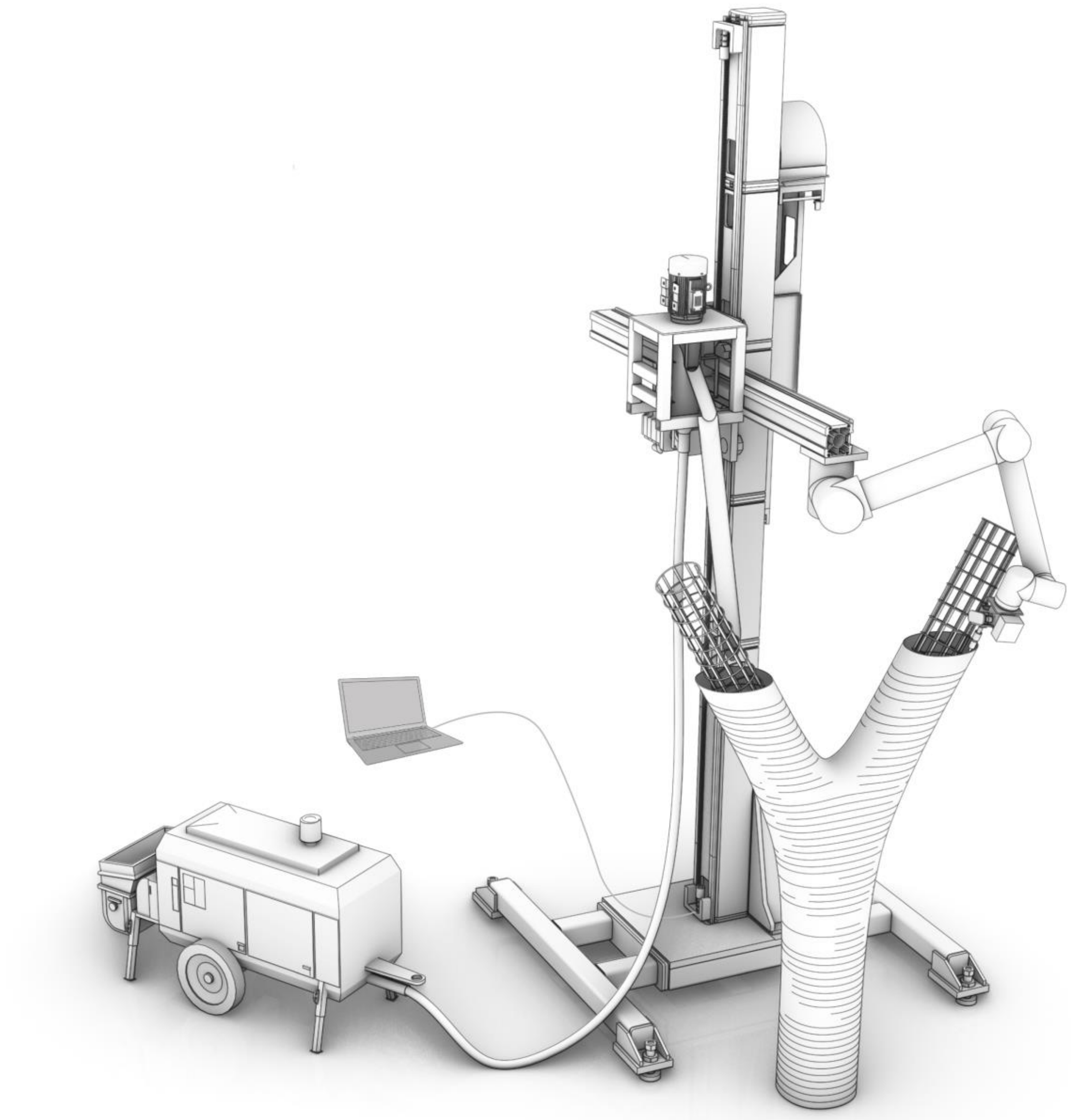


Research methodology

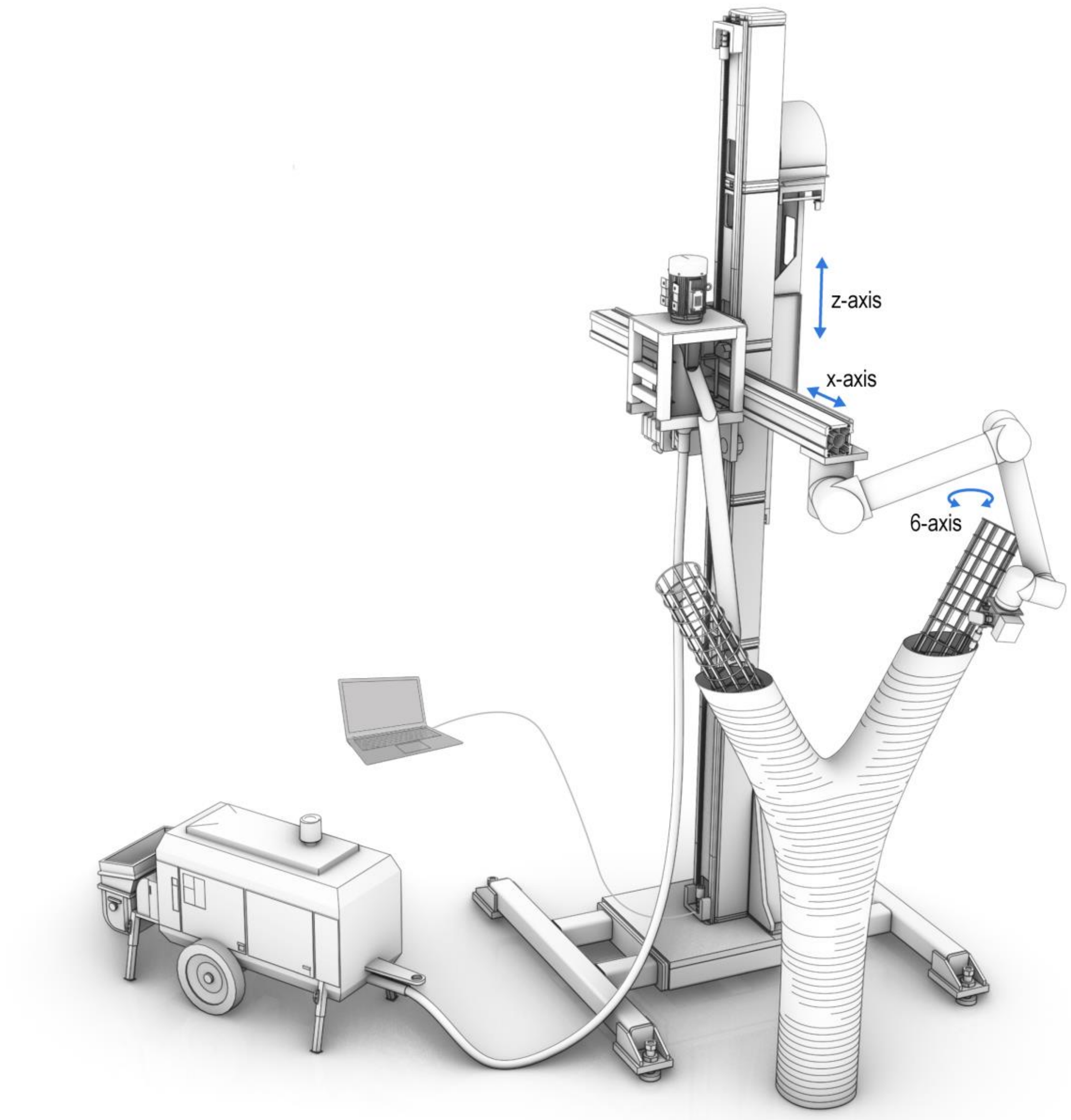



2.
METHODS & MATERIALS

Fabrication setup

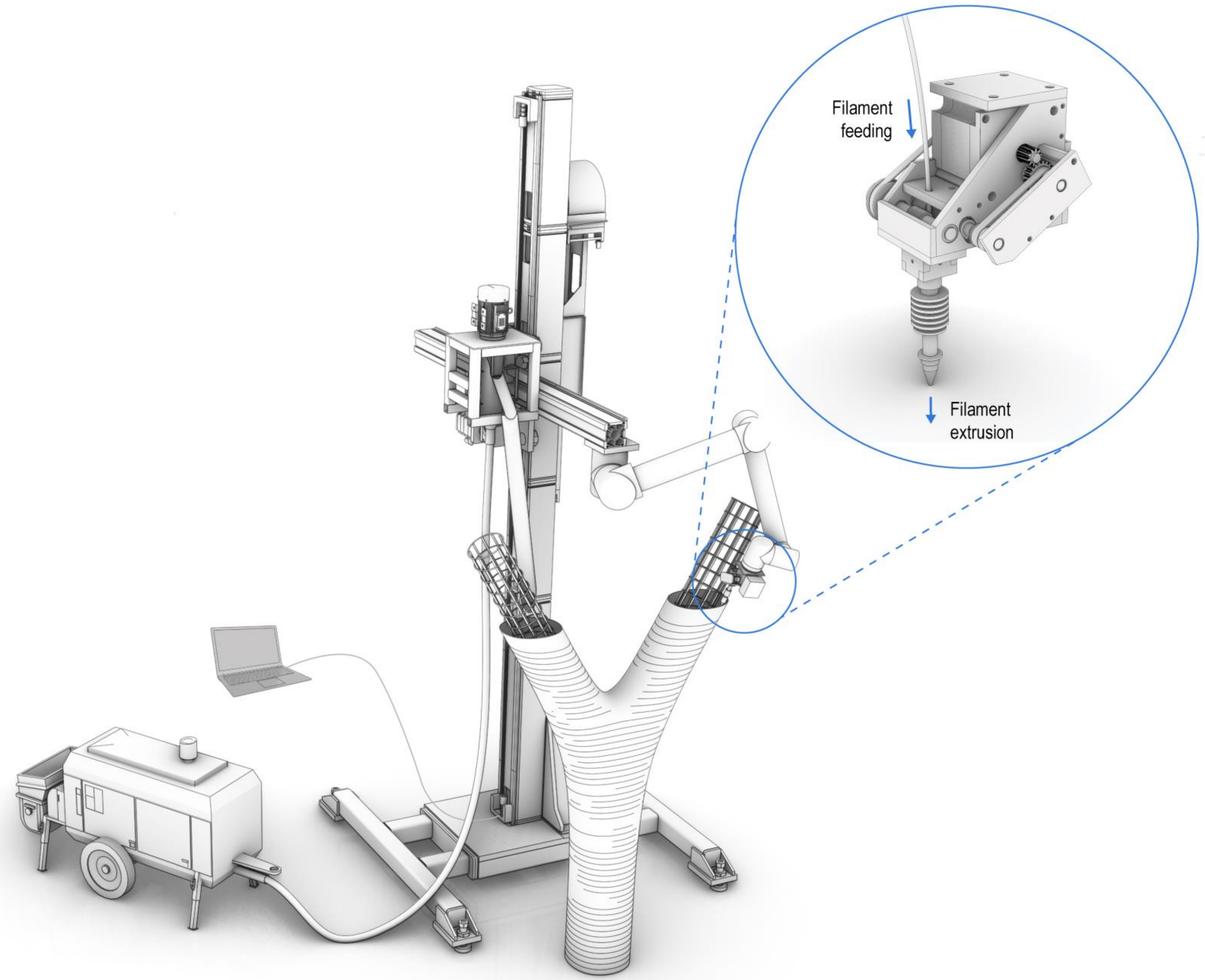


Fabrication setup



GRAMAZIO KOHLER RESEARCH

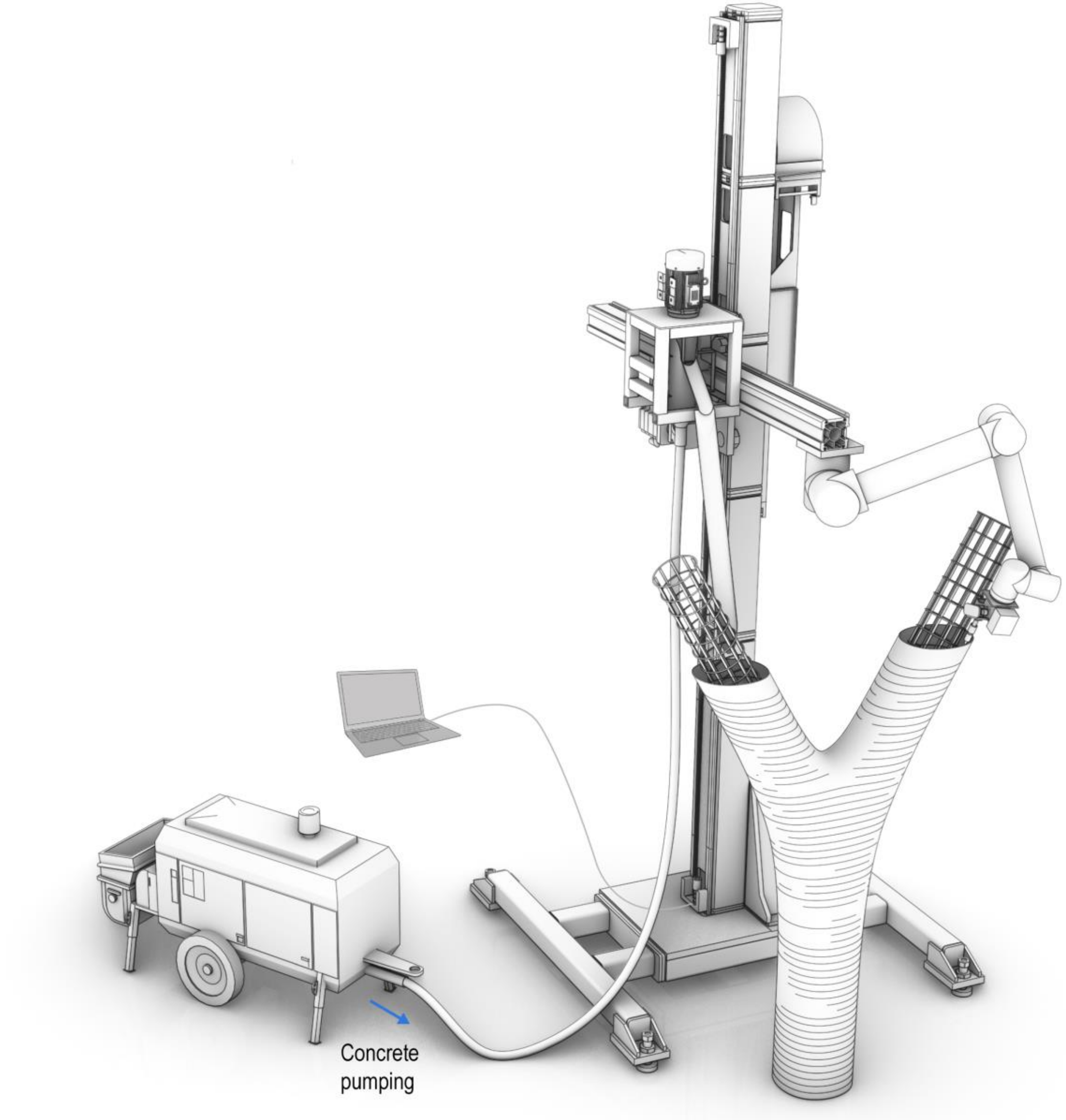
Fabrication setup



P5 Presentation
Sustainable Design Graduation

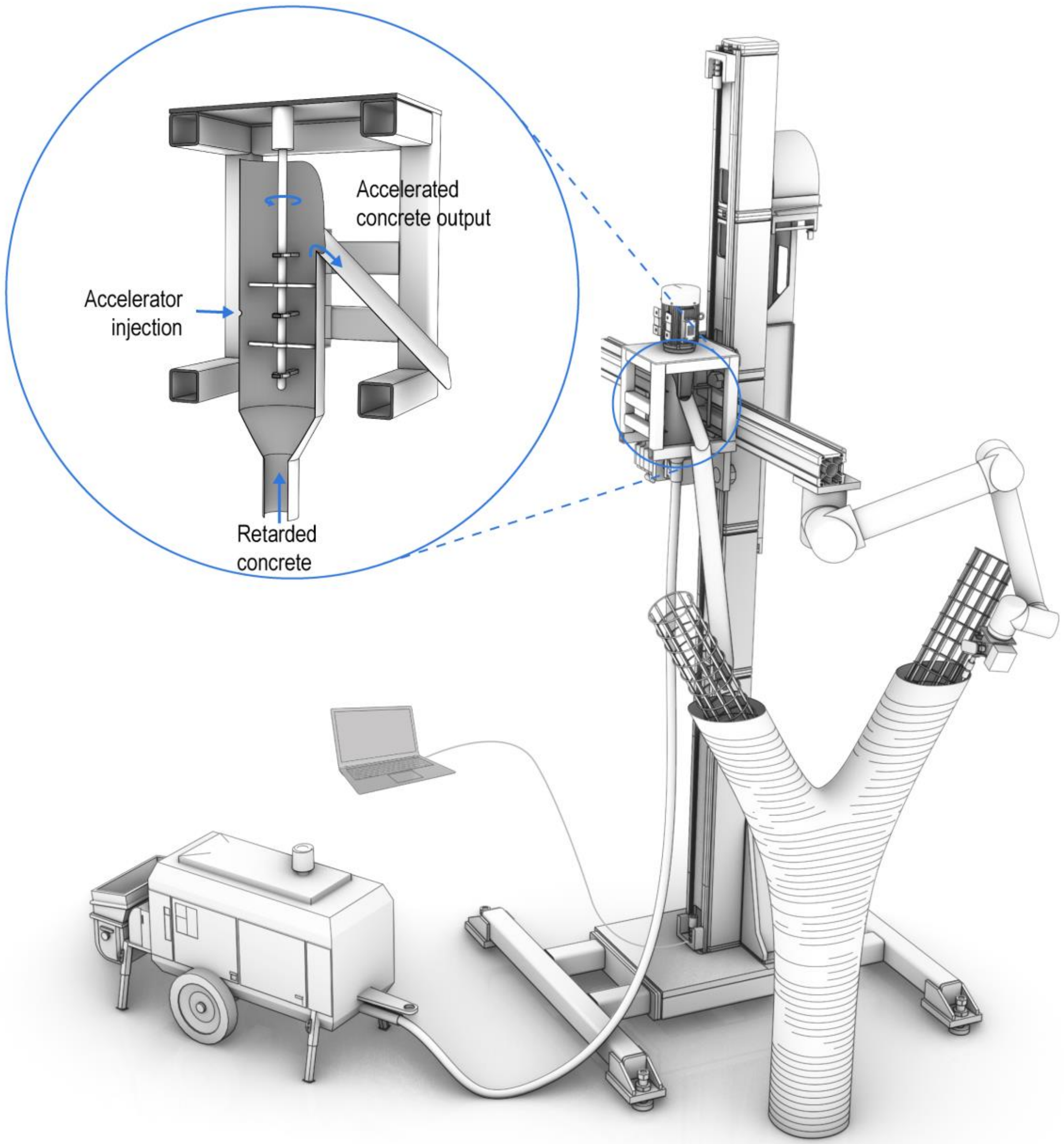
GRAMAZIO KOHLER RESEARCH

Fabrication setup



GRAMAZIO KOHLER RESEARCH

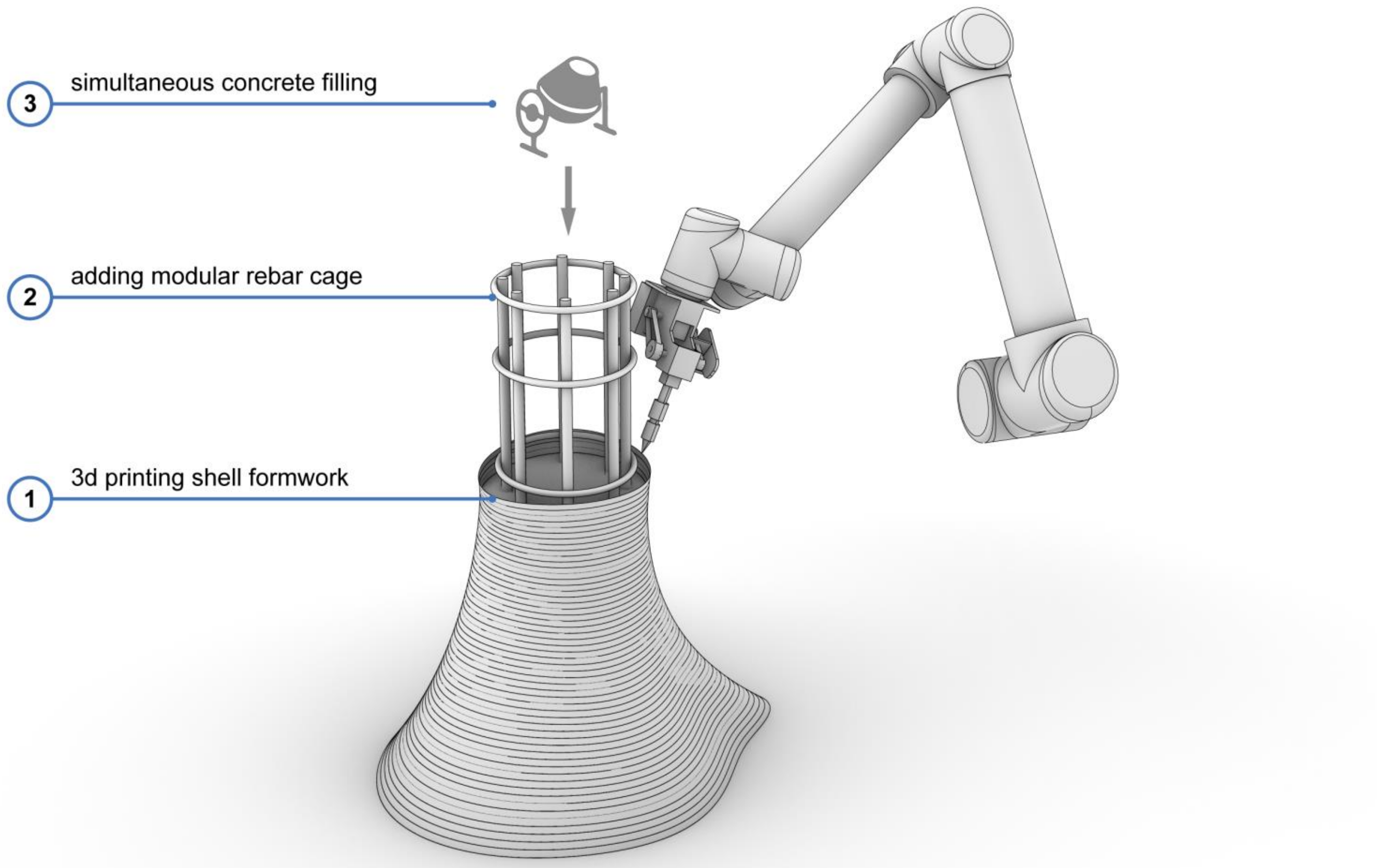
Fabrication setup



GRAMAZIO KOHLER RESEARCH

Fabrication approaches

Simultaneous fabrication



TUDelft

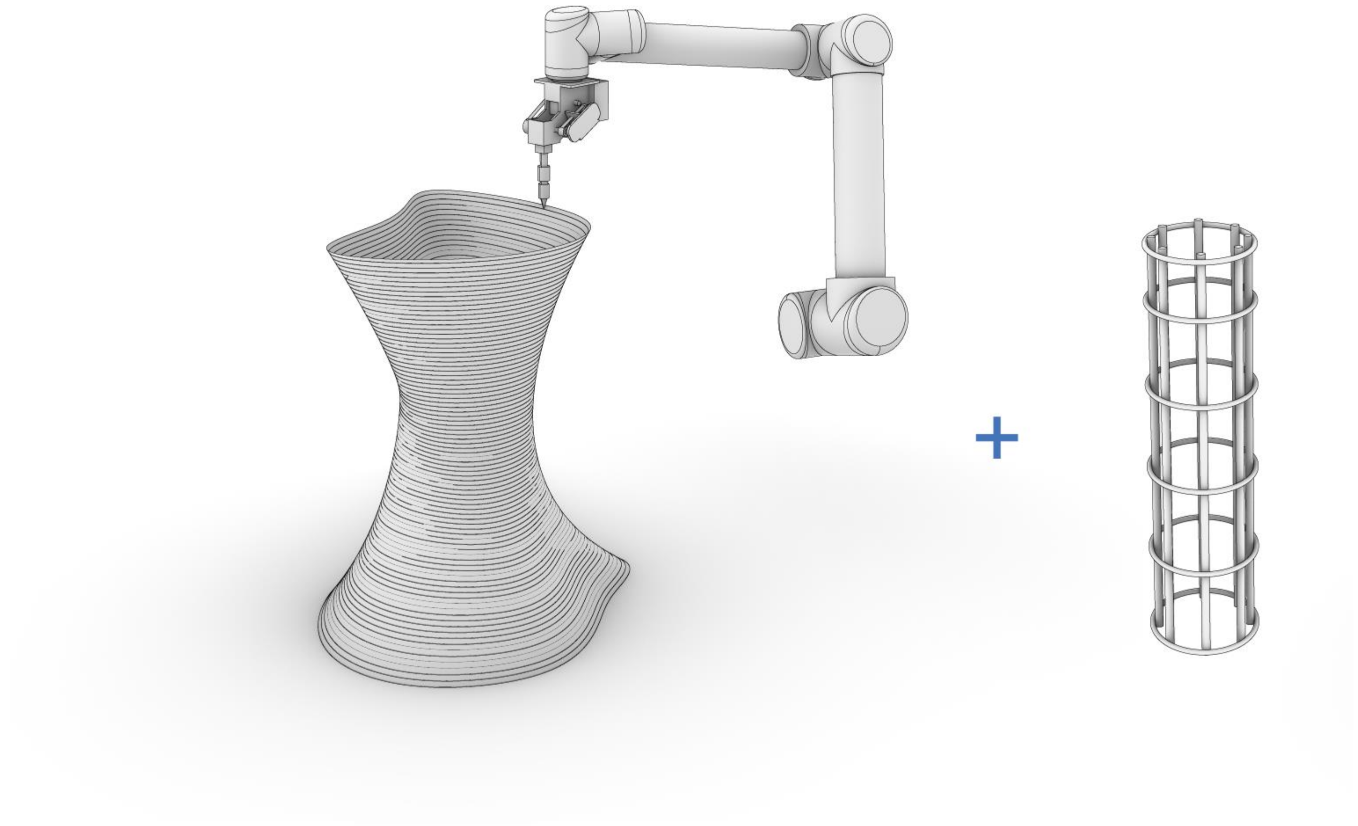
