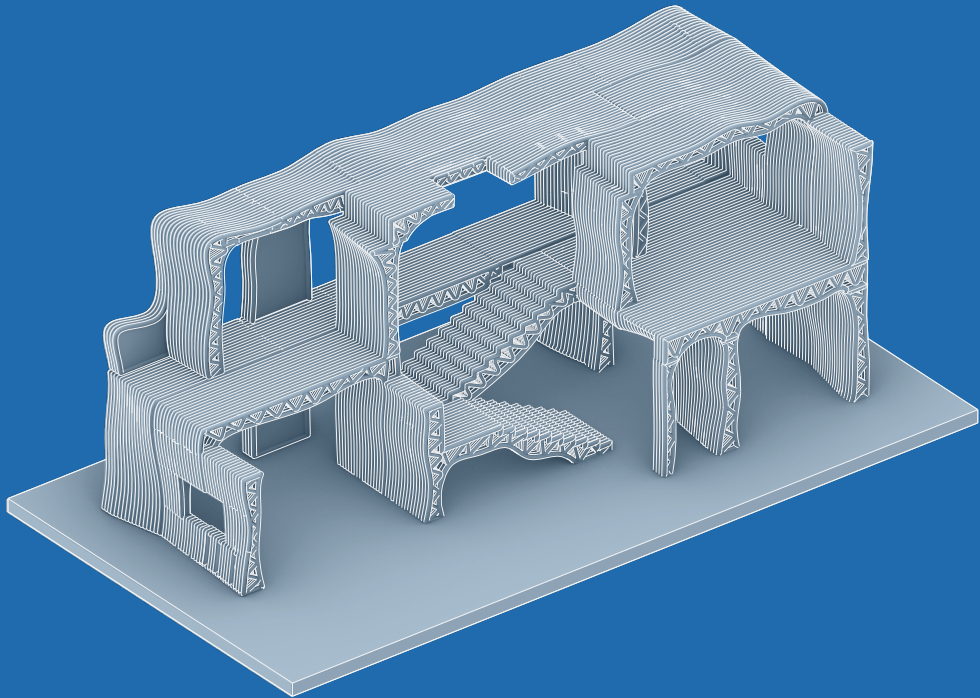


Università degli Studi di Padova
Department of Civil, Environmental and Architectural Engineering
Degree in Building and Architecture Engineering
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PREFAB 3D CONCRETE PRINTING

STUDENT:

FILIPPO MEGLIOLI

SUPERVISOR: Prof. PhD. ANDREA GIORDANO

CO-SUPERVISOR: Ing. PAOLO BORIN

EXTERNAL SUPERVISOR: Prof. PhD. ROBERTO NABONI

EXTERNAL CO-SUPERVISOR: Arch. LUCA BRESEGHELLO



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Papà, Mamma ed Elisa.

ABSTRACT - ENG

This thesis explores the use of 3D Concrete Printing (3DCP) in prefabrication from a smaller scale, with the design of a beam, to a bigger one with the ideation of a new framework and the workflow to realize it.

3D Concrete Printing is a method of additive manufacturing in construction where concrete, with very little aggregate, is extruded in layers one over the other until the object being printed is done. This technology is experiencing intensive growth as more and more commercial applications becomes available to the market.

To learn more about this method extensive research was conducted and numerous projects were analyzed to understand the relation between on-site and off-site in 3D Concrete Printing and the current commercial application of this technology.

Later as part of the CREATE group a first lab experience with the printing process was an important learning phase as the multiple problems faced made it clear that many variables can jeopardize or block the work of the day.

In this thesis is shown an experimental method for the simulation of the printed beams that otherwise could not be analyzed with standard approaches. Building on what has been learned B06 is presented: a structurally optimized beam that is ready to be printed.

Finally, a new 3D printed and structurally optimized prefabrication framework is elaborated and explained in its entirety from the preliminary design to the assembly in the construction site.

This thesis looks is part of the larger discussion that there is around 3D concrete printing that, thanks to its early stages, give great freedom on what can be theorized. The hope is that this work will help to overcome some of the challenges that 3DCP is facing for a larger and broader adoption which could have a meaningful impact on society by creating a more sustainable and fair construction practice.

ABSTRACT - ITA

La seguente tesi esplora l'uso della Stampa 3D in Calcestruzzo (C3DP) nella prefabbricazione dalla scala più piccola, con il design di una trave, a una più grande, con l'ideazione di una nuova tipologia di struttura e del processo che ne permette la realizzazione.

La Stampa 3D in Calcestruzzo è una tipologia di manifattura additiva nel settore delle costruzioni dove il calcestruzzo, con aggregati molto piccoli, è estruso in filamenti uno sopra l'altro fino ad ottenere il design desiderato. Questa tecnologia è in forte crescita come dimostrano le crescenti applicazioni in ambito commerciale.

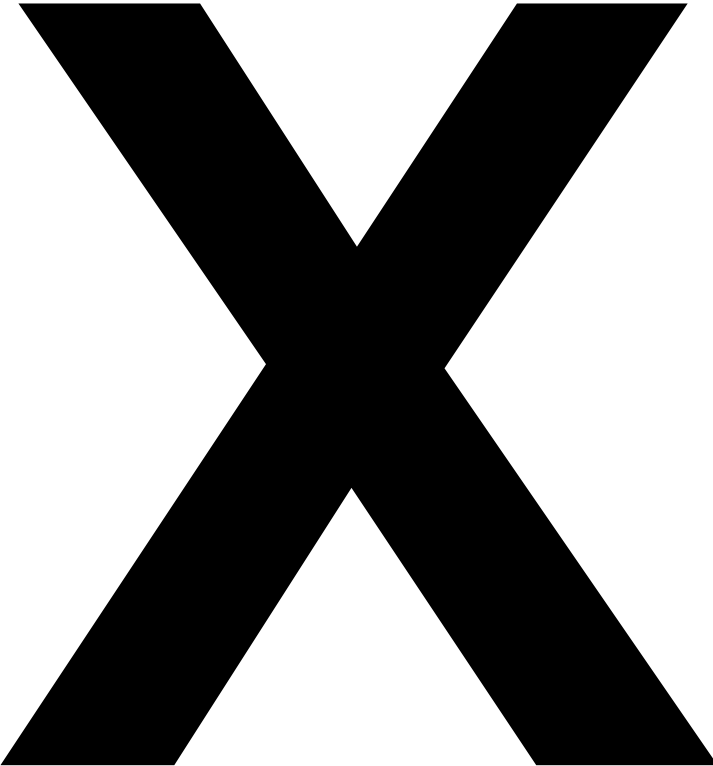
Per conoscere di più riguardo a questa tecnologia è stata una importante ricerca di numerosi progetti che sono stati analizzati e catalogati per comprendere il rapporto tra on-site e off-site nella stampa 3D e qual è la tecnologia correntemente nel mercato.

Successivamente, come parte del gruppo CREATE, una prima esperienza nel laboratorio durante il processo di stampa è stato un importante fase di apprendimento dato che le varie problematiche incontrate rendevano chiaro che molte variabili possono creare complicazioni o, in alcuni casi, bloccare il processo di stampa.

In questa tesi è spiegato un approccio sperimentale per la simulazione delle travi stampate che, altrimenti, non sarebbe possibile analizzare con approcci standard. Partendo da quello che si è imparato B06 è presentata: una trave strutturalmente ottimizzata che è pronta per la stampa.

Infine, una nuova struttura prefabbricata, stampata e ottimizzata strutturalmente è stata elaborata e studiata in tutti i suoi aspetti: dal design fino all'assemblaggio in cantiere.

Questa tesi fa parte di una discussione più ampia riguardo alla Stampa 3D con il Calcestruzzo che, essendo alle fasi di sviluppo iniziali, permette grande libertà di pensiero. La speranza è che questo lavoro possa aiutare a superare alcune delle sfide che la Stampa 3D del Calcestruzzo sta affrontando per una diffusione più ampia che potrebbe avere un impatto importante sulla società e creare un settore più sostenibile da un punto di vista sociale, ambientale ed economico.



INDEX

Abstract

Acknowledgments

1. Introduction:

- 1.1 Problem Statement
- 1.2 Research Aim

PART 1: CONTEXT

2. Construction 3D Printing

- 2.1 Indirect Printing
- 2.2 Direct Printing
 - 2.2.1 3DCP Advantages*
 - 2.2.2 3DCP Limitations*

3. State Of The Art In 3DCP

- 3.1 The Development of 3DCP
- 3.2 Built Projects Mapping
- 3.3 Technologies
 - 3.3.1 Material Mixing and Supply*
 - 3.3.2 Motions system*
 - 3.3.3 Reinforcement strategies*
- 3.4 Scales of Applications
- 3.5 Crytical Review
 - 3.5.1 A Growing Interest*
 - 3.5.2 On-Site and Off-Site*
 - 3.5.3 The Choice of a Motion System*
 - 3.5.1 New Chanllenges for Reinforcement Startegies*
 - 3.5.2 Moving to a Larger Scale*
 - 3.5.3 A Common Practice for Housing*

4. 3DCP and Off-Site

- 4.1 Precast Concrete as a Reference
- 4.2 Off-Site Advantages
- 4.3 Off-Site Limitations
- 4.4 Basic Prefabrication Framework

5. 3DCP LAB EXPERIENCE

- 5.1 Create Lab Setup
- 5.2 Preliminary Testing
 - 5.2.1 Printing Path Variables*
 - 5.2.2 Material Behaviour*
 - 5.2.2 Reinforcement Interaction*
 - 5.2.2 Temperature Influence and Ideal Timeframe*
 - 5.2.2 Troubleshooting*
- 5.3 A First Attempt at Structural Optimization

PART 2: SIMULATION AND FABRICATION FRAMEWORK FOR PRECAST 3DCP

6. Beam Simulations

- 6.1 Creation of a FEM
- 6.2 Linear Analysis
- 6.3 Non-Linear Analysis
- 6.4 Testing Results
- 6.5 New Iterations
- 6.6 Limitations of the Analysis Model

7. B06 - CASE STUDY

- 7.1 Motivation
- 7.2 Section Optimization
- 7.3 Output

8. WORKING IN SECTION: A NEW FRAMEWORK

- 8.1 Introduction
- 8.2 Preliminary design
- 8.3 Optimization Workflow
- 8.4 Preparing for Production
- 8.5 Production Workflow
 - 8.5.1 Off-Site Fabrication*
 - 8.5.2 Storage and Transport*
 - 8.5.3 Construction Site*

Conclusions

Bibliography

01

INTRODUCTION

Cement-based additive manufacturing is a process that places sequential layers of materials by a motion-controlled system to create 3-dimensional physical objects of various scale. This method gives the possibility to engineers and architects to completely change the way their work is designed and realized. Concrete 3D Printing, the focus of this thesis, allows for the creation of structurally performing building or building elements that, thanks to recent developments, can replace and therefore enrich the built environment.

The advance in computational design gives infinite possibilities to shape concrete in ways that take advantages of different tools such as topological optimization. The development of new method for structural analysis is trying to bridge the gap between what can be thought and built.

The motivations behind the use of 3DCP (3D Concrete Printing) is to reduce, thanks to structural optimization, the use of concrete and by that creating new and interesting design for greater freedom to create the desired spaces

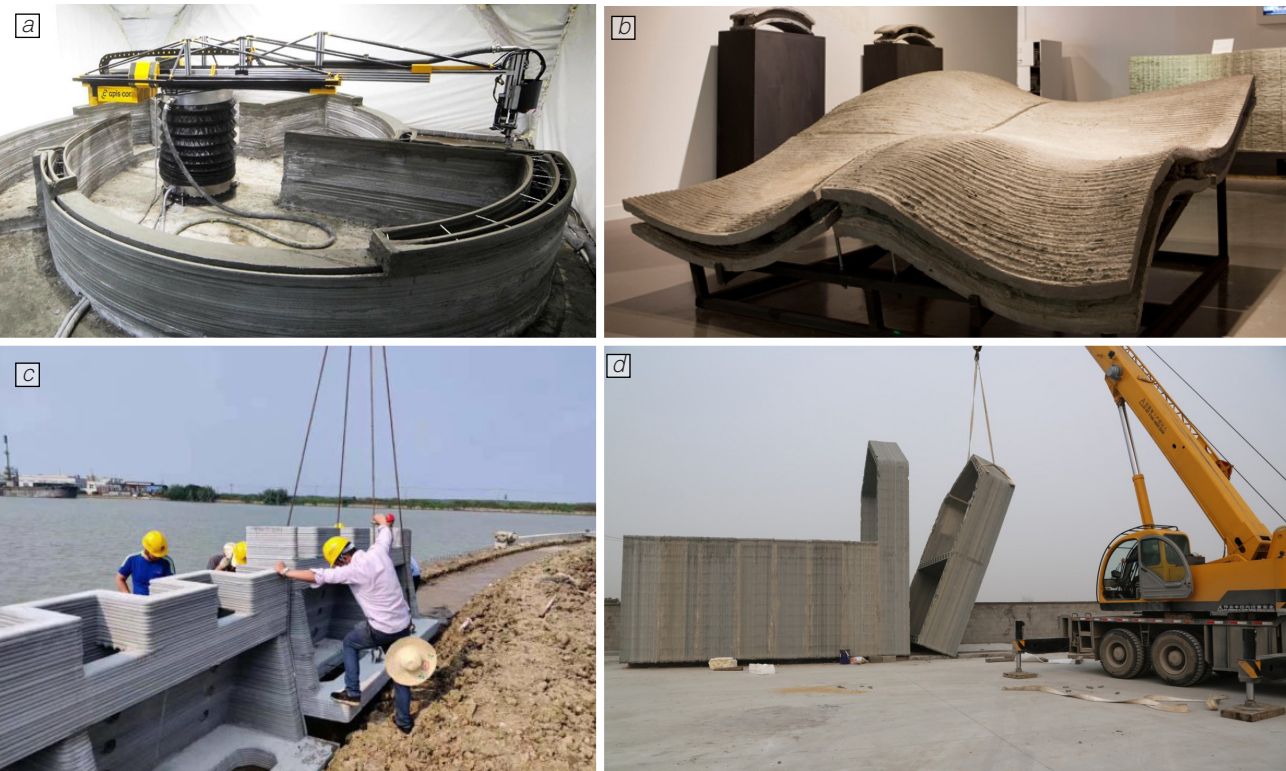


Figure 1.1

- a. In a project by Apis Cor in Russia the walls are realized thanks to an extendable swing arm
b. An intricate façade panels printed at the Loughborough University
c. A photo of the assembling process of some residential unit by Winsun
d. Example of prefabricated components by Winsun being placed.

1.1

PROBLEM STATEMENT

Concrete is the most used construction material thanks to its low cost, good strength, exceptional durability, excellent fire resistance and the fact that it can be obtained anywhere in the world. As concrete accounts for 5-7% of the global total CO₂ emission, a reduction in the use of concrete can lead to a lower carbon footprint for the construction sector. (Yu Chen, 2017)

One of the promising technology working towards this goal is 3DCP but it is a fairly recent technology, being broadly adopted just in recent years, and architects and engineers are now looking for new and promising commercial applications. Additionally, it is necessary to develop new approaches to evaluate and test the performance of the object being manufactured, a challenging task as current software and regulation are built around standard methods and shapes which would reduce the potential given by additive manufacturing in construction.

Another problem relies on the deep divide between the few commercial application

currently available and the work of research centres and universities. The few examples of 3d printed buildings focus heavily on on-site production by utilizing a method that consists mainly of the creation of a continuous wall that generates the spaces [Figure 1.1.a], a method first theorized with the name of Contour Crafting by Behrokh Khoshnevis. Meanwhile, the academic world focuses on a different approach that tries to take advantage of the new freedom given by additive manufacturing, a field initiated by the Freeform construction Project from Loughborough University [Figure 1.1.b]. This gap is positioning the work done by Universities and others even further from the market which leads to an inefficient transfer of technological innovation to the field. This thesis tries to bridge this gap thanks to the use of off-site components for the assembly of a 3d printed building, a method in some capacity initiated by Winsun [Figure 1.1.c & 1.1.d].

1.2

RESEARCH AIM

One of the aims of this thesis is to learn more about 3DCP in regards to its advantages, limitations, the technology being used and the commercial adoptions currently available. This makes it possible to learn more about an approach that isn't widely known and need additional research to learn more about the many different technologies that are usually grouped under the name 3D Concrete Printing.

The work in the lab with the CREATE group was an important part of the learning process of this work and it made it possible to understand how a structural optimization work and how the decision are taken after the feedbacks from the printing process or the analysis; within this frame, It has been considered important to find a way to execute the analysis of 3D printed objects as these require a certain level of attention due to the particular design that is generally harder to

evaluate through current tools.

Additionally, this thesis aims to find a new structural optimization approach that blends the possibility to save materials thanks to the use of T-beam with the advantages, given by 3DCP, to look at a beam design's requirement section by section and not as a whole.

An important aim of this research is to learn more about what prefabrication is and how it could greatly improve the reliability of additive manufacturing in construction and open new commercial applications. For this reason, the final aim of this thesis is to propose a new prefabrication system that takes care of every aspect necessary: design, manufacturing, transport and assembly. This approach creates new possibilities in comparison to what is currently being done and open the possibilities to print every component of a project.

PI1

PART 1: CONTEXT

02

CONSTRUCTION 3D PRINTING

Even though the construction industry accounts for 13% of the global GDP its productivity has remained stagnant with a 1% increase over the last two decades. One of the listed reasons is the increasing complexity of current projects that requires the adoption of new technologies and skilled workers. (McKinsey, 2017). Digital fabrication became, in the mid- 90s one of the solutions to the increasing complexity in concrete projects with the creation of custom moulds

(P.Carvalho, 2014). Additive Manufacturing (AM), a subset of digital fabrication, is seen as one of the innovative technologies that can fill this productivity gap and modernize a field generally resilient to changes. AM is a production method where a digital 3d model is manufactured layer after layer with the desired material. Different approaches to AM in construction can be outlined. These can be categorized in two main groups: Indirect 3D Printing and Direct 3D Printing processes.

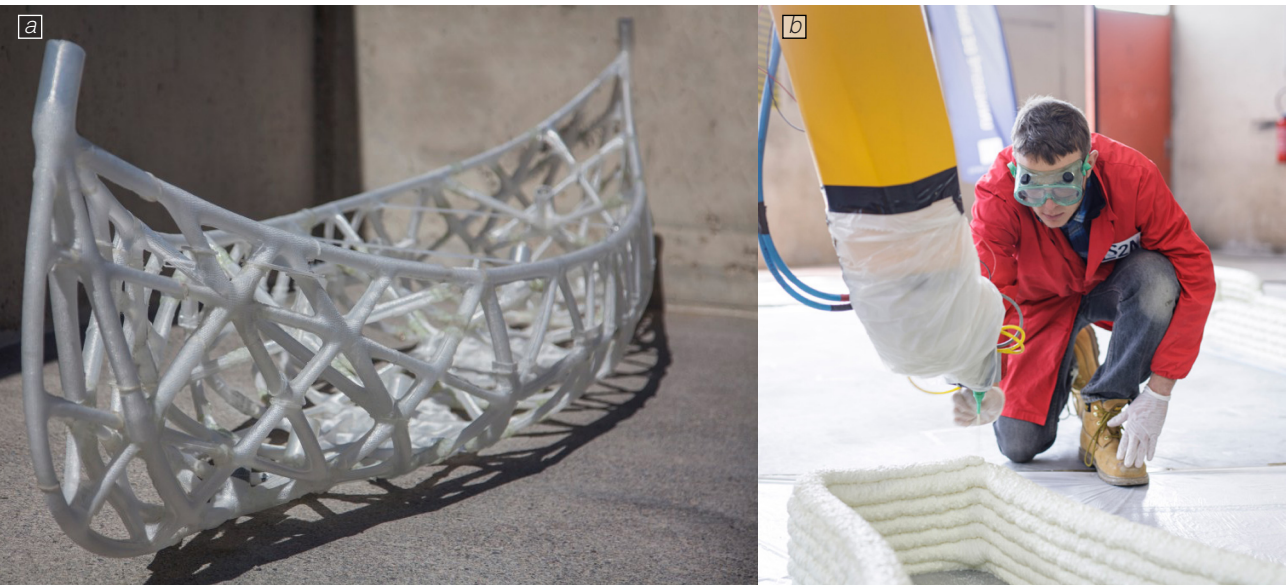


Figure 2.1

- a. *skelETHon*, a concrete canoe realized by ETH students
- b. 3D printed foam in a project from Nantes University

2.1

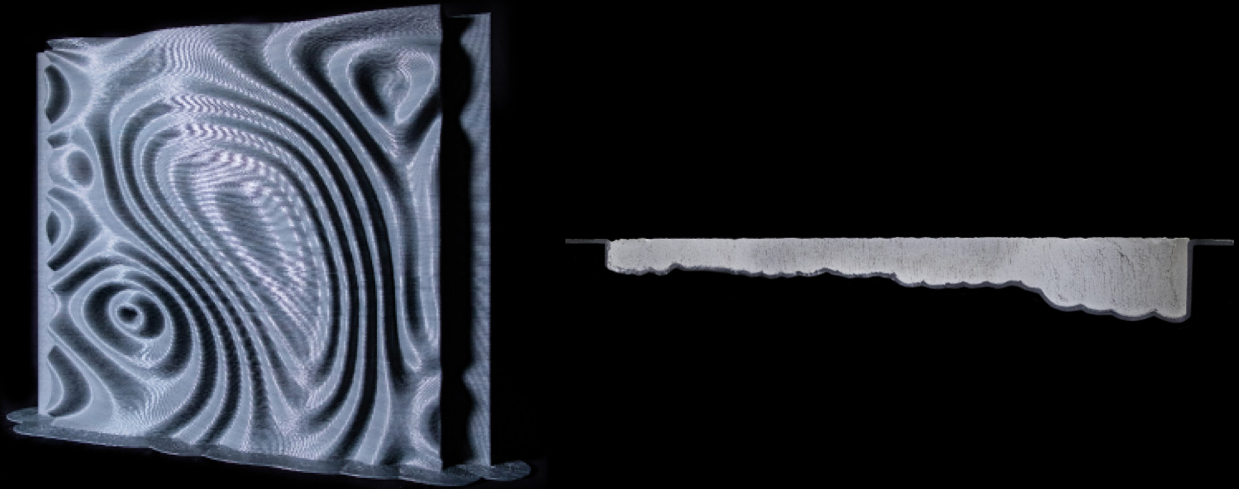
INDIRECT 3D PRINTING

In Indirect 3D Printing concrete is not the material being printed as this type of AM consists of the creation of formwork, a mould in which concrete is poured and left to cure until the outer skin can be removed. Currently, most of the formworks are realized by masons and carpenters by cutting wooden forms using a saw and putting them in place and attaching them with nails. This method of production forces the workers to awkward postures that studies have shown can lead to work-related disorders in areas such as the neck, shoulder, elbows, hand, wrists and others (M. Sadra, 2020). With 3D Printing it's possible to automate this process by extruding materials such as plastic, foam and others to manufacture a digitally-engineered formwork that allows for the creation of an elaborated concrete design. A difference can be made in regards to the life-cycle of the formwork: the mould can be single-use, stay in place or reusable.

Custom single-use formwork: In this case the formwork created is not reusable and it is used only once: after the concrete is poured

and cured the formwork is removed and during this process it is usually destroyed. This is generally needed if the complexity of the desired design does not make it possible to predict a disassembly strategy that requires a more complex design iteration. Additionally, for research or case-study purpose, it might not be necessary to reuse the formwork. In the example, for the construction of the canoe by ETH a submillimeter thin plastic formwork was 3d printed and cast in ultra-high-performance fibre-reinforced concrete. The skeleton was designed using topology and shape optimization design algorithms. After the pouring and curing of the concrete, the formwork was removed through a process that did not make it possible to save it. (ETH dbt, 2017) [Figure 2.1.a] Even though this system allows for great customization and design freedom it is also the most wasteful.

Stay-in-place formwork: Another approach is to leave in place the formwork even after the concrete has cured. This can be done in the case that the formwork has been specifically designed to be part of the project.



This might be done for aesthetical reasons or others. In the example shown in a project led by the University of Nantes foam was 3D printed to create the formwork that then was used to pour concrete. This outer layer works as thermal insulation for the house. [Figure 2.1.b] In this type of approach concrete work only as the material that creates the structure of the building. Even in this method, it is not possible to reuse the formwork and therefore it is not the most eco-friendly

Reusable formwork: An additional approach consists of the design of formwork in such a way that makes it reusable. In this type of formworks is therefore essential that the strength and flexibility of the material

are suitable for this purpose: on one side the formwork has to be strong enough to withstand the pressure from the concrete, on the other hand, the mould has to be flexible otherwise it's unlikely that it will be removable without any break. This is the least wasteful approach and opens the opportunity for mass production by replicating the process that can be found usually in a precast concrete factory. The example shown is a work from the CREATE group to 3D print several formworks that can be reused to cast other panels [Figure 2.2] This system is particularly challenging because the design has to integrate a strategy to be disassembled

Figure 2.2

A project from the CREATE group for concrete panels with reusable formwork.

2.1

DIRECT 3D PRINTING

3D Concrete Printing (3DCP) is a subset of additive manufacturing and in this process concrete, with very small aggregate, is the material being laid layer after layer to create the desired design. The use of a high-performing material as concrete enables AM to reach a vastly different scale (beam, building and infrastructure) and never-thought-before shapes are possible. Different types of 3DCP can be identified that change regarding the technology being used.

Binder Jetting: In this process, a binder is selectively poured onto a powder bed of concrete [Figure 2.3.a], by reacting with it a solid part is created layer after layer. The advantages of this manufacturing process are that no support structures are required as the solid part is supported by the surrounding material therefore challenging shape can be realized. Another advantage is the great level of precision as it can be seen from the first 3d printed pedestrian bridge [Figure 2.3.b], a project from the Institute for Advanced Architecture of Catalonia (IAAC) and Enrico Dini, considered to be the inventor of binder jetting in construction. The great limitation of this system is that the printer/powder

bed needs to be bigger than the object being printed.

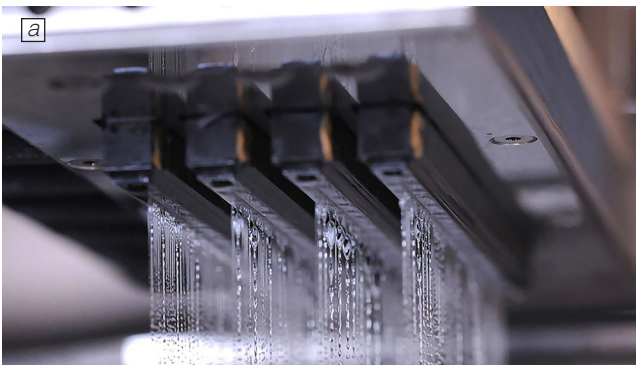
Slipforming: Also referred to as Smart Dynamic Casting (SDC) is a construction method where concrete is poured in a formwork that is open on the top and bottom side and mounted on a motion system that can move and rotate the mould, additionally with the right set up the shape of the formwork itself can be modified. In the example shown [Figure 2.3.c] in a project by ETH a flexible formwork is moved vertically and during this process it's possible to change the section of the column by working on the mould. The advantages of this system is the use of a formwork significantly smaller than the structure produced, furthermore it is possible to create with the same mould different variations of the same component. Another great advantage is the possibility to create a smooth surface, a great challenge in 3D construction printing.

Shotcrete: In this process concrete is applied layer by layer as shotcrete meaning that it is sprayed through a hose at high speed over a surface. This method allows for the possible integration of conventional

reinforcement such as steel bars as it doesn't need a printing surface completely free of obstacles. Additionally, the high speed of the concrete resolves the issue of the weak adhesion between different layers and expands the possibility for a gradual transition from the vertical to the horizontal plane (H. Lindemann, 2018). A great disadvantage of this system, as it can be seen from the example shown by TU Braunschweig [Figure 2.3.d] is that this method does not allow for great resolution and a post-refinement might be necessary.

3D Concrete Printing: This AM process replicates what is typically referred to as 3D printing. In this method concrete, with very little aggregate, is pumped into a hose and through a nozzle onto a surface where layer after layer the digital 3d model is manufactured. A motion system moves the

extruder over a surface according to the coordinates given by the control unit. This method is the subject of this work which will be from now called 3D Concrete Printing (3DCP). The choice of this system is due to the inherent advantages of the technology: the setup needed for this approach can be created with components that are already available in the market, also, the range of motion systems available make it possible to use this system for different applications at different scales. This explains why this approach is the one that is currently stepping its first step into the market and proposing buildings that have been sold or rented. Additionally, this is the approach investigated by the CREATE group and reflects the technology available in the lab [Figure 2.3.e]. The advantages and challenges of this approach will be discussed later and throughout this work.



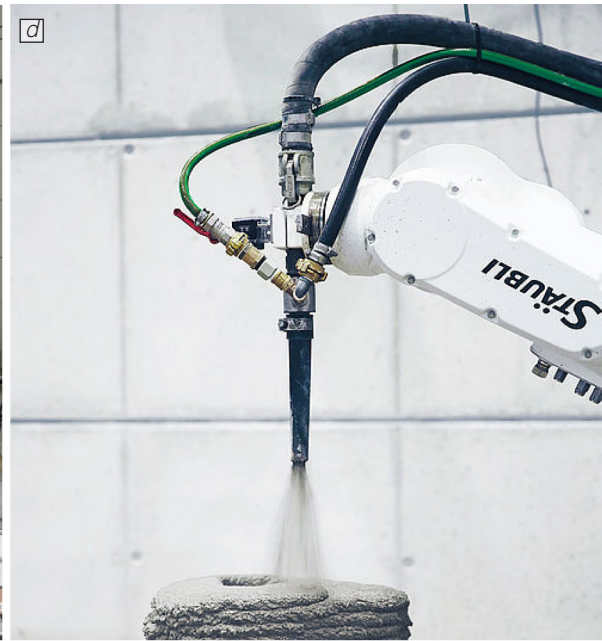
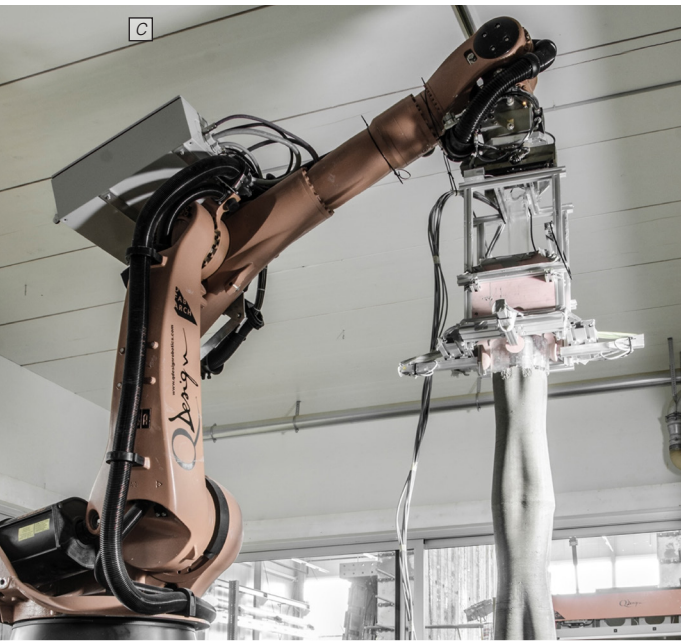


Figure 2.3

- a. Binder Jetting, Droplet of binder being poured
- b. The first 3DPrinted Pedestrian Bridge by IAAC and D-Shape
- c. Slipforming, a project from ETH with a flexible formwork mounted on a robotic arm.
- d. Shotcrete, an example of work from TU Braunschweig
- e. 3D Concrete Printing, close up of the printing process during SDU summer school 2020

2.2.1 C3DP ADVANTAGES

3DCP is likely to have a great impact on the construction industry as it has the potential to completely change the way building and the built environment is designed, engineered and constructed. Behind the push of this new technology are the evident advantages that it can bring regarding many aspects: environmental, economical and social. These improvements are discussed here.

Reduce greenhouse emission: Concrete is the largest CO₂ source of greenhouse gas at around 4-8%, only second to China and the US with 2,8 bn tonnes (The Guardian, 2019). CO₂ is produced both during the making of cement (by burning coal to create the necessary heat) and in the process of producing cement clinker by the thermal decomposition of calcium carbonate. In this regard, 3DCP can lower the amount of concrete by creating a 3D model optimized through topology optimizations and finite element analysis that should need less concrete and therefore reduce the greenhouse emission of every project (Yu Chen, 2017).

Reduce construction waste: According to the European Commission as of 2016 25-30% of all the waste generated in the EU

come from the construction and demolition (C&D) industry (European Commission, 2016). 3DCP can reduce 30-60% of construction waste by eliminating the need for formwork and reducing uncertainty. (Markets and Markets, 2016). Also, as C3DP needs smaller aggregate, many companies claim their printable concrete contains a significant amount of construction and demolition waste as aggregate (Yu Chen, 2017).

Reduce water usage: The production of concrete is a water-demanding process using almost 1/10 of the world's industrial water use. Often this strain supplies for drinking and irrigation because 75% of this consumption is in drought and water-stressed regions (The Guardian, 2019). 3D printable concrete requires a lower water content thanks to its fresh properties such as low slump and fast setting (Yu Chen, 2017).

Reduce workers injuries: As of 2018 24% of fatal work injuries in the US were in the construction industry (US Bureau of labor statistic, 2018).

3DCP can reduce 50-80% of labour cost which means it could also lower the number of workers needed therefore the number of fatalities (Markets and Markets, 2016). Additionally, the automation of multiple on-

site operations means that workers would be expected to do less tiring jobs.

