Reusable 3D Printed Concrete Slab:

An Approach Towards the Optimisation of the Usage of Concrete in the Built Environment.

S.A. Falcón Bueno

Graduation Research

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Author:
S.A. Falcón Bueno
id. 4749499

Supervisors:
Dr. Ir. F.A. (Fred) Veer
Structural Mechanics

Dr. D.P. (David) Peck
Climate Design & Sustainability

Delegate of the Board of Examiners:
Ir. K.P.M. (Kristel) Aalbers
Environmental Technology & Design

Delft University of Technology
Faculty of Architecture and the Built Environment
Master Track Building Technology

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TU Delft

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Preface

This thesis is the conclusion of the Sustainable Design Graduation Studio of the master track Building Technology at the Faculty of Architecture and the Built Environment at Delft University of Technology.

I have chosen this research because innovation, materialisation and hands-on approaches have always motivated me. The building industry is well-known for its poor aim for innovation. This means that it often stays within the same path of materialisation and sustainability. This is because innovation costs money and it does not bring immediate monetary gains. In an industry with low returns, there is no incentive for investing in innovation. Therefore, innovation has to be made in small but meaningful steps. Here, innovation can be achieved by redefining the problem. How can the production and consumption of the most globally used building material be sustainable? Given the significant share that concrete has in the building industry, the ability to optimise the composite use can have a global impact in reducing both pressure from the environment and carbon footprint. To fully exploit the potential of concrete in a cost-effective and environmentally friendly way, represents one of the greatest challenges posed to building technology today.

This research is about finding a new way to make concrete more sustainable and consequently, to reduce its harm to the environment. However, the problem is shifted from finding a sustainable composition of the material, to make efficient use of the existing concrete and exploit its full potential. This means, to exploit one of the most misused advantages that concrete offers to the building industry: its durability. With this objective, novel production methods are also explored for two reasons: first, to reduce the material waste proper of the production of concrete elements. Second, to explore new reinforcement methods to provide concrete with tensile strength. The last approach is especially important as one of the causes to diminish the durability of concrete is precisely the conventional reinforcement method.

Throughout this research, I have been guided and inspired by my two research mentors and external delegate. First, thank you Fred Veer for the critical question posed at my P1, which redefined my topic completely and shifted me to this thrilling and challenging topic of concrete and novel production methods. I am confident to say that I have found what I want to focus on in my future. Thank you also for the personal guidance when I was going through difficult decisions about my true passion. Your advice is very valuable. I would like to thank David Peck for the long talks not only about circular economy but also about science in general. Such conversations were an added value to the design of the reusable 3DCP slab as I had inputs from fields different to engineering. Thank you as well for pushing me to make efficient and short presentations, without a doubt a skill I had to learn from scratch. I would like to thank also Paul de Ruiter for his great enthusiasm and help at the moment I was 3D printing my prototypes. Thank you for always being open to help.

Especial thanks to my parents. Without their support I would never be able to achieve my master degree. Thank you for always support my dreams without questions. Thanks to my father who is always pushing me to be a better human and for always being there at moments of struggle. Thanks to my mother for the long talks about my daily life away from home and for giving me the support only a mother can. Thank you both very much for that. (*Gracias especiales a mis padres. Sin su apoyo nunca habría podido terminar mi maestría. Gracias por siempre apoyar mis sueños sin questionamientos. Gracias a mi padre quien siempre me impulsa a ser un mejor humano y por siempre estar ahí en momentos difíciles. Gracias a mi madre por las largas pláticas sobre mi vida diara lejos de casa y por darme el apoyo que solo una madre puede. Muchas gracias a ambos*).

Thanks to my girlfriend for her constant support and for pushing me to achieve goals that seem far away. Thank you also for teaching me that there is life after school.

Finally, a great thanks to my beloved Biertje group: Agata, Erron, Sofía and Valeria. Thanks for being my second family in Delft, whom I could always count on to go through tough times and share the best moments of joy. Thank you very much for that.