GRAMAZIO KOHLER RESEARCH

Fabrication approaches

Consecutive fabrication

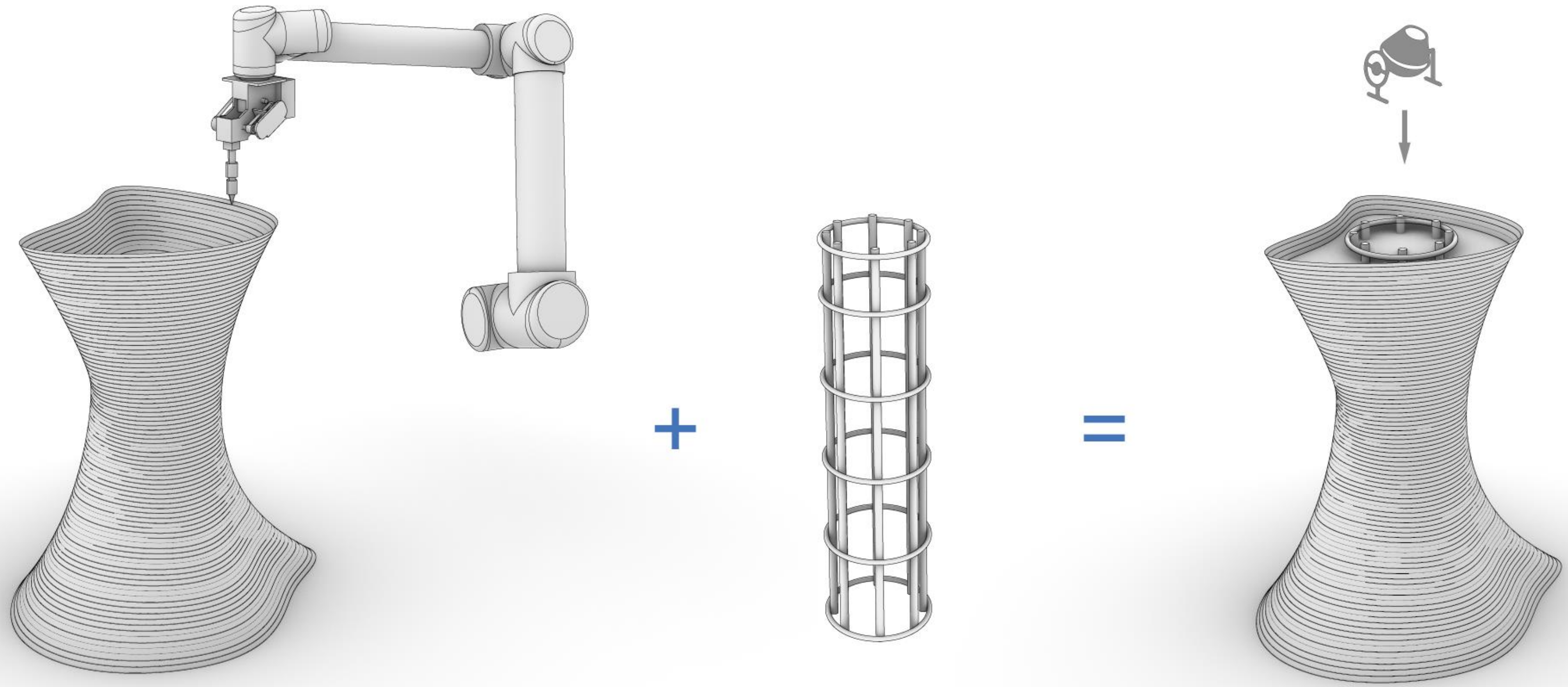
Fabrication approaches

Consecutive fabrication



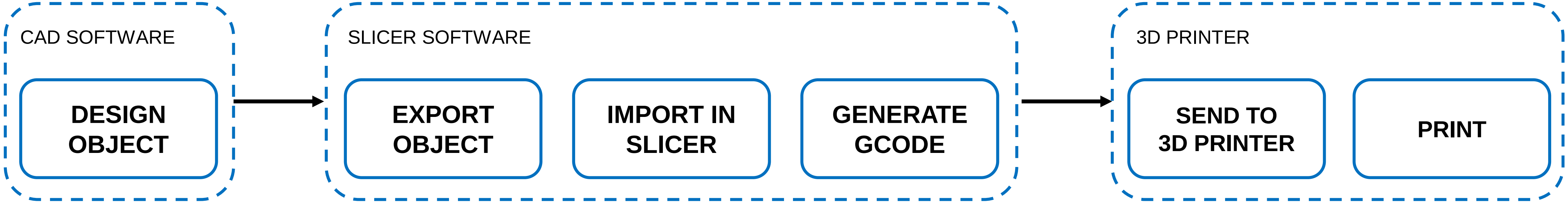
Fabrication approaches

Consecutive fabrication



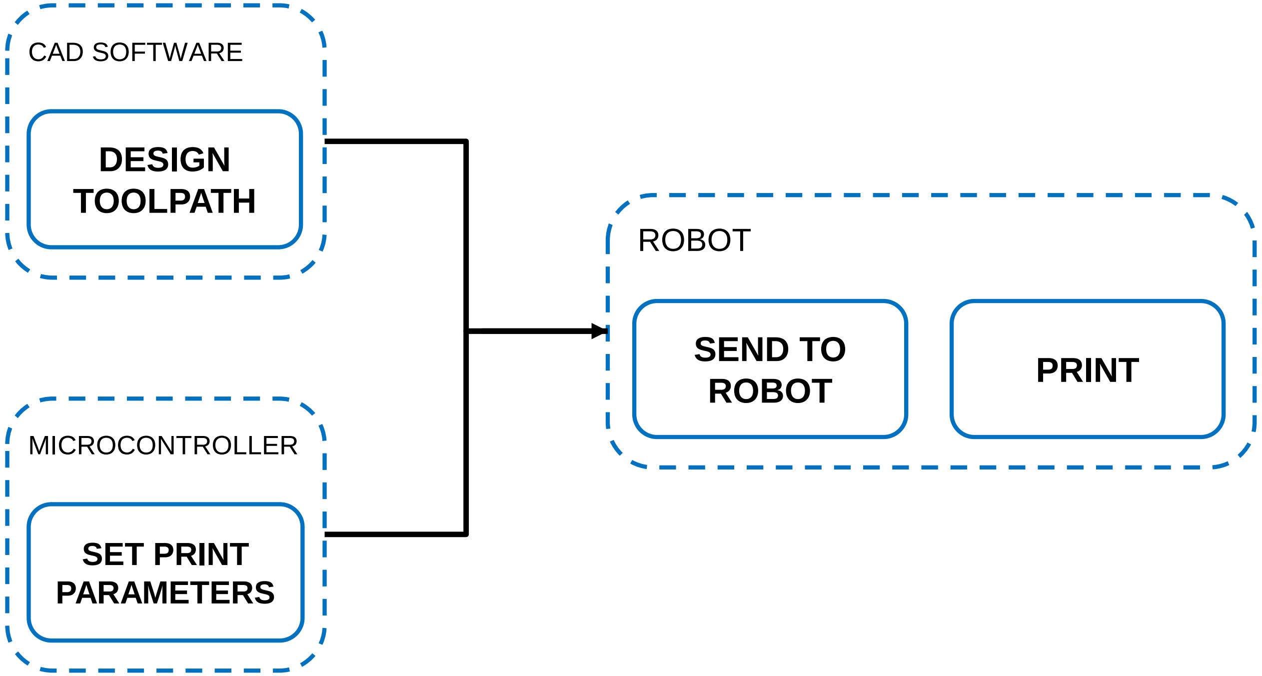
Digital design and control

Standard 3D printing workflow



Digital design and control

Robotic 3D printing design and fabrication workflow



3.
EXPERIMENTS & RESULTS

Experiments & Results

PHASE II
SCALE-UP

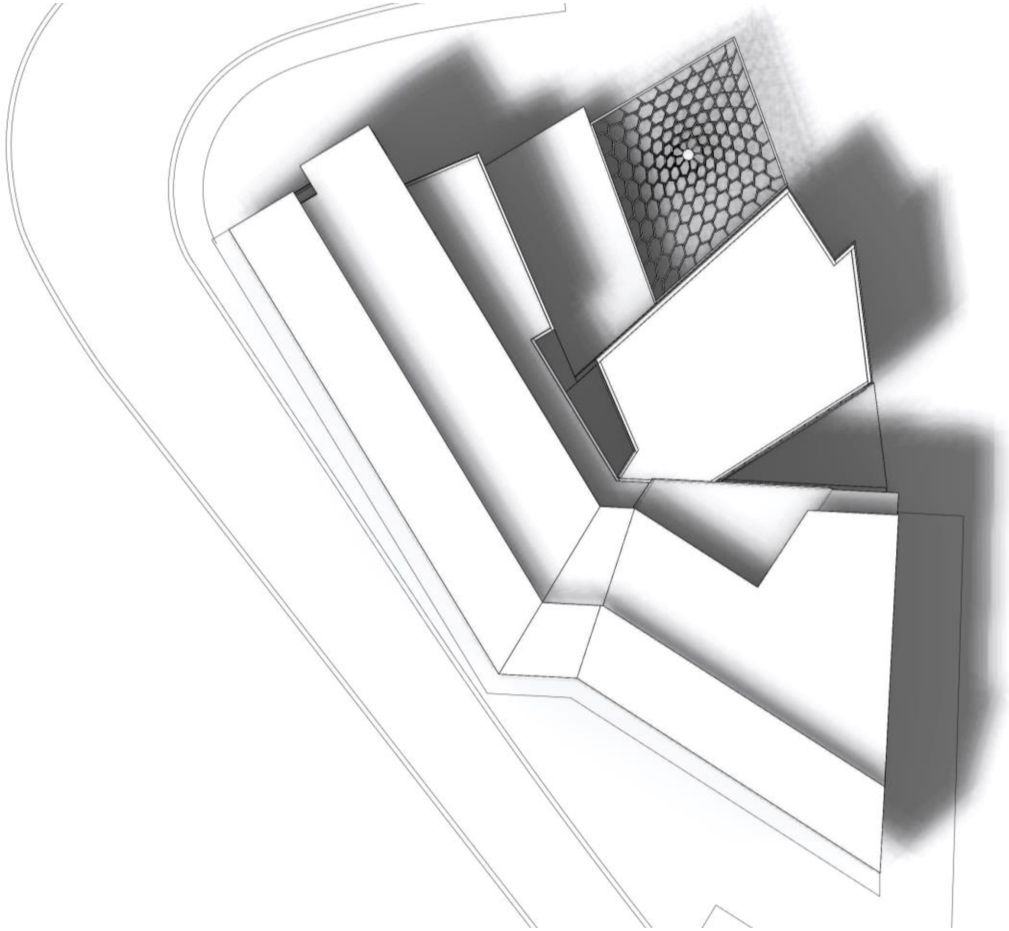
- Integration of reinforcement
- Large scale 3D printing
- Formwork pressure resistance
- Concrete temperature development