Freedom of shape: The possibility to manufacture a digital 3D model opens the possibility to realize, within limits, the most diverse and complex designs that are the result of the endless digital tools now available to designers. This gives the possibility to rethink the way a project is approached and changing the design method, one of the aims of this work.

Faster construction: The implementation of 3DCP can completely change the way buildings are realized and therefore lower the production time of a building by 50-70%. (Markets and Markets, 2016). Specifically, by automating the construction method it is expected that the need for carpenters and construction workers will decrease, and new jobs such as material experts and process supervisors will be essential for the manufacturing of these new projects. (H. Nielsen, 2021)

Cheaper construction: for all the reasons listed above 3DCP can be a cheaper construction method that can lower costs significantly. A specific number is not clear as multiple companies claim production costs that are almost impossible to verify,

additionally, some company claims have been debunked (H. Nielsen, 2021). Thanks to the possibility to lower the need for labour and material, 3DCP is referred to as the technology that can resolve the shortage of affordable housing around the globe.

2.2.1 3DCP CHALLENGES

Several materials, technological and logistic limitations are slowing down the widespread use of 3DCP in the construction field. Most of them are a consequence of the infancy stage 3DCP technology lies in. An outlook on how companies and research centres are trying to overcome these challenges is provided.

Material performance: the concrete now available from producers is mostly engineered for traditional construction methods, 3DCP has different needs which makes the study for a new type of concrete essential. The material needs to go through a liquid stage and a hydration process to be solidified for successful self-supporting during the printing process, which must end before the material becomes too dry, therefore impossible to extrude (R.A. Buswell, 2018). Some companies such as Saint-Gobain Weber are working with companies and



research centres such as the CREATE group to improve and iterate on solutions that are already being used to 3D print buildings and others.

Printer: Depending on the motion system of choice it is generally needed for the printer to have a greater reach than the dimension of the building itself. In the case of the gantry

system this limitation is evident where the frame needed for the movement of the nozzle is bigger than the project itself [Figure 2.5]

Low Resolution: As during the printing phase concrete is in a fluid state it's very hard to control the width and shape of the layer that generally has a rectangular shape with smooth edges [Figure 2.6]. This is why 3DCP

Figure 2.5

Comparison between the project and the printer used (COBOD BOD 2)



has a very low resolution which makes it hard to integrate printed elements with other building components including mechanical, plumbing and electrical. (R.A. Buswell, 2018). To overcome this challenge the industry is looking for new ways to further control the material and the result of its extrusion.

Legislation: As 3DCP is generally new in the construction industry the legislation poses a great challenge. At the same time there is great interest and a lot has been done in this regard as it is shown from the growing number of projects being realized with cooperation from local authorities.

Figure 2.6

Example of cross section of 3D print

03

STATE OF THE ART

3.1

THE HISTORY OF 3DCP

A History of the development of 3DCP regarding its technology and utilization has been conducted. The events noted are an important moment in the development of the idea of 3DCP therefore even though there are different approaches and technologies all of this milestone demonstrates the history and evolution of 3DCP as a technology and its applications.

Some precedent first explored the possibility to integrate manufacturing processes in construction, this is the case of the machine to build a wall by W.E. Urschel in **1941** where an extruder was moved manually around a central pin and created a circular envelope.

But the origin of the history of 3DCP is generally associated with the presentation of the patent by prof. Behrokh Khoshnevis in **1995** where he first theorized a manufacturing system that used a construction fluid material (USPTO, 1995).

A Large-scale adoptions of this method was proposed in **2004** by prof. Khoshnevis as a system to print the contour of the walls of a house. From this point forward there is a growing interest as it is reflected by the increase of publications published. (J. Chung, 2020).

In **2008** Loughborough University started

to work on Concrete 3D Printing in the frame of a project called “freeform construction” that aimed to explore the potential of this AM process to generate complex designs.

It is important to preface that the difficulties to find clear information about many projects makes it hard to truly understand to which extent 3DCP has been integrated into the building. Additionally, it’s hard to define a clear winner in the race to 3D print the first house: the possibilities for companies to find multiple and different methods to integrate AM in construction would force a comparison within different approaches. As of now even though many claim to have 3D printed a house only the walls of the house so far have been printed: other components such as foundations, stairs and ceilings are generally realized with standard construction methods.

2014 has been adopted as the start of the “development phase”, the focus of the state of the art, because in this year Winsun presented the first example of a large scale adoption of 3DCP by assembling 3D printed components to create 10 one storey houses that, according to the company, can be printed for under 5000\$ (BBC, 2014).

In **2015** Winsun also announced that they realized a 5 storeys building which makes it

the highest 3D printed building. It is important to note that, even if the company advertises many of their projects as 3D printed buildings, it is unclear the extent to which conventional construction is part of the construction: in some cases, it seems like conventional beams and columns have been realized and then prefabricated printed walls are later positioned into the frame. It is also important to note that all of these projects have not been put into the market, so even if they were built it is unclear if local authorities declared these houses habitable.

In **2016** Apis Cor, a robotic construction company now based in Boston announced that thanks to the cooperation with the Dubai Municipality they were able to 3D print the biggest building: a public building of 640 m² (Apis Cor, 2019). As the construction phases were made public it is safe to say that the majority of the building, apart from the foundation, stairs and ceilings, were 3D printed on-site. This is the first example of a 3D printed building that later went into use and is currently part of the client assets.

In Europe, the implementation of AM in construction is more recent. The real milestone for the continent is the creation in **2017** by COBOD, the global leader in 3DCP automation system provider, of the first approved 3D printed building in the region: a single storeys office space located in Copenhagen near the company's facility.

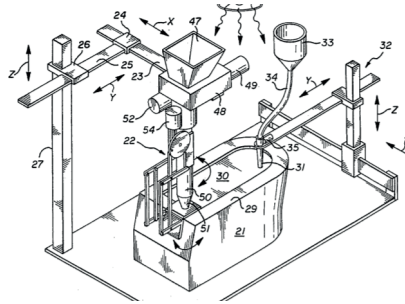
Another important moment is in **2018**

the inauguration of Europe's first 3D printed pedestrian bridge as the result of a collaboration between TU Eindhoven and Royal BAM, a Dutch construction group. In this case, several components were printed off-site, assembled and then thanks to post-tensioning the structure achieved the needed strength and was permitted to be located in Gemert, a small town in the Netherlands.

In **2019** an interesting project from ICON, a construction technology company based in Austin, gave credibility to the commercial feasibility of the field by creating several 3D printed houses with a wooden roof that was the result of the partnership with New Story, an NGO, to provide housing to houseless people.

In **2020** COBOD in collaboration with Kamp C, a centre for sustainability and innovation in construction, has built the first example of a two storeys building 3D printed. The level of refinement of the structure also shows the possibility of this technology.

Finally, in **2021** in The Netherlands, in the frame of the "project milestone" the first of 5 residential houses was built and rented which thanks to the cooperation between PERI, a German scaffolding company, and COBOD it was possible to 3D print a two storeys house that according to plan, will be put into the market to become the first sold and lived building in the continent.



**FIRST THEORIZAZION
OF C3DP**

Prof. Khoshnevis - USA

1995



**RESEARCH ON FREE
CONSTRUCTION**

Loughborough Univer

2008

1941

MACHINE TO BUILD WALL

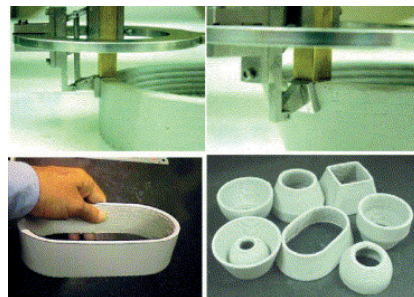
Urschel - USA



2004

FIRST EXAMPLE OF 3DCP

Prof. Khoshnevis - USA





FORM

University - UK

START OF THE
DEVELOPMENT
PHASE



HIGHEST 3D PRINTED
ASSEMBLED BUILDING

Winsun - China

2015

2014

FIRST 3D PRINTED ASSEMBLED HOUSES

Winsun - China





**FIRST 3D PRINTED BUILDING
IN EUROPE**
COBOD - Denmark
2017



**3D
HO
ICC
20**

2016

BIGGEST 3D PRINTED BUILDING
Apis cor - Dubai



2018

FIRST 3D PRINTED BRIDGE
TU Eindhoven - Netherland





**PRINTED COMMUNITY FOR
HOUSELESS
INDIANS - USA
2019**



**FIRST COMMERCIAL
HOUSING PROJECT
TU Eindhoven
2021**

≡
ds

2020

**FIRST PRINTED MULTIPLE STOREYS BUILDING
COBOD - Denmark**



3.2

BUILT PROJECTS MAPPING

The projects selected for the state of the art of 3DCP are intended to return an overview of the achievement in the field of extrusion-based projects from 2014 to March 2021. The state of the art aims to give a clear depiction of how 3d printed concrete construction have gone so far and what could be the possible integrations and applications. The projects have been found online and thanks to the multitude of articles, papers and the website of various companies. For this research social media posts were also helpful to find and verify the information found.

The projects all fall within the building field at a different scale, design objects such as vases, benches and furniture have not been included if they were not considered to be a significant example of 3DCP for the construction scale. Other materials such as clay and ceramic have been included in the selection for the similarities with concrete regarding consistency and printing process.

To categorize this project different and useful information were noted. Even though there are usually different authors for the same project only the company that seems to

be in charge of the construction of the project was noted. The name of the project, if not available, was given; the year of completion of the project was also noted. Other information collected have to do with the material extruded, the motion system used, the type of reinforcement integrated and the project scale which will be later explained. Finally it was noted if the project was created on-site or in an off-site facility and if the building was assembled or notes, meaning if it was created thanks to the combination of different smaller components, most likely printed off-site.

The result is 104 projects by 36 different research institutes and companies:

Thanks to the work done to categorize these projects it is possible to have a deeper knowledge of a project. Significant aspects of these projects and technology have been further investigated like the material mixing and supply system, the motion systems and the reinforcements integrated into the building. It has been considered useful to focus on the project's scale, which will be later defined.

STATE OF THE ART IN 3DCP

AUTHOR	NAME	YEAR	COUNTRY	MOTION SYSTEM	MATERIAL	REINFORCEMENT
Loughborough University	Wall	2012	United Kingdom	Gantry system	Concrete	No Reinforcement
WinSun	10 houses - One-Story	2014	China	Gantry system	Concrete	Standard
Total Kustom	Concrete Castele	2014	USA	Gantry system	Concrete	No Reinforcement
WinSun	1100m ² Luxury Cottage	2015	China	Gantry system	Concrete	Standard
WinSun	Global Highest 3DCP*	2015	China	Gantry system	Concrete	Standard
Xtree	Democrite wall	2015	France	6-axis Robotic Arm	Concrete	No Reinforcement
Total Kustom	Hotel Suite	2015	Philippines	Gantry system	Concrete	No Reinforcement
HuaShang Tengda	3DP Villa	2016	China	Gantry system	Concrete	Standard
WinSun	Shandong Bingzhou Creative Industry Park	2016	China	Gantry system	Concrete	Standard
WinSun	Wave Building	2016	China	Gantry system	Concrete	Standard
WinSun	Steel Structure Prefabricated	2016	China	Gantry system	Concrete	Standard
BetAbram	Stair	2016	Slovenia	Gantry system	Concrete	Wire Mesh
SCG SRI	Y-BOX	2016	Thailand	Delta system	Concrete	No Reinforcement
WinSun	Dubai Government Office	2016	United Arab Emirates	Gantry system	Concrete	Standard
Apis Cor	Public Building*	2016	United Arab Emirates	Swing Arm	Concrete	Standard
Apis Cor	House	2016	Russia	Swing Arm	Concrete	Between Layer
Loughborough University	Curved printing path	2016	United Kingdom	Gantry system	Concrete	No Reinforcement
DTI	3DCP of post-tensioned element	2017	Denmark	6-axis Robotic Arm	Concrete	Post-tensioned
COBOD	The Bod*	2017	Denmark	Gantry system	Concrete	No Reinforcement
University of Nantes - The Nantes Laboratory of Digital Sciences	YHNOVA	2017	France	Movable 6-axis Robotic Arm	Foam	Standard
Xtree	Stormwater regulator	2017	France	6-axis Robotic Arm	Concrete	No Reinforcement
Xtree	YRYS Concept House	2017	France	6-axis Robotic Arm	Concrete	No Reinforcement
Bruil	Prefab Printing	2017	Holland	6-axis Robotic Arm	Concrete	No Reinforcement
IAAC	Terraperforma	2017	Spain	6-axis Robotic Arm	Clay	No Reinforcement
SCG SRI	Triple S	2017	Thailand	Delta system	Concrete	Between Layer
CyBe Construction	R&Drone Laboratory	2017	United Arab Emirates	Movable 6-axis Robotic Arm	Concrete	No Reinforcement
CyBe Construction	Manholes	2017	United Arab Emirates	Movable 6-axis Robotic Arm	Concrete	No Reinforcement
AMT Specavia	Yaroslavl AMT project	2017	Russia	Gantry system	Concrete	Standard
Construction Engineering Research Laboratory	Barrack	2017	USA	Gantry system	Concrete	No Reinforcement
Xtree	Inspection chambers	2018	France	6-axis Robotic Arm	Concrete	No Reinforcement
Xtree	Art Deco columns	2018	France	6-axis Robotic Arm	Concrete	No Reinforcement
Constructions 3D	Double skin wall with internal structure	2018	France	Boom Arm	Concrete	Standard
Tu Eindhoven	3d concrete bridge*	2018	Holland	Gantry system	Concrete	Post-tensioned

Figure 3.1

Spreadsheet in Excell of the database

3.3 TECHNOLOGIES

Different components define the technological system used by companies and research centres to manufacture their projects. It is possible to identify certain elements that are generally part of a setup. These components are:

1. Design:

This is the digital model of the desired model that is then translated into a machine-ready script to run the motions system.

2. Materials:

Depending on the desire of the author It's what is being extruded through the nozzle and, layer after layer, realize the projects.

3. Material mixing and supply:

It is the part of the system that, in the case of 3D Concrete Printing, is in charge of the mixing of the materials and their supply to the nozzle. Depending on the technology in place two systems can be identified which will be now discussed:

- Batch process
- Continuous mixing process

4. Motion Systems:

To move the nozzle according to the script obtained by the digital model it is necessary

to have a computer-controlled system that can move the extruder in the desired position.

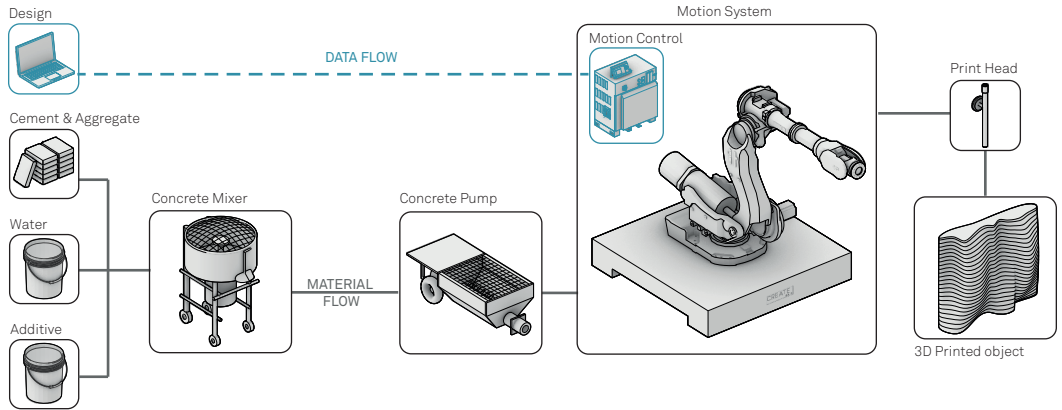
5. Print head:

Otherwise called nozzle is the components from which the material is extruded onto a surface or in the construction site.

3.3.1 MATERIAL MIXING AND SUPPLY

Batch Process: this is the most basic system that can be realized with technologies that are fairly easy to find in the field. In this process, the cement, aggregate, water and additive are all mixed in a standard mixer. Once the material is ready to be printed is then transferred to a concrete pump that will push the concrete through a hose to the nozzle to then create the desired design. This is the system that is generally used in facilities that are working on smaller-scale objects that do not need a great supply of material. The disadvantage of this system is that it's not possible to make any changes in the mixture once the printing process has begun and therefore it is likely that if the material prop-

BATCH PROCESS



CONTINUOUS MIXING PROCESS

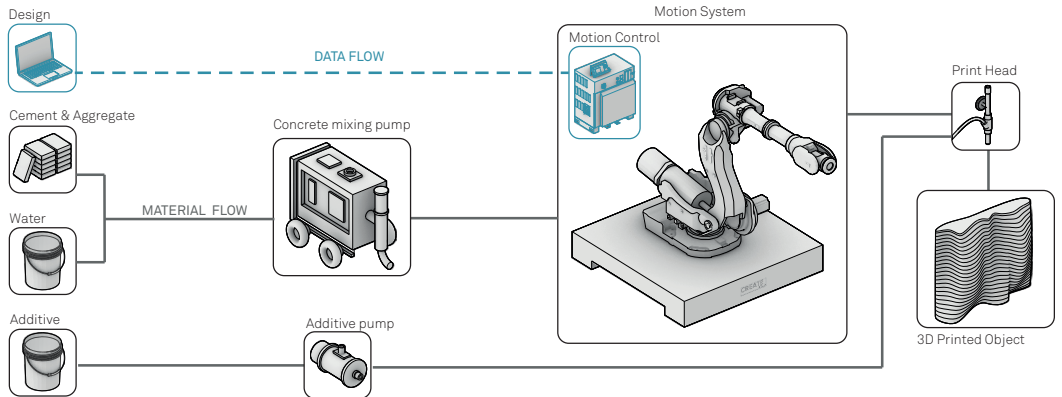


Figure 3.2

Diagrams of material mixing and supply systems

erties are not satisfactory the entire batch has to be changed. Additionally mixing additives such as an accelerating agent before the material is pumped through the nozzle can improve the quality the material but also cause the clogging of the hose, a problem often encountered in the experience in the CREATE Lab which uses this system.

Continuous mixing process: this method has been specifically created for 3DCP and is a system where cement and water are mixed on-demand during the printing process. In some cases, the additive is later added to a mixing reactor just before the extrusion. The possibility to continuously mix the material makes it possible to change the water/cement ratio according to needs. Additionally, the possibility to add additives such as accelerating agents before extrusion gives the possibility to adjust the ability of the concrete to cure in case, for example, that the freshness of the layer is creating a problem in the stability of the print

3.3.2 MOTION SYSTEM

Different options regarding the motion systems are available and the choice of one over the other comes down to the size of the

project and the construction method. A list of the different systems encountered during the project's research is here presented:

Gantry System: The most typical 3-axis Computer Numerical Control (CNC) that use a cartesian system. The printing head is mounted on an overhead bridge and is moved from a large gantry robot with three degrees of freedom. This technology is preferred because it can carry heavy loads and they are relatively simple, inexpensive to build and versatile (A. Paoloni, 2019). However, as they generally need to be bigger than the print itself, they are quite voluminous [Figure 3.3.a]

6-axis system: A programmable robotic arm with 6-axis degrees of freedom. The motion is allowed by the rotation of the different joints that connect the robot's components and it's the motion system that can be usually seen in the manufacturing field. The great freedom of rotation is a great advantage that opens to new possibilities during the printing process. The great limit of this system is the reduced reach which can reduce the possibilities during the printing phase and limit the use of this robot for smaller models as can be seen from the example shown at the IAAC [Figure 3.3.b].

Movable 6-axis system: In this case,

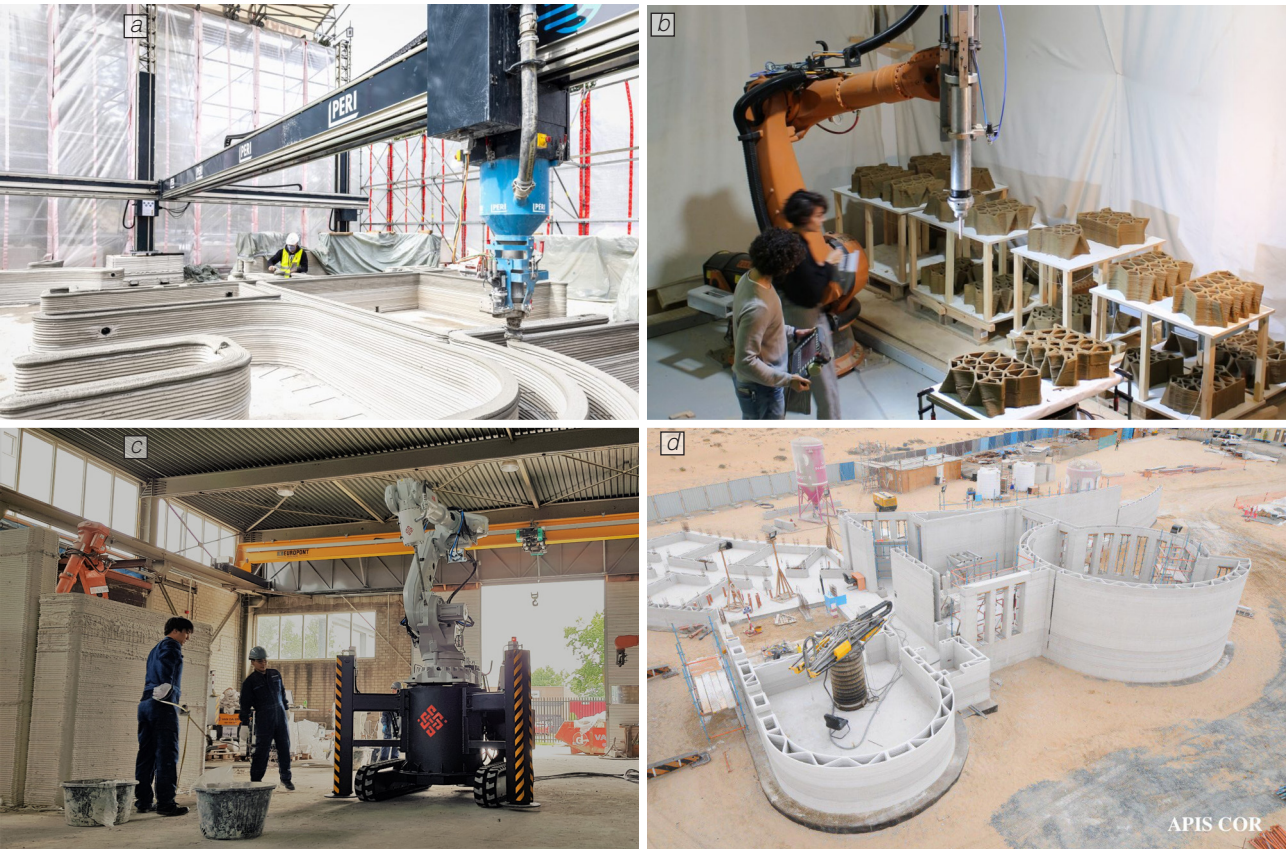


Figure 3.3

- a. A gantry system (COBOD BOD 2) used by Peri for its project in Wallenhäusen
- b. A 6 axis Robotic Arm in use at the IAAC
- c. A Movable 6-axis robotic arm developed by Cybe Construction
- d. A Swing Arm used to manufacture the biggest 3D printed building by Apis Cor

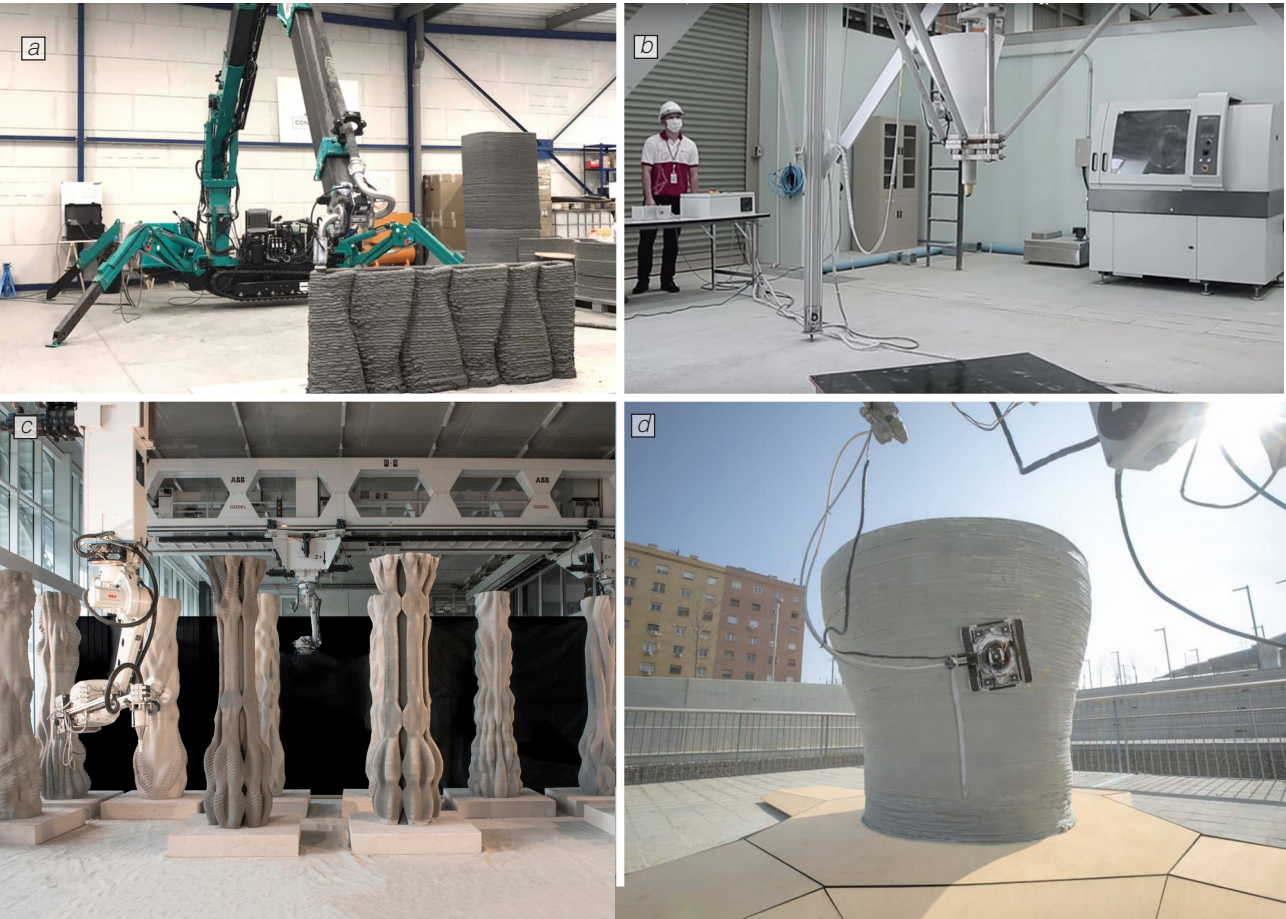


Figure 3.4

- a. Example of Boom Arm adapted for 3D construction printing by Constructions-3D
 b. A delta System from WASP used by Siam Cement Group
 c. A hybrid systems in the Robotic Fabrication Lab of the ETH
 d. Photo of one of the three mobile robots created by IAAC

a 6-axis robotic arm is mounted on an additional movable system [Figure 3.3.c]. Cybe Construction, a technology company from the Netherlands, is the main provider of this solution for the construction industry. The great advantage of this system is that it greatly extends the reach of the robotic arm and suits it for large scale construction.

Swing Arm: A 3-axis CNC using a polar coordinate system. This motion system could be compared to a tower crane, a construction-site machine that is usually used to lift and lower heavy objects. In the case shown Apis Cor, to realize a public building in Dubai, used this motion system with an extendable arm that increases the reach of this system [Figure 3.3.d]. The disadvantage of this technology is the need to move it to a different location to manufacture the entire building.

Boom Arm: This motions system can be easily found in construction as a lifting system that can bear heavy loads. In this technology, the base of the arm is mounted on a turntable to allow for rotation. Additionally, in the solution for 3DCP offered by Constructions-3D [Figure 3.4.a] the boom arm is mounted on a movable platform.

Delta: A parallel robot consisting of 3 arms capable of fast 3-axis motion. This motion

system is composed of three arms that are connected in a joint that host the printing head. Due to the limited printing range of this system it is suited for smaller projects, in the example shown WASP provided the printer to Siam Cement Group (SCG) the largest cement manufacturer in Thailand [Figure 3.4.b].

Hybrid: Commonly, companies and universities are cooperating with producers to develop new and improved motion systems that can help them overcome some issues or test new possibilities. In many cases this means the creation of a hybrid system that combines more technologies. This is the case of the system of the Robotic Fabrication Lab (RFL) of the ETH Z that is equipped with a robotic arm mounted on a gantry system, this allows respectively for great freedom and great reach [Figure 3.4.c].

Mobile robots: This type of motion system includes experimental robotic devices designed specifically for 3DCP. In the example, an experimental motion system by IAAC is shown. Three small robots were designed to work together for the creation of the same object: the first laid the foundations, the second elevated the structure and the third one (in the picture) was in charge of the surface refinements [Figure 3.4.d].

3.3.3 REINFORCEMENTS

In the analysis, based on the information available, details about the system of reinforcement were noted. All systems that were aimed at reinforcing the printed object were noted and categorized as reinforcement. It is important to note that due to the difficulties to find clear information about the project it is possible that the reinforcement system implemented might be different from the one noted. A list of the different types encountered is here shown to ease the understanding of future discussions.

No reinforcement: In this case, no type of reinforcement was noted [Figure 3.5.a]. This can be due to both the difficulties of integrating reinforcements system during the printing phase and the fact that for how 3DCP is being investigated a common approach is to design structures that do not need reinforcement. The disadvantage of this system is that, due to the concrete properties, the material always needs to work in compression, an important constraint for the design.

Standard: In this system, steel bars are positioned in a mould that is 3D printed within the envelope of the 3D printed wall. Later concrete or grout is poured and left to cure

to create a column-like component in a way that is the closest to conventional methods [Figure 3.5.b]. The advantages of this system is that thanks to its similarity to a standard method of reinforcement it facilitates the effort to investigate the structural performance of the project.

Post-tensioned: It's a conventional technique for reinforcing concrete where, in the case of 3DCP, tendons are passed through the printed objects and pulled tight and anchored on the edge of the system. In the example shown, to create a bridge, Royal BAM and TU Eindhoven post-tensioned 6 similar objects through tendons that were passed through the cavity designed in the cross-section [Figure 3.5.c].

Transversal: In this case transversal plastic or metal components are positioned between layers to improve the strength of the print and reduce the possibility of buckling or collapse. The advantage of this system is that the positioning of these elements can be easily done by a robot and therefore automate even further the printing process [Figure 3.6.a].

Wire Mesh: This method can be seen as the adaptation in 3DCP of ferrocement, a form of reinforced concrete. In this system a plastic



Figure 3.5

- a. Example of a wall with no reinforcements integrated in the structure.
- b. Close up of steel bars integrated within a wall envelope.
- c. A printed bridge reinforced with post-tensioning



or steel wire mesh is positioned between layers of the same path to strengthen the structure and ideally reduce the possibilities of cracking by improving the reaction of the object to tensional stresses [Figure 3.6.b].

Metal support: In this case metal support can be used to allow for the assembly of all the elements that compose the structure, which is the case of the pedestrian bridge completed in Shanghai by Tsinghua University that needed support to position the components of the arch structure [Figure 3.6.c].

Steel Cable: In this approach investigated from TU Eindhoven, a steel cable is entrained into a filament of printed concrete [Figure 3.6.d]. A device was specifically developed for this approach and it uses a servo-motor driven spool that feeds steel reinforcement cable into the concrete filament just before it leaves the print nozzle. This type of approach can achieve significant post cracking deformations and post cracking strength. (F. Bos, 2018)

Figure 3.6

- a. Integration of transversal steel bars between the layer of a wall.
 b. Example of a wire mesh positioned in between two layers in a project from Winsun
 c. For the assembly of a printed bridge in Shanghai a metal support was needed.
 d. Example of the integration of steel cable during the printing process by TU Eindhoven.

3.4 SCALES

One important aspect of the project that helped to better understand the project and its importance within 3DCP's story is its scale. The scale is a property that defines and identifies a project based on its dimension, extent and achievement. Analyzing the projects in the database, four categories can be outlined.

One storey building: This category includes projects that, for what it can be seen, are organized just on one level and do not have a 3D printed second floor. In this case the projects encountered are mostly residential, public and military buildings. As it can be seen in the project shown of a house for the homeless in Austin by ICON, a Texas construction technology company, just the walls result to be 3D printed and other components such as the roof are created with conventional methods, in this case with wood [Figure 3.7.a].

Multiple storeys building: In this category are grouped the projects that have two or more levels above the ground. The achievement regarding this scale is the possibility to create buildings that go beyond the ground floor and that show the possibility for C3DP to expand

outside the one-storey house, a necessary step to follow the market's need. Even in this case, it is important to note that some components such as the ceiling between levels and the stairs are not 3D printed but created with conventional methods [Figure 3.7.b].

Building element: This category includes columns, staircase systems, walls and arches which often are intended to be an iteration of prefabricated components that could be then assembled on site. In the example shown ETH Zurich's students created a series of columns that were later used as scenography for a dance performance [Figure 3.7.c].

Infrastructure: Finally in the infrastructure category were grouped projects that were looking to different applications outside the residential and public building field. The only examples of this are bridges and their feasibility pushes the technology in one of the most performance-driven designs and one of the focus of this work: horizontal structure. In the example is shown the first fully 3D printed pedestrian bridge from Royal Bam and Tu Eindhoven [Figure 3.7.d].