Abstract

Concrete consumption is one of the major environmental issues of our time. This building material is used twice as much as all the other building materials combined. Furthermore, the United Nations predicts that human global population will reach 10 billion inhabitants by 2050. Correspondingly, it is projected that due to global migration from land to cities, almost 75% of the world's population will be urbanized. For the building industry, this means that in thirty years we will roughly equal the entire volume of the construction made in the world's history. In other words, the consumption of concrete is predicted to double over the next three decades. Given the importance that concrete has for the building industry, the ability to optimise the material usage can have a global impact in reducing both pressure from the natural environment and carbon footprint. To fully exploit the potential of concrete in a cost-effective and environmentally sensible way represents one of the greatest challenges posed to building technology today.

The research question has been formulated based on this problem statement: **How can a prefabricated structural concrete slab be designed to optimise the use of concrete, minimise material waste and allow for efficient (dis)assembly and reuse to extend its exploitation life?**

Currently, one of the main issues to reuse concrete elements is the implementation of steel rebars as reinforcement. This type of reinforcement corrodes and causes internal cracks in the concrete elements. This means that after time, the element cannot be reused as its structural capacity is compromised. This has led this research towards investigating novel strategies to provide concrete with tensile strength. Fibre reinforced concrete (FRC) emerges as a potential solution. However, it is well known that the performance of FRC largely depends on the orientation of its fibres. To achieve this, production methods that can achieve a controlled fibre orientation are also reviewed. Here, 3D printing concrete (3DCP) emerges as an approach worthy to be explored. It has been observed that the fibres orient parallel to the deposition of the concrete layer. If this strategy is applied, this means that a printing path can be programmed and, the fibres will orient accordingly. A general outlook of 3DCP characteristics is reviewed in this research. Consequently, such characteristics are applied to the design of the reusable 3DCP slab.

Besides the material characteristics, Circular Economy (CE) presents strategies to exploit the full potential and retain the optimal value of the physical environment. Principles of the CE are reviewed in this research through literature study. Special consideration has been put in the principle of Design for Reuse (DfR) as the objective of this research is to enable multi service-lives of the new 3DCP slab. Suitable aspects have been identified and applied to the design based on the properties of concrete and fabrication techniques. Here, the engineering of dry mechanical connections is sensible

as the 3DCP slab can be efficiently demounted without the need to break or cut part of the slab. The simplicity of the connections is crucial in this research as this translates into savings of energy and CO_2 emissions due to a rapid building process. Furthermore, the simplicity of the connection means an easy replacement upon damage without affectation to the whole concrete slab. The engineering and mechanical performance of the connections are addressed in this research.

To conclude the research, the utility of the reusable 3DCP slab is studied. The results are compared to those of a traditional concrete slab and conclusions are drawn to assess the relevance of this new approach to reduce concrete consumption. Economic utility, policies and business models are excluded from this research as they are not the main focus and due to time constraints.

This master thesis answers the research question by designing a concrete slab that can optimise the usage of concrete. This is achieved both by material characteristics, production process and the engineering of demountable connections. However, further physical research and testing are needed to properly evaluate the production process and its applicability to the current design. Nevertheless, the result looks promising.

Keywords: *concrete, concrete slab, design for reuse (DfR), circular economy (CE), dry connections, 3D printing concrete (3DCP), fibre reinforced concrete (FRC).*