PHASE III
CASE-STUDY

- Design
- Detailling
- Fabrication

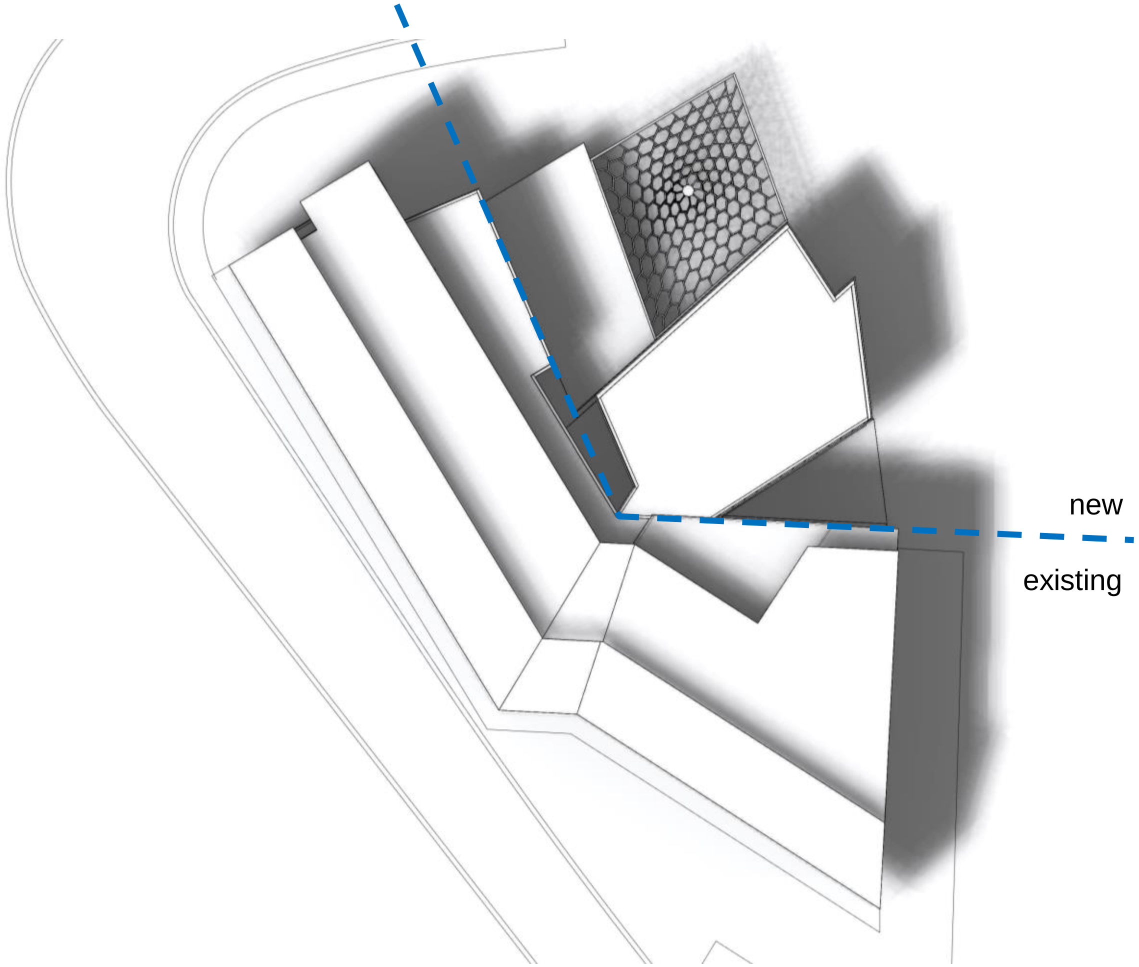
Phase II: Scale-up

Basler & Hofmann case study



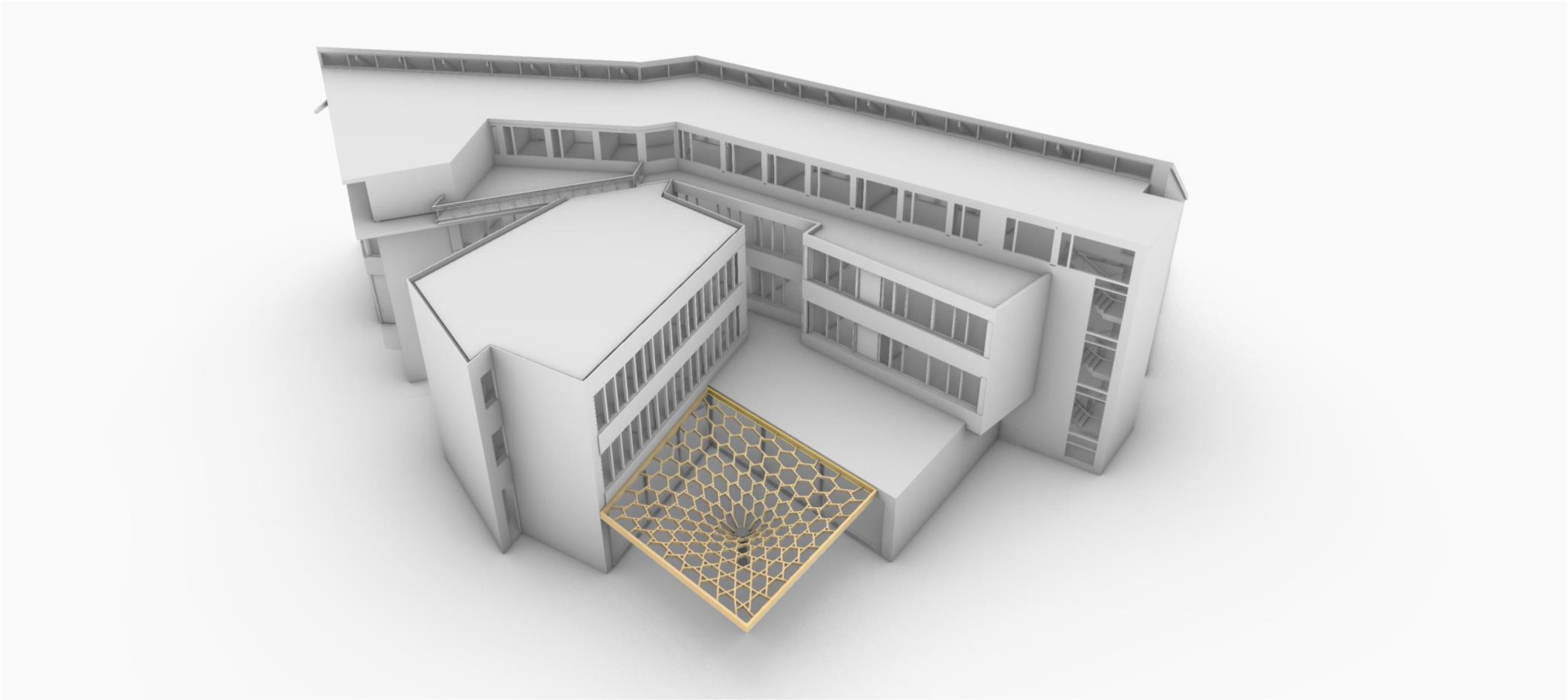
Phase II: Scale-up

Basler & Hofmann case study



Phase II: Scale-up

Basler & Hofmann case study

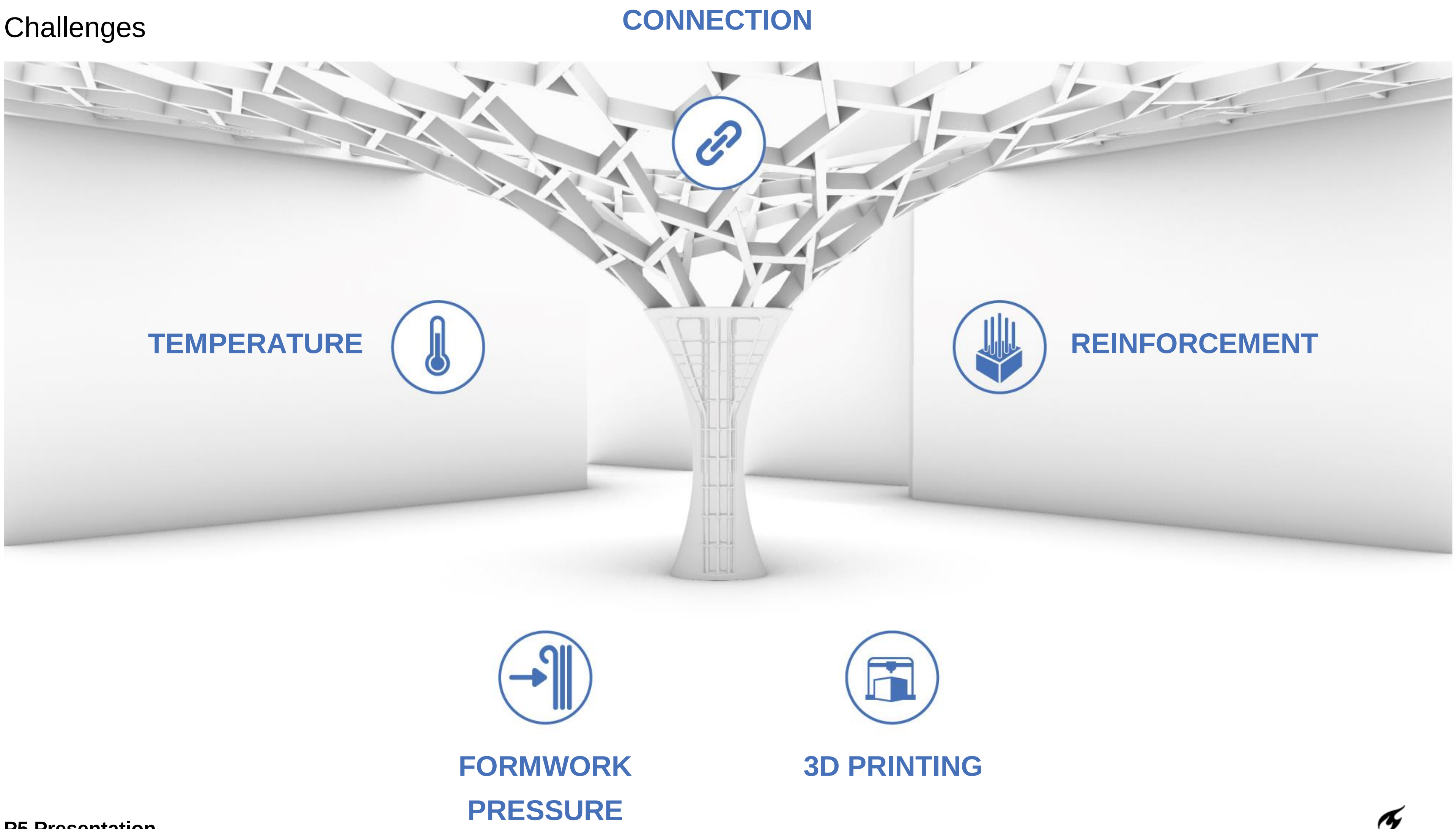


Phase II: Scale-up

Starting point

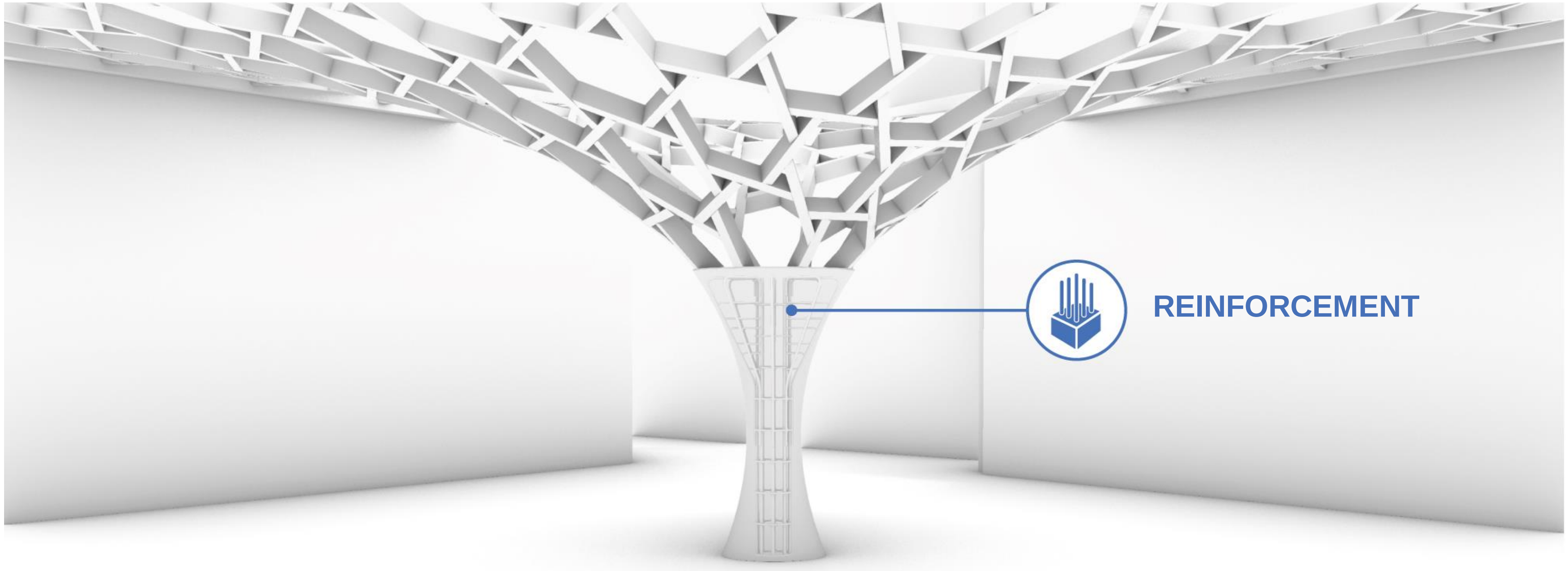
Phase II: Scale-up

Challenges



Phase II: Scale-up

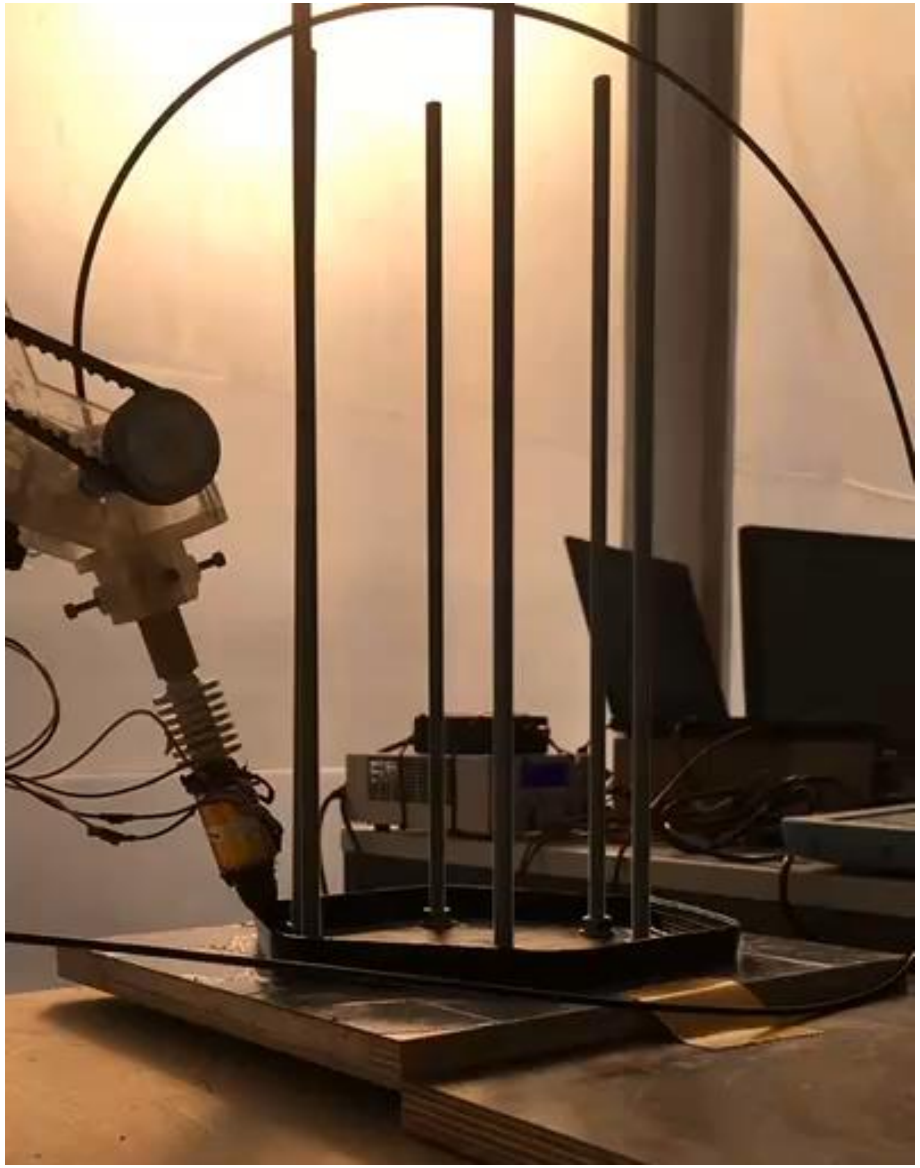
Integration of reinforcement



Phase II: Scale-up

Integration of reinforcement

// Simultaneous fabrication



Phase II: Scale-up

Integration of reinforcement

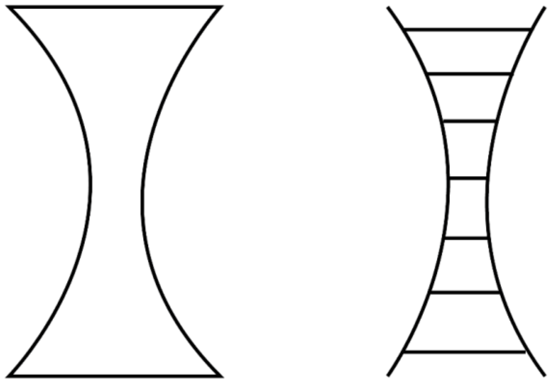
// Consecutive fabrication

Phase II: Scale-up