Figure 3.6

- a. A one storey building in a project for a homeless community in Austin.
- b. A multiple storeys building printed with a gantry system.
- c. An example of building element: a column manufactured by ETH's students
- d. E bridge realized by Royal Bam in The Netherlands

3.5 CRITICAL REVIEW

3.5.1 A GROWING INTEREST

A geographical analysis of the projects realized was conducted in relation, also, to the year that the project was announced. In the map for each project, a dot was placed and the colour indicates the year of completion: darker shades of blue have been used for more recent projects, lighter colours for older projects [Figure 3.9].

Thanks to the study of this map it is clear that Dubai, Europe, Shanghai, and North America are the main epicentres of 3DCP thanks especially to many companies in the business. It is important to note that the role of the Chinese company Winsun is hard to estimate due to the lack of information.

The effort in some country is reflected by a government effort in the field: Dubai has announced that 25% of the new building will be made using 3d printers by 2025 (World Economic Forum, 2018), the Danish government has funded the project “3D Construction Printing” which launched project such as COBOD who is the main global provider of gantry systems for 3DCP. Many of the projects in other countries such as the USA and France have been realized by companies or start-ups in the business.

The interest and advancement in the field are reflected by a growing number of projects announced each year. In just 8 years the number of projects has increased rapidly: from just 2 projects in 2014 to 33 in 2020 [Figure 3.8].

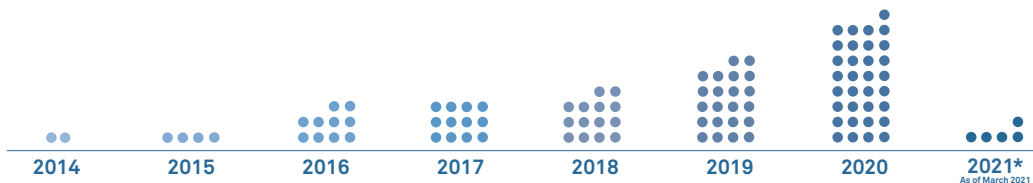


Figure 3.8

Number of projects/year. Each dot represents a project.

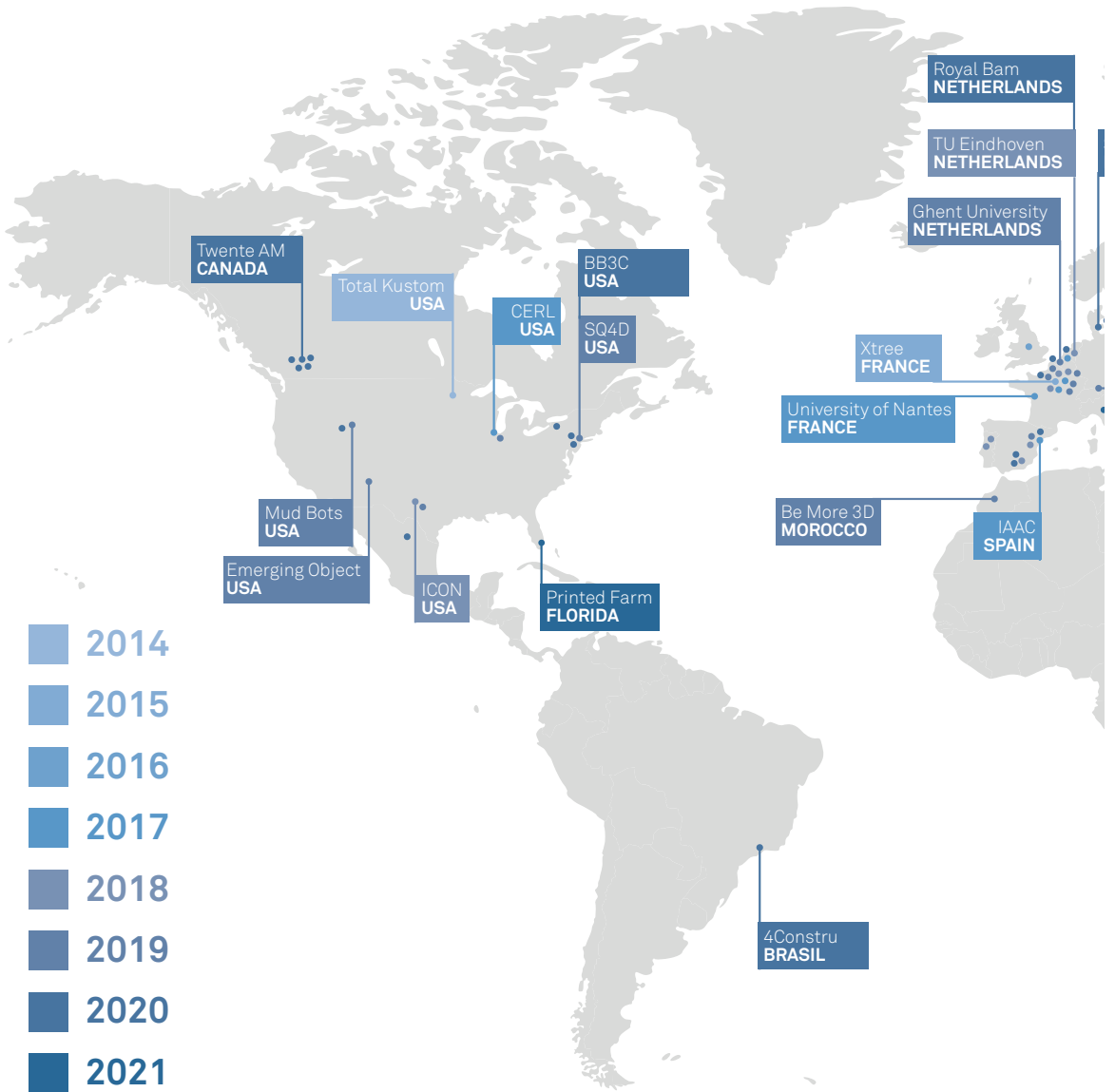




Figure 3.9

Map of locations of projects. Darker color are used for more recent projects

3.5.2 ON-SITE AND OFF-SITE

Based on the project found it is clear that there is no strong preference between On-Site or Off-site production with almost equal numbers on both sides: 57 projects are manufactured Off-Site and 43 on-site with just 1 exception that tested a blended version between the two.

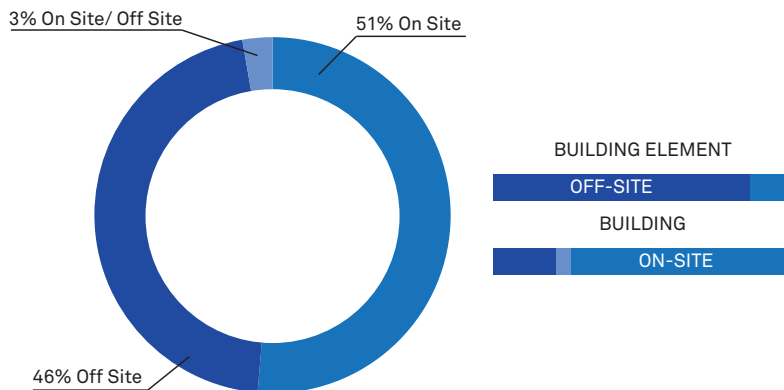
If this data is then put into relation with the project scale there is a clear difference: a building element is generally printed off-site (87%), buildings are generally realized on site (66%).

This can be explained by the difference between the two main work fields: on one side prefabrication is being developed through the

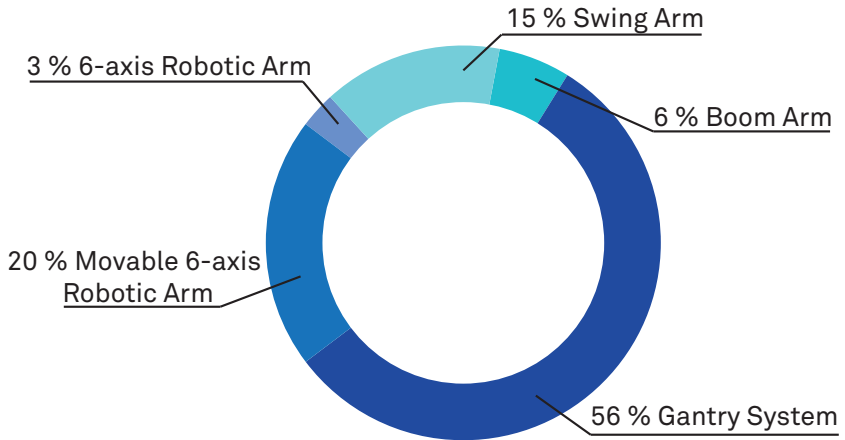
study of objects printed off-site that could be then assembled on-site to create the desired structure. On the other side, many companies are working towards the goals of 3D printing an entire building on-site.

3.5.3 THE CHOICE OF A MOTION SYSTEM

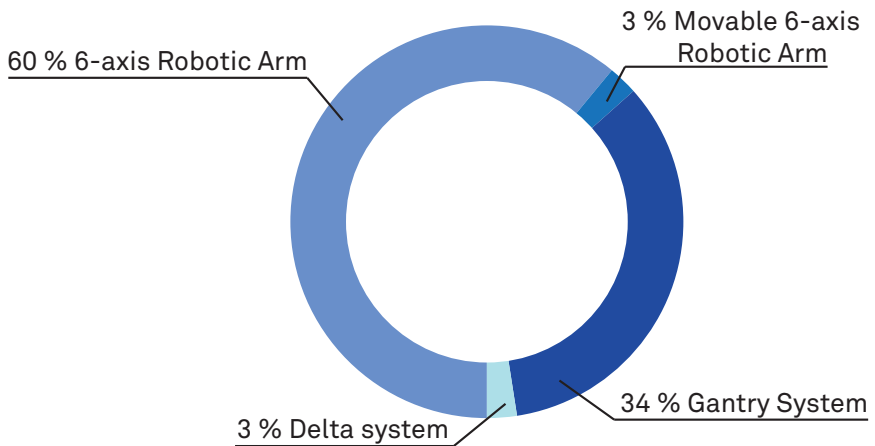
Even though there are multiple motion systems it is possible to draw a clear preference relatively on the decision to print on-site or off-site. In on-site operations, the most used systems are movable 6-axis robotic arms and gantry systems. Both of this technology share the possibility to reach a great printing area, a necessary property when the goal is to manufacture an entire



ON-SITE



OFF-SITE



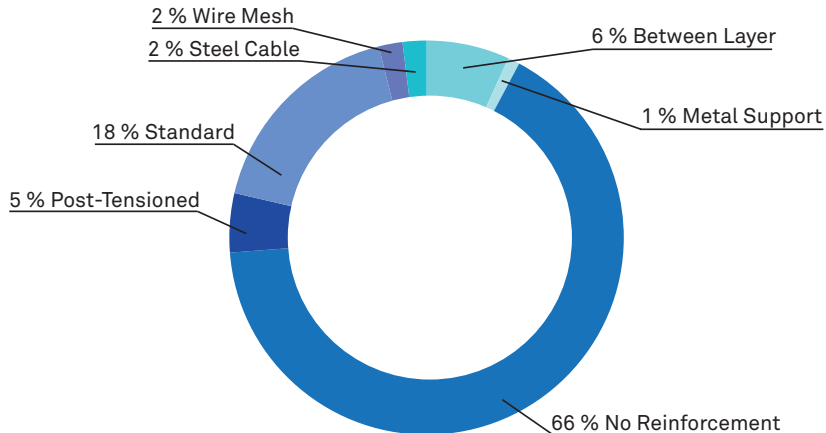
building. In off-site, the preferred system is 6-axis robotic arms which is a technology that can be usually found in manufacturing. Even in this case the scale of the work influences the choice of the system: building elements, which as shown are generally realized off-site, are smaller objects that do not require great reach to be printed.

3.5.4 NEW CHALLENGES FOR REINFORCEMENT STRATEGIES

Even though as prefaced there are doubts regarding the strategy of reinforcement used in the project it is possible to see a tendency

in 3DCP's projects of two different types of approaches. The main one is to not integrate any type of reinforcement in the structure (68 projects), the reasons for this are two. First, in 3DCP to create a building, instead of creating the usual beam/column frame, a continuous wall is usually printed and creates the entire structure, by doing so the structure works mostly in compression reducing the need for reinforcement. Second, the integration of reinforcement it's challenging as it would require two robots to work together without interfering with the work of the other, in this case steel bars are likely to disturb the path of the printing robot.

The second most adopted reinforcement



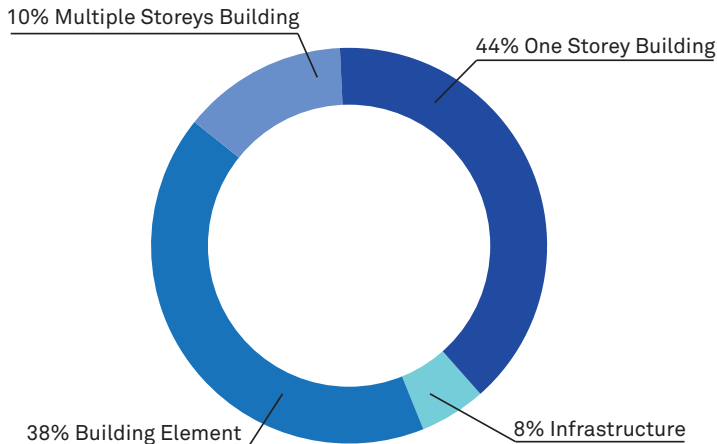
strategy is to integrate standard reinforcement through the pouring of cement or grout in a printed mould where steel bars are positioned (18 projects). Another approach used is post-tensioning which is mainly used for horizontal structures such as bridges (5 projects). Finally, some additional methods are not widespread and are limited to 2 projects (Wire Mesh and Steel Cable) or 1 (Metal Support).

3.5.5 MOVING TO A LARGER SCALE

In the field, the effort is split between the creation of buildings and the realization of building elements (52 vs 45). Both goals

aim to integrate the use of C3DP in the construction industry either to replace the entire construction process or some prefabricated components. While all projects work as prototypes it's fair to say that building components are the ones that are generally designed for research purposes to improve the knowledge around certain specific topics or components.

It is important to note that in the last 6 years the improvement in 3DCP has made it possible to achieve some important goals such as creating some of the most challenging structures: a bridge (6 projects) and a multiple storeys building which already account for 10% of the projects.



This goes to show the potentiality of additive manufacturing in construction, a relatively new approach.

3.5.5 A COMMON PRACTICE IN HOUSING

It is important to note that for the majority of the one and multiple storeys buildings found there is a common approach in how the project is realized: in all the examples shown [Figure 3.10] the houses are realized through the vertical extrusion of a floor plan that creates all the interiors spaces of the building. This method is the one that

is used to realize the majority of buildings because it minimizes risk (as it doesn't have any overhang) and it allows to move on-site all the operations. However, there isn't great freedom in what can be done and close the possibility to print other parts of a building such as stairs, foundations and ceilings which are realized with conventional construction methods. Additionally, this closes the opportunity to work with other printing directions and integrate the discovery done by research institutes and universities. Providing an alternative to this approach is part of the aim of this thesis.

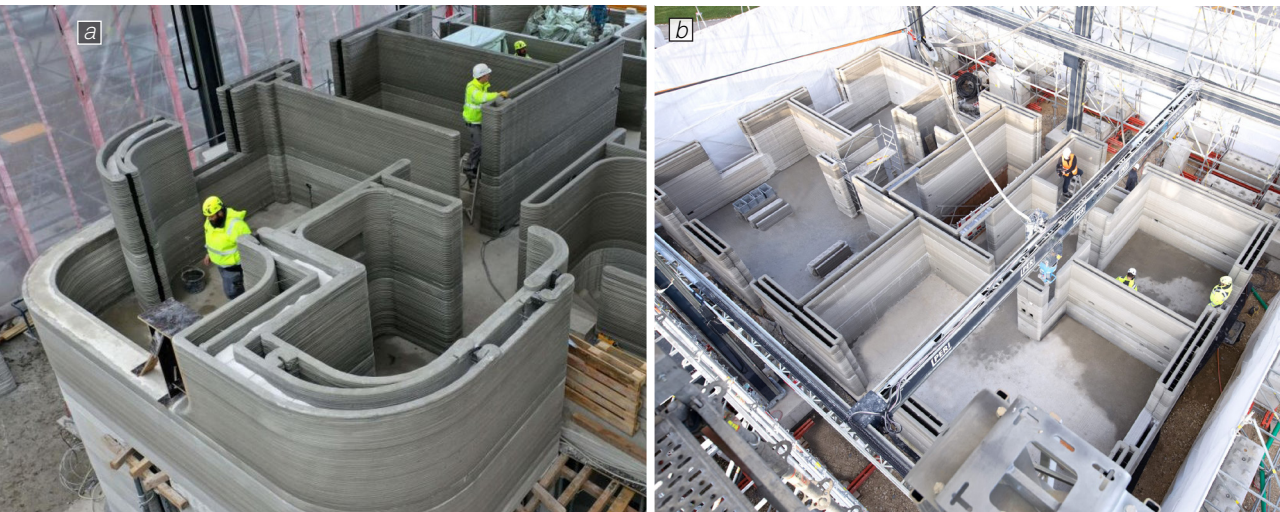




Figure 3.10

a. A residential house by PERI in Beckum, Germany
b. Printing of an apartment block in Wallenhausen, Germany by PERI
c. A public building in Dubai printed by Apis Cor

d. A project by Printed Farms in Florida, US
e. A house printed by SQ4D in the US
f. loss up of a building being printed by BetAbram, Slovenia

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4

3DCP AND OFF-SITE

4.1

PRECAST CONCRETE AS A REFERENCE

As of now many of the buildings found take advantage of the possibility to print an entire building on-site; the research question that it's interesting to ask is: how can the printing of buildings change in case that we want to shift the majority of operations off-site? What benefit can prefabrication of printed components have on the state of the art and how can we achieve that?

The immediate parallel with the proposed shift is with precast concrete.

Precast concrete is an off-site construction method of creating beams and columns that are cast in a reusable formwork and cured in a controlled environment from which the precast elements have to be sent to the construction site to then assemble the project. According to engineer and designer needs, endless different configurations and shapes can be achieved by the right combination of materials, formworks and reinforcements. The possibility to have deeper control over the environment, material, formwork and general process of creation of the beam ensure good quality of mix, placement and curing (Won-Kee Hong,

2020).

With the same philosophy by shifting the production off-site it could be possible to improve and change the way 3DCP is thought and used currently in the construction fields. The new proposal aims to change how also the structural integrity of the building is achieved. Currently, three main systems can be found in the precast concrete field:

Large Panels: In this case, panels that can withstand loads are located both in vertical and horizontal orientation to create the structure [Figure 4.1.a]. In this system, depending on the positioning of the panels, it possible to use different components that might include thermal insulation, reduced or improved structural response. This system is mostly used for the construction of schools, hospital, office and houses. (Riccardo dal Pino, 2009)

3d load-bearing components: In this case, 3d dimensional precast concrete elements are assembled to create the body of the structure. They are usually assembled on-site and it's a system that was used especially during the '50 and even though

they guarantee the possibility to reduce the on-site refinement and reducing the time they are complicated to produce and transport. Other systems are preferred to this one. (Riccardo dal Pino, 2009). A similar approach that includes 3DCP has been developed for “project milestone” by TU Eindhoven and other commercial partners where the body of the house is realized through the assembly of 3D printed blocks that create a futuristic design possible thanks to the freedom of form given by 3DCP [Figure 4.1.b].

Frame system: This system replicates the cast-on-site structure by maintaining the needs for vertical and horizontal elements such as column and beam that combined

create the three-dimensional framework that allows for great freedom to create different possible combinations on the internal space. In this system, once the structural system is generated and the different loads are determined, the precast components will be modelled according to the case needs and then produced. The freedom given by this system makes it the choice that is usually made for projects that need big spans and few constrain like industrial and commercial buildings. This freedom is the reason why this system is the one that has been used as the reference of this thesis and a focus will be later provided.

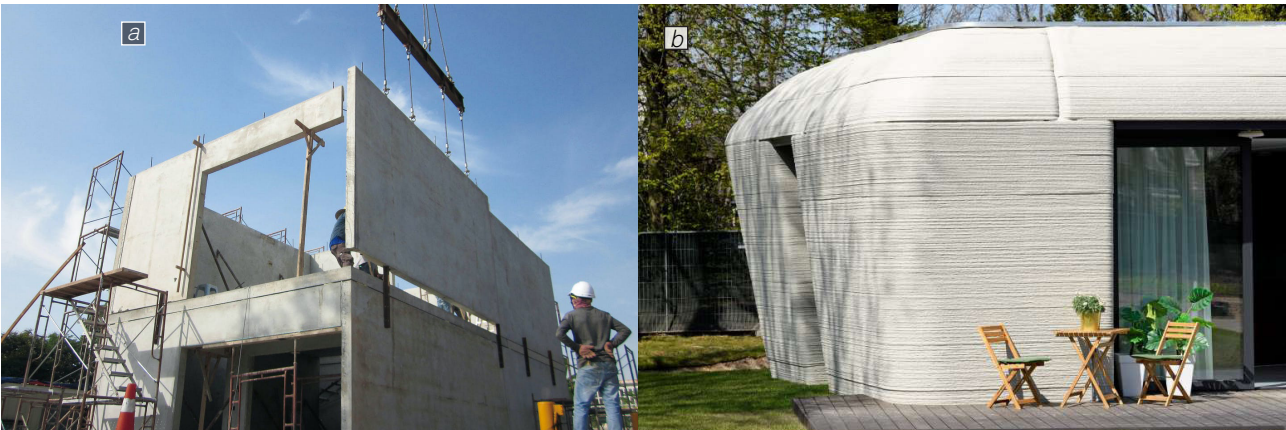


Figure 4.1

a. An example of prefab building made o large panels being assembled. Image by eco-business.come.

b. The first house of 5 that will be 3D printed in Eindhoven, The Netherlands, as part of the Project Milestone

4.2

OFF-SITE 3DCP ADVANTAGES

Moving the manufacturing process off-site can have a great impact on what is possible with 3DCP, to understand what, a comparison can be done between 3DCP on-site and off-site. The idea is to find ways on how the same new approach provided by precast concrete can change the way buildings are now being printed. The research question is: which positive effect could prefab and off-site production bring to the current state of the art in 3DCP?

Improved quality control: As shown from the picture [Figure 4.2.a] many projects like the one shown usually need additional protection from the outside environment to have greater control over the variable that might interfere with the perfect adhesion between layer by fastening the drying process of the concrete and maybe deposit some particle on the printed material. By moving the product in a controlled environment it could be possible to control the mentioned variable and other such as the temperature of the material and printing environment. It's also guaranteed that no additional elements such as foliage or dust from other construction processes could create any

issue in the making. All of these changes allow for a greater quality of the final product

Length Reduction: The possibility to prefab component of the building even before of the pouring of the foundation shorten the length of the construction project by giving the possibility to have the needed component delivered on-site when needed, a common advantage that in precast concrete offer a 20% reduction in the construction time compared to cast-in-place method (L. Jaillon, 2007).

Freeform shape: By moving the production off-site and creating a system where the structural integrity of the building is achieved by assembly it's possible to treat every component of the frame as a different printing process that requires a different setup: it can be printed on one side or the other, it might require additional support or hardware. Finally the possibility to create a system that can be assembled open new possibility to 3DCP by allowing to print even other components such as the ceiling, which so far has been created with conventional systems [Figure 4.2.b].

Maintenance: Assembling the different

components to create the structure allows, in case it's needed, to operate maintenance on a specific part of the building without having to operate any drastic change to the complete structure and jeopardize the structural system: as of now many projects rely on a structural system that consists of a load-bearing wall [Figure 4.2.c] changes for any modification require additional analysis

to understand the impact of it. With the frame system, as it happens in the case of precast concrete, it would be possible to replace any components such slabs or walls that do not have a critical structural function [Figure 4.2.d] and with that improve the thermal efficiency of a building, add windows or change the plumbing and electrical system.



Figure 4.2

- a. During the print of a residential building in Beckum, Germany, an external protection was built around the construction site
 b. Example of a ceiling for a printed house realized with standard method through the use of wooden slab as formwork
 c. Example of a wall that is the main vertical structural feature. Project Gaia by WASP
 d. Example of prefabrication framework being assembled. The wall's panel are not part of the structural system.

4.3

OFF-SITE 3DCP CHALLENGES

As expectable, the idea to move all operations off-site has also some downsides which are those typically related to the precast concrete. The limits to the implementation of this system are the following:

High Cost: The creation of a manufacturing off-site production plant will require important investments to rent or buy a facility and all the expensive equipment needed for the print such as robots, mixing pumps, control units and others. These expenses make this strategy profitable only if the number of projects built offsets the initial capital cost.

Connection: The joints between the different components of the system are an

essential part of the creation of the structural integrity of the building. This process requires skilled workers which are an additional cost. The low resolution of 3D concrete printing makes it also harder to achieve good adhesion between the elements of the framework. (Uk Essay, 18)

Transportation: The main limitation of prefabrication is the need to transport all the objects printed to the construction which is likely to be distant from the manufacturing plant. This cause limit to the dimension of the object that can be created and push the use of this technology to standard shapes which are easier to store but jeopardize the aim of 3DCP.

4.4

BASIC FRAMEWORK

The creation of a framework through the use of prefabricated 3D-printed components offers great flexibility of use and combine the advantages of 3DCP with those given by prefabrication. To guide the definition of a new structural and non-structural system it's useful to introduce a basic precast concrete framework, in this case the frame system shown is a structure of 4X10 m [Figure 4.7]:

In this system there are different components, to facilitate the discussion and guide the following work it has been considered useful to define the typical dimension of each component, this was done by cross-checking different catalogue of prefabrication company and their offer for a smaller building as the one shown. The components are:

Beam: is the horizontal component of the precast framework and is in charge of transferring the horizontal loads to the vertical elements such as columns. Its design is determined by the stress and load that is intended to bear and present longitudinal and transversal reinforcements. It's typically made in one of the three key shapes (PCI, 2020):

- Rectangular

- T-Beam
- I-profile
- L-profile

Beams with rectangular sections are used for cast-in-place systems as they are easier to make. Cross-sections such as T and I profiled are mainly used for prefabricated components. (Martin Peck, 2014)

The choice between this shape is based on the structural needs, the geometrical coherence of the building and the needs to reduce the use of concrete to create a structure that can be as light as possible without compromising the stability of the building.

For this work, it's established a typical dimension for this component to facilitate the following steps.

Range [Figure 4.4.a]:

- Length: from 4 to 8 m
- Height: from 40 cm to 80 cm
- Width: from 20 cm to 30 cm

Column: is a component of the precast concrete frame that allows for the vertical expansion of the structure. Its function is to transfer the load from the beam to the foundation as a vertical load. A column can be one storey or multiple storeys high and

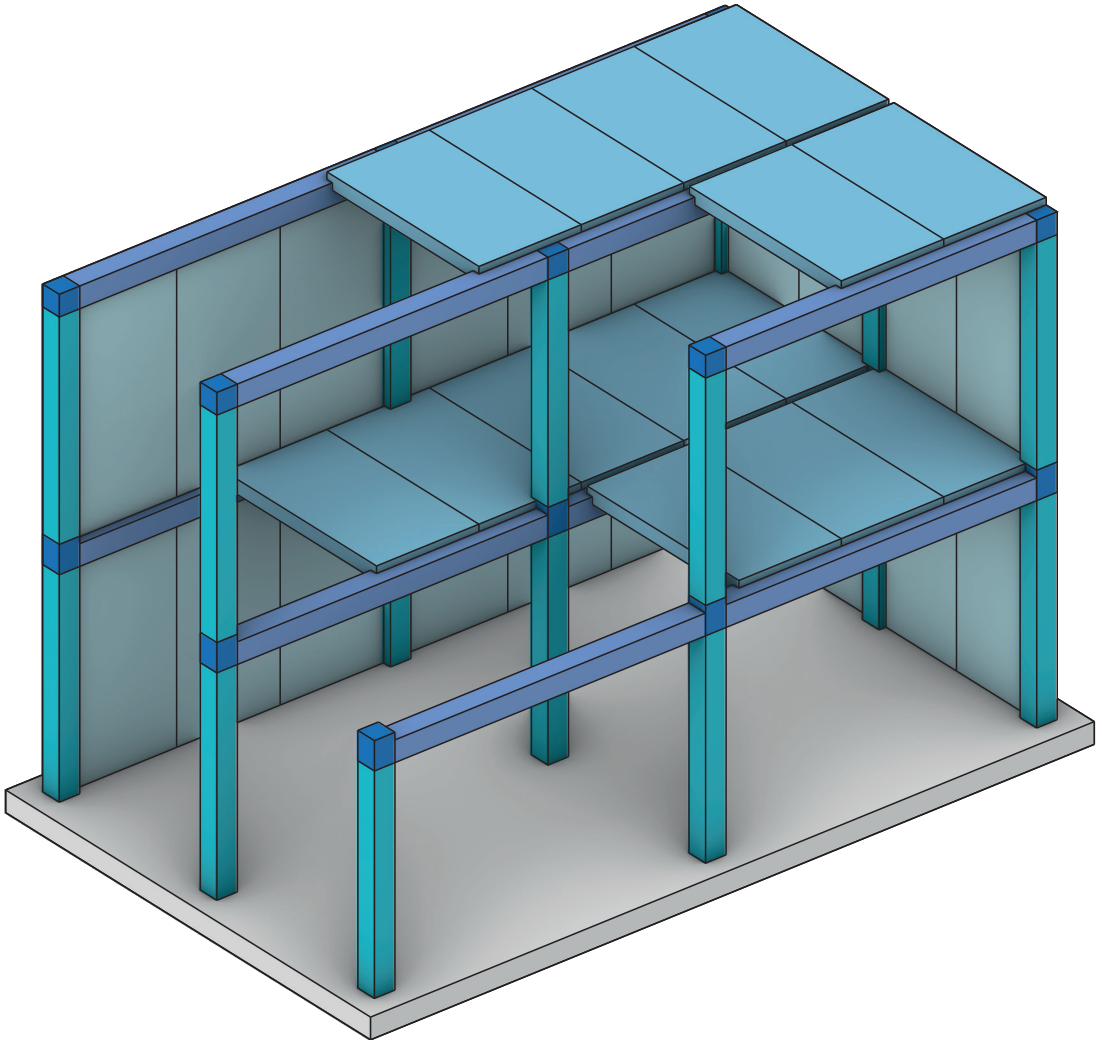


Figure 4.3

Example of a basic prefabricated frame system of 4X10 meters

its shape can be heavily influenced by the type of connections needed to assemble the structure as thought. In the case of the column, the needed joints are those with the foundation or a beam. Generally, the cross-section of the column consists of a rectangular shape, longitudinal and transversal reinforcement are located along with the elements. Concrete columns have generally a rectangular section dictated by the load of the structure.

Range [Figure 4.4.b]:

- Height: from 3 to 6 m
- Length/width: from 30 to 40 cm

Slab: the 2-dimensional components of the 3d dimensional system that allow for the creation of the ground/upper level and roof.

Slabs transfer vertical actions from the slabs dead weight and others into beam, column or wall, therefore they are load-bearing components:

- Ground-bearing slabs are slabs that are used for the ground floor in case that the building is sited on non-reactive soil and therefore is not suitable for a cast-in-place foundation. Generally, this type of slab presents some type of reinforcement such as steel bars. (McKinney, 2006)
- Suspended slabs are used to generate the floors on the upper levels and in some cases also the roof. Different improvements can be made to make the elements as light as possible to

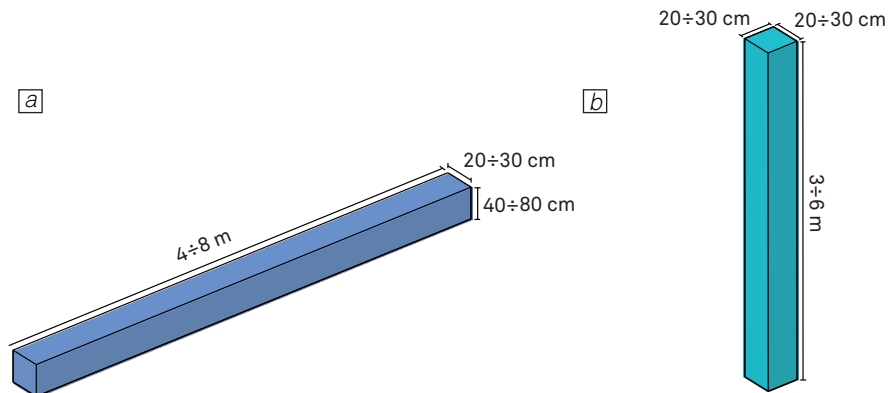


Figure 4.4

- a. Example of a beam and its typical dimension
 b. Example of a column and its typical dimension

improve the strength to weight ratio.

Slabs can be cast-in-site, made of semifinished components that require a final casting on-site or entirely prefabricated. To reflect the laboratory availability and research work only non-prestressed slabs will be considered.

Double Tee slabs are also widely used. It's a structural component that resembles two T-beams linked to each other. The bond between these slabs is created with the pouring of concrete on-site or by sealing the joints. Other U-shaped slabs with two external webs placed closed to each other and then sealed are also used. An additional layer of concrete can be poured on-site to

secure the link between the slabs and to activate load-bearing in the plane of the slab. (Martin Peck, 2014) Ribbed slabs offer a similar solution that is used also without prestressing. In the case of a roof ceiling, the component needs additional care on its thermal dissipation, protection against water and moisture and protection coating.