Content

Chapter 4: Research Conclusions and Recommendations

Bibliography

Chapter 1

INTRODUCTION

The concrete conundrum

Context

"Concrete is the foundation of modern development. With this material, humans have been able to build roofs to shelter billions, to fortify defences as protection against natural disasters and to provide structures for healthcare, education, transport, energy and industry" (The Guardian, 2019). The importance of concrete for modern prosperity can be deducted from the ever-existing presence of this material in the evolution of civilization. The basic concrete ingredients (sand, gravel, cement-like binder and water) were being mixed already during Egyptian times. The Romans mastered the composite to create wonders such as the Pantheon in Rome, which stands over 2.000 years. At the end of the ninetieth century, industrialised concrete allowed the construction of the first skyscrapers. This allowed the densification of urban areas which enabled economic affluence. Later, rivers of concrete were poured after the world wars as the material offered an inexpensive and simple way to rebuild cities. Nowadays, concrete provides the foundation of super-rapid economic development. It allows the construction of railway tracks, bridges, tunnels, airports, hospitals, industrial complexes and energy stations. The former provides some of the many reasons for civilization to rely so strongly on concrete: the raw materials required for its production are easy to be obtained, it has exceptional durability, it is strong, it is cheap compared to other building materials and it provides with much design flexibility to architects and engineers.

The comprehension of the benefits that concrete provides is crucial to understand its close relation to modern civilization. Correspondingly, such comprehension provides with the reason of why it is challenging to find a proper substitute building material. However, some of those benefits such as the ease of production and low cost have encouraged the linear-use model of concrete elements. Such model is based on the acquisition, use of one lifetime and disposal of such elements. This implies two things: First, the full durability potential of concrete is not exploited. Second, new concrete elements need to be produced constantly. This means that raw materials need to be continuously extracted, which generates a serious burden on our natural environment. As development is expected to continue, the need for gentrification and urbanisation is projected to grow. Urbanisation implies an increasing demand for housing units. Thus, the need for concrete will endure. Reports from Chatam House (2018) predict 3 billion people potentially living in slums by 2050. This means that new rapidly deployable housing solutions are needed. Therefore, the focus should be put on strategies to utilise concrete's full potential to enable sustainable development.

Circular economy is a concept that presents strategies to exploit the full potential and retain the optimal value of the physical environment. This implies an economy in which products and material utilisation are optimised, therefore polluting emissions and waste are reduced as the manufacture of new products is diminished. These are reasons for both European and national levels to be interested

Previous: Mexico City aerial view. Retrieved from López Luz, Pablo. 2013. *Terrazo*. http://www.pablolopezluz.com/works/view/1

in making a transition from the current product use model towards a circular economy. With the programme "Nederland Circulair 2050" (Ministry of Infrastructure and the Environment & Ministry of Economic Affairs, 2016), the government of Netherlands aims to stimulate strategies to use materials efficiently. Correspondingly, similar objectives have been expressed at the European level to enable sustainable development. To achieve this, the circular economy dictates four levels at which the optimal value and resource efficiency of products can be obtained: maintain, reuse, remanufacture and recycle. The order of the levels is descending and determined by the amount of energy and raw material needed to retain the value of a useful product. This means that for instance, product reuse is preferred over its recycling. Product reuse is the objective of this research as it allows to exploit one of the most misused advantages of concrete: its durability.

Based on the growing demand for housing units, their short service-life compared to the technical-life of concrete and in light of economic and governmental developments, innovation in the field of reusable concrete elements is of growing importance. A result of this practice involves a change towards considering buildings as material banks for the future.

Problem Statement

"In the time it takes you to read this sentence, the global building industry will have poured more than 19.000 bathtubs of concrete" (The Guardian, 2019). Concrete consumption is one of the major environmental issues of our time. Being used twice as much as all the other building materials combined, its utilisation is close to 25 gigatons per year (Gursel, et al., 2014). This means that more than 3,8 tons of concrete are used globally per person every year. Just between 2011 and 2013, China produced more concrete (6,6 gigatons) than the United States did during the whole 20th century (Duballet, et al., 2018). According to the United Nations, the estimated global population in 2018 was 7,6 billion people and it is expected to reach 10 billion by 2050. Correspondingly, it is projected that due to global migration from land to cities, almost 75% of the world's population will be urbanised (Jensen, et al., 2016). Such development will put enormous pressure on the world's resources. Furthermore, looking specifically at the construction industry, such development means that we could roughly equal the entire volume of the construction made in the world's history (Jensen et al., 2016). In other words, the consumption of concrete is predicted to double over the next thirty years.