Integration of reinforcement

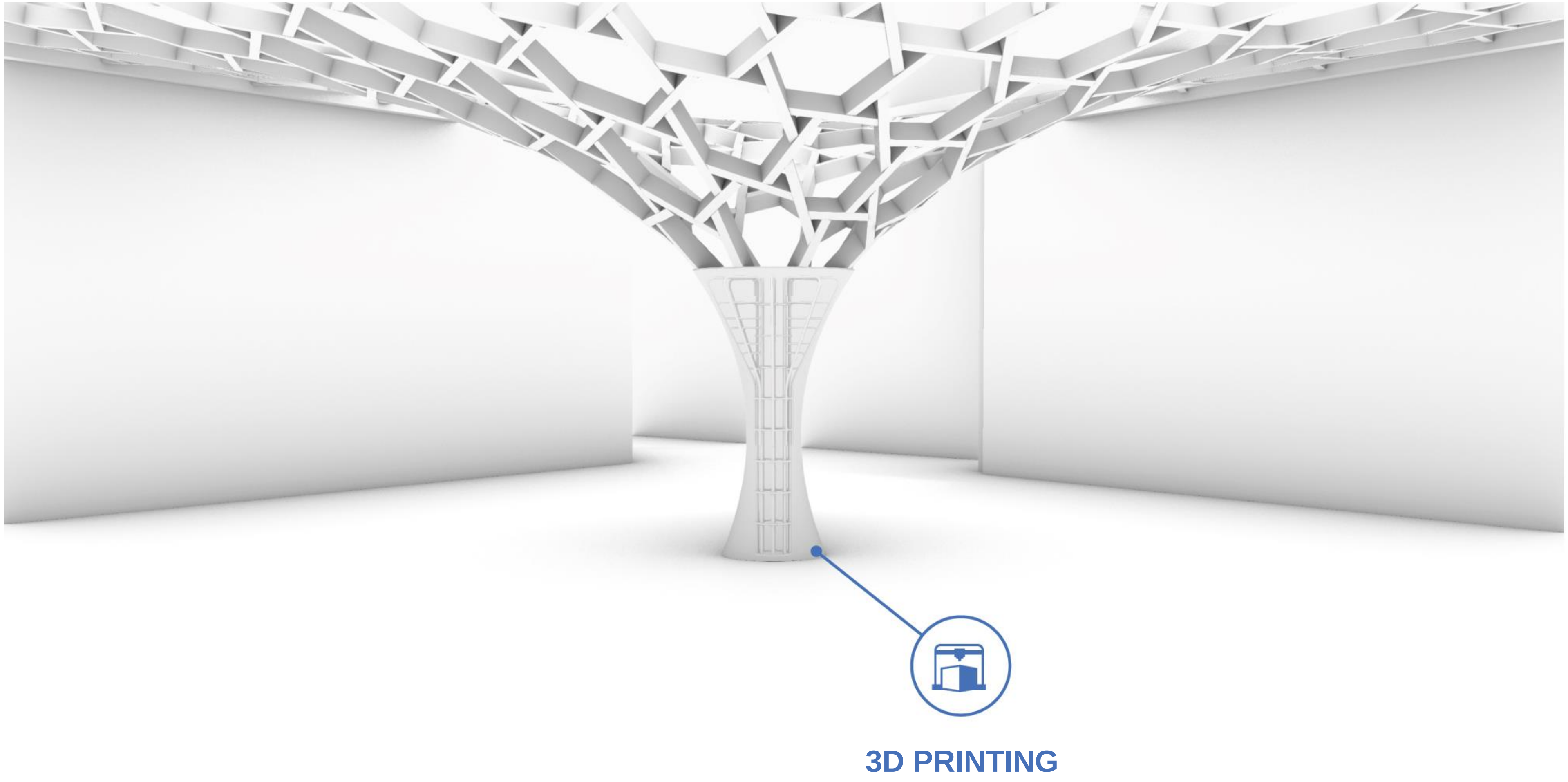
// Conclusions

- Fabrication of reinforced columns using consecutive fabrication is feasible.
- Highly dependent on concrete properties.
- Geometric limitations because of reinforcement



Phase II: Scale-up

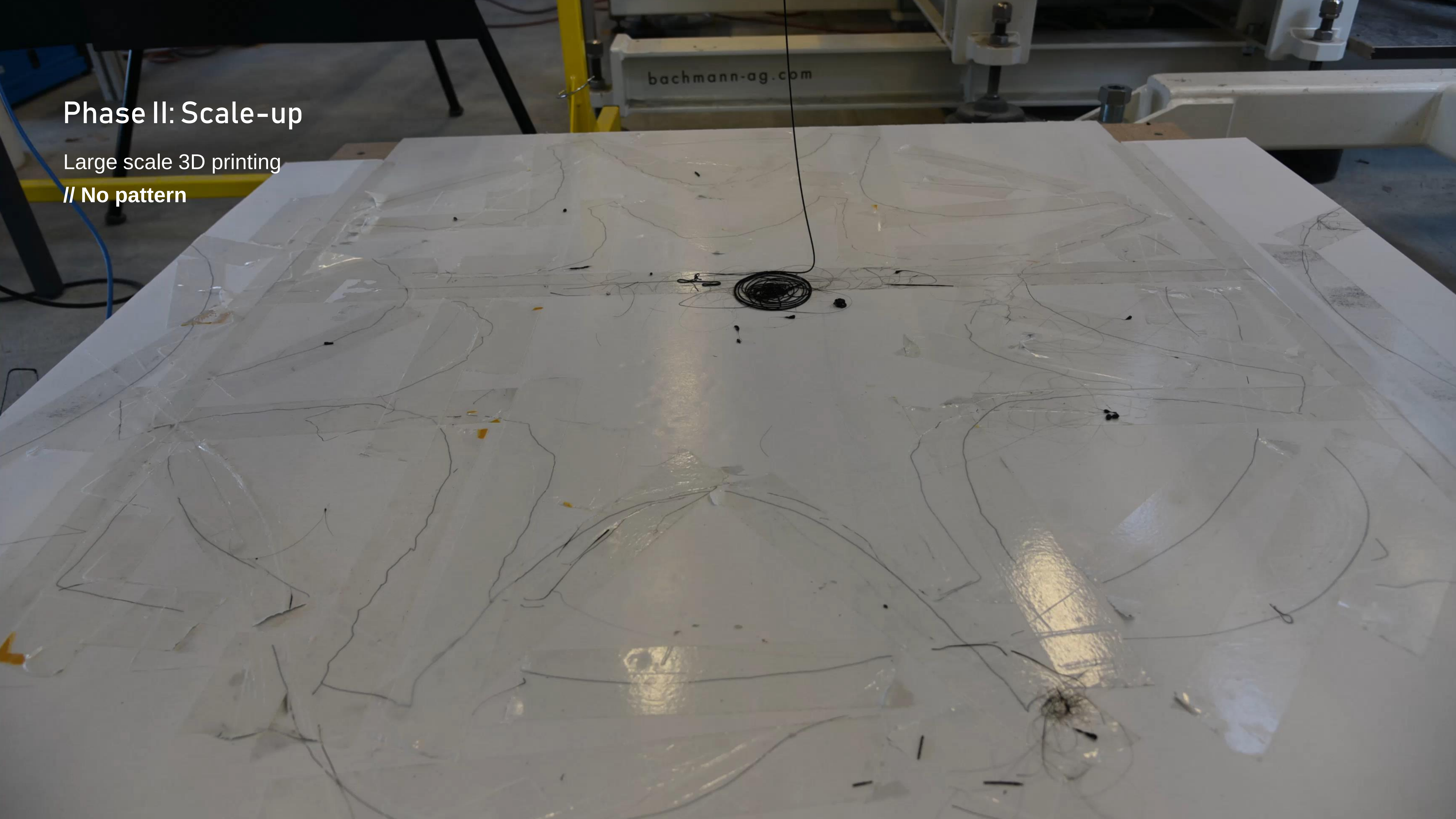
Challenges of large-scale 3D printing



Phase II: Scale-up

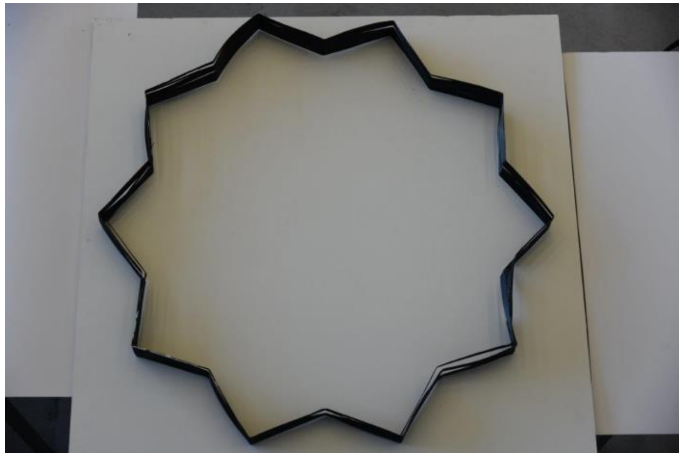
Large scale 3D printing

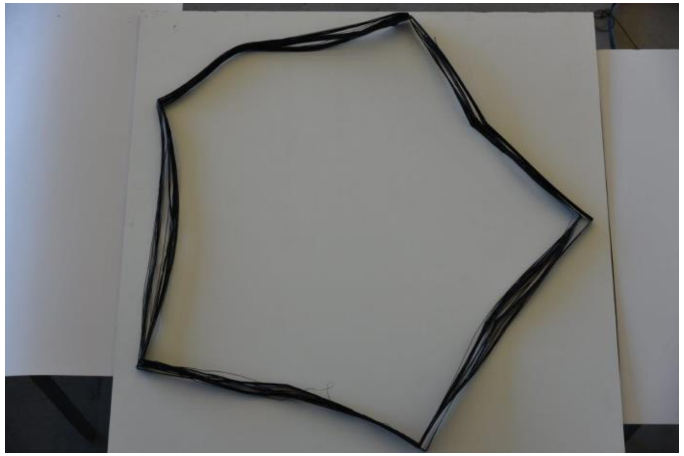
// No pattern

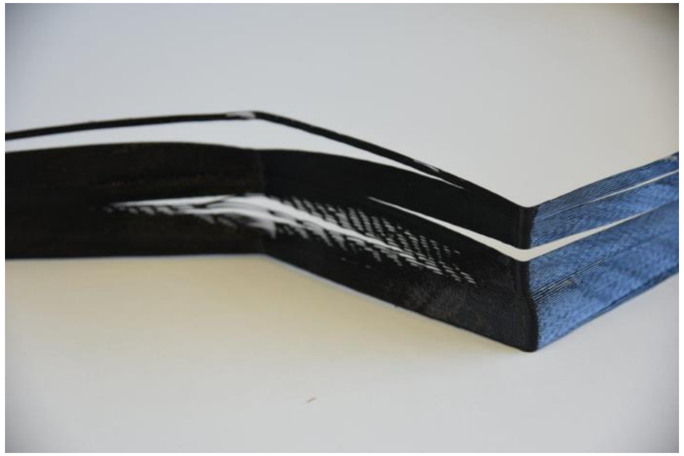


Phase II: Scale-up

Large scale 3D printing

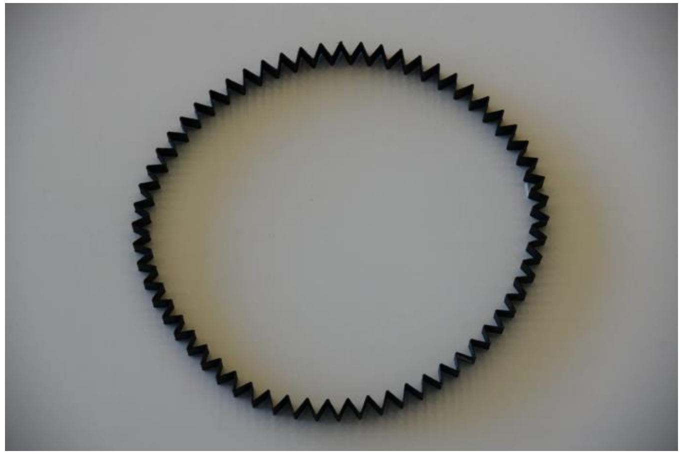
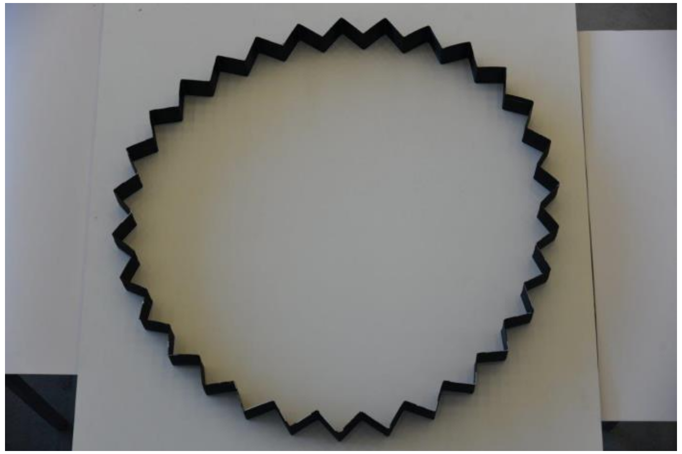
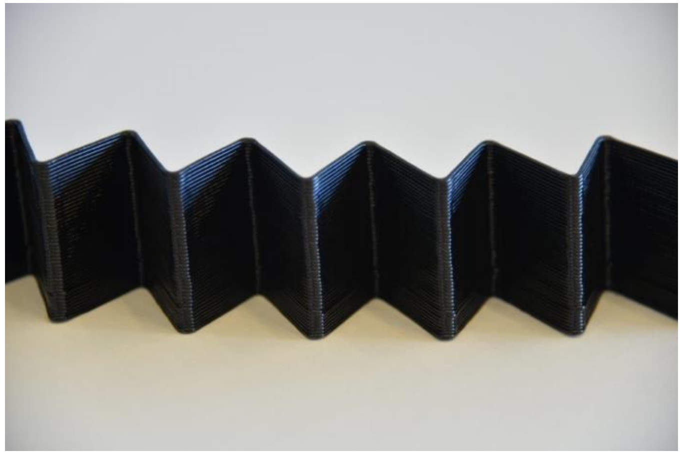
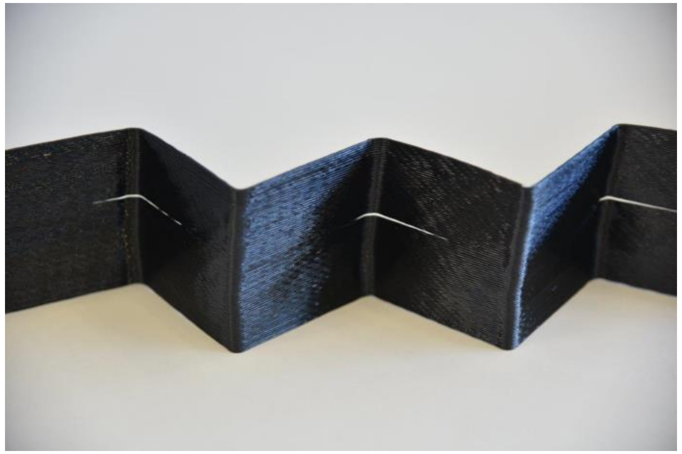