Range [Figure 4.5.a]:

Normal Slab:

- Span: from 3 to 7 m
- Height: from 20 to 32 cm
- Width: Up to 3 m

Ribbed Slab:

- Span: from 7 to 10 m
- Height: from 45 cm to 70 cm (max)

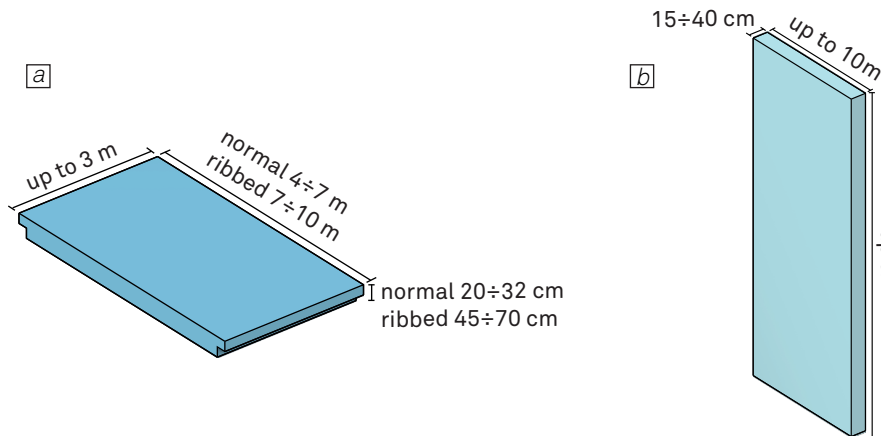


Figure 4.5

- a. Example of a slab and its typical dimension
 b. Example of a wall and its typical dimension

height)

- Width: Up to 3 m

Walls: the elements that allow for the creation of an enclosed space and, in some cases the creation of a façade that can have a meaningful impact on the aesthetic and performance of the building. Walls can be non-load-bearing and load-bearing components that can have a structural function in the case of the lateral forces due, for example, to the wind. In this case, the wall work as a bracing element. In the case of this thesis the wall will be considered as a non-load-bearing component, therefore some of the design decisions to make include the wall behaviour about its thermal dissipation, noise reflection and architectural needs (windows, colour, etc...). Walls are generally realized as two shells linked together that include an insulation system to guarantee thermal efficiency.

Range [Figure 4.5.b]:

- Height: up to 4 m
- Length: up to 10 m
- Thickness: from 15 to 40 cm

For handling and transportation matters it was considered useful to consider shorter walls even though lengths of up to 10 m are possible.

Stair: Stairs are essential components

that allow for the creation of livable spaces by creating connections between different levels within the building. In the case of off-site production, precast stairs are thought of as a one-piece that is usually supported by landing on the level needed, the joints are also filled with elastomeric bearing. Precasting stairs is a very challenging process, especially in the case of multiple steps or curved system that make the job harder and require highly skilled workers. (Martin Peck, 2014).

Joints: An important part of an off-site type of construction that relies heavily on assembly is the connections that are operated on-site: the behaviour of the structural system is ruled by the connection between the monolithic system (Nerio Tullini, 2016). The joints can be of different type and they can block any type of relative movements between the components and transfer normal, shear forces and momentum to the other elements. The choice between one system or another is done in a way that reflects the structural model used for the analysis. Usually, the structural engineer communicates the local forces and momentum and the manufacturer's engineering department decide the right joints (Ivan Holly, 2020)

There two main categories of joints: "wet"

or “dry” joints:

- Wet Joints: In these types of connections, it's needed the pouring of concrete to create the joints between the components that need to be linked. Two main types of wet joints can be identified but both require the components linked to have some extruding reinforcement [Figure 4.6.a]. In one case all the steel bar are placed in the desired position and then, thanks to a pour form, the connection is created [Figure 4.6.b & 4.6.c]. These types of connections can be created between any components but it requires additional support for

the elements and it slows down the on-site operation by having to wait for the concrete to cure. Another type of connections consists of the use of sleeves which have to be integrated within the column or beam design. The extruding reinforcement from one component is inserted in the sleeves of the other and the gap is then grouted to ensure adhesion and form the joints [Figure 4.6.d & 4.7.a]. A great limitation of this system is the need to control that the grouting is perfectly executed, which is very hard to do (Ivan Holly, 2020). Due to the low level of detail possible with 3DCP this type



of system result to be quite hard to be implemented in a possible connection for printed beam and column: the pour form would hardly perfectly follow the profile of the components and the risk of spills it's high.

- Dry Joints: In this case there isn't any need for concrete or grout because the connection doesn't require any pouring to be executed. There are two different types of dry joints with very different performance. In one case additional hardware such as steel plate, metal angle and bolt is used to create the connection. There is a great variety of this type of connection but the main

idea is that a metal component such as a plate is welded or bolted to the column or beam thanks to the reinforcement [Figure 4.7.c]. These metal add-on can be used to create the desired connection by being welded or bolted. The type of metal component and connection varies based on the type of joints required by the structure: a beam-column connection require a higher level of adhesion than a wall-wall [Figure 4.7.b]. The disadvantages of this method are that it requires additional work and skilled personal both on-site and off-site. In this case it is possible to think that this method could be applied to printed



Figure 4.6

- a. Example of extruding reinforcement from a beam which will be used to create the connection with other components
 b. Example of extruding reinforcement from a mesh of beams
 c. Example of interlocking reinforcement which will then create the connection
 d. Example of steel bars entering into the sleeves of another elements

components but it requires a certain level of precision that could be hard to deliver because, for example, the steel plate must be perpendicular to both components so that the connection realized is proper. Another type of dry joints consists of the creation of a geometrical interaction that ensures the connection. The most common example of it is the link created between column and beam through corbels which could be part of the concrete body of the column [Figure 4.7.d] or metal support [Figure 4.7.e]. Bearing pads are integrated to distribute the load evenly and metal angles could be added to ensure the stability of

the joint. The great limitations of this type of connections are that they do not guarantee moment connection and therefore they might not protect against little movements. This system is also vulnerable to lateral loads such as the one typical during an earthquake (Won-Kee Hong, 2020).

In the field, there are very different versions of joints and they usually consist of the combination of those listed above in a way that respects the needed design and ensures structural stability. In some cases, for example, a beam to column connections with corbels can also include the use of bolted to ensure the connection and create a momentum connection.





Figure 4.7

- a. Close-up of steel bars entering into the sleeves of another elements
- b. Steel sleeves are extruding from the profile of this wall and they are part of the system that link the different panels
- c. A steel plate is welded on the bottom of a column and it will connect the beam to the frame
- d. Example of a geometrical connection made possible thanks to the presence of corbels
- e. Geometrical joints made possible through the use of a metal corbels added to the column

05

3DCP LAB EXPERIENCE

5.1 CREATE LAB SETUP

The setup being used at the CREATE Lab is a batch mixing setup that requires a mixer and a pump system which was a PFT ZP3 XL in which the material is poured once ready to be printed. The material is pumped into a hose connected to the motion system, an ABB IRB6650S that controls the cylindrical nozzle

through which the material is extruded onto one or multiple pallets positioned at the foot of the concrete slab that works as a platform for the robot. The motion system is controlled by a unit that is operated by the person in charge of it.

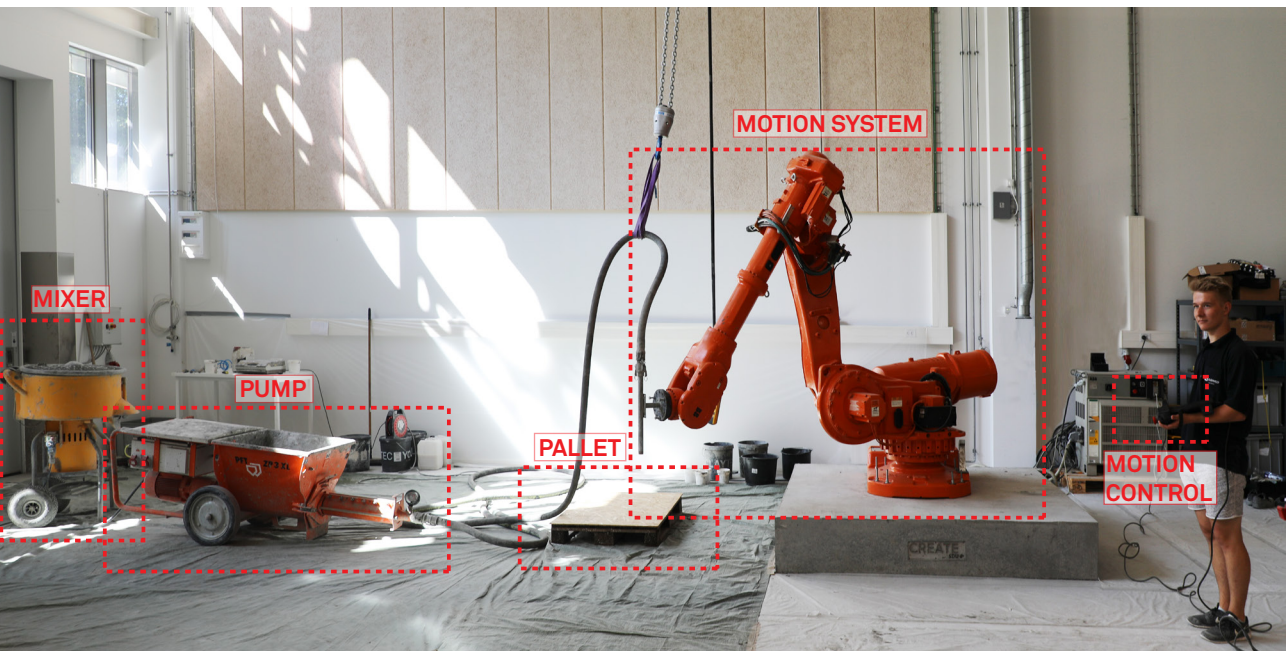


Figure 5.1

A picture that shows the setup at the CREATE lab

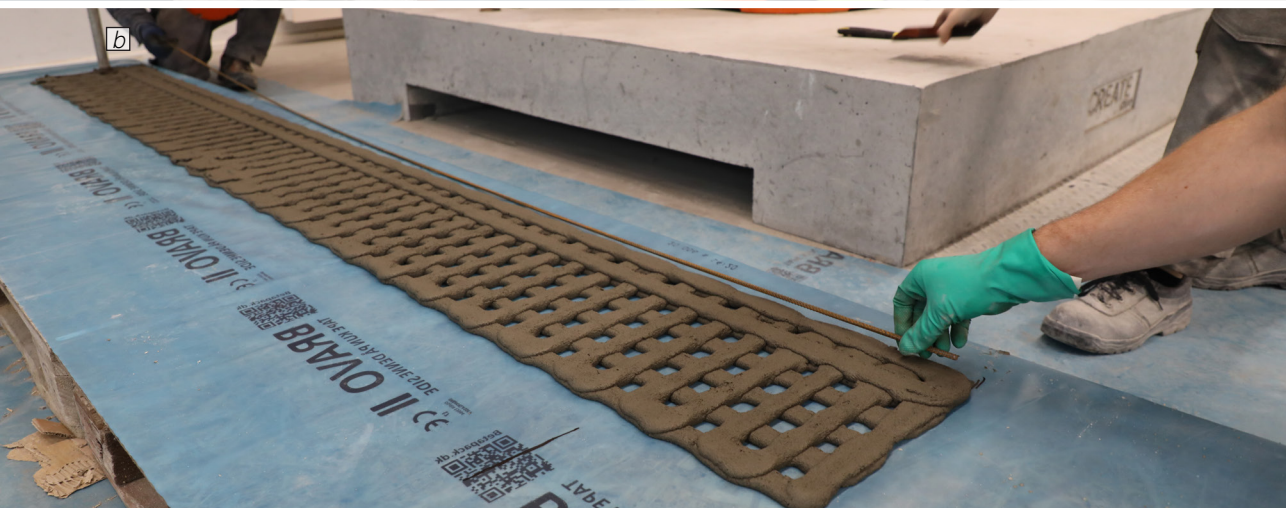


Figure 5.2

- a. A photo of the CREATE lab
b. A close-up during the printing process

5.2

PRELIMINARY TESTING

The research conducted at the CREATE Lab focused on horizontal structures. The final aim of this work was the creation of a structurally optimized beam.

The work in the lab worked as a first approach to 3D printing and a learning phase. Particularly in this period, many tests were done to better understand the factor that influences the buildability of the print and, thanks to PhD student Luca Bruseghello a focus was done on how certain variables can influence the shape of a layer. Additionally, a focus on the behaviour of the material and its interaction with the reinforcement was operated by graduate Philip James Douglas, Simon Andreasen & Mads Sørensen. Finally, the author of this thesis operated a focus on the temperature of the batch made it possible to further understand the needs of the material and allowed for the creation of an ideal timeframe and certain tips.

5.2.1 PRINTING PATH VARIABLES

A great challenge during the printing process is being able to deliver the right

height and width of the layer as it should reflect the one predicted during the design of the object. This is hard to manage as the changing property makes it necessary to change the variable that can be controlled: the height of the layer, the speed of the robot and the speed of the pump. PhD student Luca Breseghello as part of his work looked for a way to find the right setting for a certain design. This was possible thanks to the creation of different specimens, each one with a different combination of the variables listed. The path printed were then sawed and the section scanned. Finally through the study of the data collected it was possible to create a tool that gives the possibility to predict, as best as possible, the shape of the layer.

5.2.2 BUILDABILITY TESTING

All the prints done also worked through the goals of determining the best combination of path variables, material properties and object design to ensure a successful operation that culminates with properly realized specimens

ready for testing.

The most common problem that can be encountered during the printing process are:

Buckling: As 3D concrete printing consists of the deposition of one layer over the other the weight that is subsequently applied on the material it's expectable that if the material properties are not sufficient the print can change shape under the pressure following a process called buckling.

Collapse: Even though one of the great advantages of 3DCP is the possibility to create deeply elaborated shapes this is limited from the fear of collapse which is the abrupt fall of the structure due, during the printing phase, to the load that is continuously applied over each layer. This happens because the material is wet and have very little of the strength that it will develop once it has cured.

Layer Inconsistency: A great issue is that, due to the many variables at play, the layer that is expected to be printed might not be the one that is realized, the reason that has been individuated during the experience are the following:

Changing viscosity: as the concrete is curing the material extruded become increasingly stiff, this changes the width of the layer and homogeneity of the distribution of the material along the structure. This is partly fixable if the person in charge adjusts

the speed of the robot to achieve a similar width, still, this creates a quality problem in the specimens

Non levelled pallet: In the case of the CREATE lab the pallets used are standard wood pallets with clean and planar surfaces on top. Commonly the pallets, especially if 2 or more are needed, are not levelled and the printing plane that the robot envisions present some slight irregularity. Even though this doesn't have massive consequence in the works it does diminish the design refinement as the first layer have an irregular shape that can alter the material distribution.

5.2.3 MATERIAL BEHAVIOUR

The material used during the research at SDU was a pumpable and small aggregate concrete in which water is added to start the hardening process. To make this material suitable for printing, additive were added to accelerate the hardening process and make it printable. Additionally, short monofilament polypropylene fibres were needed to improve the tensile performance of the material. A study of the behaviour of the printed concrete was conducted by M. Sc graduate Philip J. Douglas. To do so multiple specimens were obtained with the grinding of printed slabs [Figure 5.3]. The research aimed at studying

the anisotropic behaviour of the concrete, in particular in the case of 3d printed concrete. Digital image correlation was used to determine the behaviour of the cylinder.

The finding verified the presence of an anisotropic behaviour in the material even though the failure during the compression test is suggested to be linked to a structural behaviour of the geometry of the specimens due to the air bubbles that create great irregularity. This also meant that the direction in which the cylinders were ground relative to the printed slab influenced the final strength. A general reduction between 50-90% of the load-bearing capacity compared to cast

cylinders was noted, the most vulnerable to this decrease is the Y-direction meanwhile the X-direction was found to be the preferable one [Figure 5.4]. It is also discovered that a higher water/concrete ratio guarantee a higher stress-related performance of the mixing but it also lowers the buildability of the concrete during printing time. Following the producer-suggested ratio is recommended as it allows for great buildability and strength.

5.2.3 REINFORCEMENTS INTERACTION

A study of the mechanical performance

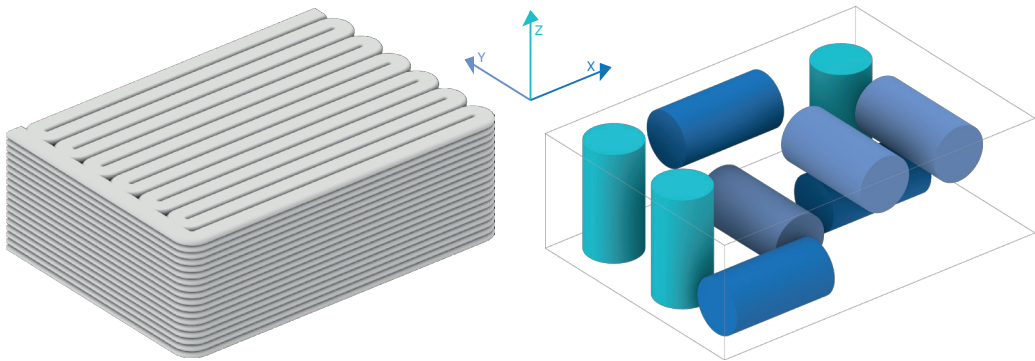


Figure 5.3

One of the specimens printed and the cylinder grinded from it. From Philip James Douglas Thesis.

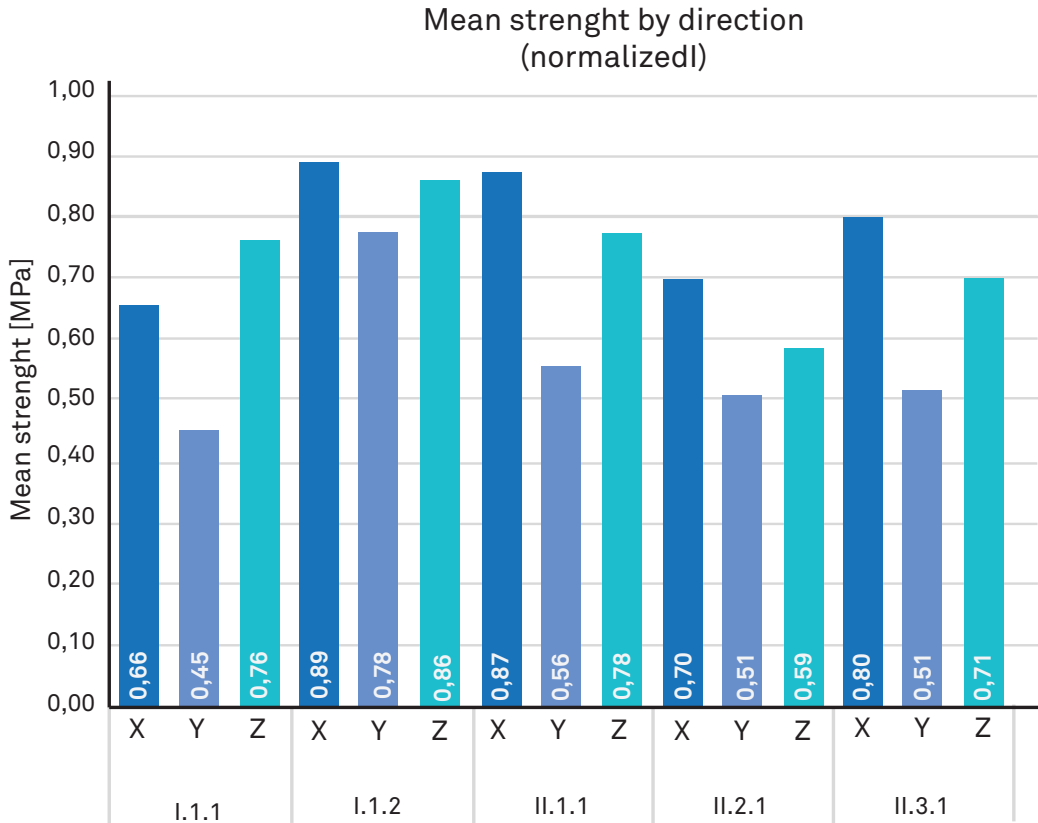


Figure 5.4

Normalized mean strength by direction in MPa for each cylinder, different batches are here shown. From Philip James Douglas thesis

of reinforcement and 3D-printed concrete was conducted by M. Sc graduate Simon Andreasen & Mads Sørensen. This was investigated through 28 printed specimens with protruding rebar tested with a pull-out experiment. The printing direction varied between tests [Figure 5.5] and they were designed to break in cone failure or combined cone-pull out failure to replicate the failure in bending cracks around the reinforcement. Cast specimens were included in the study as references.

A pull-out test was then conducted for all

the specimens and the results were noted. In Direction 1 the cracks were only located in-between filaments where the rebars were also placed. This is likely caused by a reduced adhesion between filaments due to the bad adhesion between rebar and concrete.

In Direction 2 the results proved optimal bonding between reinforcement and concrete and the location of the cracks suggested that the surfaces between filaments are generally weaker. Generally, a homogenous point of reference has not been found but the results suggest that the print directions has a great

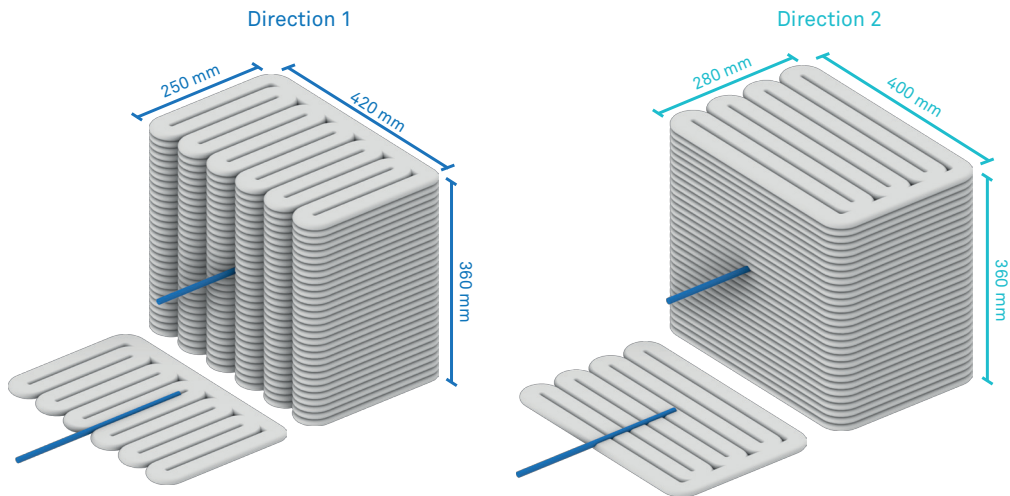


Figure 5.5

3D model of the direction 1 and 2 specimens

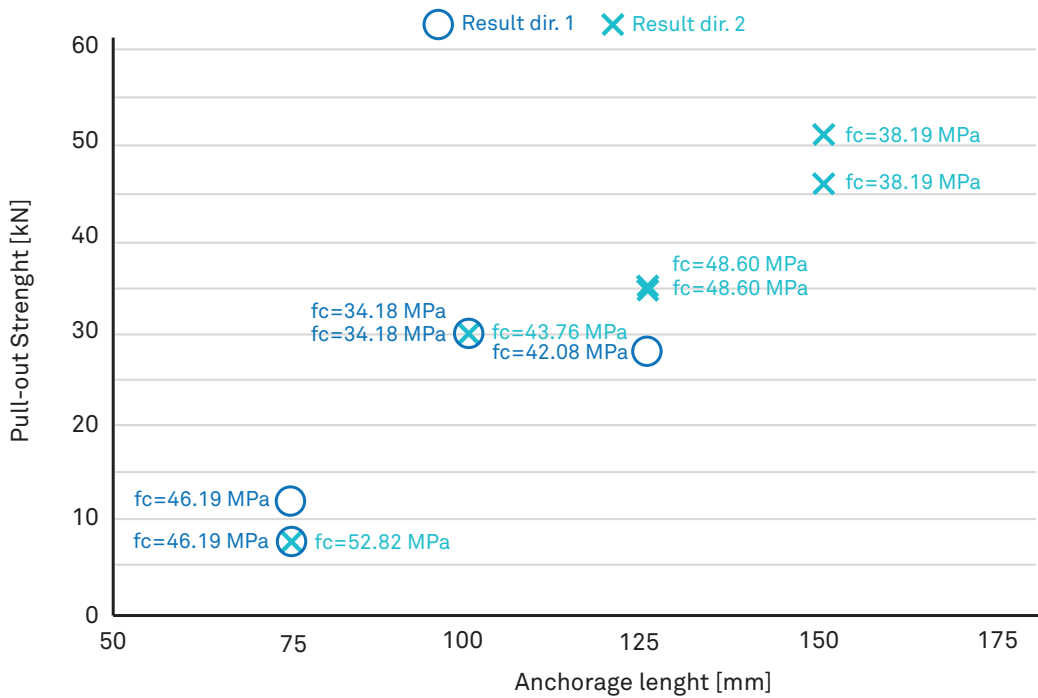


Figure 5.6

Comparison of pull-out test result, as functions of anchorage length and compressive strength.

influence on the type of failure mechanism: direction 1 is prone to splitting and direction 2 is more likely to fail in a cone failure which shows great adhesion between rebars and concrete. Additionally, direction 2 can withstand a higher load than the Eurocode expect. Therefore direction 2 is the printing direction that is suggested for future designs.

5.2.3 TEMPERATURE INFLUENCE AND AN IDEAL TIMEFRAME

During the print of the various specimens or objects the ambient and batch temperature has been collected. This task aimed to better understand the relation between the temperature and the problem faced with the print. Another important aim of this research was to define an ideal timeframe in which the printing process is suggested to run to reduce risks such as the clogging of the hose that brings the concrete from the pump to the nozzle, a problem that required intensive work to be fixed. Generally, for every batch the following information were collected:

Ambient Temperature: The challenge in picking an ambient temperature is that while the mixing and preparation of the concrete happened outside of the lab, in a nearby

shed, the printing of the objects happened inside the Lab. In this process after the pouring of all the necessary material is done the mixer is quickly moved inside the Lab and the main door is closed. The lab is equipped with a heating system that, in our experience, is set to bring the lab to a temperature of 20°. The operations didn't allow for the creation of a fixed ambient temperature. To have the best result possible it was decided to measure the external temperature once or twice during the day and the ambient internal temperature as soon as the mixer was brought inside until the temperature was close enough to 20°.

Batch temperature: In regards to the batch the temperature was measured once the mixer was brought inside and ideally every 5-6 minutes. Once the printing process started, and the material was poured into the pump, the time was noted and from that moment the temperature might have been measured either from the mixer or the pump. It is important to notice that the batch starting temperature is deeply influenced by the material temperature. As for safety needs, it was discouraged to store the material overnight in the Lab. The external temperature had a great influence on the material and therefore batch temperature. It

was later tried to control as much as possible the temperature of the materials.

Starting print time: The moment when the print started was noted, this happened once the material was considered to be ready to be printed which usually meant that the stiffness allowed for the deposition of one layer over the other.

Start of mixing: this value represents the moment when all the material have been poured inside the mixer and most likely the mixer was brought inside the laboratory.

End of the print: It was also noted when the printing process ended which is considered to be the time in which the last temperature was collected. It has to be noted that in some cases due to necessity within the printing process this data was not written down.

Problem: In case that the hose got clogged it was noted to understand what might have caused that issue. In another case maybe the material wasn't buildable even after the printing process started and the material was put once more in the mixer and/or pump.

Batch composition: To understand the behaviour of the concrete it was also noted that possible difference in the material used in each batch. Generally either the amount of water and accelerant changed, the last

one was considered to have a determining influence over the possibility of encountering any problem.

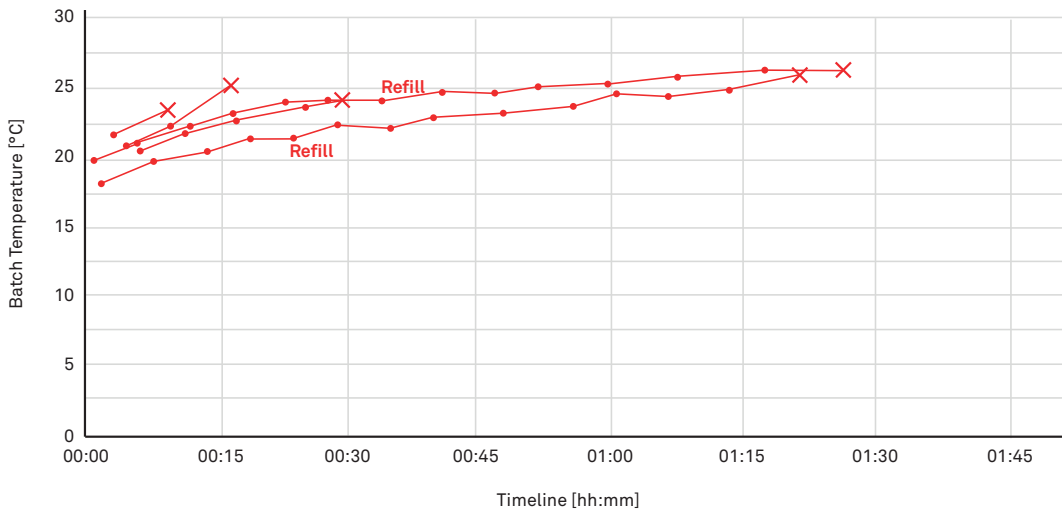
In total for 34 different batches, divided into 12 different days, the information listed before were collected and wrote into an excel file which made it possible to then compare the data and understand how the material behaves, in particular to the batch temperature. The graph obtained gives a general view of what would be the ideal printing timeframe.

A great challenge was to find the limits of the ideal timeframe, for both of them, it was considered ideal to calculate the average of the value recorded. This is more direct for the start of the print with a bottom limit for the ideal timeframe of 25 minutes from the start of the mixing. For the upper limit of the timeframe it must be noted that the reason that can cause the end of the printing process can be multiple: the hose might have gotten clogged, some batched were smaller than others or simply there wasn't a need to wait for some other issue to be fixed. For these reasons and to better reflect the purpose of this graph all the batch where the hose got clogged or the printing time was under 50 minute were excluded.

5.2.3 TROUBLESHOOTING

In our experience, it was clear that the batches that later ended up clogging the hose were the ones that had a higher percentage of accelerant and therefore the speed of growth of the temperature was higher. This was noted during the operation of the 17/10/2020 were one batch with a 2% of accelerant that became warmer faster than the others done the same day. In multiple cases, it was needed to put the extruded material back in the

pump or mixer. This could happen for multiple reasons: the material wasn't properly mixed, the consistency of the concrete wasn't ready to print or some error in the script forced us to restart the printing. The problem is that the extruded material has a much higher temperature due to the friction between the nozzle and hose with the concrete. Generally, after 45 minutes the material temperature stabilized but in the case of a refill (red) the temperature kept on growing, in both cases the hose got clogged.



✗ The hose got clogged

Figure 5.8

In this graph are shown the batches that caused the hose to get clogged, in the case of a refill it is marked along the dot in which time, more or less, it was done.

5.3

A FIRST ATTEMPT AT STRUCTURAL OPTIMIZATION

An important step of the research was to investigate a way to use the possibilities given by 3DCP to optimize the design of a beam. To facilitate the printing process and design the approach was to print the beam on the side. As part of the research on 3DCP at the CREATE group, 3 beams were designed, simulated, printed and tested. The elements printed all present the same A_s (reinforcement area) of 226 mm² for the section, it is just located differently according to the design. The designs are the following:

B01: This beam consists of a standard beam that is printed and used as a reference to compare the performance of the next beams. This design is also part of the thesis of graduate Simon, Philip and Mads and is used as a reference to evaluate the performance of the designs investigated.

B02: This beam is a first attempt in

realizing a structural optimization by reducing the amount of concrete used thanks to the creation of rectangular voids spread uniformly on the beam. The amount of concrete used is reduced by 60 Kg (from 302,40 Kg to 240,61 Kg)

B03: In this case, the beam is designed by following the shape of the isostatic lines found through the IsoLines tool of Karamba3d which require as input the point of which the isostatic lines are obtained, in this iteration the points given are the one positioned at a constant distance along the vertical line in the mid-span of the beam, this has been done to guarantee that the section in the middle doesn't have any discontinuity. The amount of concrete used for the print of this beam (294,61 Kg) is very similar to B01 (302,40 Kg) which is mostly because the frame of the B03 is slightly bigger than B01 and B02.