There are multiple reasons that make this men-made composite the ideal material for the building industry: First, it has a very low environmental impact compared to other building materials. Concrete only has a big carbon footprint because such huge quantities are being used. Second, concrete has an excellent price-performance ratio. It is relatively cheap compared to other building materials, it has good strength, exceptional durability and excellent fire resistance. Third, the raw materials required for its fabrication can be obtained from practically anywhere in the world. Fourth, it is a material that provides with much design flexibility to architects and engineers. It turns naturally from a fluid to a solid state, being able to flow and fill moulds and upon hardening, sustain considerably large loads.

However, the massive production and consumption of concrete generate a serious burden on our environment. The concrete mixture consists of aggregates, cement and water. The manufacturing processes of cement consume considerable quantities of energy and emit massive amounts of greenhouse gases. According to Chatam House (2018) and James Mitchell (2008), the cement industry alone is responsible for 8% of the total global CO_2 emissions. Reports from The Guardian (2019) state that if the cement industry were a country, it would be the third largest emitter of CO2 in the world, just behind China and the U.S. (*figure 1*). Correspondingly with the increase of concrete consumption, cement production is projected to rise in the next three decades, reaching almost 5 billion tonnes per year (Chatam House, 2018). *Figure 2* compares the projection of global demand for the five most used materials by 2050.
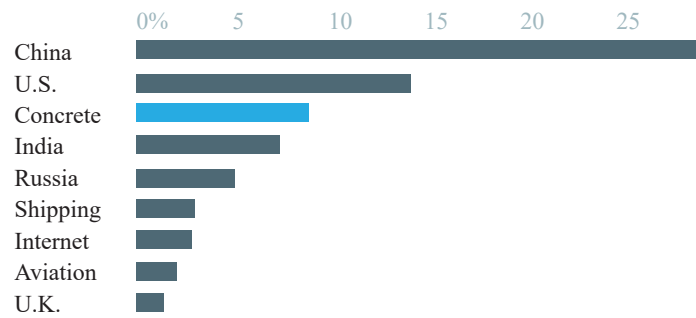
Figure 1: If concrete were a country it would be the third largest carbon emitter in the world [1]
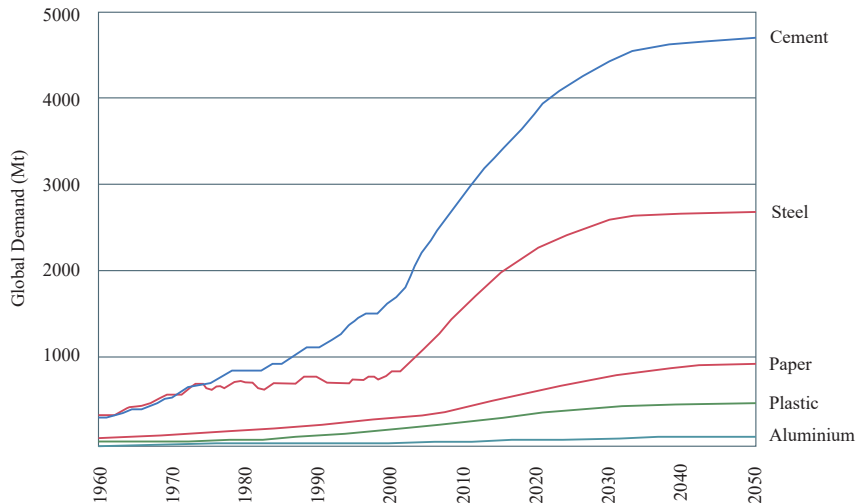

Figure 2: Global demand for the five key materials, historic from 1960 and forecast to 2050 [2]

Research groups, universities and private companies are studying the replacement of cement in the concrete mixture. Those substitutes are commonly referred to as supplementary cementitious materials (SCMs) and include goods such as fly-ash, slag and silica fume. However, this approach has brought new challenges. Increasing the amount of SCMs in the concrete mixture should also consider other parameters such as availability. The geographical distribution of fly-ash is uneven worldwide and silica fume and slag are in limited supply. This means that they cannot satisfy a long-term global demand (Chen, et al., 2018). Nevertheless, the concrete mixture is only one-third of the environmental problem.