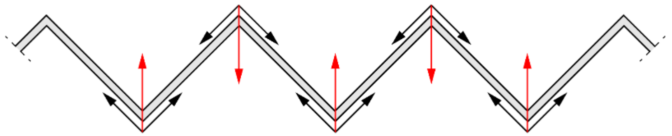
Phase II: Scale-up

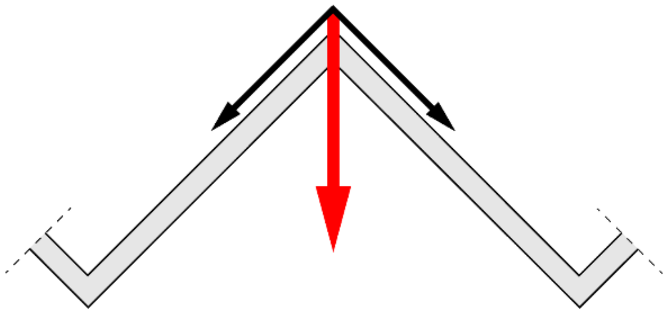
Large scale 3D printing

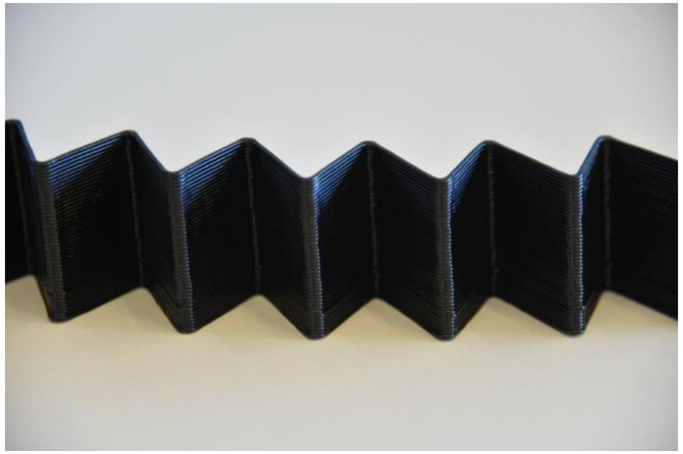





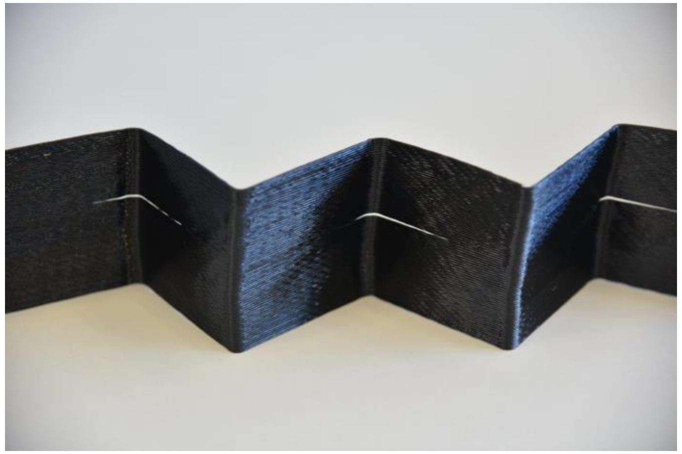
Phase II: Scale-up

Large scale 3D printing







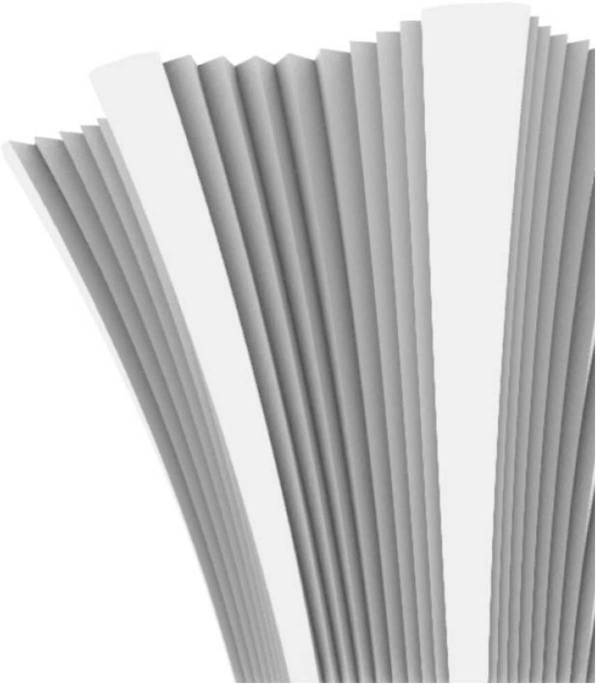



Phase II: Scale-up
Large scale 3D printing
// Undulated zigzag pattern
bachmann-ag.com

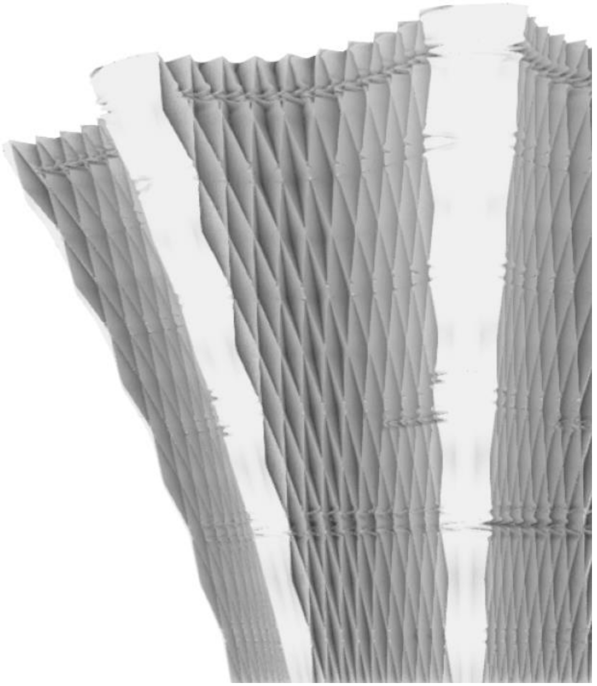
Phase II: Scale-up

Patterns

no pattern



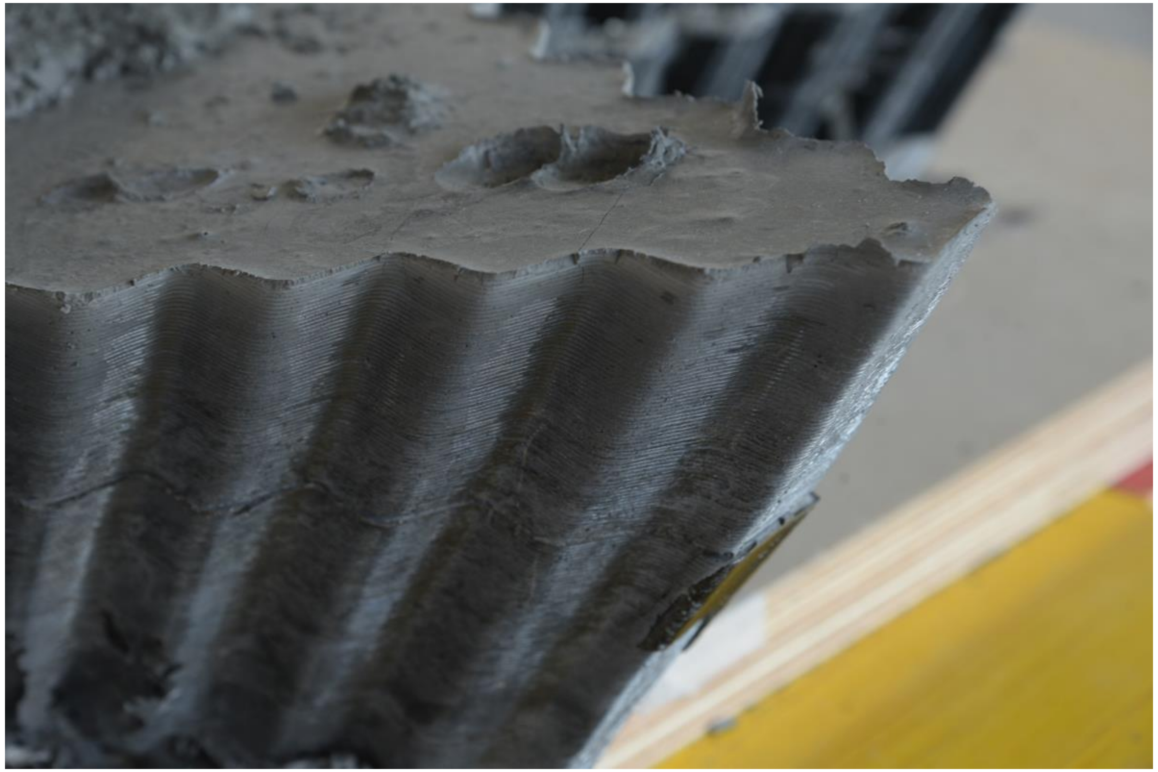
undulated zigzag pattern



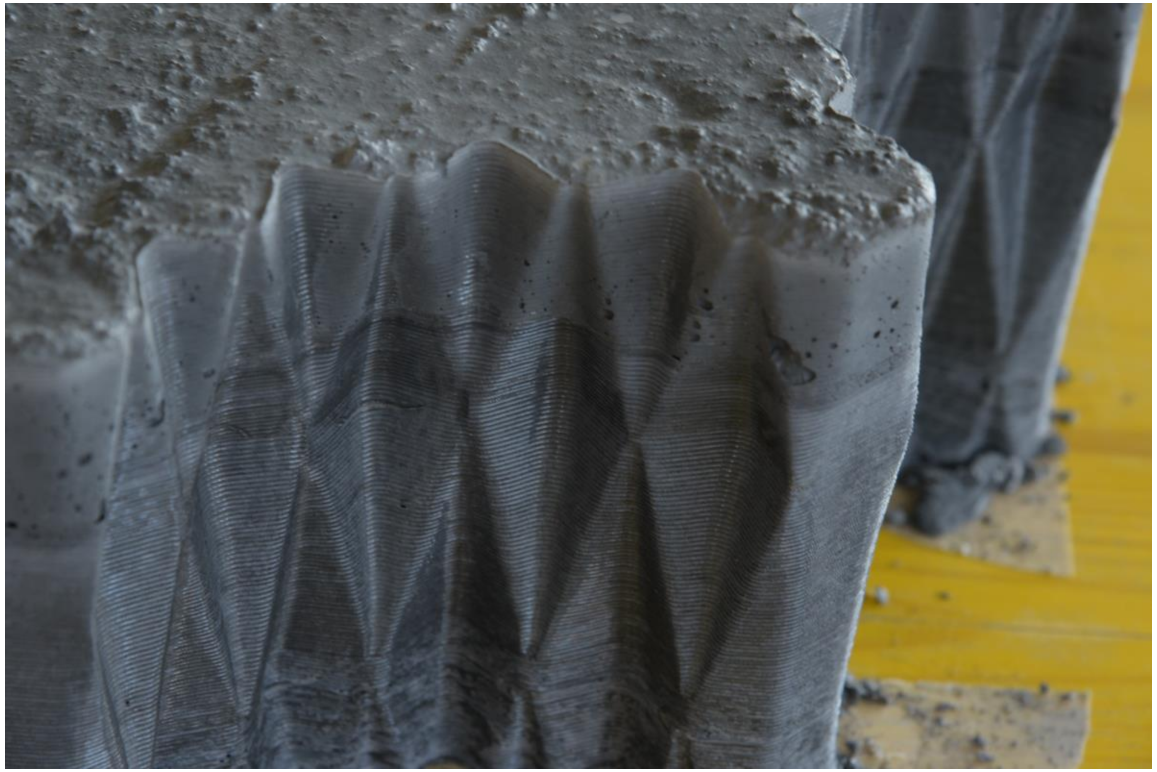
diamond grid pattern

Phase II: Scale-up

Patterns



undulated zigzag pattern



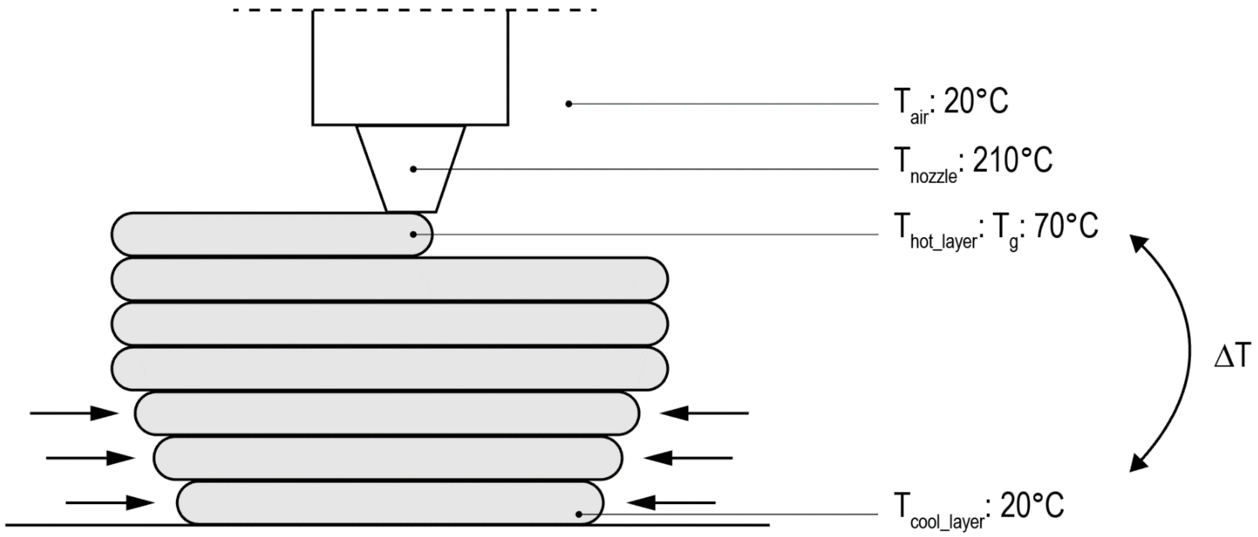
diamond grid pattern

Phase II: Scale-up

Large scale 3D printing

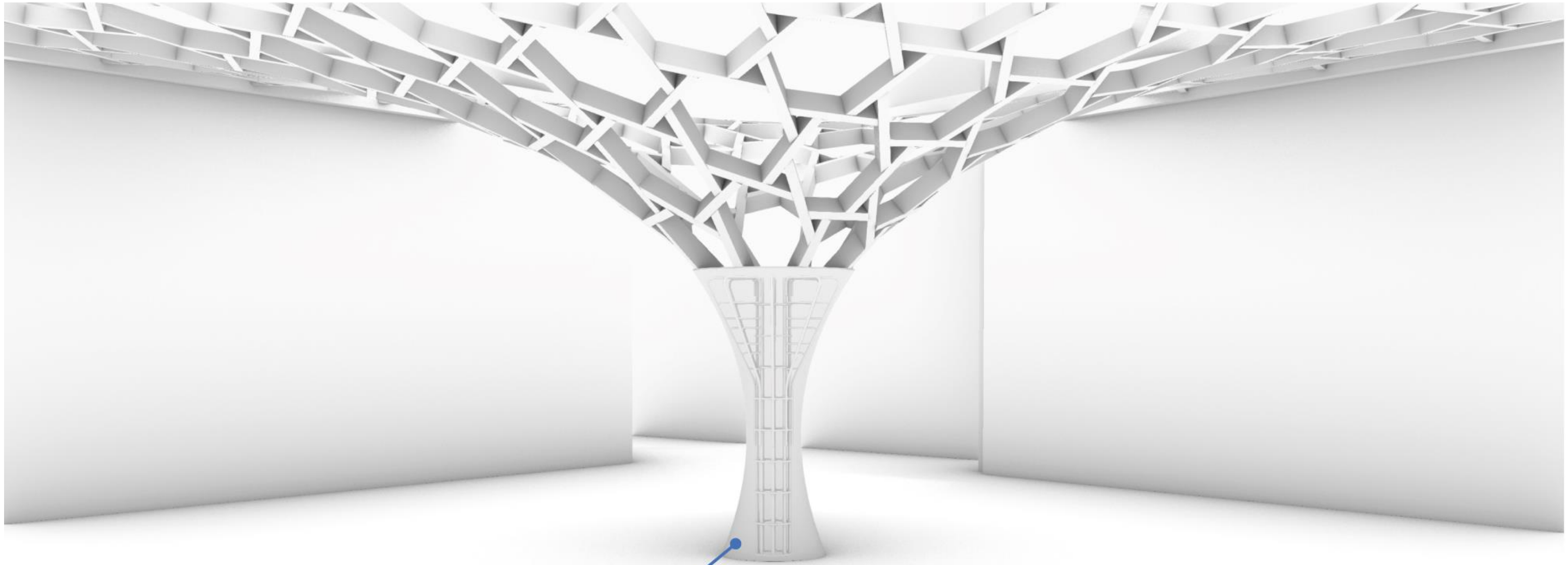
// Conclusion

- Layer delamination is caused by shrinkage in the longitudinal direction of a layer.
- When the length of a straight line is too long (>30mm) layer delamination is likely to occur.
- Layer delamination can be avoided by creating an undulated pattern.