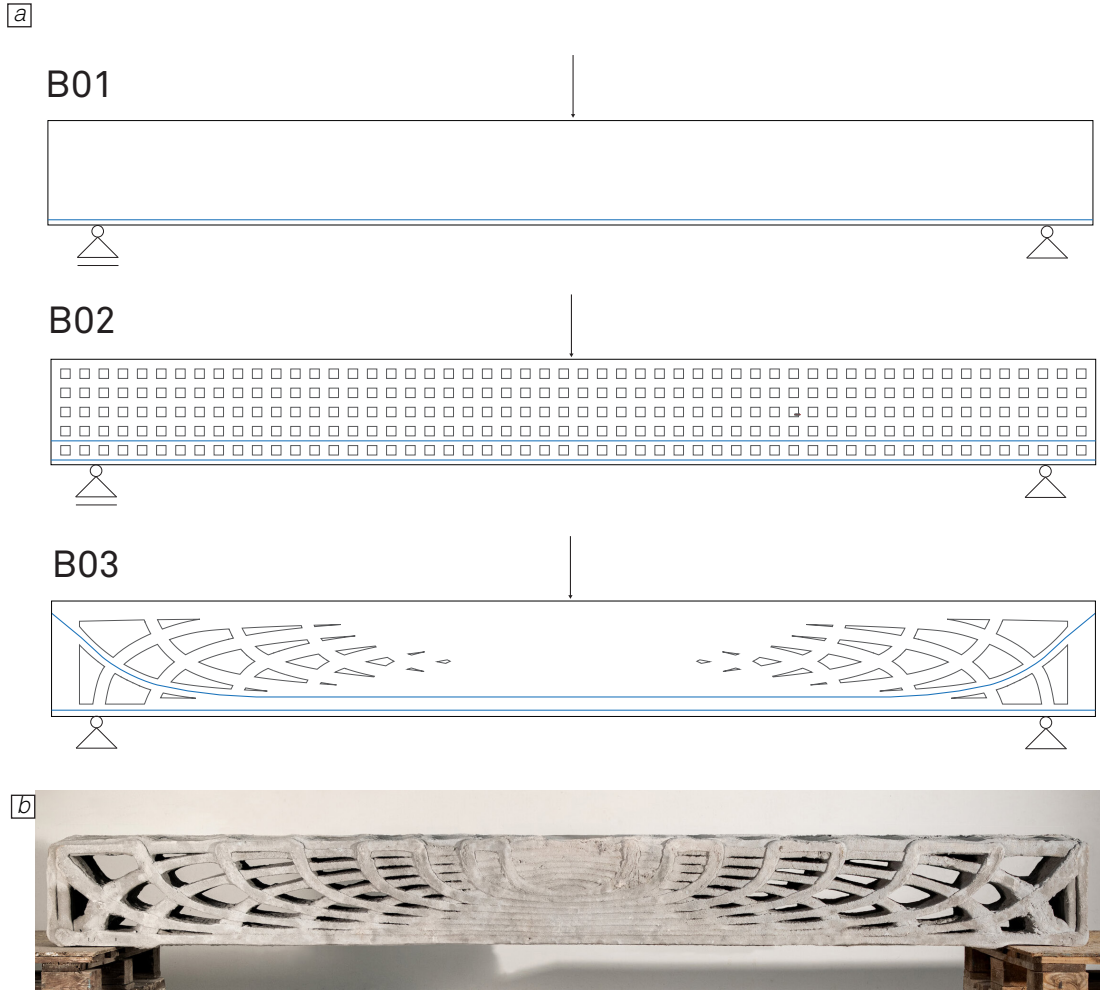


Figure 5.9

a. Design of B01, B02 and B03. The blue lines represent the location of the reinforcement
b. One of the two specimens of B03 printed

P2

**PART 2: SIMULATION AND
FABRICATION FRAMEWORK
FOR PRECAST 3DCP**

06

BEAM SIMULATIONS

To improve and better understand the behaviour of the beams, FEM simulation was performed. Two software were used to compare and corroborate the results: Sofistik and Karamba3D.

Sofistik is a well-established software used by developers for different projects from the smaller to bigger scale and it is created by Europe's leading manufacturer for construction software for analysis, design and detailing, Sofistik AG. In a push to expand the software possibilities, it is now available for download the Sofistik Rhinoceros/

Grasshopper Interface which opens the door for the creation of parametric analysis models.

Karamba3d is a parametric structural engineering tool for Grasshopper that operates analysis of beams and shells which can be parametrized and integrated into various optimization algorithms.

Both software are used to operate the simulation here shown but karamba3d, differently from Sofistik, cannot operate non-linear analysis, an essential part in the analysis of concrete structure.

6.1 CREATION OF A FEM

Finite Element Model (FEM) is a very common numerical method for virtual verification which makes it possible to achieve linear and non-linear solutions to engineering problems and it is an approach that can be used to predict the behaviour and fracture of different designs. (Yiling Lai, 2020) To find the solution the object being analyzed is divided into smaller parts, called finite elements.

It is imperative to find a way to discretize the subject of the analysis as accurately as possible so that the simulation can predict as accurately as possible the behaviour of the

object in real life. In common software like Sofistik usually, the generation of a FEM for a beam is done through the interpolation of a section along the beam's axis. However, the manufacturing approach being investigated by the CREATE group [Figure 6.1] doesn't make it possible to use this method as the 3D models of the beams designed are the result of the extrusion of a surface perpendicularly to the beam's axis. Therefore a new approach is necessary and it is here investigated and shown.

To find the best way to create the FEM, some initial testings were done in Sofistik and it

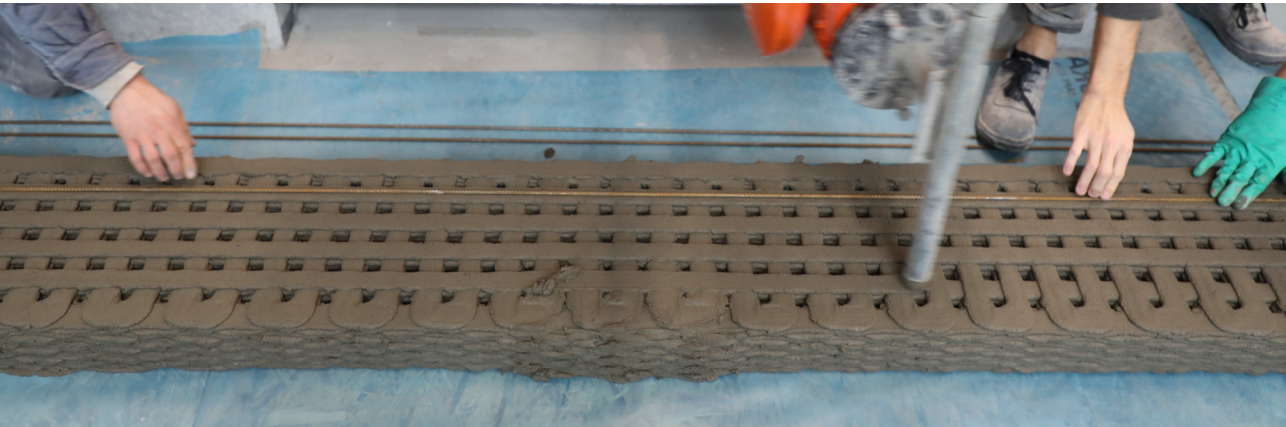


Figure 6.1

B02 while being printed, the same direction and method is kept for all beams.

was thought that to create a FEM that better reflects the design it was optimal to consider each layer as a structural surface with the same thickness of a layer. The supports are structural points positioned at the bottom of the surface at 0,12 m from the external border of the surface. To connect these surfaces it was thought to create a coupling between the border of the surfaces [Figure 6.2]. The coupling is a reciprocal connection that can be created between two lines or two points and define the condition under which the involved elements are coupled. In this case, the connection is fixed, meaning

that it does not allow for any degrees of freedom between the two items linked. Once the structural model has been defined in Rhino/Grasshopper is fed into the software, Karamba3D requires a mesh and the shape of it will be the one used to create the FEM, differently Sofistik gives the possibility to set certain criteria but it generates the FEM inside its main software where the text files generated in Grasshopper are read. Once the discretization is done the load are applied in the location chosen and the analysis executed.

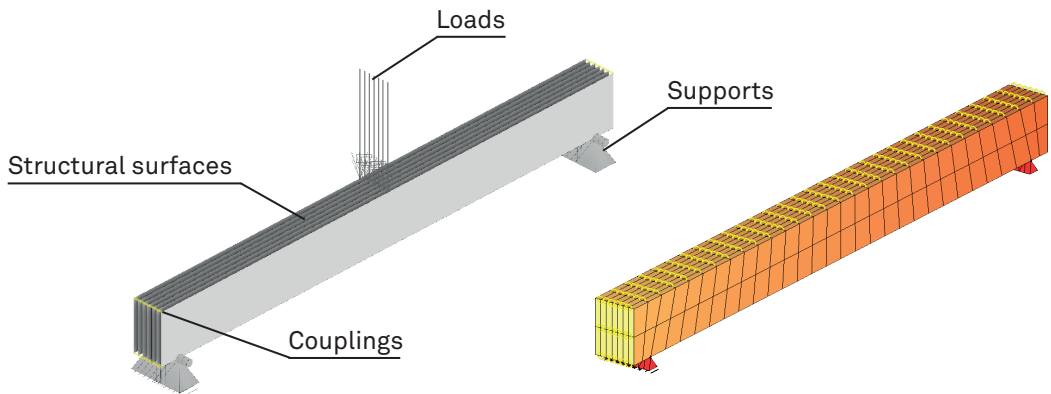


Figure 6.2

FEM model generated in Sofistik, each layer is generated through a structural surface. In yellow are shown the couplings that link the different surfaces.

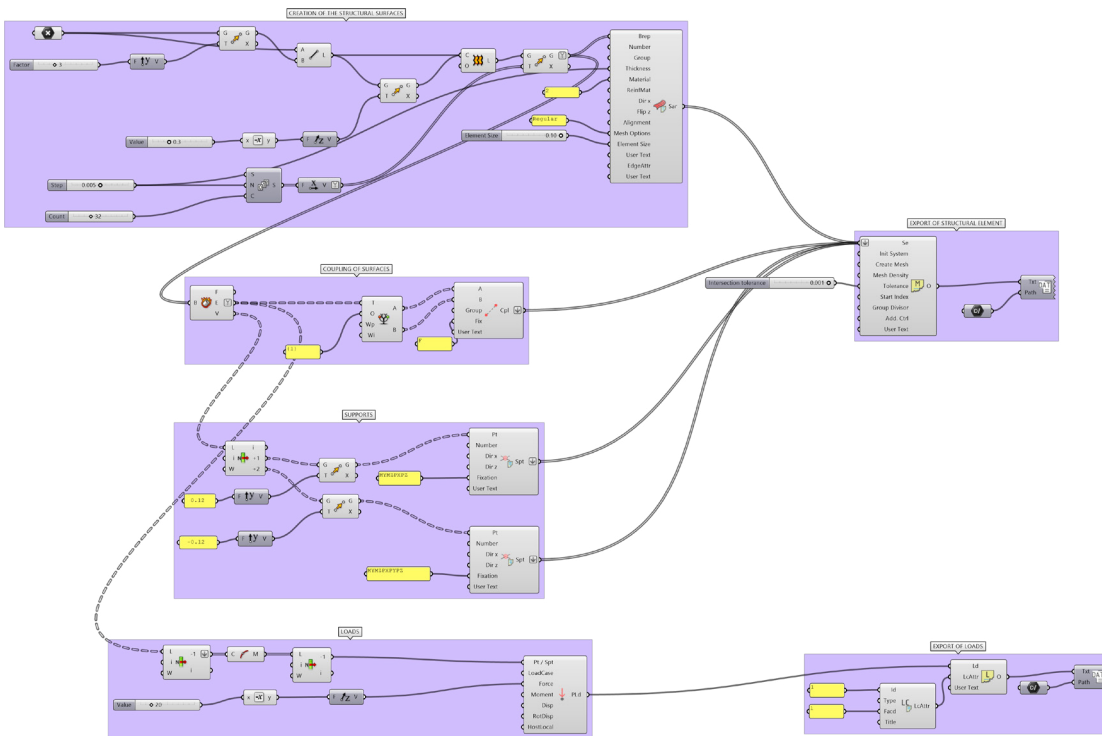


Figure 6.3

The GrassHopper script generated to realize the analysis in Sofistik. Different .dat file are generate which are read into the Sofistik main software. The .dat. file contain the information about the structural elements of the structure and the loads

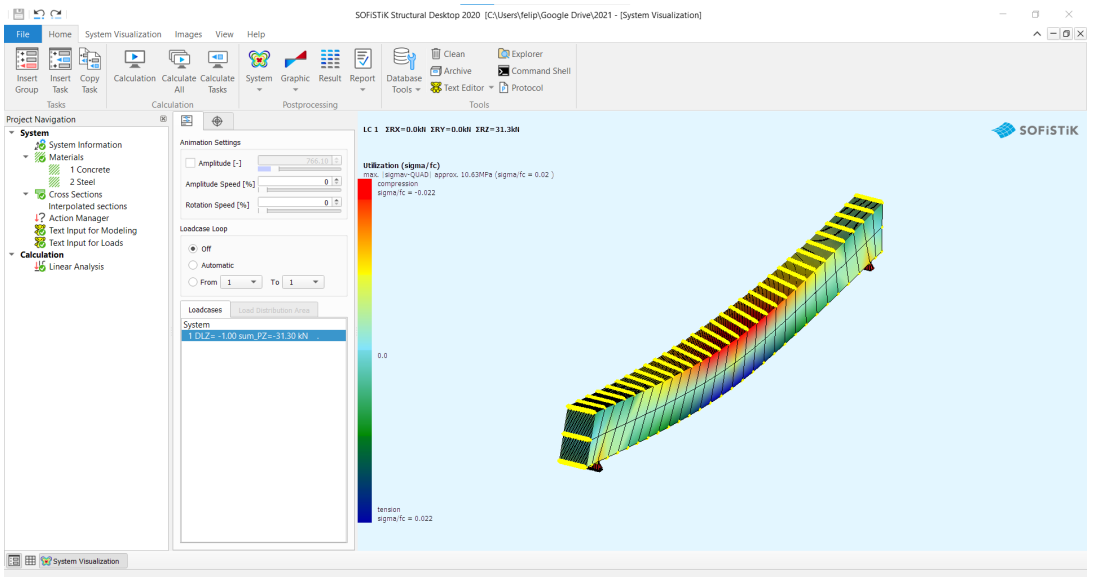


Figure 6.4

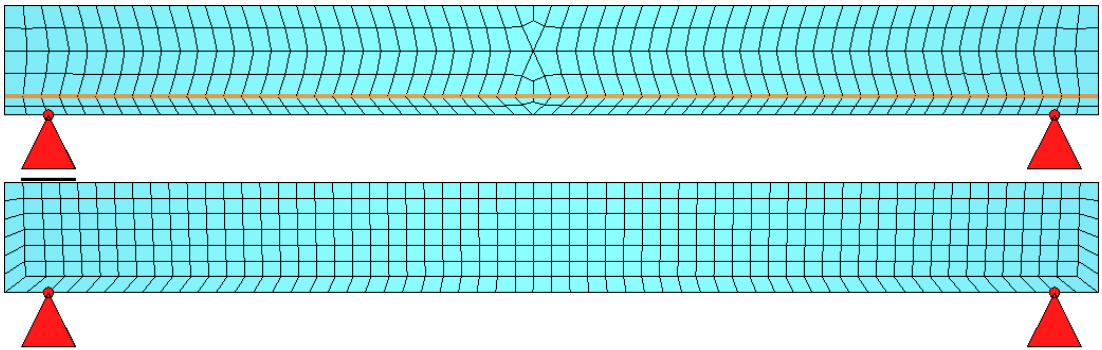
An example of the interface of Sofistik. On the left in the project navigation is possible to define the materials, import geometry such as sections, beams and structural area. Under "calculation" it is possible to operate the task chosen. On the right it is possible to see the FEM coloured according to the results of the analysis

A relevant topic of discussion for this thesis, and in 3DCP, is the integration of reinforcement and its reaction with concrete. The idea investigated here is the use of a structural line with the same section of the steel bar used for the creation of a beam to generate a reinforced FE model of the beam. Sofistik, once it generates the FEM, considers the line as part of the surface and creates a perfect adhesion that replicates the behaviour of a steel bar in a beam. An example of one surface is shown here and the difference in the displacement and stress

of the FEM prove that the structural surface and line are working together. Additionally, by increasing the radius of the reinforcement there is a difference in the stresses and displacement, which prove once more the efficacy of this system.

Ideally, the most realistic FEM would be the one that creates a surface for each layer and includes the structural lines in the layers where the reinforcement is placed. With this strategy, the generation of the FEM and its analysis would have taken too long and therefore is used only one structural

[a]



[b]

FEM	Compression Stress [Mpa]	Tensile Stress [Mpa]	Displacement [mm]
Reinforced	15,78	13,18	1,93
Not Reinforced	16,38	14,01	2,01
Difference	-0,6	-0,83	-0,08

Figure 6.5

a. An example of the FEM created by Sofistik. Above without a structural line as reinforcement, below a structural line is created to replicate the presence of the reinforcement

b. AA table that shows the comparison of the performance in Sofistik of the beam with and without reinforcement. There is a reduction in the value of compressive stress, tensile stress and displacement

surface with the same width of the beam. The structural lines are positioned according to the design and their section is calculated so that it reflects the real one. As an example, it is shown that B02 has $\Phi 6$ mm steel bars located in two different levels, on the first, there are 5 bars, in the second 3. It has been calculated the total area of reinforcement for the first and second level (A_{s1} and A_{s2})

$$A_{s1} = 3^2 * \pi * 5 = 141 \text{ mm}^2 \quad (6.1)$$

$$A_{s2} = 3^2 * \pi * 3 = 85 \text{ mm}^2$$

In the FEM just one structural line for each level is positioned to simulate the presence of the reinforcement. The radius r_1 and r_2 of the section of the structural lines are here calculated:

$$r_1 = \sqrt{\frac{A_{s1}}{\pi}} = 6,71 \text{ mm} \quad (6.2)$$

$$r_2 = \sqrt{\frac{A_{s2}}{\pi}} = 5,19 \text{ mm}$$

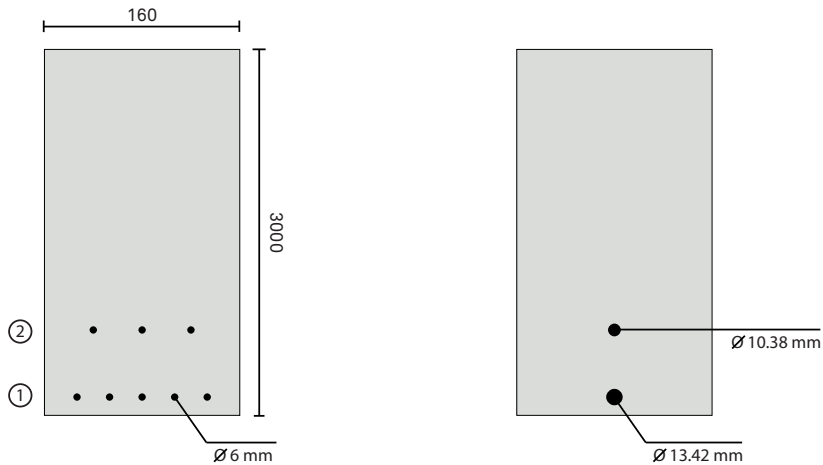


Figure 6.6

An example of how the FEM is created by using just one structural line for each level with an area that reflect as much as possible the real beam.

6.2

LINEAR ANALYSIS

Linear analyses were operated both with Karamba3D and Sofistik and we extracted the value of displacement, compressive and tensile stresses as a result of a 50kN load applied at the centre of the beam. During the analysis, it became clear that the position of the load had an important role in the value of the compressive stress: for the FEM's elements on which the load was directly applied upon the value of compression was much higher than those around it. The same goes for the support which often generated very high values close to their location. To

avoid these problems the stresses close to the supports have not been considered to determine the highest value noted and the load has been applied as a line-load or distributed over multiple points. By looking at the value of the compressive stress it is clear that B02 is the beam that has the highest value of compression on the mid-top part of the beam, this is likely due to the reduction of the section that is operated on the beam: throughout the design, little square voids are created homogeneously so that less material is needed to create the beam, this is also done

SOFISTIK				
BEAM	Tensile stress [Mpa]	Compression stress [Mpa]	Displacement [mm]	Mass [Kg]
B01	13,1	16	1,94	302,40
B02	18,9	23,92	2,81	240,61
B03	10,5	13,82	1,59	294,61

at the middle-top of the beam where the max compressive stress is located. At this point the height is reduced to 28 mm which reduce the area in compression which inevitably mean that the value of the compressive stress becomes higher than other beams. The same point can be made by looking at the tension. Going forward it makes very little sense to reduce the section uniformly and maybe concentrate this reduction in areas of the beam that are not under great compressive or tensile stress. By looking at the compressive stresses it seems that B03

is the beam that performs the best with a maximum compression value of 13,80/16,18 MPa compared to 16,00/19,65 MPa of B01. This can be due to the improvement made possible thanks to the structural optimization and by the slightly bigger dimension of the beam. Even by looking at the displacement, it is clear that B02 is the beam that performs the worst with a value of 2,81/2,52 mm compared to 1,94/1,82 mm of B01 which, as predictable, performs better. It is curious to note that B03 with a displacement of 1,59/1,51 mm is the beam performing the best.

SOFISTIK				
BEAM	Tensile stress [Mpa]	Compression stress [Mpa]	Displacement [mm]	Mass [Kg]
B01	13,1	16	1,94	302,40
B02	18,9	23,92	2,81	240,61
B03	10,5	13,82	1,59	294,61

Figure 6.7

Results of the Linear Analysis operated both in karamba3D and Sofistik. The weight of each beam is also shown

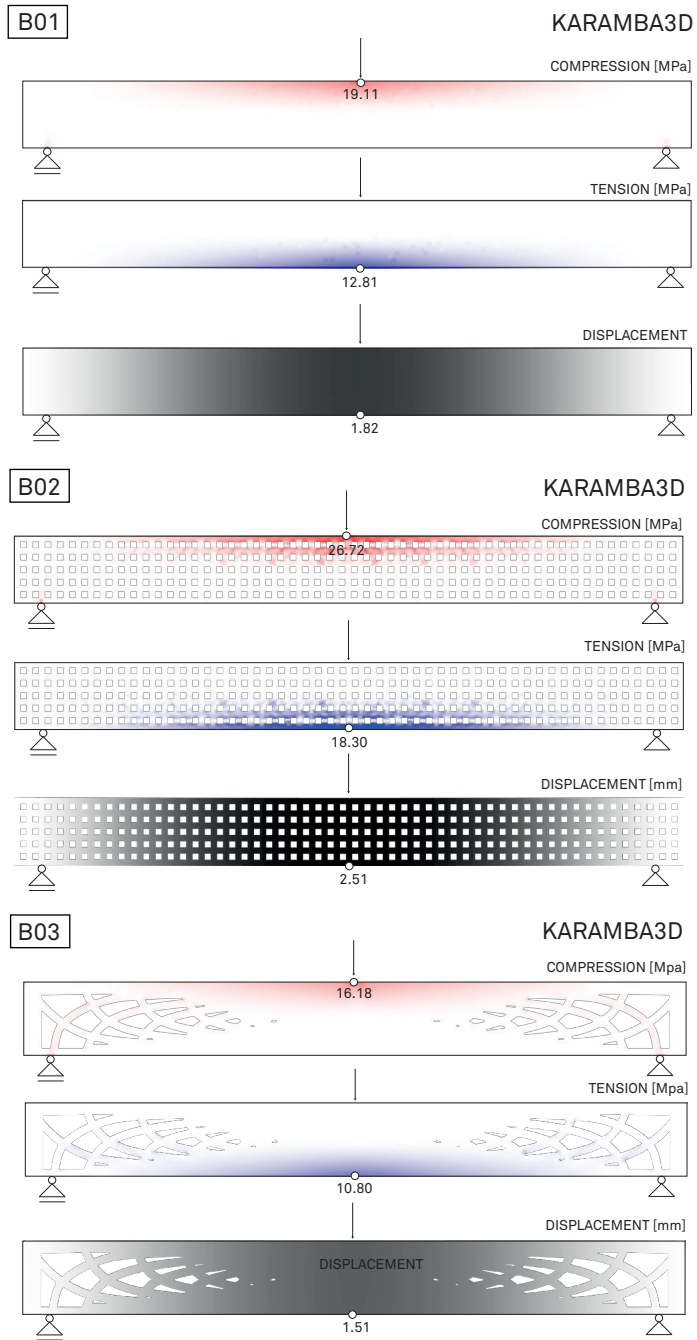


Figure 6.8

Visualization of the results of the beams's Karamba3D linear analysis

BEAM SIMULATIONS

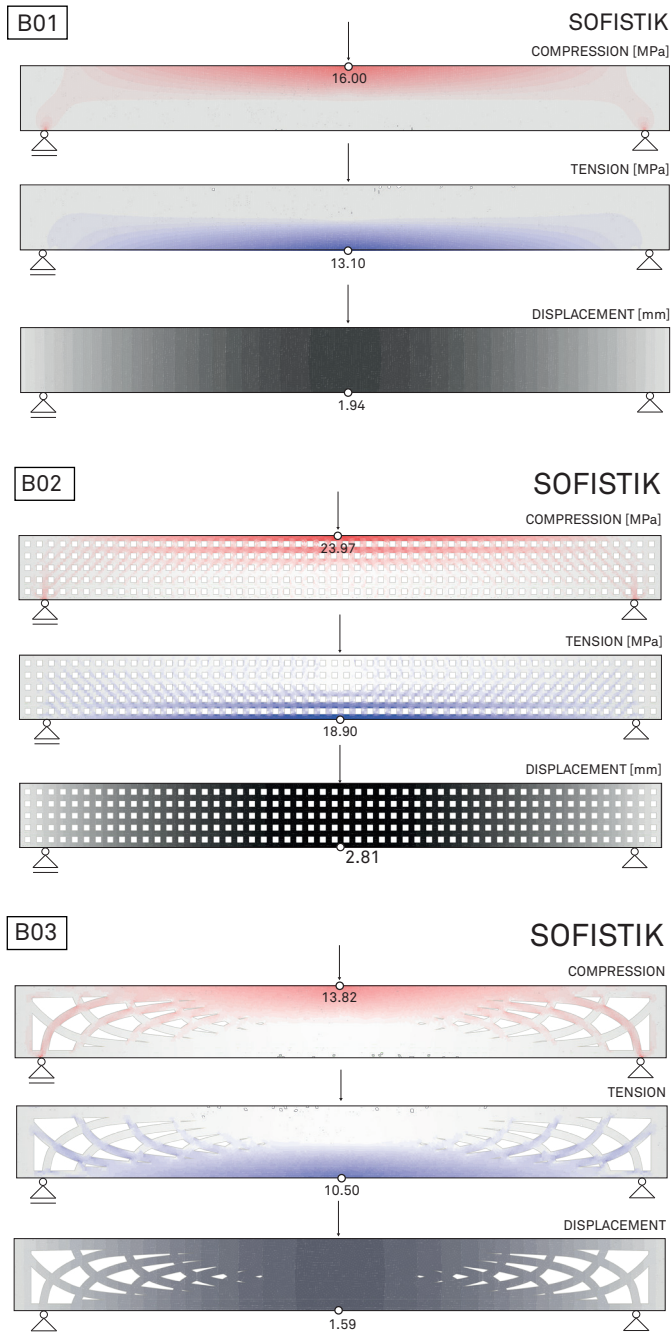


Figure 6.9

Visualization of the results of the beams's Sofistik linear analysis

6.3 NON-LINEAR ANALYSIS

Using Sofistik, a non-linear analysis of the beams was performed. In this case, the value of the tensile stress has been calculated by looking at the axial forces of the structural lines and dividing these forces for the areas of the structural lines.

Even the non-linear analysis confirms that the B02 is the one that performs the worst for the reasons described above. The tension of the reinforcement also shows that the highest value is found in this beam.

Another interesting piece of data that could be found is the values of the shear

stresses which give another information on how the beam behaves: with a value of 1,32 MPa the best design is the one of the B01 which, with its uniform section, guarantees better performance. B03, with its particular design, is the one that performs the worst with higher stresses generally located in the edges of smaller voids such in the case of the maximum value of 3,27 MPa. This predicts that probably the failure for both beams will be at shear, not the case for which a beam is generally designed.

SOFISTIK - NonLin				
BEAM	Compression stress [Mpa]	Shear stress [Mpa]	Displacement [mm]	Mass [Kg]
B01	17,29	1,32	4,07	302,40
B02	19,5	1,93	5,01	240,61
B03	16,9	3,27	4,01	294,61

Figure 6.10

Results of the Non-Linear Analysis operated in Sofistik. The weight of each beam is also shown

BEAM SIMULATIONS

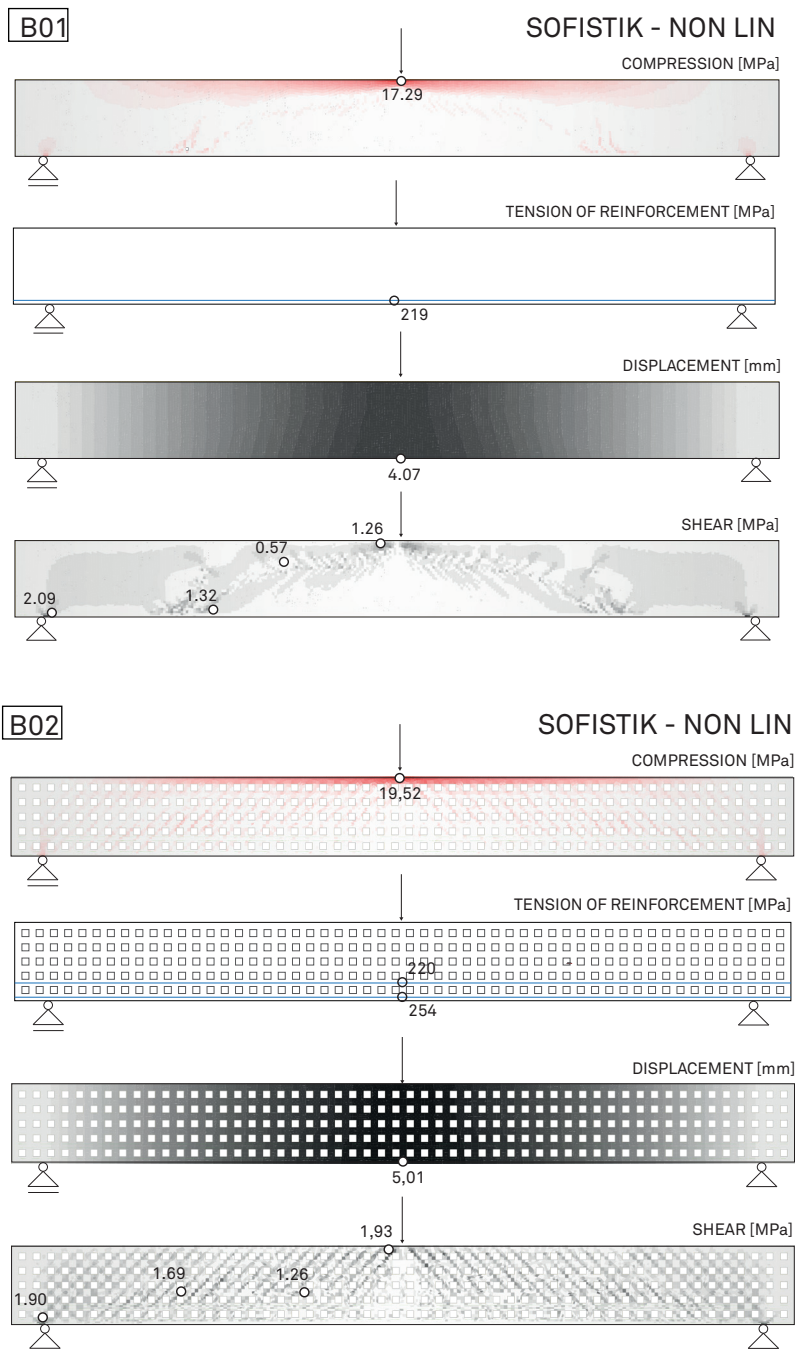


Figure 6.11

Visualization of the results of the beams's Sofistik non-linear analysis

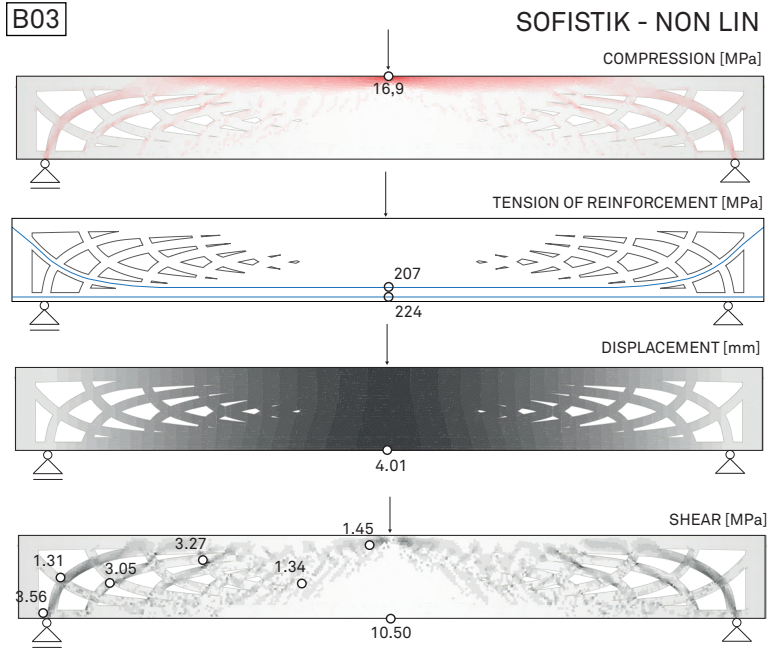


Figure 6.12

Visualization of the results of the beams's Sofistik non-linear analysis

6.4

TESTING RESULTS

After two specimens for each beam were printed and cured they were tested in a 3-point bending test, the surface of the beam, which generally presents irregularity, was ground down with a concrete grinding disc and the beam was placed on supports that allow rotation. The system used to apply the load is a frame structure in which is located a hydraulic actuator. A deformation sensor was used to measure the deformation at mid-span. Additionally, a digital image correlation (DIC) system was used to control the deformation on the surfaces of the beam.

The failure loads for each beam were

noted and B02 has the highest failure loads (56,5/43,3 kN), this is likely due to the age of the concrete as it cured for 35 days, compared with 24 for the B01. With a value of 18,1/19,8 kN B03 is the beam that performed the worst.

As predicted B02 and B03 had a shear failure which isn't ideal for beams. This type of failure also makes it hard to compare the effect of the structural optimization operated for each: it is necessary to reach a bending failure which would make it possible to consider the failure loads as a measure of the beam's strength.