Phase III: Case-study

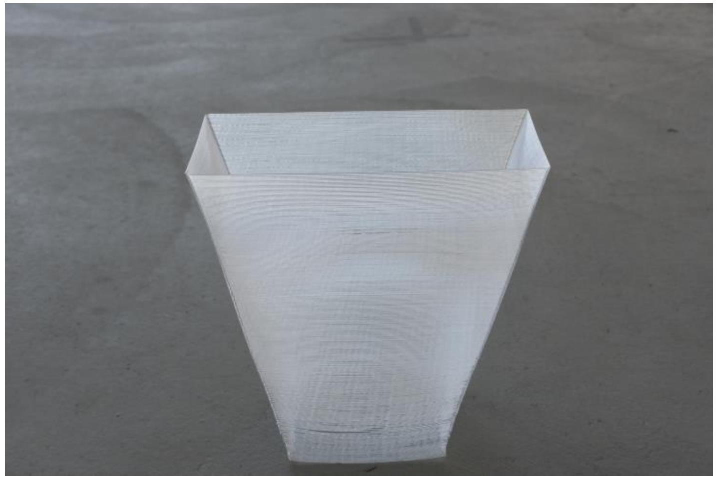
Challenges

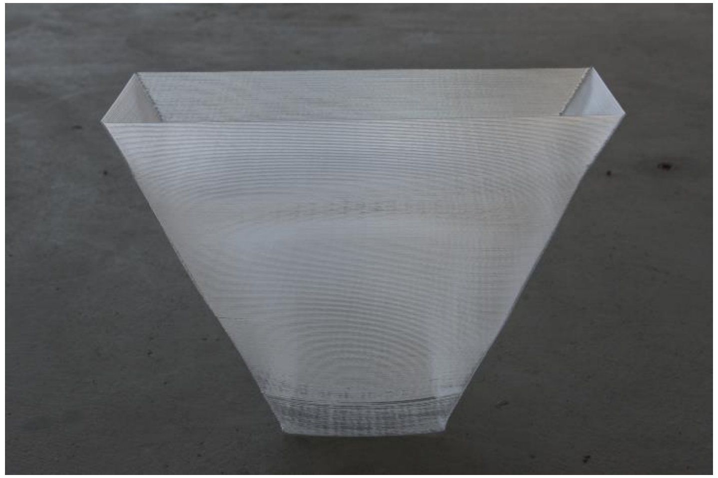


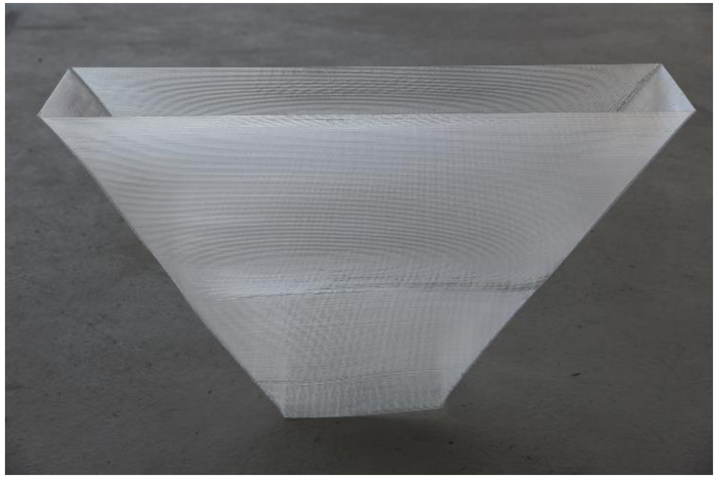
FORMWORK PRESSURE

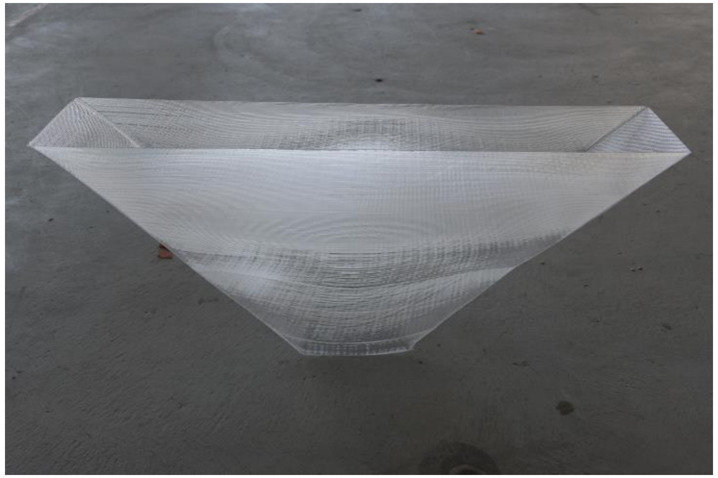
Phase II: Scale-up

Formwork hydrostatic pressure resistance


15°

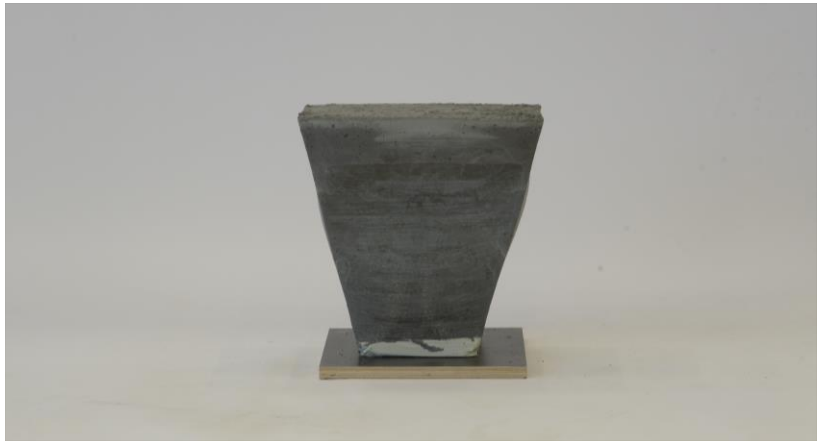

25°


35°

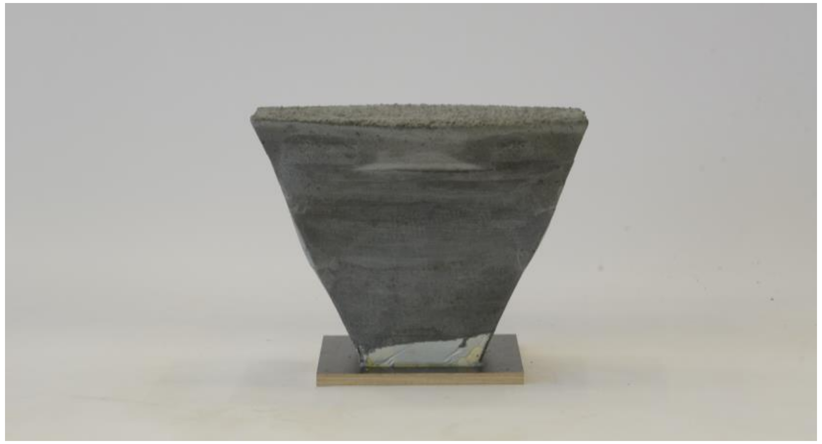

45°

Phase II: Scale-up

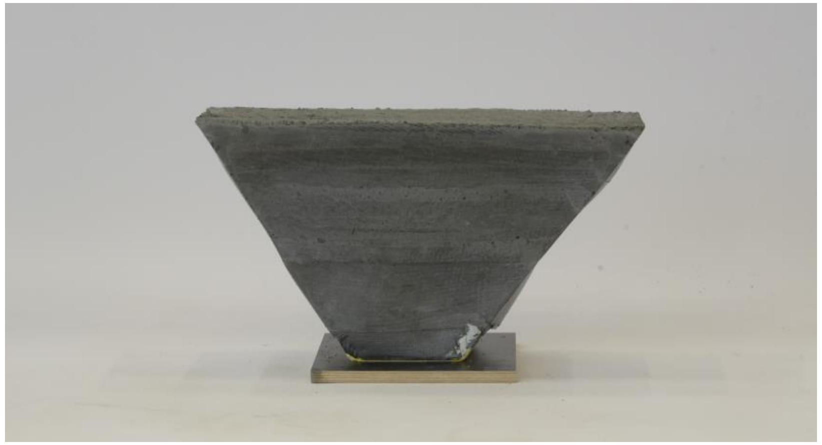
Formwork hydrostatic pressure resistance



15°



25°

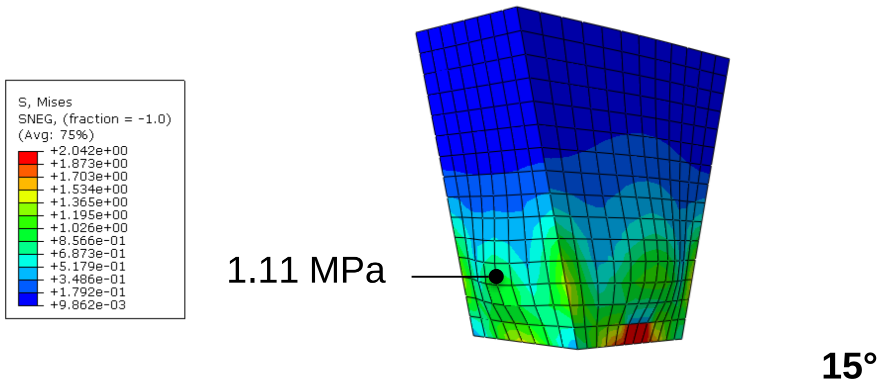


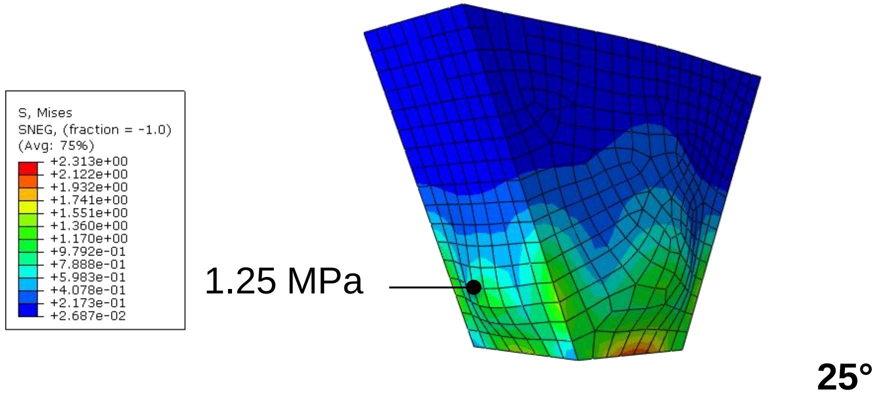
35°

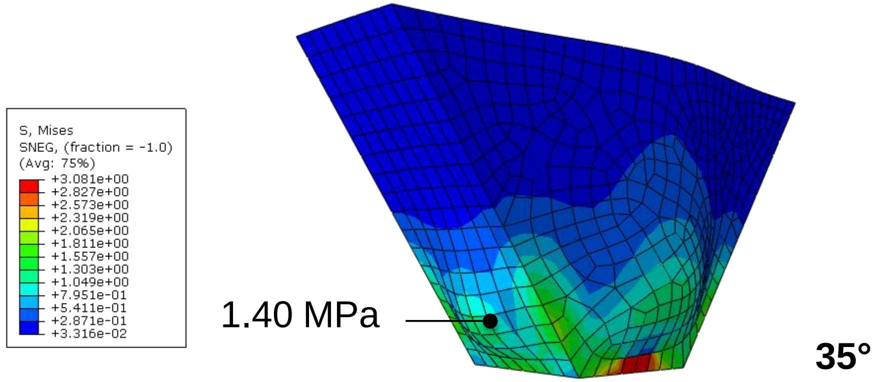
45°

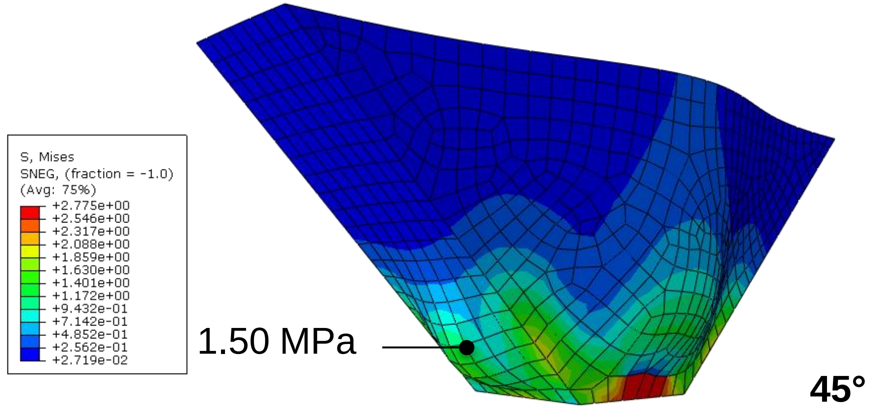
Phase II: Scale-up

Formwork hydrostatic pressure resistance







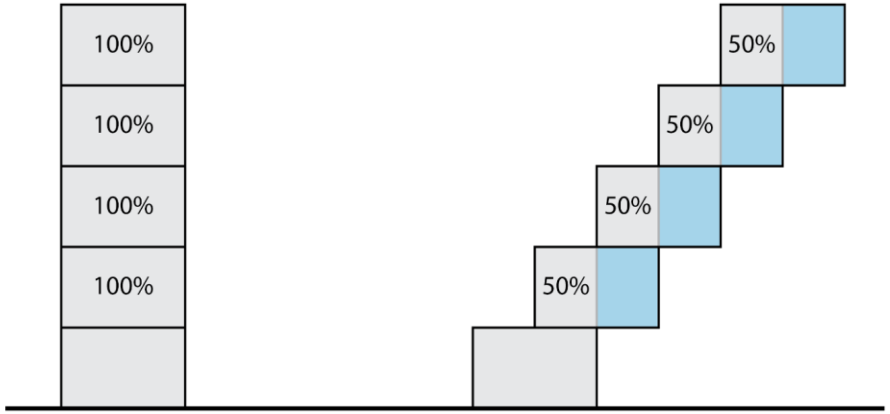


Phase II: Scale-up

Formwork hydrostatic pressure resistance

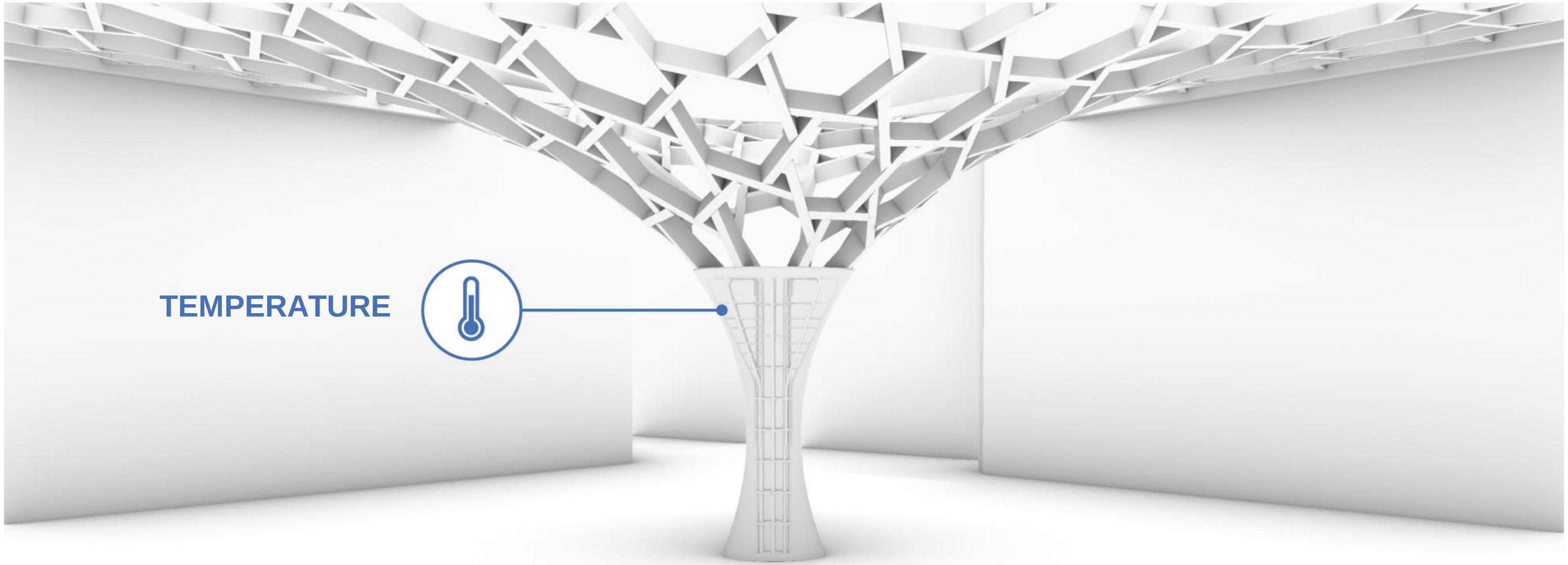
// Conclusion

- To match models with physical performance more research is needed.
- When simulating overhang, a reduction in structural performance should be taken into account
- Simulation can give an indication of structural performance under hydrostatic loading.



Phase II: Scale-up

Challenges



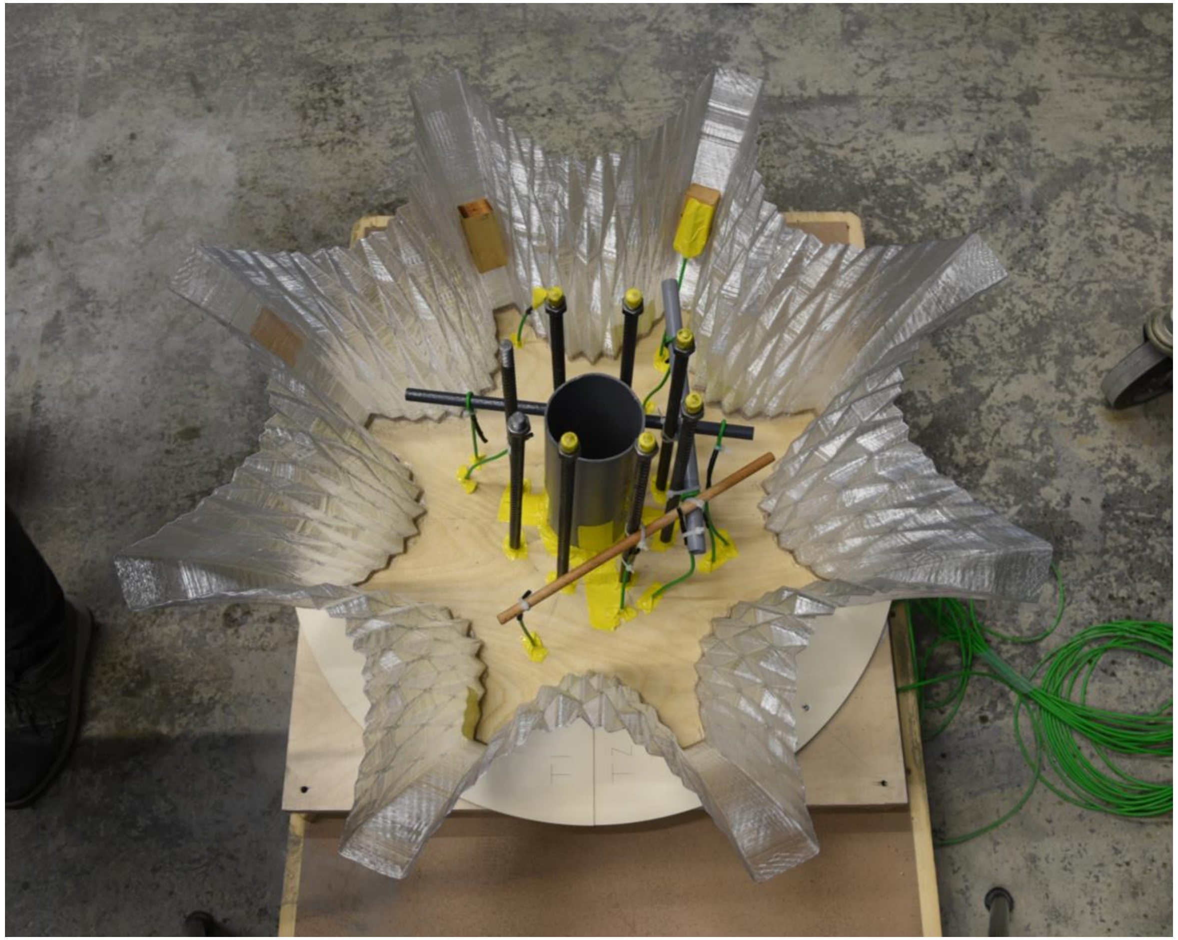
Phase II: Scale-up

Temperature development of hydrating concrete

// Experimental setup

- 3D printed formwork
- 10 thermocouples

• Total volume	95L
• Filling rate	2mm/min
• Total filling time	2.5hr
• Hydration time	50 minutes
• Maximum liquid concrete	100mm



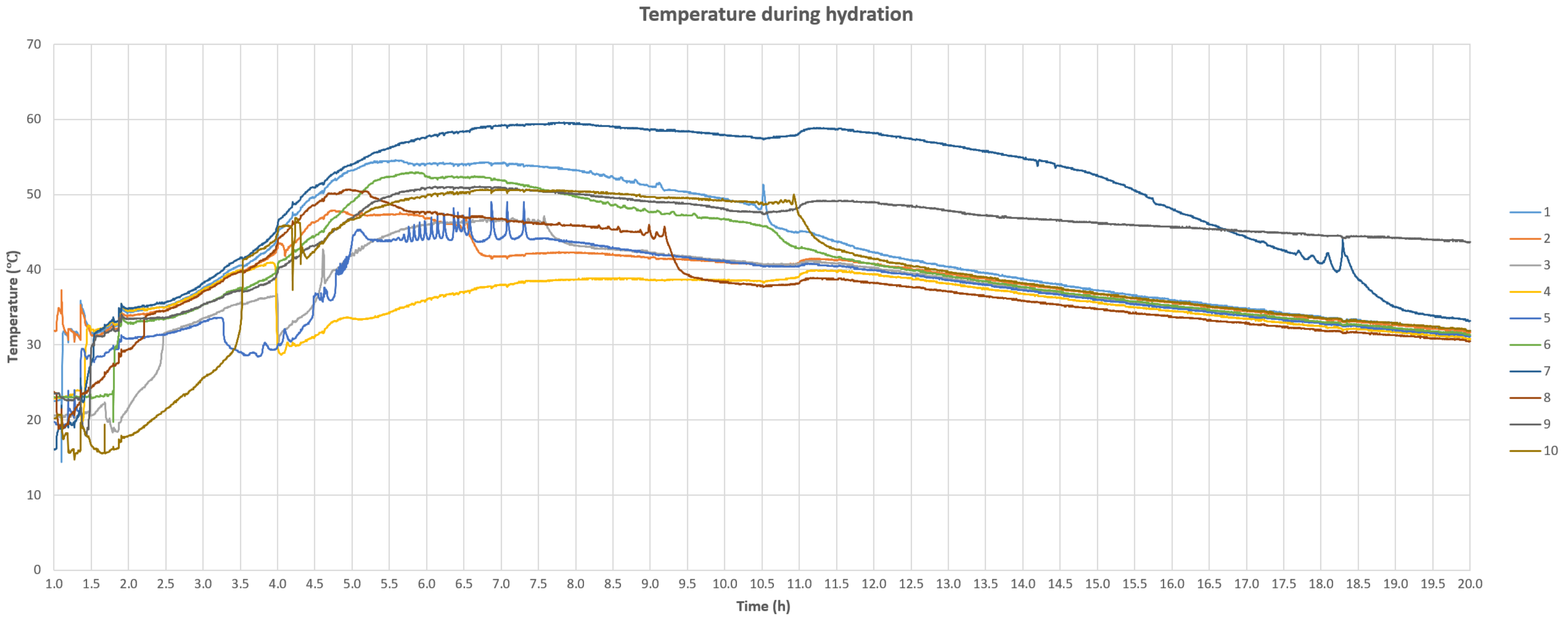
Phase II: Scale-up

Temperature development of hydrating concrete

// Timelapse of filling

Phase II: Scale-up

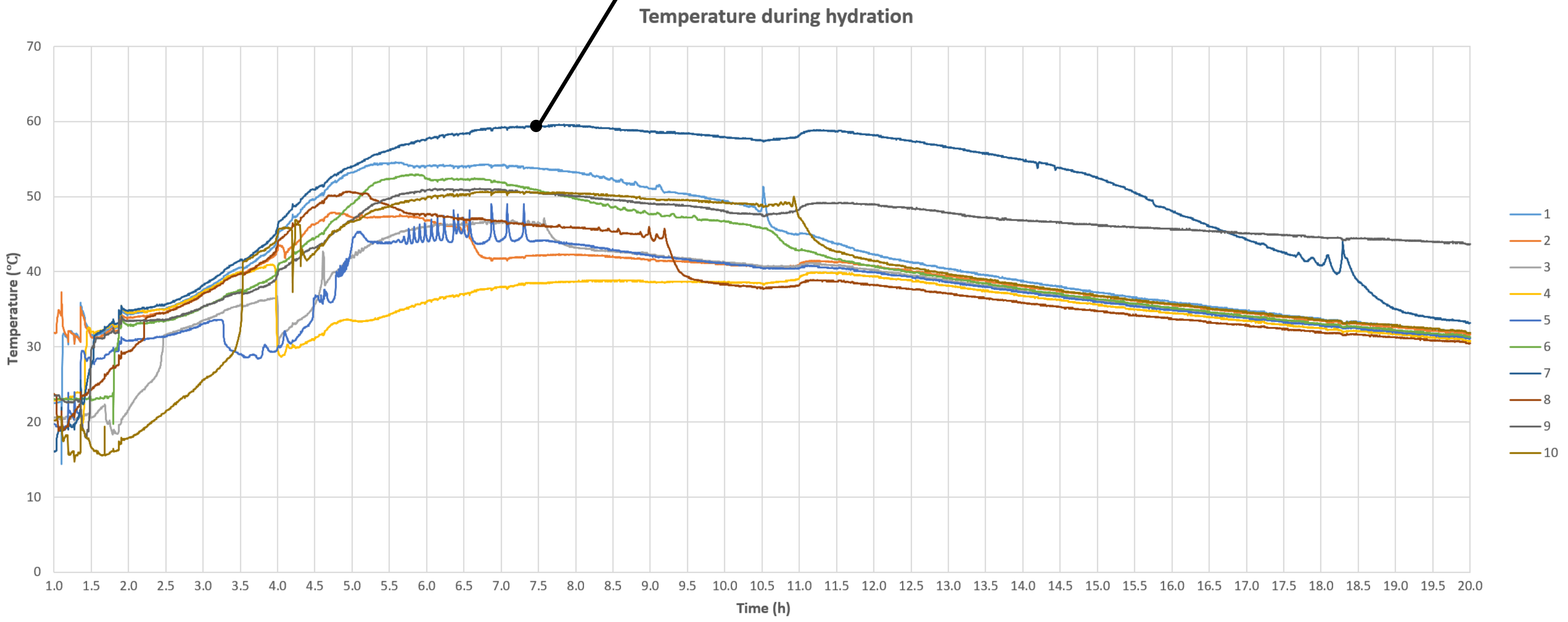
Temperature development of hydrating concrete



Phase II: Scale-up

Temperature development of hydrating concrete

59.5 degrees, 7:45 hours

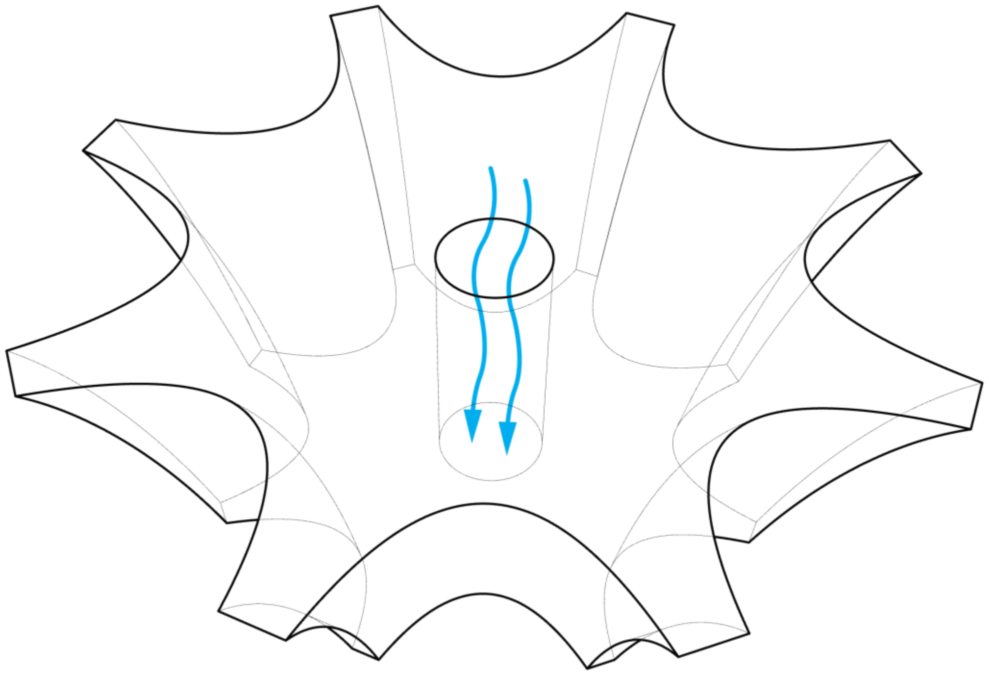


Phase II: Scale-up

Temperature development of hydrating concrete

// Conclusions

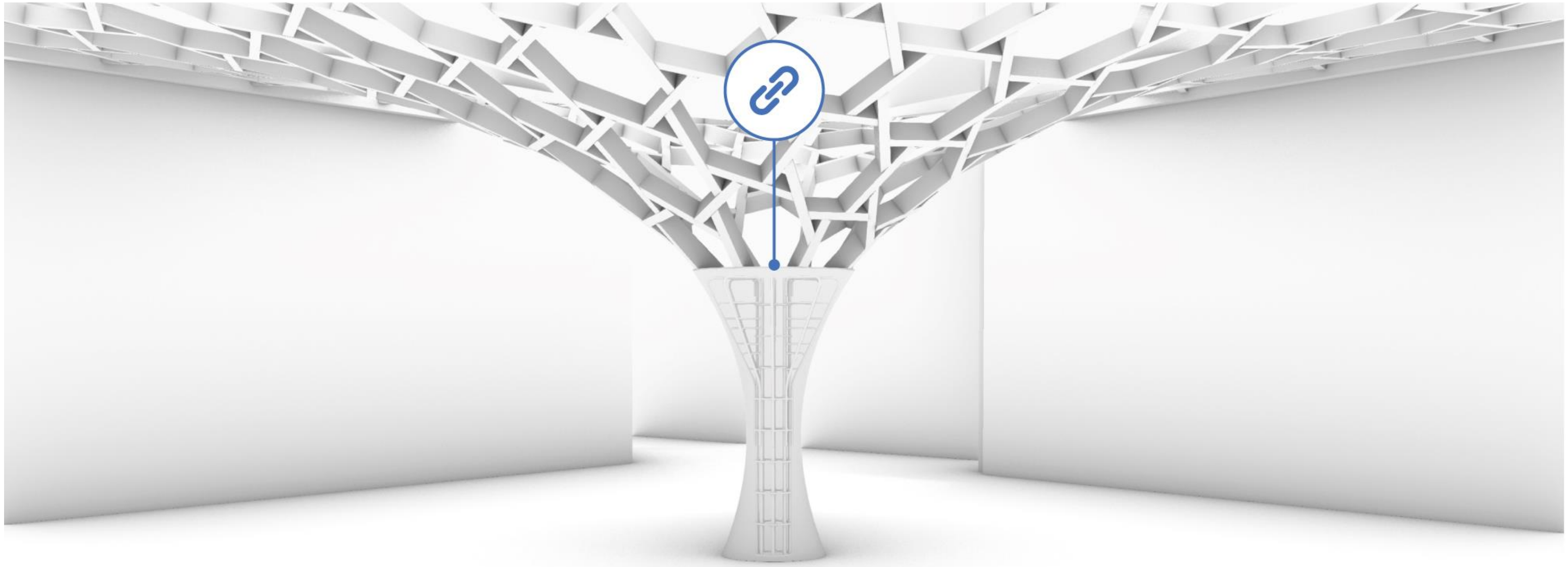
- High temperatures are reached within the concrete because of the large mass and high cement content.
- High temperatures could cause cracks and lower final compressive strength of the concrete.
- Temperature can be reduced by lowering cement content, reducing the mass or applying active cooling.