Testing			
BEAM	Failure Load [kN]	Concrete Age [Days]	Type of failure
B01 I	45,8	24	Bending
B01 II	41,6	24	Bending
B02 I	56,6	35	Shear
B02 II	43,3	35	Shear
B03 I	18,1	35	Shear
B03 II	19,8	35	Shear

Figure 6.13

Results of the 3-point bending test

6.5 NEW ITERATIONS

Building on what has been learned and found, some new iterations of B03 have been designed. Linear and non-linear analysis of these beams have been executed but only non-linear analyses are here used to discuss the improvements.

To generate the design of these beams is used the “Line Result on Shell” tool by Karamba3D which generates the isostatic lines of given points. The choice of these points is an important criteria that can greatly change the design of a beam and its performance. For the B03 the points chosen were located on a vertical line positioned at the mid-span of the beam. New iterations of this beam have been explored.

For B04 the point at which the isostatic lines are considered are points of a horizontal line located at the middle of the beam. This generates a design that has lower values of shear stress compared to B03 with a maximum of 2,09 MPa (compared to 3,27 MPa). Still, these values are higher than B01 and B02 making it probable that B04 will have a shear failure. With a mass of 297,73 Kg, it is very similar to the weight of B03 but there

is a clear improvement to the performance of the beam with a lower maximum value of compressive stress (12,05 MPa vs 16 MPa); the value of the displacements is slightly lower (3,43 mm for B04 and 4,01 mm for B03). For this beam all the isostatic lines of tension are reinforced with a steel bar; this has been done to prevent any form of cracking/failure. As it can be seen from the analysis of the beam the reinforcement located at the bottom of the beam have higher values of stress, this could be a motive to choose steel bars with a smaller radius and save additional material.

B05 and B05b are two variations of the same approach in which there is a more aggressive reduction of weight that concentrate the remaining material in the top mid-span of the beam where there is the highest compressive stress. The material saved is around 20,21 % (60 Kg) for B05 and 23,65 % (70 Kg) for B05b. The difference between the two is the number of isostatic lines of tension used to generate the beam: for B05 there are 6 isostatic and for B05b 5. The analyses show that B05 performs better

in regards to the displacement, compressive and tensile stress. At the same time, the shear stress is lower for B05b, still, the values of shear stress for B04 (2,09 MPa), B05 (3.22

MPa) and B05b (2,74 MPa) are higher than the value of B01 (1,32 MPa) and B02 (1,93) meaning that even the new iterations are most likely to experience a shear failure.

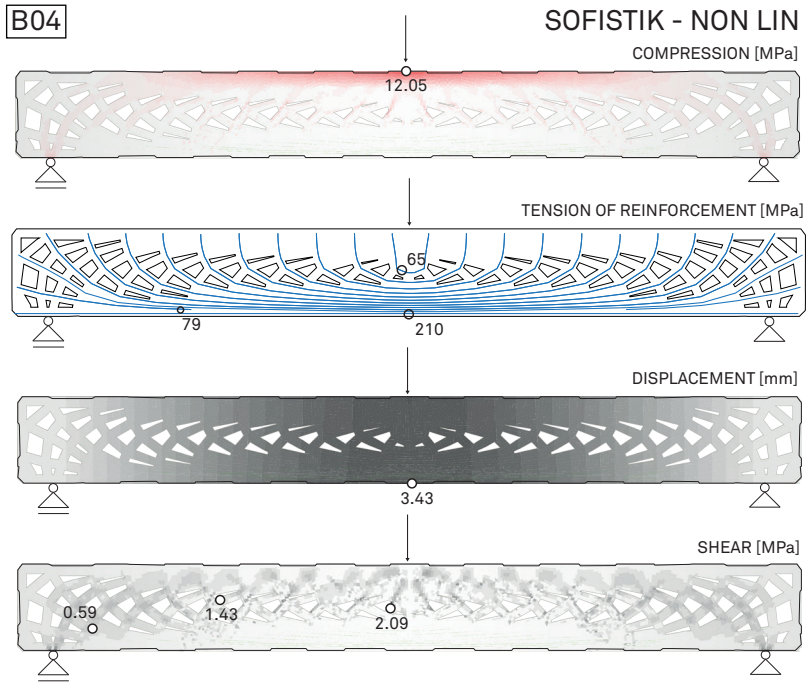


Figure 6.14

Visualization of the results of the beams's Sofistik non-linear analysis

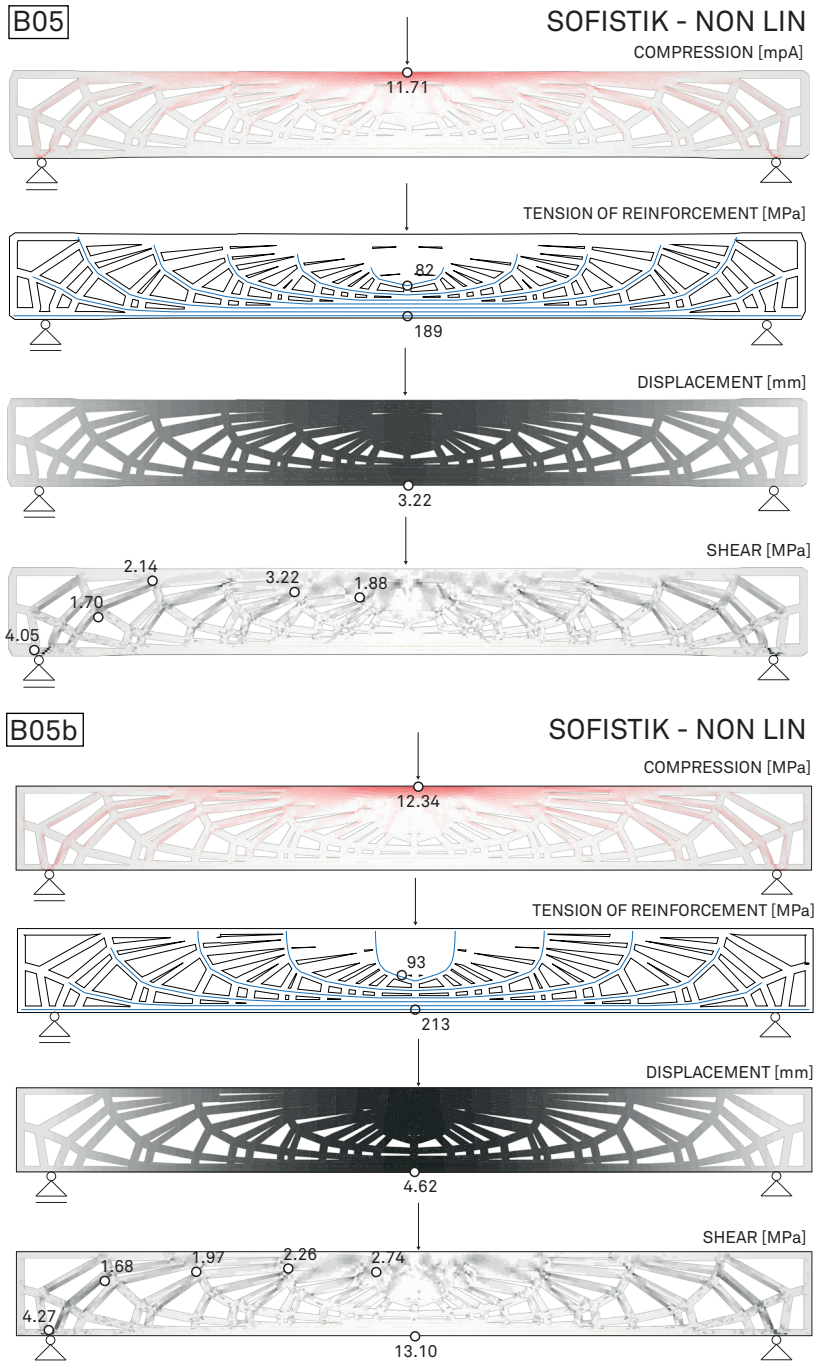


Figure 6.15

Visualization of the results of the beams's Sofistik non-linear analysis

6.6

LIMITATIONS OF THE ANALYSIS MODEL

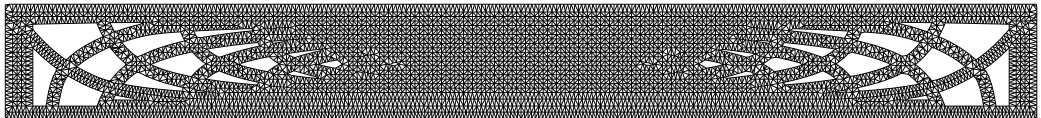
The analysis approach explained here takes some freedom in regards to standard finite element modelling for construction and therefore it has certain limitations which could be future points of improvement.

One limitation has to do with how the FEM was created: the main goal of this approach was to create a model that was as close as possible to the beam designed but, as standard methods do not allow for great freedom the approach proposed create the FEM of the beam with a surface area, a tool that is generally meant to be used for walls or ceiling. Additionally, the reinforcement were created through the use of a structural line, a component that is generally used for the creation of beams. This could cause some inaccuracy in the solution.

Another limitation is a very common

problem in finite element modelling: the shape and dimension of the finite elements should be as regular and as homogeneous as possible but due to the intricate design of the beams designed this has been particularly challenging. In Karamba3D there is greater control over this because Grasshopper makes it possible to generate the mesh that is then used to create the FEM. Meanwhile, Sofistik doesn't allow great control over this process within their Grasshopper plugin. This is why generally the model in Sofistik has irregular shapes at Sharpe edges or at particularly small parts of the design. For future improvement, it could be possible to create a .dat file that, if read by Sofistik, could make it possible to create the FEM element by elements in Grasshopper.

Karamba3D



Sofistik

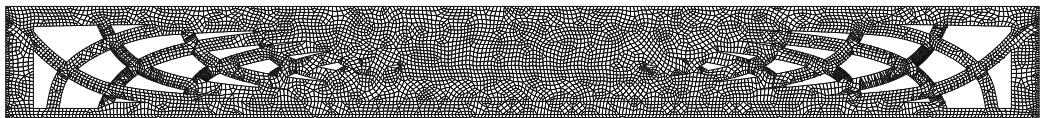


Figure 6.16

FEM models generated by Sofistik and Karamba3D.

07

B06 - CASE STUDY

7.1 MOTIVATION

Building on the work done so far and the knowledge gained during the research on the prefabrication field, the state of the art of 3DCP and thanks to the participation with the research at the CREATE group it is now shown B06, a case study for the structural optimization of a horizontal structure. This beam has been designed, simulated and optimized for printing.

For this beam a different approach has been explored: it has been thought to study the possibility of creating a horizontal

structure that blends what is typically perceived as a beam and a slab. The reason behind this is to save material by the use of a T-beam and creating what can be seen as a ribbed slab. For this structural optimization, it has been considered interesting to use the Italian building code (NTC18) and what has been studied during the degree as a starting point to find an approach that makes it possible to study the height and width of a T-beam so that only the minimum need section is designed.

7.1 SECTION OPTIMIZATION

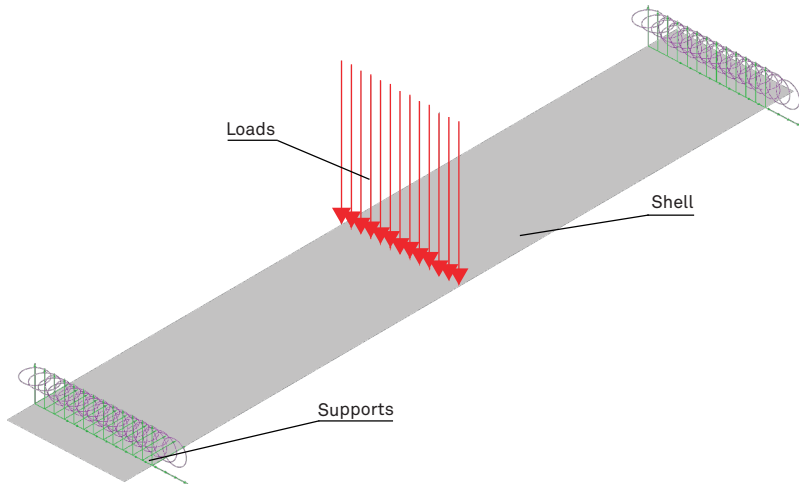
To design this beam the general approach was to design different T-beam positioned one close to the other which would create a ribbed slab. To do so different data were necessary: the beam's axis, the value of the moment along the axis and the value of the shear force.

In the first iteration, it was thought to have 3 T-beam that would create a slab with a

width of 500 mm and a length of 3000 mm. In Karamba3D it was analysed as a shell with this dimension and the loads and support that reflects the system used up until now [Figure 7.1.a].

The tool "Line Results on Shell" of Karamba3D makes it possible to see the maximum momentum line of the shell; by giving as input the point in the middle of the

a



b

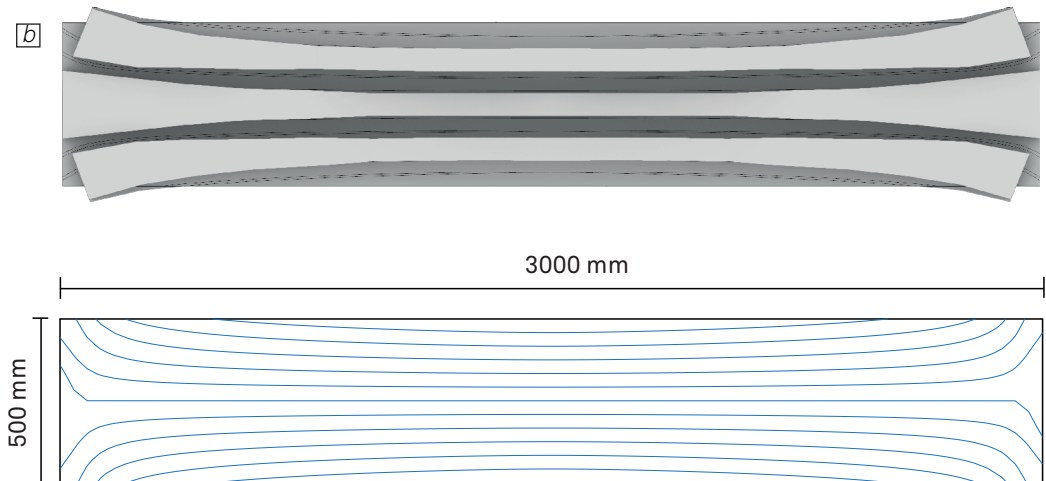


Figure 7.1

a. The structural system design and analysed in karamba3D. The load (the red arrows) is distributed along the centre of the beam, which reflects what would happen during the test of the beam
 b. The lines of maximum momentum and the corresponding T-beams that were designed.

beam the resulting lines are parallel to the centre and close to the support they move outward [Figure 7.1.b]. These lines were initially used as the beam axis [Figure] but, for reasons that will be explained, the part of the beam that close to the supports will have a rectangular section, this means that there is very little difference in the use of these lines or 3 straight, parallel lines. For this reason, and to facilitate the design, it has been thought to simplify the design and use 3 straight lines located at a distance that is determined by the value of the moment.

Karamba3D calculates the value of the moment (kNm/m) for each face of the mesh of the shell. It was noted that closer to the centre the value of it is generally higher

therefore a challenge was to place the beam's axis in a way so that all the T-beams would have the same momentum. To do so a function $f(x)$ that describe the changing value of the momentum was created by using the value given by Karamba3D as the Y coordinate and the X coordinate of the centre point of each face [Figure 7.3]. The integral of this graph is the area bounded by its graph and it is the value of the momentum (kNm) that is needed for the design of the beam. To divide the area into three equal parts (A_1, A_2 and A_3) in Grasshopper it was created a script that, after dividing the area into 3 parts with different cutting planes, sorted the combination where the difference between the areas was minimum. By doing this it was

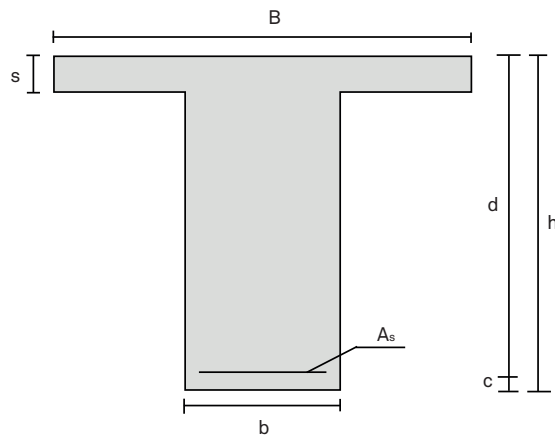


Figure 7.2

Example of section of a T-beam.

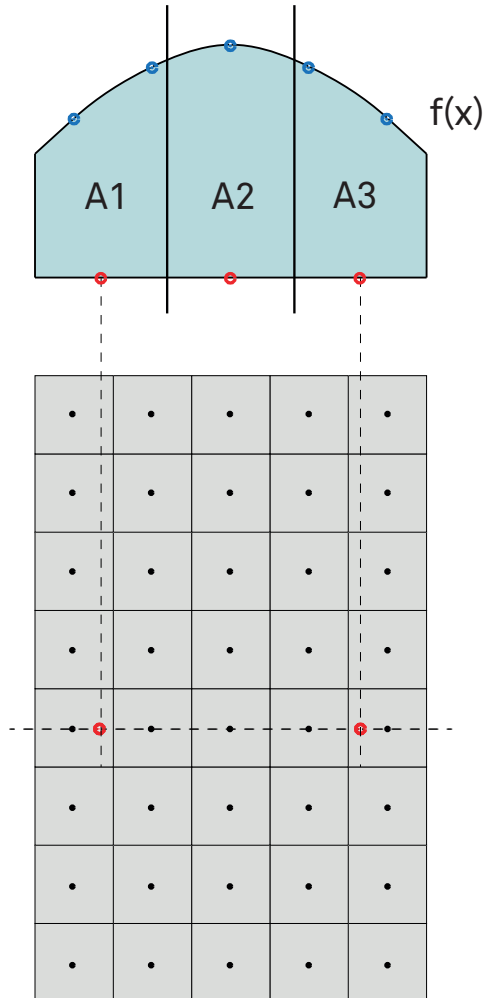


Figure 7.3

An example of the procedure described to find the position of the beam axis for each row (the red dot in the picture)

possible to use the middle of the bottom edge of each area (red dot) as the point in which the beam's axis should be placed so that the 3 resulting beams would have the same moment. To generate the section [Figure] two values are used: the shear forces and the moment. In this case, as each beam is designed separately, the value of the shear force is the load applied divided by the number of T-beams and divided by 2.

Meanwhile, the value of the momentum is evaluated every 50 mm and for each of these points the section is designed, the beam is the result of the loft of these sections. Usually, to calculate the value of stress of the reinforcement in a generic concrete section it is used the equation:

$$\sigma_s = \frac{M_{Ed}}{0,9 * d * A_s}$$

Where:

σ_s = stress of the reinforcement

M_{Ed} = moment applied

$0,9 * d$ = the arm of forces in the case of cracked section

A_s = area of reinforcement's cross section

For all the beams discuss until now it has always been kept the same area of reinforcement: 226 mm². The aim is to find the minimum possible d, to do so the stress of the reinforcement should be the maximum possible which in our cases would be:

$$\sigma_s = f_y = \frac{f_k}{\gamma_s} = \frac{550 \text{ MPa}}{1,15} = 478,26 \text{ MPa}$$

Where:

f_k = material strenght

f_y = reinforcement yield strenght

γ_s = safety factor

Now it possible to calculate for each section which height bring the reinforcement to reach that value:

$$d = \frac{M_{Ed}}{0,9 * f_y * A_s}$$

This is the minimum height possible for the section, by looking at the momentum of the beam. This calculus is operated by grasshopper for each section with its different value of momentum. It must be noted that s, the height of the flanges, have been calculated at each point but, as it happens

in the field, a value of 30 mm was kept fixed for all the sections to simplify the design and because it guarantees that the flanges, and the flanges only, are under compressive stress. To optimize the section according to the shear force it has been calculated the minimum section needed for a beam that are not shear reinforced. According to the Italian building code (NTC18)

$$V_{Ed} \leq \max (V_{Rd}, V_{min})$$

V_{Ed} = shear force applied to the section. V_{Rd} e V_{min} are two different values that can determine the strength of the beam. V_{min} , as the name suggests, is the minimum acceptable

$$V_{Rd} = \left[\frac{0,18}{\gamma_c} * k * (100 * \rho_l * f_c)^{\frac{1}{3}} + k_1 * \sigma_{cp} \right] * b * d$$

$$V_{min} = \left[0,035 * f_c^{\frac{1}{2}} * k^{\frac{3}{2}} + 0,15 * \sigma_{cp} \right] * b * d$$

Where:

$$k = 1 + \sqrt{\frac{200}{d}} \leq 2,0$$

$$\rho_l = \frac{A_s}{b*d} \leq 0,02$$

σ_{cp} = compressive stress

$$k_1 = 0,15$$

In our case there isn't any compressive stress so $\sigma_{cp} = 0$. To calculate the minimum acceptable b it is considered $V_{Rd} = V_{Ed}$ and $V_{min} = V_{Ed}$. In the equations b is isolated:

$$b_{Rd} = \left[\frac{V_{Ed}}{\left[\frac{0,18}{\gamma_c} * k * (100 * \rho_l * f_c)^{\frac{1}{3}} * d^{\frac{2}{3}} \right] * b * d} \right]^{\frac{3}{2}}$$

$$b_{min} = \frac{V_{Ed}}{\left[0,035 * f_c^{\frac{1}{2}} * k^{\frac{3}{2}} + 0,15 * \sigma_{cp} \right] * d}$$

Out of this value the minimum was chosen to be the b used for the creation of the section

$$b = \min (b_{Rd}, b_{min})$$

Still, by doing so it was noted that the factor k requires the height of the section to not be any lower than 200 mm which greatly limit the possibility to operate an optimization, therefore the limit imposed by $k < 2,0$ has been ignored. A minimum is chosen in grasshopper but to compensate for the freedom taken, once the section becomes shorter than 200 mm the area of the corresponding section is used as a constant value that has to be

maintained. This means that when the limits posed by k , or other requirements, are not respected and the value of b is calculated so that the area of the last acceptable section

is maintained up until the last section. The result of this approach has been explored for the previously mentioned slab/beam [Figure 7.4].

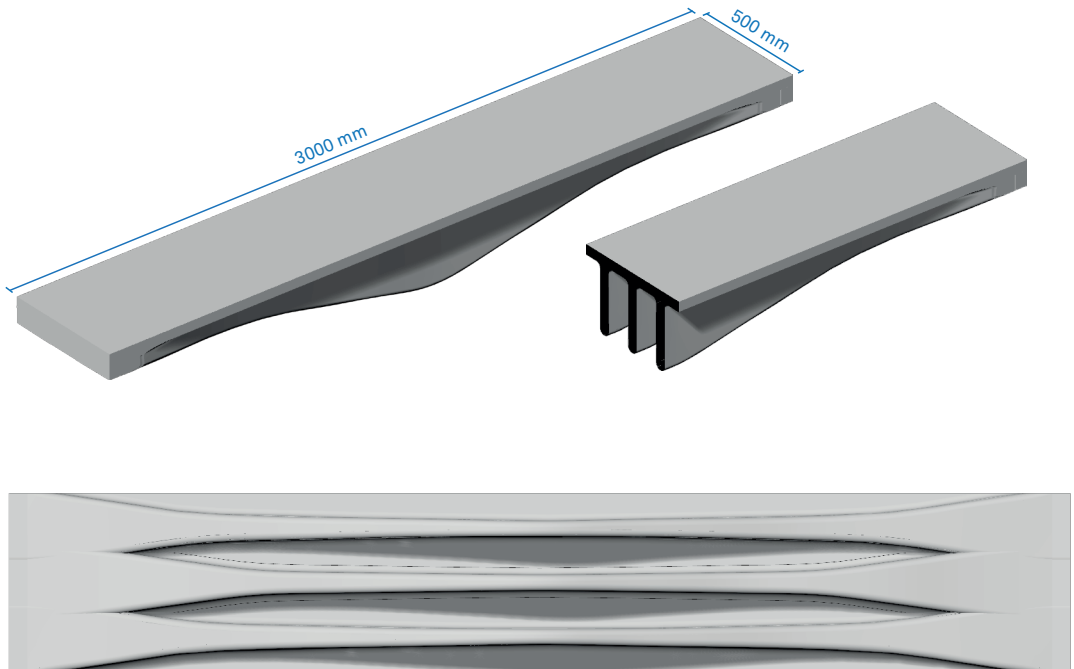


Figure 7.4

A first iteration of the approach discussed

7.3 OUTPUT

In the final iteration of the design certain changes were done. The width of the components was reduced to 300 mm so that it could be tested and only two T-beam were designed. After the design was completed the final shape was refined to make it more pleasing. The final maximum height of

The beam is 396 mm and the minimum width of the beam is 66 mm. In this design from the middle to the edge of the elements the width increases and the height decreases

to a minimum of 110 mm. With a weight of 270,91 Kg B06, if compared to B01, saves around 30 Kg of concrete for its creation and thanks to the non-linear analyses executed it is possible to understand the performance of this component. With a compressive stress of 9,43 MPa it is the lowest found so far which is likely due to the design of the T-beam which guarantees a higher area under compression. It has to be noted that the maximum value of the stress is not located in the middle

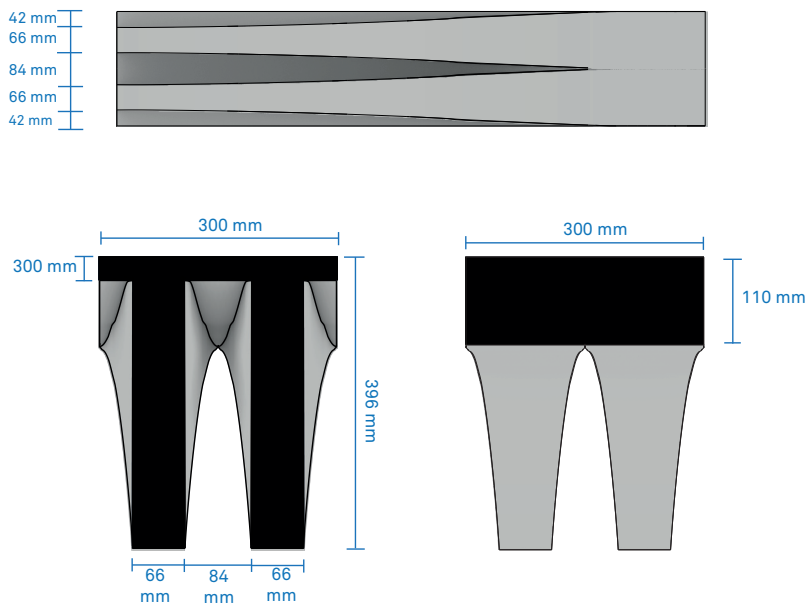


Figure 7.5

B06 the final design of the structural optimization investigated

beam but closer to the support, this could be because most of the weight is located at the centre of the beam. Also, the value of the shear stress (1,18 MPa) is the lowest out of any beam, even B01 (1,32 MPa), which makes it probable that the beam will not have a shear failure. However with a displacement of 5,50 mm it is the highest calculated so far. The tensile stress of the reinforcement seems to be close to constant through the beam, which proves the accuracy of the calculation operated and is an example of clear optimization where the material is used at its full potential differently from the other design where the reinforcement were under

lower stress closer to the supports.

Additionally, it has been thought a strategy to manufacture this beam, the approach is to print this component starting from its flat side by creating a continuous slab at the bottom, later at the edge, where more material is needed, some other material is extruded like shown in the picture. After this, the central part of the beam is printed with a similar approach and with the same printing direction. Finally, two steel bars Φ 12mm are positioned on top of the print and one final layer is printed above it to ensure the adhesion of the reinforcement to the components

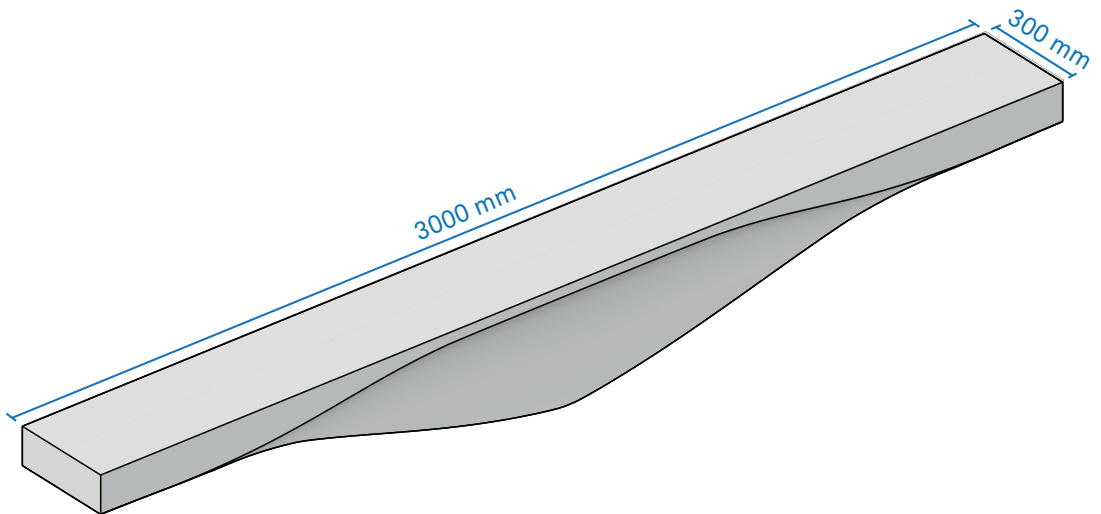


Figure 7.6

B06 the final design of the structural optimization investigated

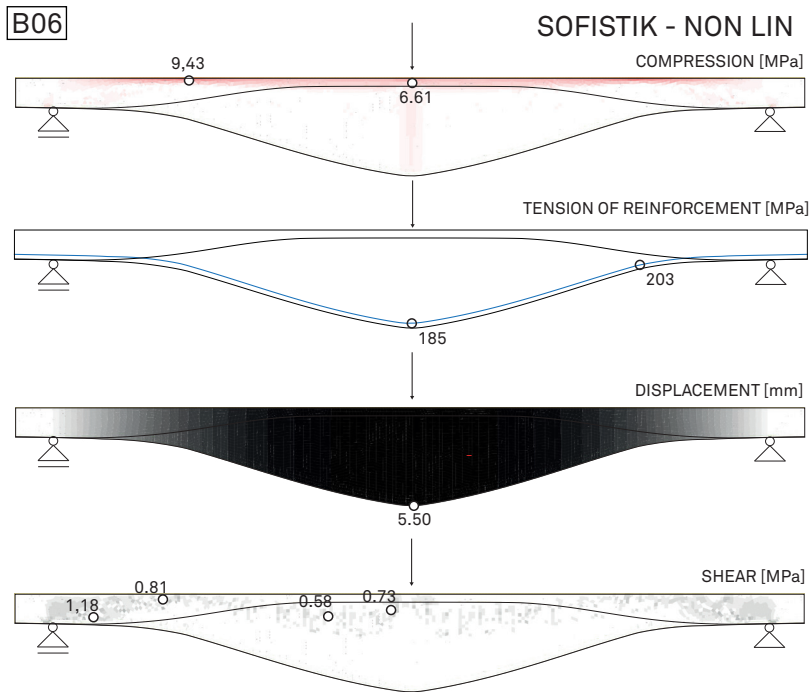


Figure 7.7

Visualization of the results of the beams Sofistik non-linear analysis

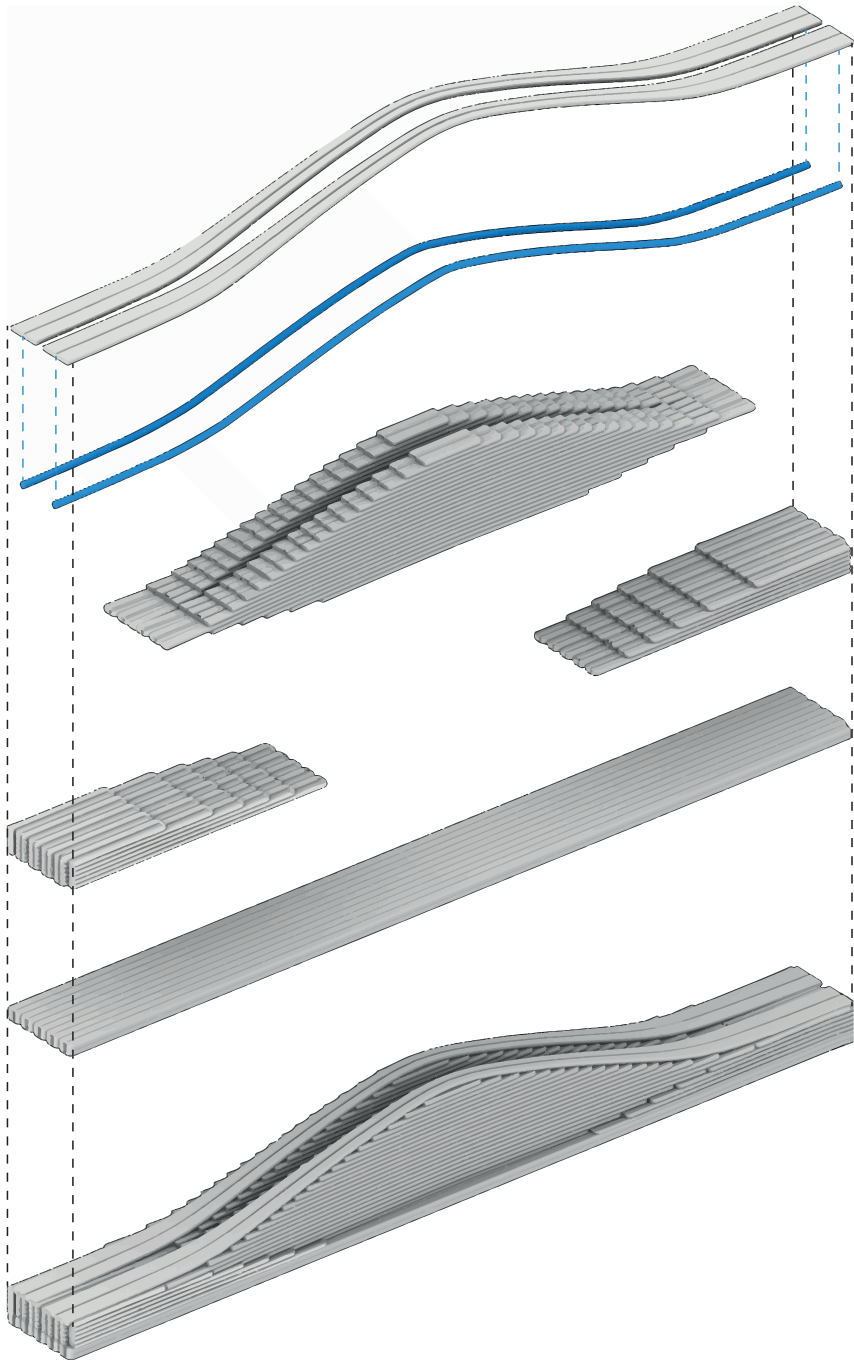


Figure 7.8

The fabrication approach of the B06. In blue the reinforcement.