Phase II: Scale-up

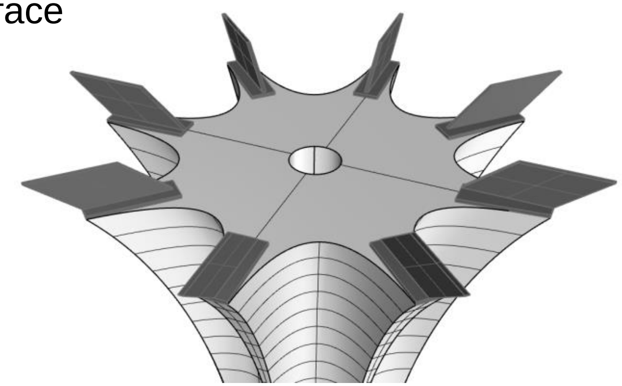
Connection detail

CONNECTION

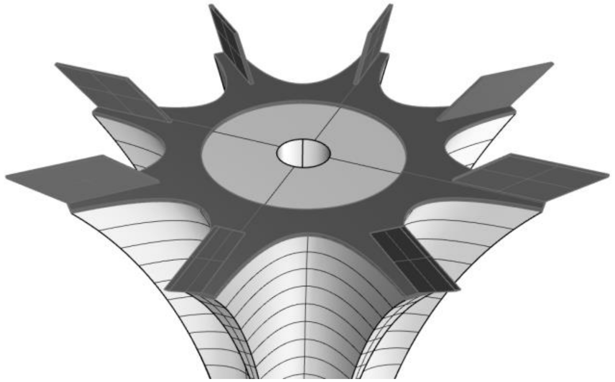


Phase III: Case-study

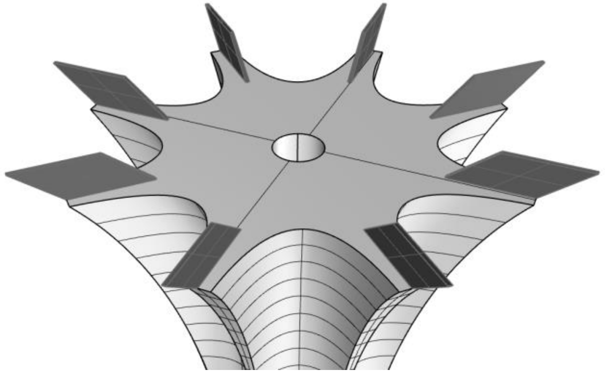
Timber – concrete interface



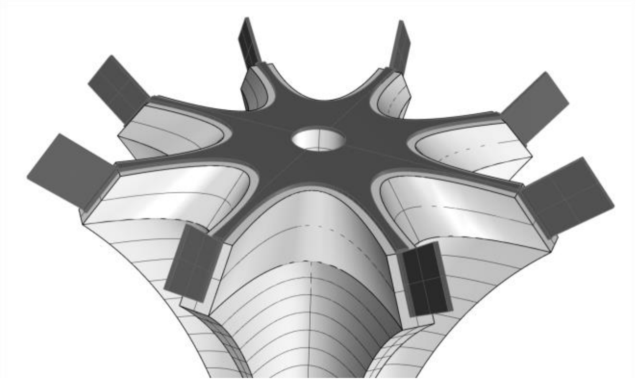
8 plates with fins



1 ring with fins



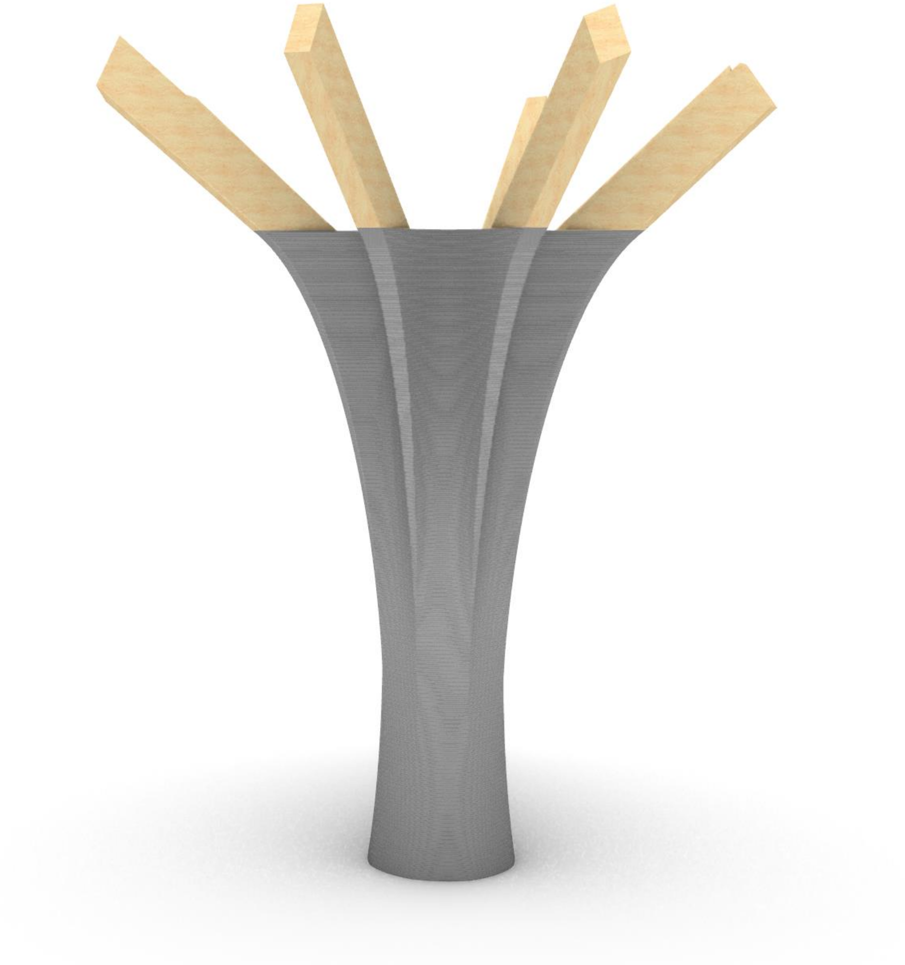
8 fins in concrete

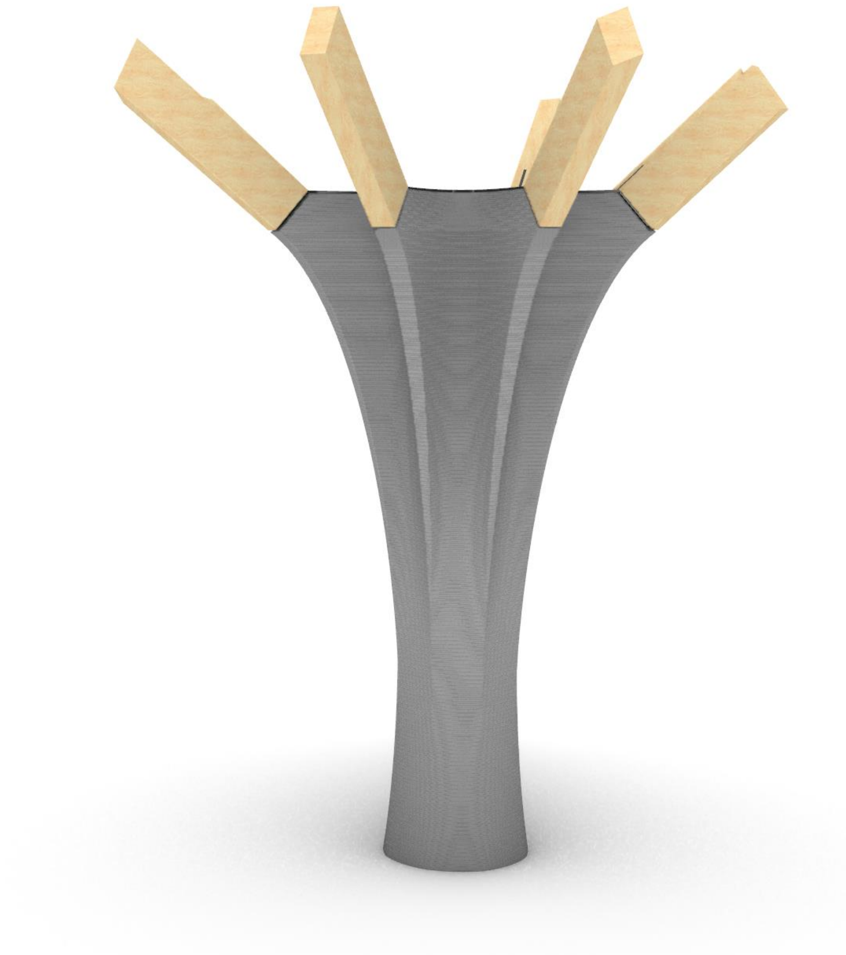


perpendicular fins

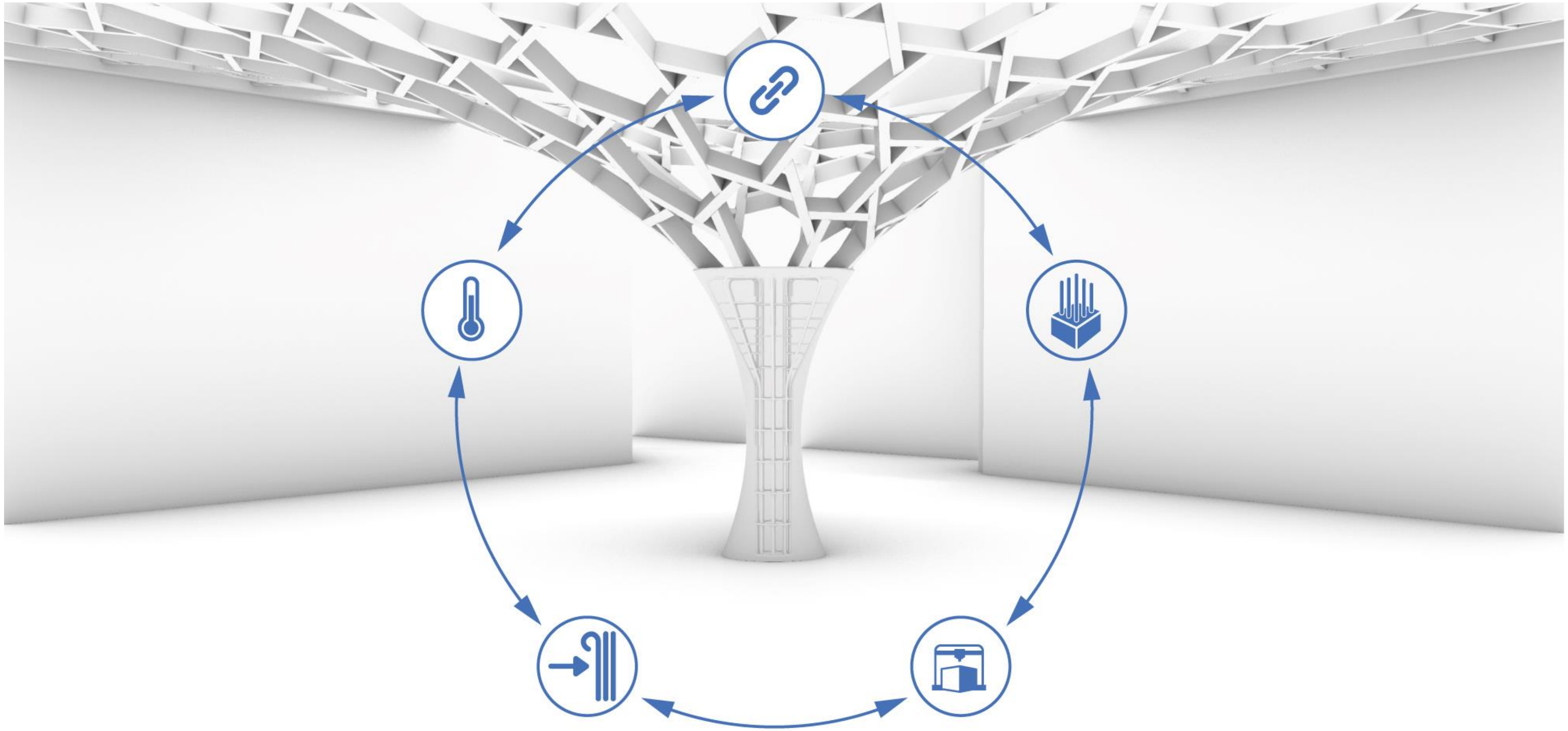
Phase III: Case-study

Timber – concrete interface

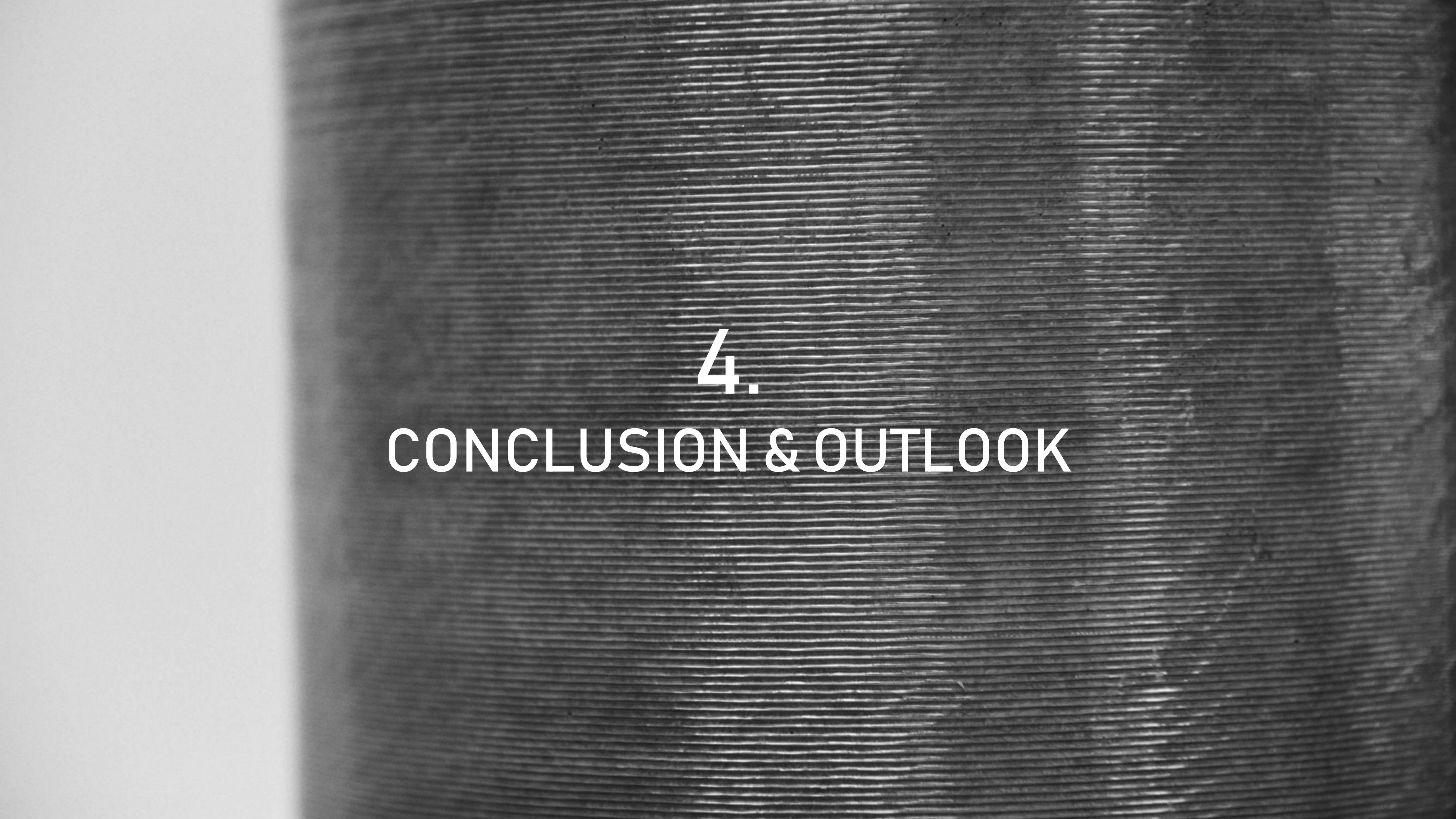




Phase III: Case-study



EGGSHELL



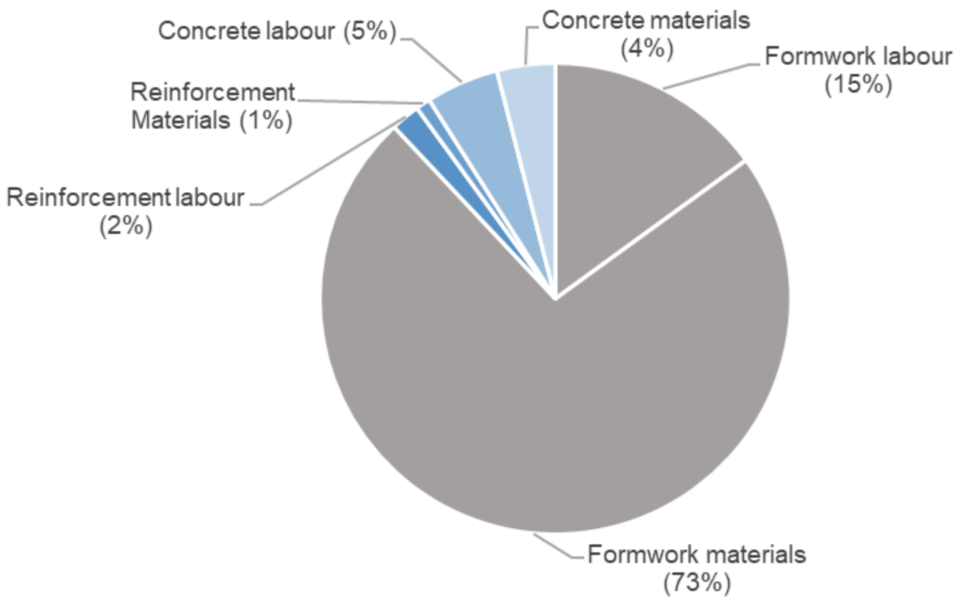
4.
CONCLUSION & OUTLOOK

Conclusions

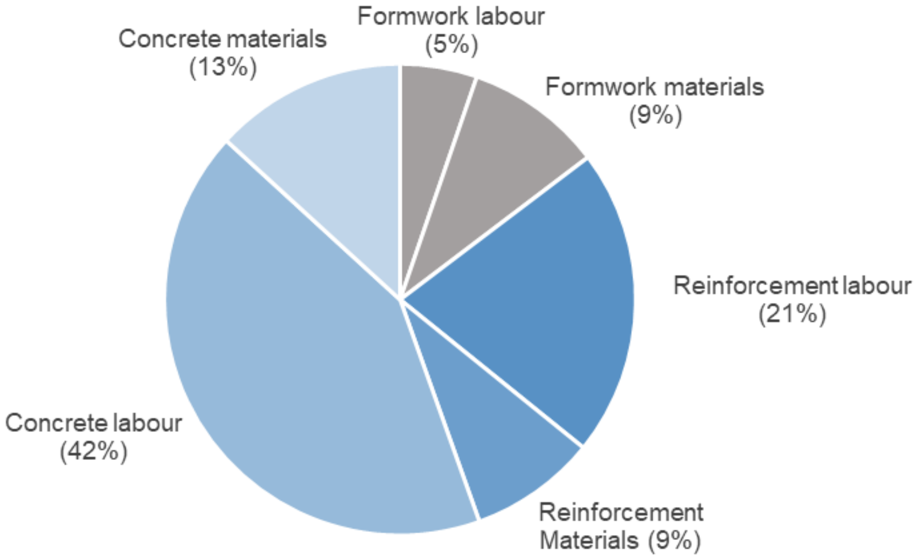
- Thin-shell formwork is feasible for the production of full-scale, structural columns.
- A formwork to structure weight ratio of 1:100 can be achieved.
- Reinforcement is a limiting factor in geometric freedom.
- 3D Printing, material processing and reinforcement all need to be synchronized.
- Portion of costs spend on formwork is much lower compared to existing methods.

Conclusions

CNC-milled formwork



Eggshell formwork



Outlook

- Alternative materials
- Recycling of shell formwork
- Alternative reinforcement
- Feedback during fabrication
- Digital concrete casting
- Improved design tool

Acknowledgements

Gramazio Kohler Research (Prof. Fabio Gramazio & Matthias kohler)

Ena Lloret-Fritschi

Fabio Scotto

Joris Burger

Nizar Taha

Physical Chemistry of Building Materials (Prof. Robert Flatt)

Heinz Richner

Andreas Reusser

Thibault Demoulin

Bruno Pinto Aranda

Concrete Structures and Bridge Design (Prof. Walter Kaufmann)

Jaime Mata-Falcon

Thank you for your attention

Bibliography

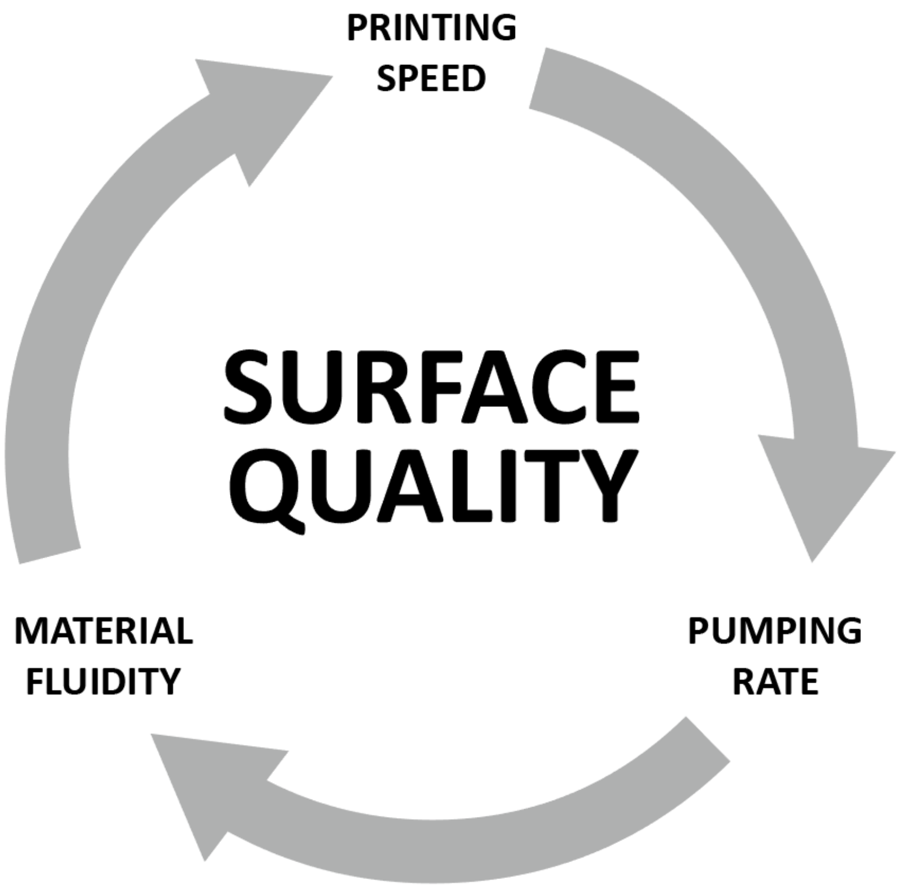
- P. J. M. Monteiro, S. A. Miller, and A. Horvath, “Towards sustainable concrete,” *Nat. Mater.*, vol. 16, no. 7, pp. 698–699, 2017.
- R. H. Lab, “Think Formwork – Reduce Costs,” *Struct. Mag.*, no. April, pp. 14–16, 2007.
- H. R. Schipper and S. Grünewald, “Efficient Material Use Through Smart Flexible Formwork Method,” no. 1, pp. 1–8.
- T. Ulrich, “Enabling and Expanding Geometries for Smart Dynamic Casting,” ETH Zurich, 2017.
- A. Weilandt, M. Grohmann, K. Bollinger, and M. Wagner, “Rolex Learning Center in Lausanne: From conceptual design to execution,” in *Proceedings of the International Association for Shell and Spatial Structures (IASS) Symposium 2009, Valencia*, 2009, pp. 640–653.
- E. Lloret *et al.*, “Complex concrete structures: Merging existing techniques with digital fabrication,” *Computer-Aided Design*, vol. 60. pp. 40–49, 2015.

EGGSHELL

design and fabrication of non-standard, structural concrete columns using 3D printed thin-shell formwork

Phase I: Explorations

Synchronizing printing speed, pumping rate and material fluidity



Formwork costs

	CHF	%
Formwork labour (5%)	132	5%
Formwork materials (9%)	235	9%
Reinforcement labour (21%)	528	21%
Reinforcement Materials (9%)	218	9%
Concrete labour (42%)	1056	42%
Concrete materials (13%)	330	13%
TOTAL	2499	

Phase II: Scale-up

Large scale 3D printing