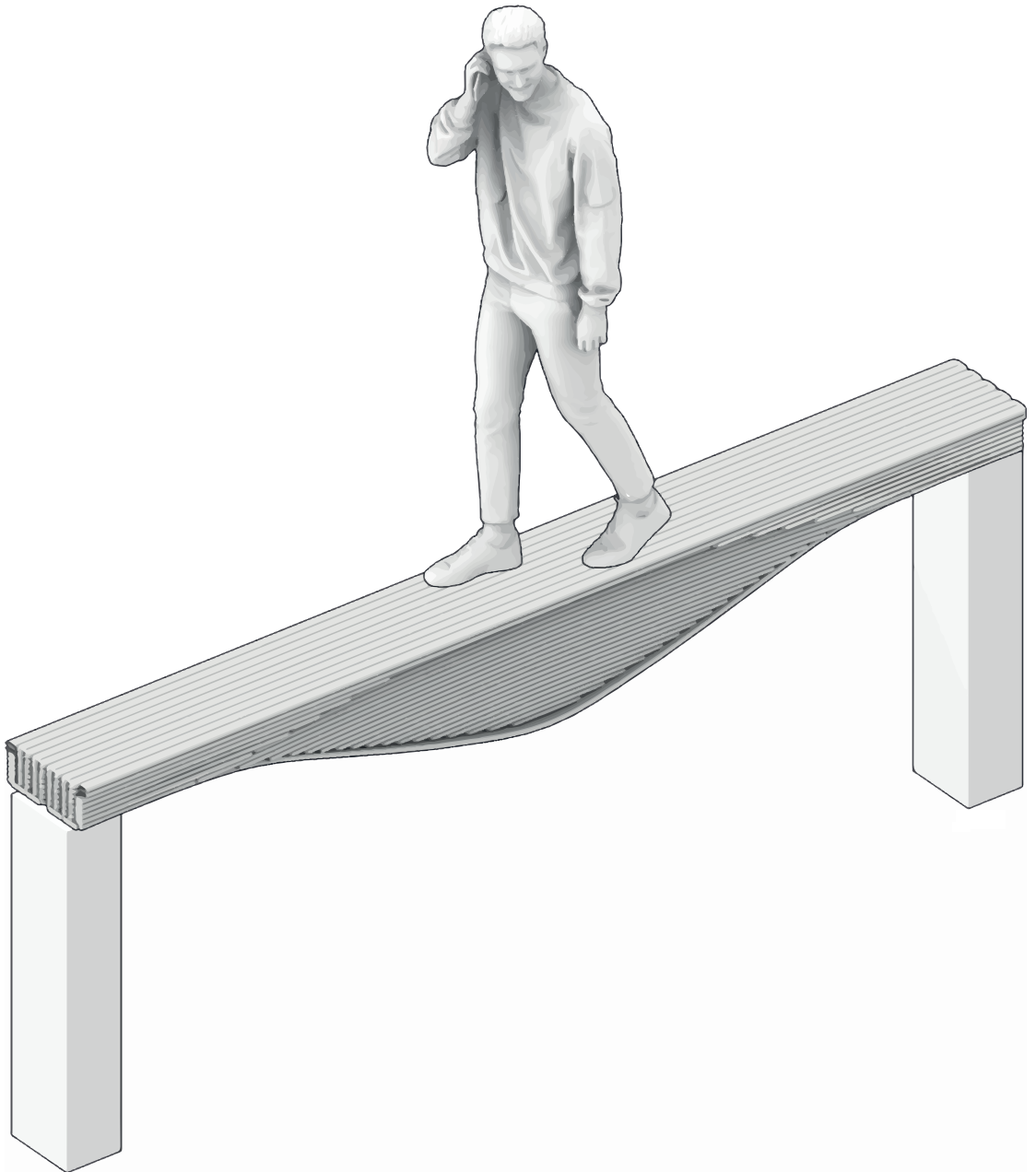


Figure 7.9

Visualization of B06 in a basic frame

08

WORKING IN SECTION: A NEW FRAMEWORK

8.1 INTRODUCTION

Currently, as shown, the majority of houses and 3D printed buildings are realized on-site and are the result of the extrusion of a floor plan. To challenge this limited method a new prefabrication system has been investigated in its entirety: from the design to the fabrication and finally to the construction site. In this new approach, the project's design is defined in sections instead of the floor plan, a different point of view which was also adopted for the optimization of the beams by the CREATE group, a condition that helped theorise this system. To take full

advantage of 3DCP an optimization workflow tailored for a bigger scale was developed to minimize the use of concrete and maximize the performance of the structure by creating an efficient and interesting design. The creation of this project requires a special focus on the new manufacturing approach that does not need formwork and offers great freedom of design, a proposal for a production workflow will be shown. Finally, as the last part of this new prefabrication approach, the components are assembled in the construction site.

8.2 PRELIMINARY DESIGN

This new approach in prefabrication is presented in the case of a small residential unit. The design of this house is generated by starting from a simple rectangular, two-storey section on which small changes are operated and the resulting 6 sections once extruded create the preliminary design.

The 6 sections have a maximum length of 14,1 m and a maximum height of 6,3 m and create the structural system of a two-storey residential house. 2 of these 6 sections are those that create the external enclosure of the building and therefore present a more dense design, still the non-structural parts are not part of the focus of this work. These

sections are extruded for a width of 0,3 m, the other 1,5 m. Once the results of the extrusion are placed one close to the other it is possible to observe the architectural space. [Figure 8.3].

On the ground floor, two main spaces are meant to host the kitchen/dining room and the living room. In the middle of the building, there are stairs and other connecting spaces. On the first floor, there are two bedrooms, one smaller that has a small terrace. The internal spaces have a height of 2700 mm and the thickness of the concrete frame is 300 mm. This design is the starting point as it will be later optimized.

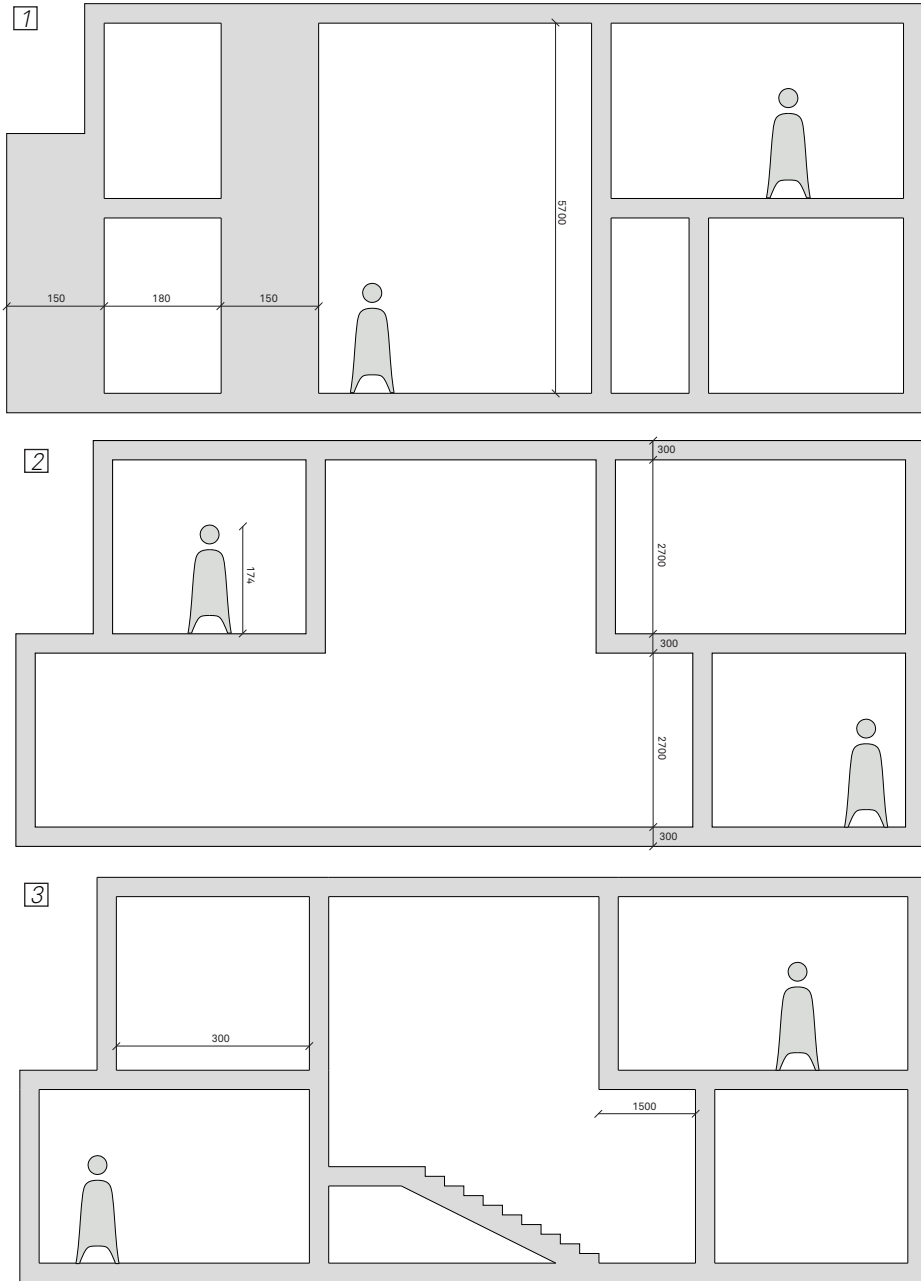


Figure 8.1

Sections. All measurement are in millimeters.

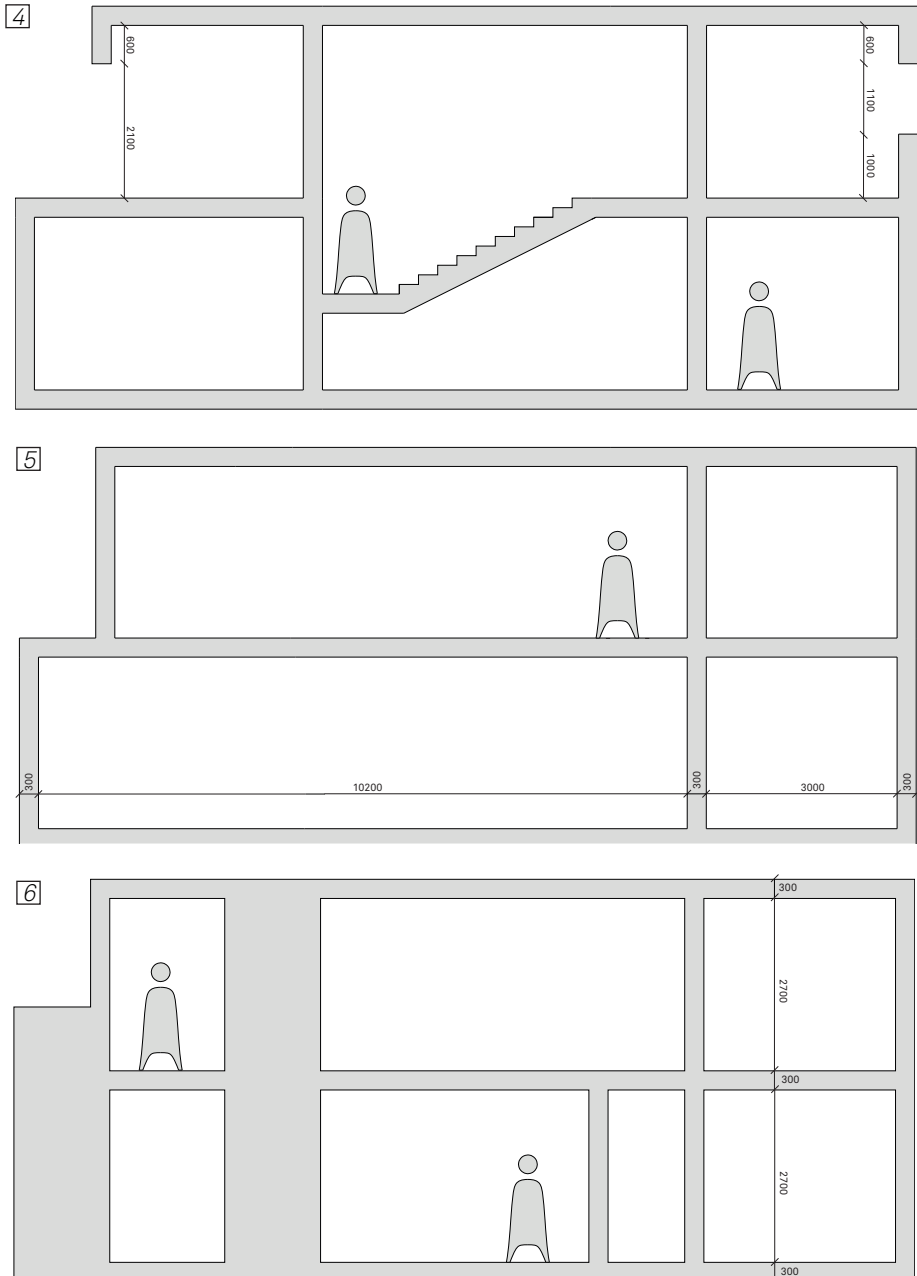


Figure 8.2

Sections. All measurement are in millimeters.

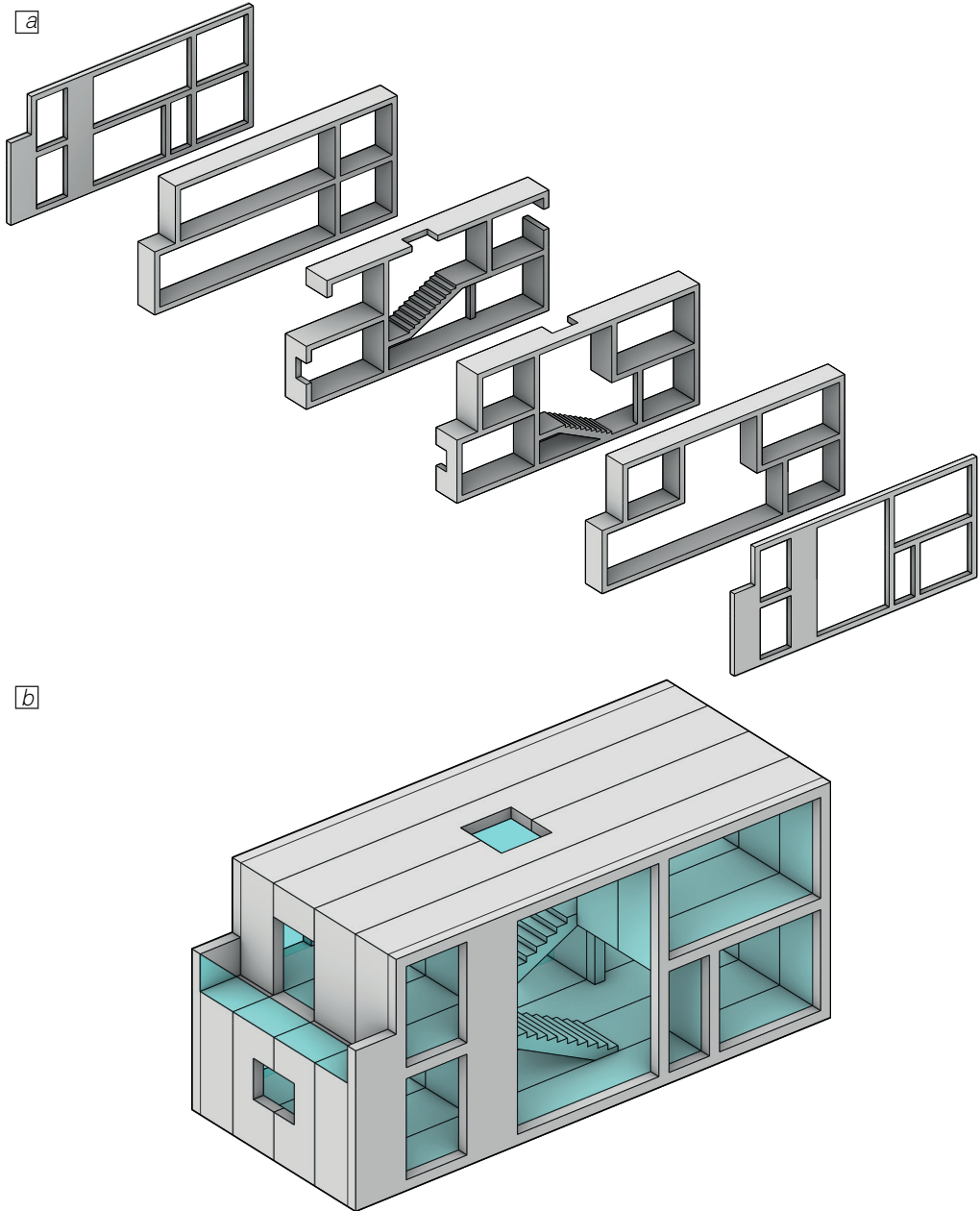


Figure 8.3

a. The resulting sections positioned in the right order.

b. The complete preliminary design as the result of the positioning of the different sections. Only the structural system of the project is here shown. Other parts of the building are not the focus of this thesis

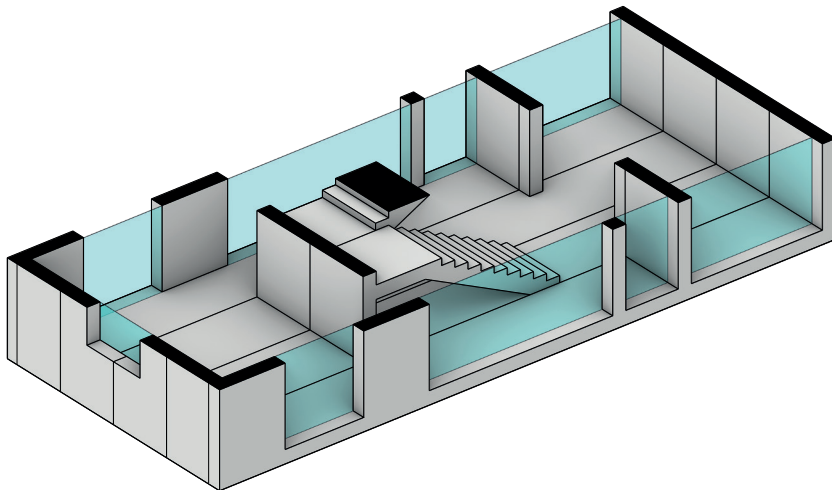
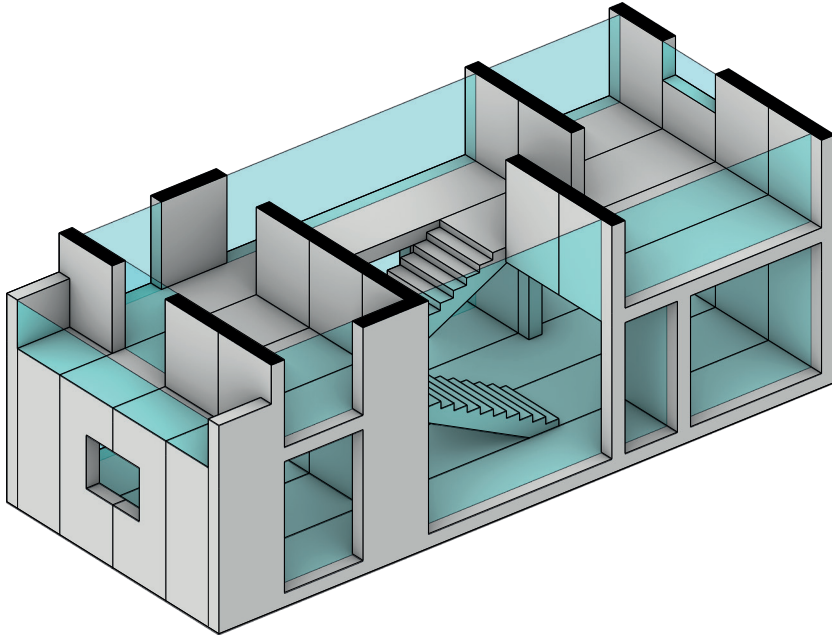


Figure 8.4

Focus on the first (above) and ground floor (below)

8.3 OPTIMIZATION WORKFLOW

To reduce the usage of concrete made possible by the freedom given by 3DCP it has been considered interesting to operate a structural optimization of every section that composes the projects. To do so two tools have been used: Karamba3d and Octopus.

Octopus is a component for Grasshopper that similarly to Galapagos, the built-in alternative offered by GH, operates evolutionary optimization which is a type of optimization that is strongly inspired by nature. In evolutionary computation, the process of natural evolution is used as a model for a strategy to find the best solution for the given problem which is a goal defined by the users. (Hoffmann, 2001). For these types of algorithms, there are genes which

are numerical values that can be used for different combinations and each set of values define a unique solution. The fitness values are those that Octopus, depending on what is chosen by the user, try to minimize or maximize by trying different combinations of the genes. In this approach, not all possible combinations are explored: Octopus learn from each iteration and changes accordingly the focus of the following calculations. The choice of this particular tool is due to the great flexibilities and choices possible: differently from Galapagos, more than one fitness value is possible, the mutation rate between two different iterations can be set and it is possible to decide the “elitism” of the algorithm meaning that it is possible to

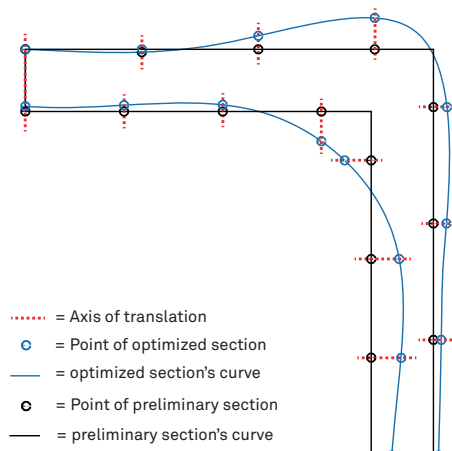


Figure 8.5

A diagram that shows how the section is modified by Octopus.

decide the tendency with which it focuses on certain strategies and iterate on them. For the optimization of the sections, the genes are the amplitude of the vector of translation of the control points of the curve that define the section. A value between -0.1 m and +0.1 m is allowed [Figure 8.5]. The fitness values that have to be minimized are the maximum value of compressive-tensile stresses and the area of the section. The current limitation of this approach is the possibility to only operate linear analysis and having to work with the entire section which means that a serious number of control points are needed making the work of Octopus much harder as a very high number of combinations are possible and the best solution might not be the only one. In a possible future implementation, it might be explored to analyse every component separately. The optimization has been operated to the 6 sections shown before, the results of the optimization are here shown [Figure 8.6]. By focusing on a small part of a section it is clear that thanks to the optimization explained the shape of the section tends to follow the direction of

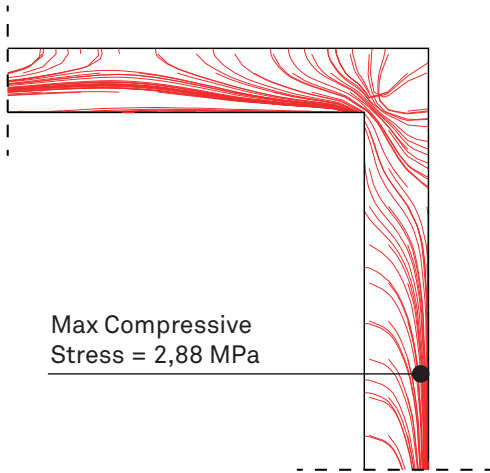
the isostatic lines and there aren't any sharp edges after the optimization. By looking at the entire section it is interesting to see that despite the high number of control points and despite giving as fitness value only the maximum values of stresses, the section still result to be well optimized in its entirety. By comparing the value collected of the before and after it is interesting to see that there is a clear and important reduction in the maximum value of compressive and tensile stress with an average reduction of 41,09% for the maximum compressive stress and a reduction of 43,37% for the maximum tensile stress. The reduction in the area of the section, and therefore the material, is less aggressive with an average of 7,79 %. It is interesting to note that section 5 had an impressive reduction of 87,61% for the compressive stress and 82,92 for the tensile. Finally is shown the new design with the optimized section. For the generation of this design, to create continuity, it has been though to operate a loft between all the section.

Shape Optimization			
Section	Reduction of Max Complex [%]	Reduction of Max Tens [%]	Reduction of Area [%]
Section 1	29,45	49,24	8,14
Section 2	27,63	30,02	9,44
Section 3	23,54	31,86	4,23
Section 4	46,14	39,68	3,44
Section 5	87,61	82,92	11,85
Section 6	32,17	26,49	9,65
Average	41,09	43,37	7,79

Figure 8.6

Percentage of improvement achieved for each section thanks to the structural optimization here proposed

PRELIMINARY DESIGN



OPTIMIZED DESIGN

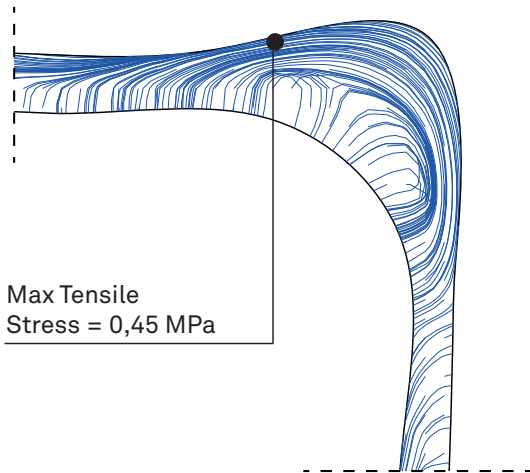
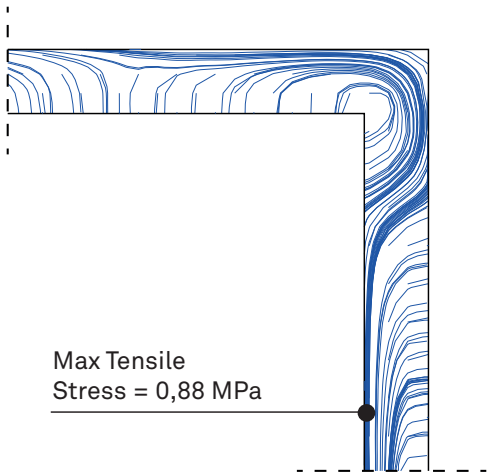
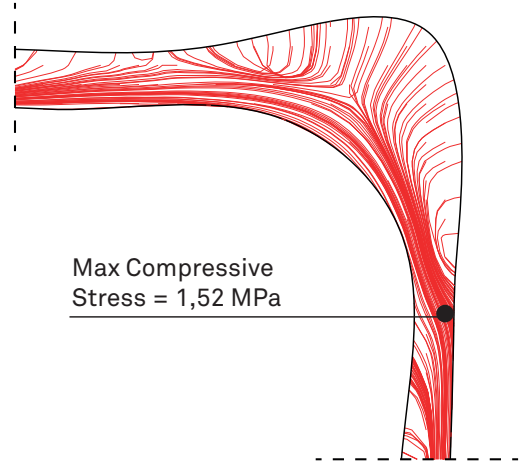
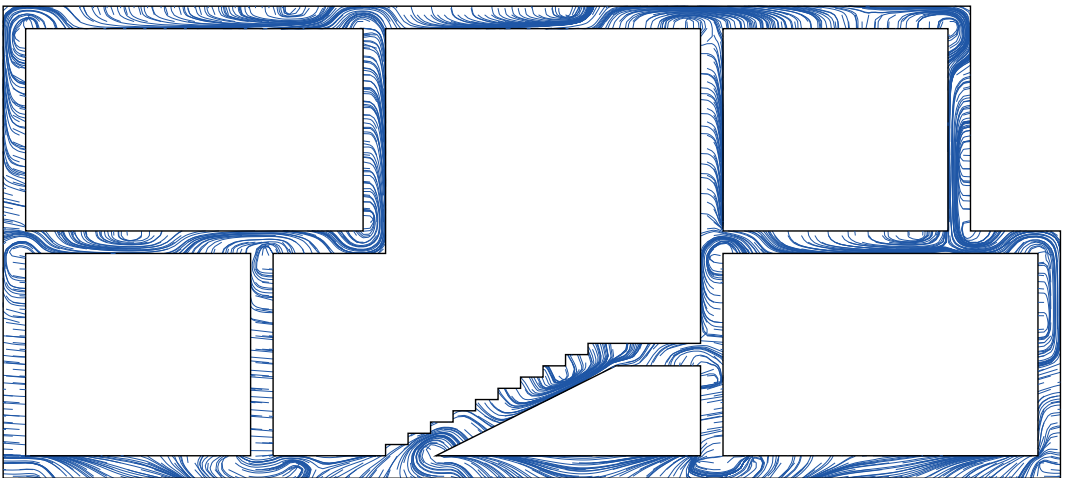
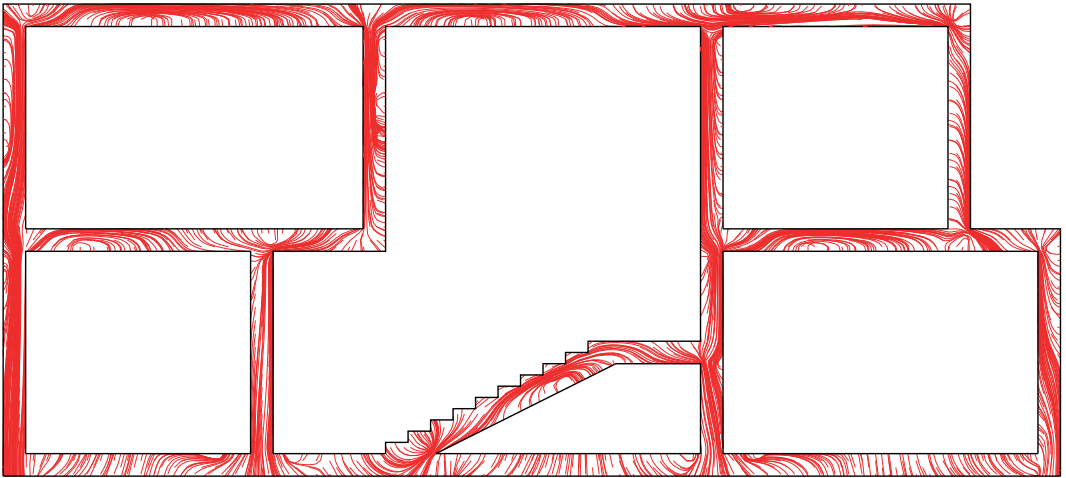


Figure 8.7

Focus on structural optimization. The isostatic lines show that the approach tends to follow their shape, the max value of compressive and tensile stress shows the improvement in the structure.

PRELIMINARY DESIGN



OPTIMIZED DESIGN

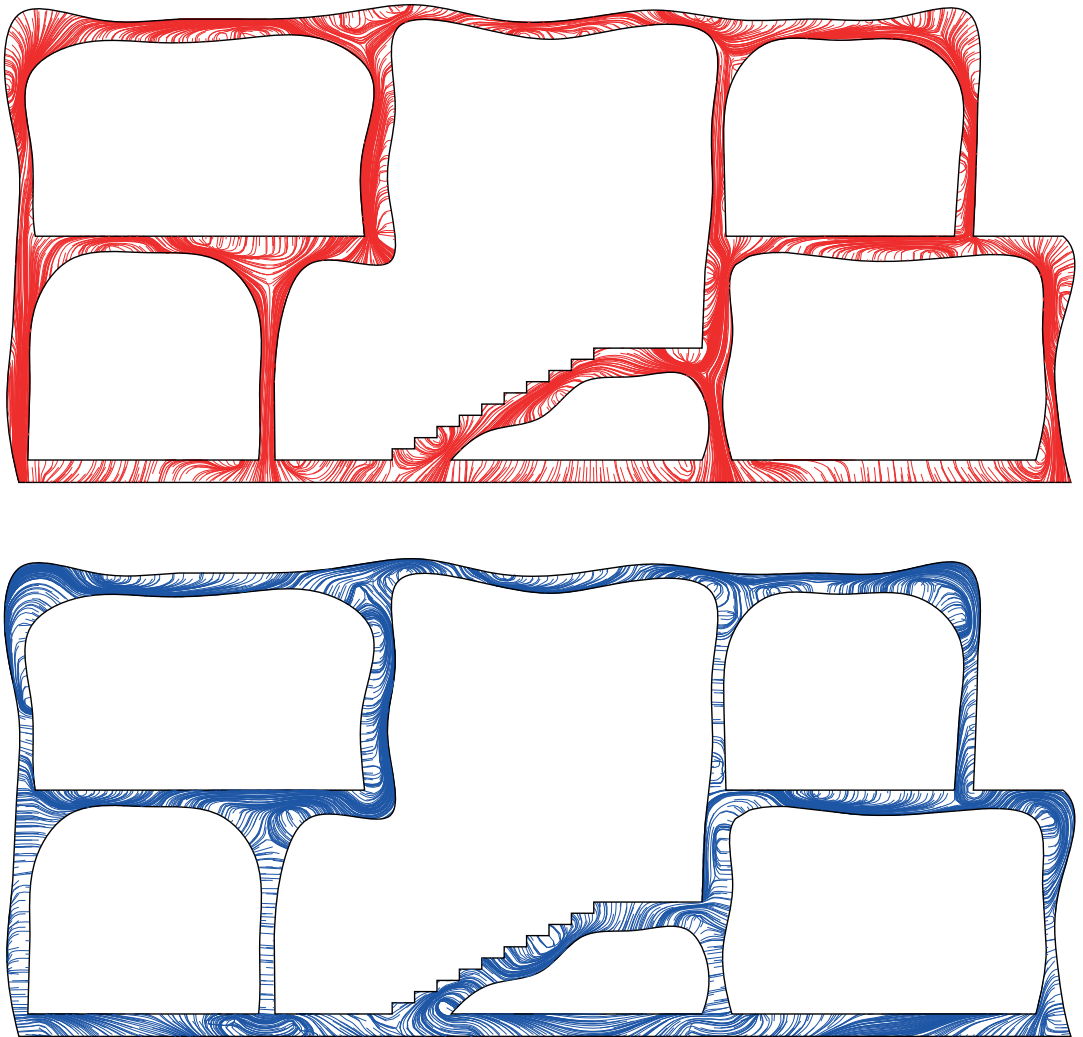
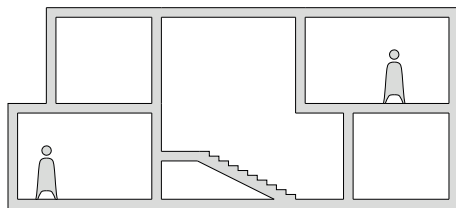
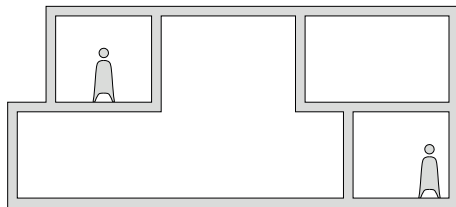
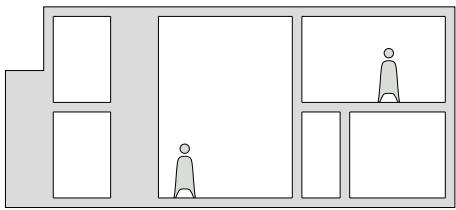


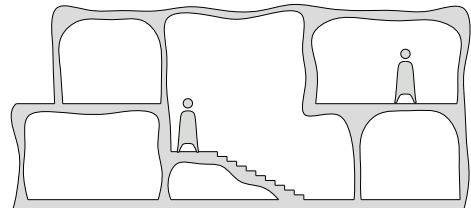
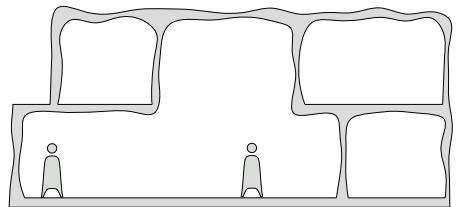
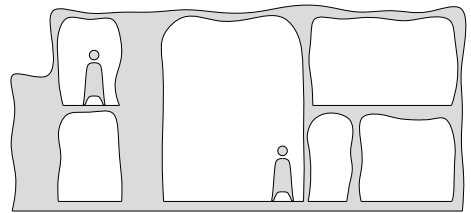
Figure 8.8

Before and after the structural optimization of an entire section. The isostatic lines of compression and tension are shown

PRELIMINARY SECTION



OPTIMIZED SECTION



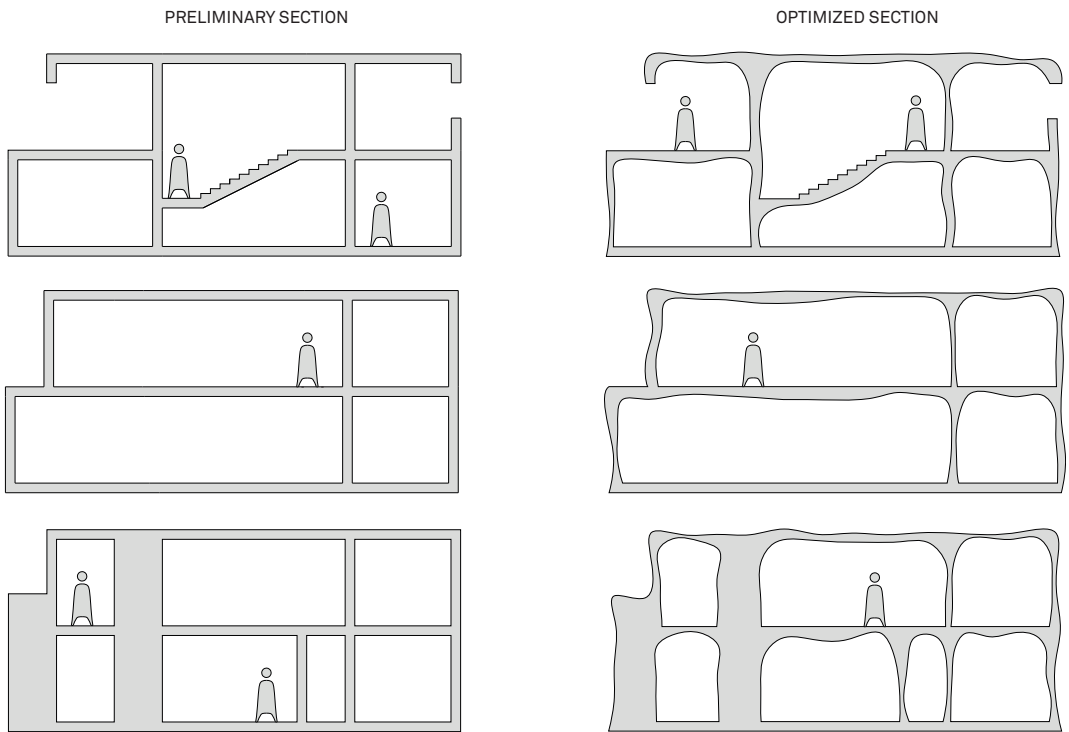
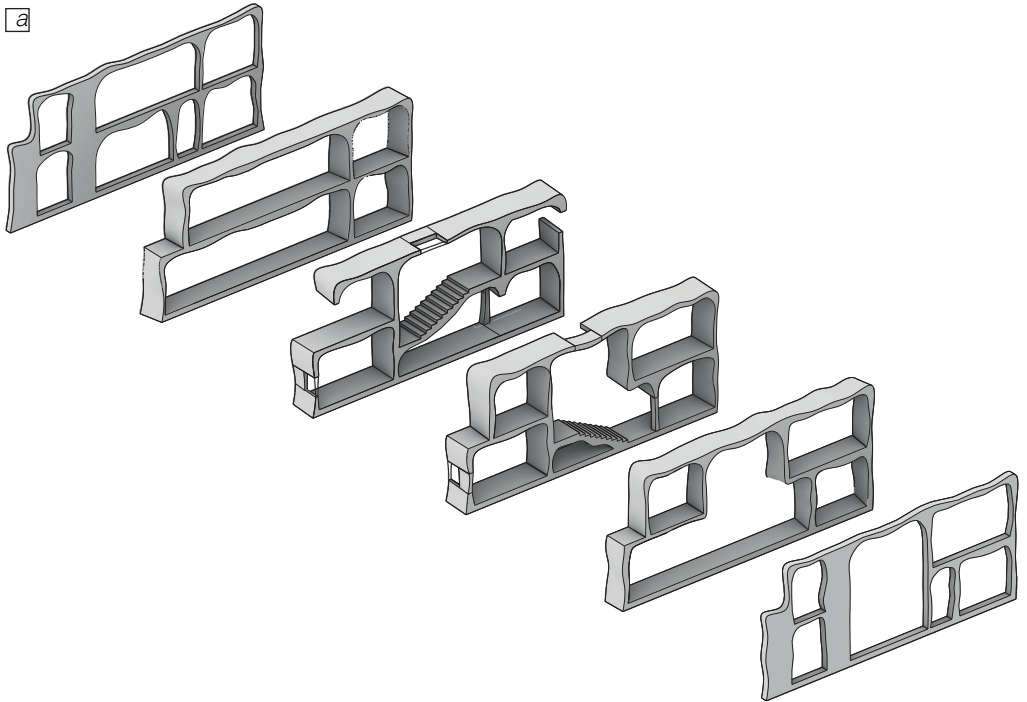


Figure 8.9

Before and after the optimization of all sections

a



b

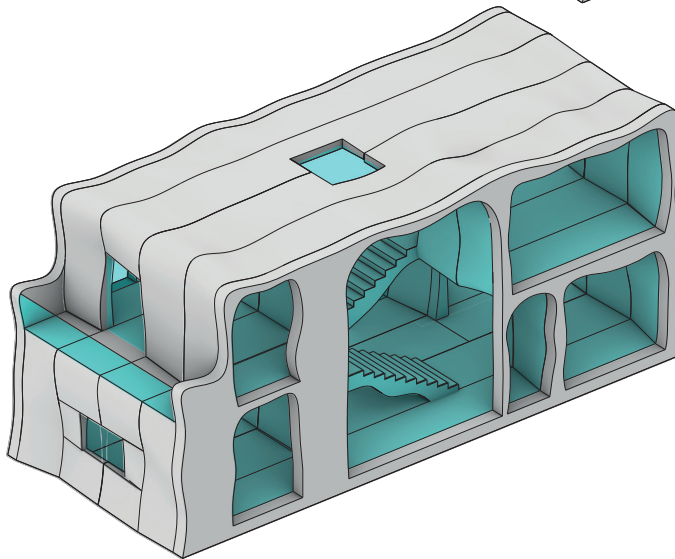


Figure 8.10

a. The optimized sections positioned in the right order.

b. The complete optimized design as the result of the positioning of the different sections. Only the structural system of the project is here shown. Other parts of the building are not the focus of this thesis

8.4

PREPARING FOR PRODUCTION

Once the optimization is done the resulting sections can create the final design. To do so it has been operated a loft between the sections to guarantee an esthetical continuity . As the project need to be realized the section need to be prepared for production. A key factor in prefabrication is the transport which inevitably forces the framework to be divided into different components. To do so the research around precast concrete and prefabrication became helpful in determining the best approach possible. The joints chosen for this type of design are the most common: grouting and cast-in-place concrete generally guarantee great adhesion between the component and are generally easier to create. In some cases corbels

were created as the freedom of design of 3DCP makes it easier and non-expensive; this is the case, as an example, of the stair located in the middle of the structure. After this is done the printing direction of choice is the one that generally guarantees the best performance for reasons already listed. Another interesting topic of discussion in the production of these components and this framework would be the toolpath that creates the infill of the component as it can be optimized to be structurally efficient, this part has not been investigated and the strategy for infill represented is a basic zig-zag toolpath that can be generally found in current 3D printed projects.

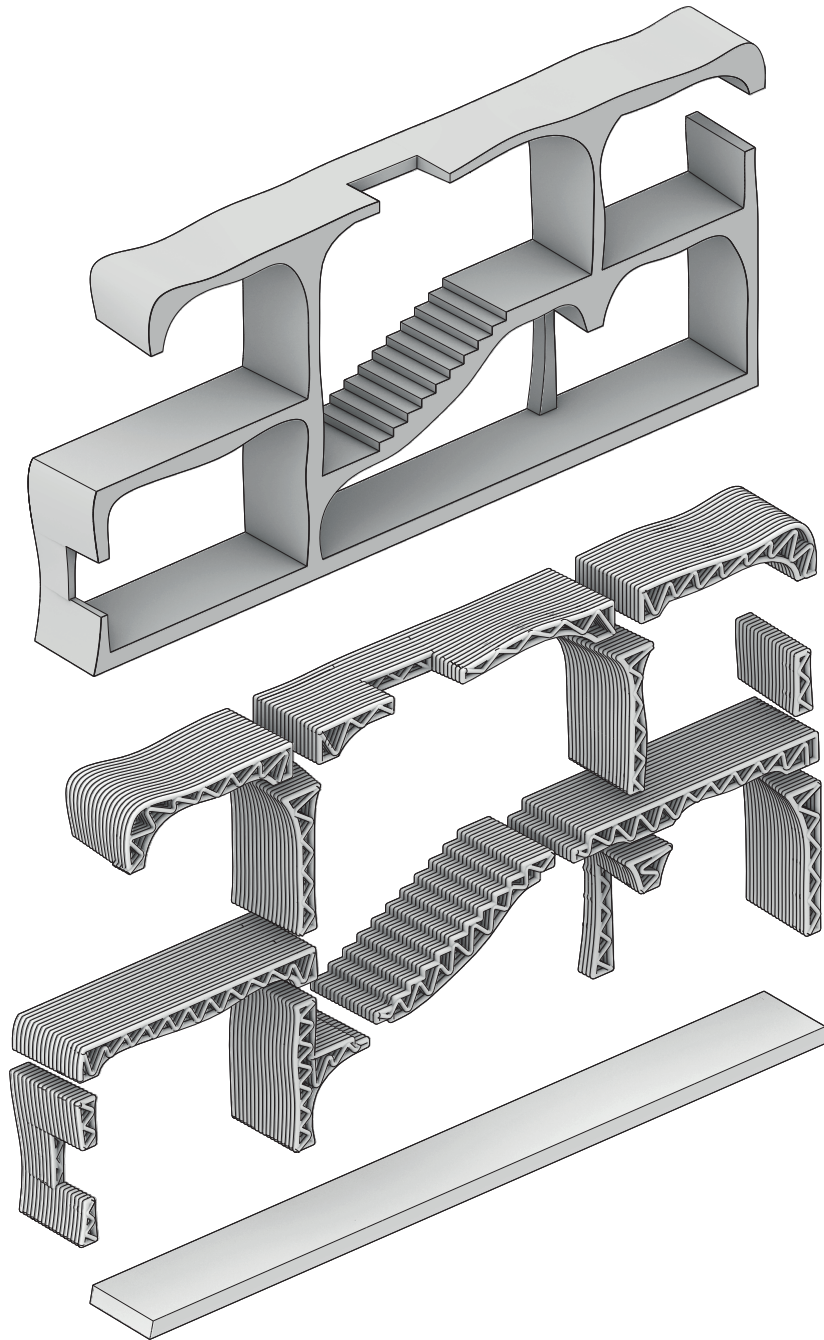


Figure 8.11

Example of how the section is divided into the different components. It is also shown the printing direction: The foundation are meant to be realized with standard method and are not subject of optimization

8.5

PRODUCTION WORKFLOW

To complete this prefabrication approach is also proposed a system that, thanks to its 3 phases, can create a workflow that can bring a project to reality by manufacturing the components, transporting them to the construction site and assembling them. The sections, during this process, are divided into different components to ease the transport from the manufacturing plant to the construction site. To generate this process the usual process for precast concrete is used as a reference and the advancement given by 3DCP are used to create a new type of manufacturing, an approach that is typically called digital fabrication.

8.5.1 OFF-SITE FABRICATION

The fabrication of the components of the section happens in an off-site location in a facility that is composed of two different types of units here shown which can be replicated as many times as necessary to respond to the production needs. The material supply unit is the part of the facility that is in charge of the storage of the material needed for the production process. To deliver the material to

the fabrication unit a crane is used to move the crane bucket which can contain concrete: a lifter is used to move other materials like reinforcement. In the fabrication unit inside of a security cage two 6-axis robotic arms on rail work together to manufacture the components. One robot oversees the extrusion of the concrete which is supplied by a pump and the other robot is in charge of the placement of the reinforcement, or other elements, during the printing process. The printing surfaces are steel pallets that can be moved by the crane and placed in a curing area where the printed components are left to cure in a controlled environment until they can be shipped or stored outside the building. A control unit next to the cage gives the possibility to the operator to control and manage the production inside the fabrication unit. The clear advantage of this system, compared to the conventional prefabrication method is that, as formworks are not needed, once the print of an object is done it is possible to immediately start the print of a different one. Likewise, for each different design, there is not the need to create a formwork which is expensive and requires time.

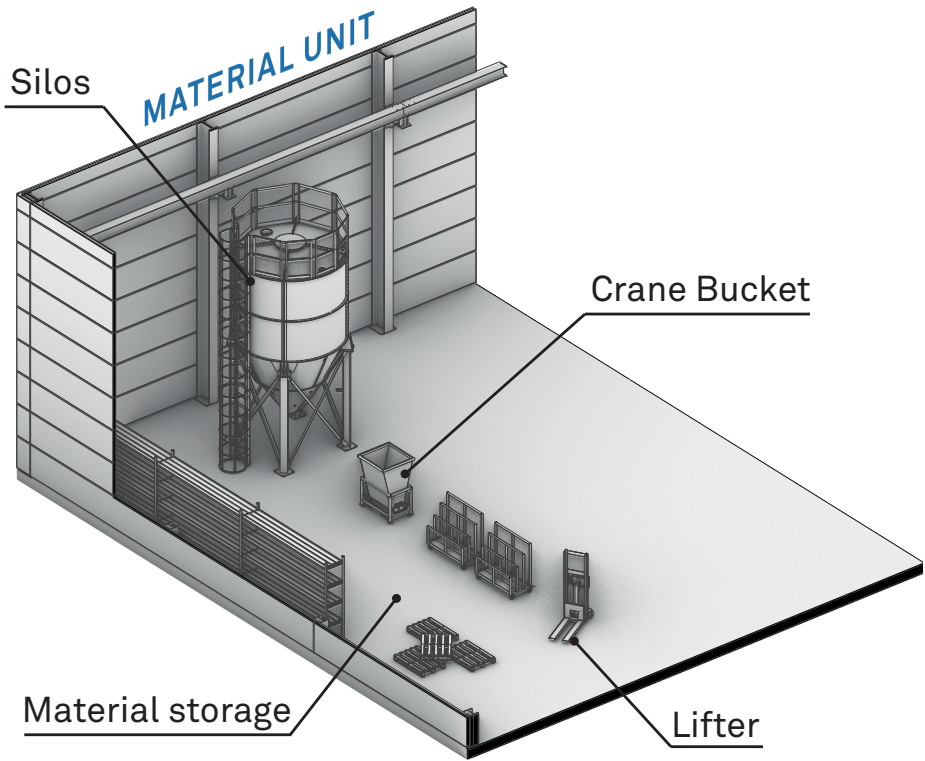


Figure 8.12
Material Unit of the off-site production

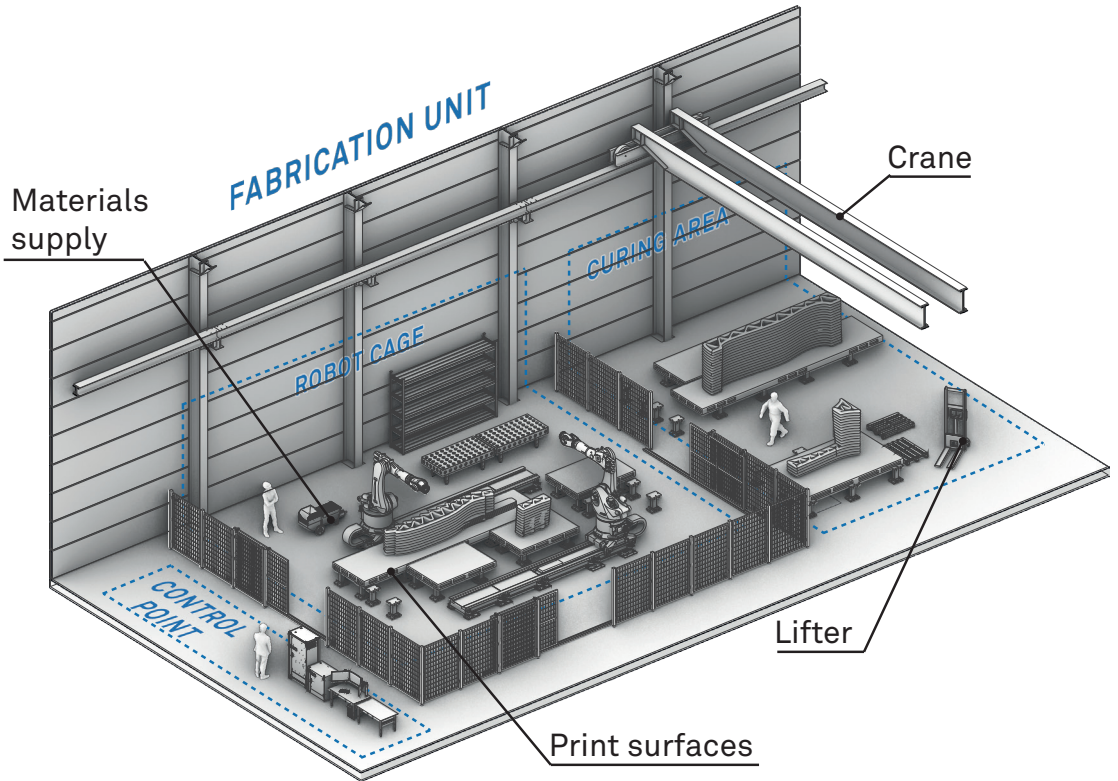


Figure 8.13

Fabrication Unit of the off-site production

8.5.2 TRANSPORT

A key part of prefabrication is the transport of the part of the framework to the construction site and it also can be a great cost. The best type of vehicle to facilitate and speed the transport is the Inloader, a type of semi-trailer typically used for the transport of concrete and glass which greatly facilitate the loading operation as it has removable pallets

which can be used to store the material in the facility. The back of the Inloader can also be lowered thanks to its air suspension and make it easier to load the components. The maximum volume that can be transported with this type of semi-trailer is 1,55x10,2x3,8 m, which is a very important criteria that determine the maximum dimension possible for the components

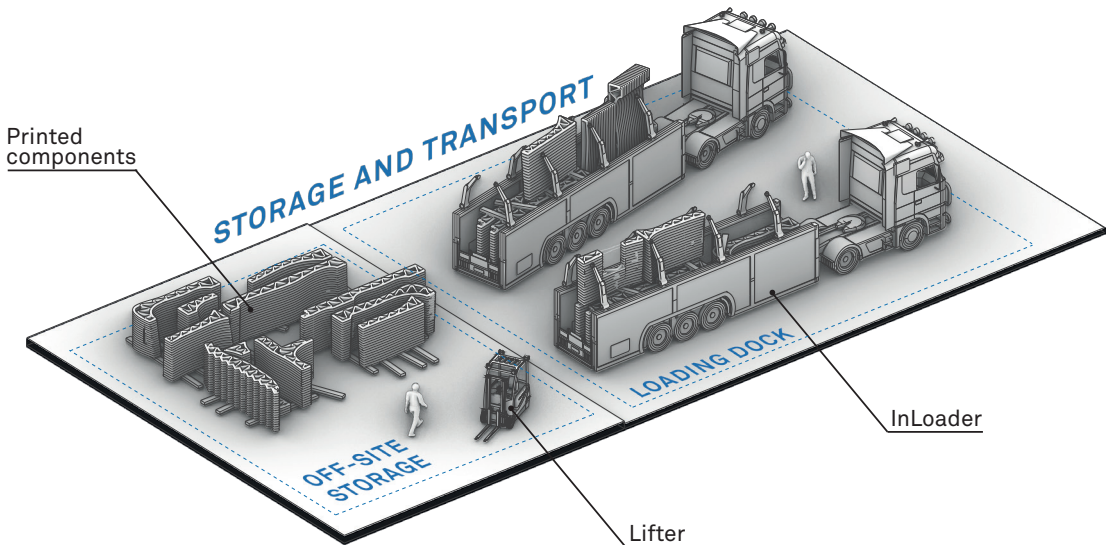


Figure 8.14

Storage and transport of the components printed

8.5.3 CONSTRUCTION SITE

The components are meant to be delivered in the construction site only when needed, therefore a space for storage isn't created and the printed objects are directly taken from the Inloader. To do so it is essential to have a lifting system that makes it possible to elevate the components and move them into place, the motion system of choice is a mobile crane system with an extendable arm which is ideal for the lifting of heavy materials, it is also movable which extends its possible reach. Putting into place the components is the most delicate and important task which

requires specialized workers that need to be able to align correctly all the components together so that the joint can be created properly, a determining factor in the integrity and value of the structural system. It is important to note that the low resolution of 3DCP can create multiple problems as a clean and flat surface is often needed to place the components correctly and, most importantly, create the joint. Still, the freedom of shape can give a new push in the research of how the joint between this component can be created, but this is not the focus of this work. Here it is shown a frame of the work in progress while the project is being assembled.

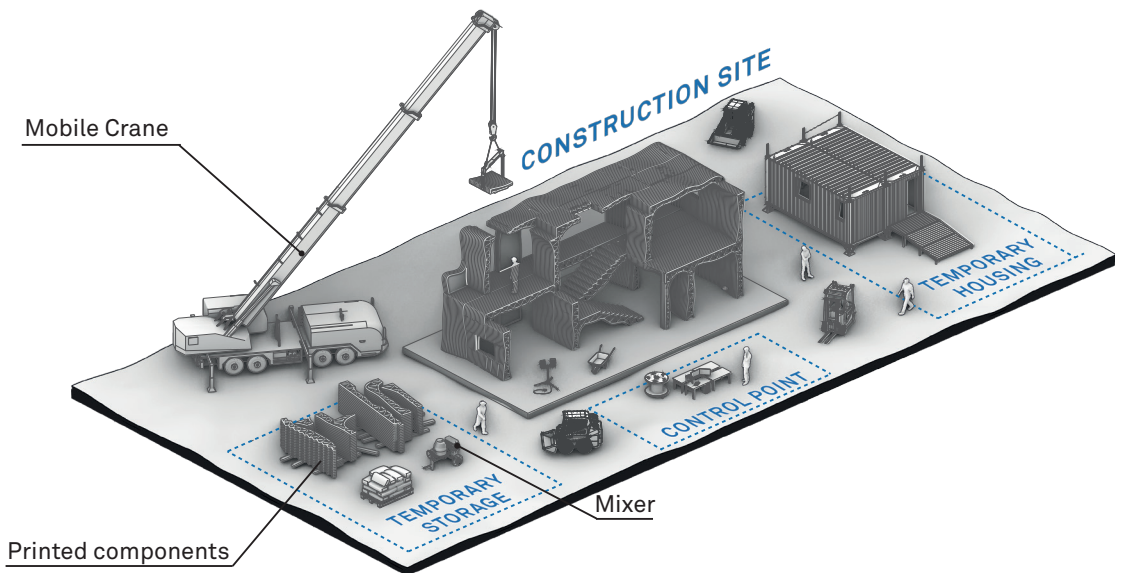


Figure 8.15

Assembly of the project in the construction site

CONCLUSIONS

What has been shown in this thesis is a work on 3D concrete printing and its current and future applications. To so it was imperative to learn more about a technology that is, for the most part, unknown to the public and in the construction field.

- Intensive research was done over the project printed worldwide that shows the challenges that this technology is facing. Additionally, it was possible to learn more about how currently there are two different type of players in the field: companies that are trying to realize residential houses and public buildings and research institutes that are testing the possibility of this technology with, mostly, experimental specimens being realized. This put the effort of these two types of players further from each other with a weak transmission o knowledge.
- An important part of this thesis was the proposal of a system for the creation of a Finite Element Model that could be adaptable to the special shapes that are realized with 3D concrete printing, this new approach takes some freedom in regards to

standard practice but it was possible to operate linear and non-linear analysis of design that otherwise would be challenging to simulate.

- During the experience in the lab, the data collected about the temperature and about the print made it possible to ideate an ideal timeframe in which the printing should happen to avoid any issue with buildability or the hardening of the material which can generate great problems and could stop the process. Still, the temperature collected were particularly challenging to measure and a complete connection between temperature and the behaviour of the material has not been found.
- Building on the experience in the lab B06 was designed: a beam that blends the possibilities given by 3DCP with the possibility to save material by T-beams. A proposal for the production has been shown but there are reasonable doubts regarding the ability of the system to deliver the precise shape of the layer that was needed.

- Finally a new printed and structurally optimized prefabrication system has been developed in its entirety from the preliminary design to the assembly in the construction site, creating a workflow that is challenging standard practice of precast concrete. This has been done to bridge the gap between the work done by research institutes and companies so that there could be an efficient transfer of knowledge. Even though there are some point of discussion about the structural behaviour of this framework its approach remains valid and offer a new approach which could bring new possibilities to 3DCP

An important step forward would be the realization of the B06: the result of the 3-point bending test could give important feedbacks in the approach used to generate the design and validate an approach that is different from the one currently investigated

by the CREATE group.

Another step would be the validation of the system used to create the simulation with the comparison of this method with conventional ones, this could also help to find new solutions to generate the FEM that is closer to the one the software was designed for.

An additional future research interest could be about the new framework as the structural interaction between the different sections was not taken into great account during the ideation of the system. Also, the strategy for infill has not been investigated and it opens further possibilities for optimization and the reduction of the material needed for the creation of the projects.

Finally, it is clear that the 3DCP has created a connection between the digital and real-world in construction and giving much more freedom to and challenges to designers and engineers who are currently working together to make the best out of this opportunity.

BY

BIBLIOGRAPHY

PART 1:

McKinsey, 2017, Reinventing Construction: A Route to Higher Productivity, <https://www.atalayaleasing.com/insights/2019-06-03-construction-modernization-how-can-productivity-improve>

Pedro Carvalho, José Pedro Sousa 2014, Digital Fabrication Technology in Concrete Architecture, In: eCAADe 32.

Mohammad Sadra Fardhosseini, Ali Karji, Carrie Sturts Dossick, Hyun Woo Lee, Houtan Jebelli, Sean Beatty, 2020, The Cost-Effectiveness of Integrating Digital Fabrication for Concrete Formworks, In ASCE Construction Research Congress 2020.

ETH dbt, 2017, <https://dbt.arch.ethz.ch/project/concrete-canoe/>

H. Lindemann, H. Kloft, N. Hack, 2018, Gradual Transition Shotcrete 3D Printing In Advances in Architectural Geometry 2018.

The Guardian, 2017, Jonathan Watts, <https://www.theguardian.com/cities/2019/feb/25/concrete-the-most-destructive-material-on-earth>

Yu Chen, 2017, A critical review of 3D concrete printing as a low CO₂ concrete approach. In: Yu Chen, Erik Schlangen 2017, Sustainable Cementitious Material for 3D Concrete Printing, pp. 167-188.

European Commission, 2016, https://ec.europa.eu/environment/waste/construction_demolition.htm

US Bureau of labor statistic, 2018, <https://www.bls.gov/charts/census-of-fatal-occupational-injuries/number-and-rate-of-fatal-work-injuries-by-industry.htm>

Markets and Markets, 2016, 3D Concrete Printing Market.

Henrik Lund-Nielsen, 2021, <https://www.youtube.com/watch?v=zsflK4YzjKg>

R.A. Buswell, W.R. Leal de Silva, S.Z. Jones, J. Dirrenberger, 2018, 3D printing using concrete extrusion:

A roadmap for research, In: Cement and Concrete Research, Volume 112, 2018, pp.37-49.

US Patent and Trademark Office, 1995, <https://patents.google.com/patent/US5529471>

Jihoon Chung, Ghang Lee and Jung-Hoon Kim, 2020, A Systematic Review of the Geographic and Chronological Distributions of 3D Concrete Printers from 1997 to 2020, In: Proceedings of the 37th ISARC, Kitakyushu, Japan. Pp 84-89

Nathalie Labonnote, AndersRønnquist, Bendik Manum, Petra Rüter, 2016, Additive construction: State-of-the-art, challenges and opportunities, In: Automation in Construction, Volume 72, Part 3, 2016. Pp. 347-366.

Behrokh Khoshnevis, 2004, Automated construction by contour crafting-related robotics and information technologies, In Automation in Construction, Volume 13, Issue 1, 2004, pp. 5-19.

BBC, 2014, <https://www.bbc.com/news/blogs-news-from-elsewhere-27156775>

Apis Cor, 2019, <https://www.apis-cor.com/dubai-project>

Alexander Paolini, Stefan Kollmannsberger, Ernst Rank, 2019, Additive manufacturing in construction: A review on processes, applications, and digital planning methods, In: Additive manufacturing, Volume 30

World Economic Forum, 2018, <https://www.weforum.org/agenda/2018/05/25-of-dubai-s-buildings-will-be-3d-printed-by-2025/>

Freek P. Bos, Zeeshan Y. Ahmed, Rob J.M. Wolfs, Theo A.M. Salet, 2018, 3D Printing concrete with reinforcement, In: High Tech Concrete: Where Technology and Engineering Meet, pp.2484-2493

PART 2:

Yiling Lai, Yuchen Wang, Robert Ireland, Ang Lliu, Digital Twin Driven Design, 2020, pp 109-138

A. Hoffmann, Artificial and Natural Computation, 2001, In: International Encyclopedia of the Social & Behavioral Sciences, 2001, Pp. 777-783