Once the concrete mixture is ready, there is still a considerable amount of labour and material involved in building concrete structures. This translates into an addition of energy requirements and costs. Moulds need to be made, reinforcement placed, concrete cast and upon hardening, moulds need to be removed. *Figure 3* illustrates the share-cost associated with this process. Such process has been constantly optimised to reduce costs and improve production. The result is an abundance of standardised concrete elements that can be produced in large series, which helps to recover the

1 Rebuild from The Guardian. 2019. *We're wholly dissapointed: The industry responds to Guardian concrete week.*
2 Rebuilt from Allwood, Julian M, and Jonathan M Cullen. 2009. *Steel, Aluminium and Carbon: Alternative Strategies for Meeting the 2050 Carbon Emission Targets.*

investments. However, this approach has brought two major issues: First, structural and material optimisation in the production chain is inferior to the costs and profits. Consequently, this has resulted in repeated and over-dimensioned concrete elements in the built environment. Current fabrication techniques for producing material-optimised concrete elements are hardly sustainable economically or environmentally, even if the built structures are highly efficient. Adjusting a standardised element to reduce material use is currently not cost-effective. For this reason, it is promising to look at the integration of novel fabrication technologies and concrete so that an evolved production process has both an economic and a sustainable motive. The second issue is that at present, formwork represents roughly 55% of the overall cost of concrete structures (Jipa et al., 2017). Additionally, formwork results in a significant source of waste, given that all of it is disposed of sooner or later, contributing to an ever-increasing production of waste. Formwork is likewise the limiting factor in today's lack of freedom in the shape of the built environment that architects and engineers face.
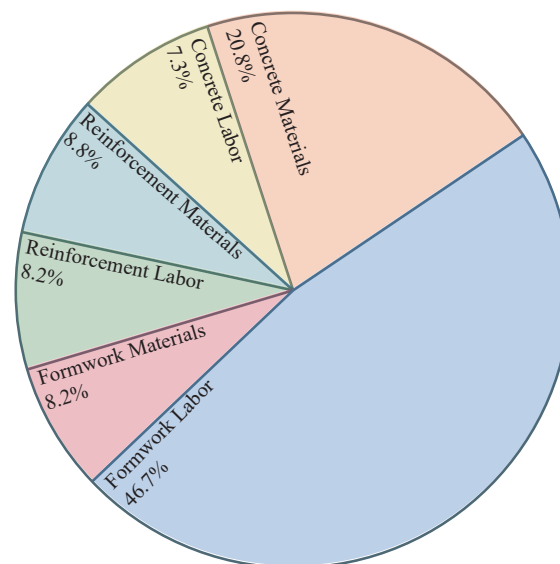

Figure 3: Share-cost associated with the current fabrication process of structural concrete elements ³

The framework of the issue with concrete consumption is completed by the current linear-use model. This model is based on the acquisition, use of one lifetime and disposal of the concrete element. With structural elements having the biggest share, the construction sector generates a large portion of all types of waste. On average, more than 2,2 billion tonnes of demolition waste are produced each year. This is more than three times as much as all the household waste (Schut, et al., 2015). Building products are created to last one service-life of maximum 70 years depending on the type of building. Furthermore, little consideration is paid to what becomes of a product when it reaches the end of its service-life. Hardly any account is taken of the possibility of disassembling the structural elements and reusing them in another building elsewhere. *Image 1* illustrates a demolition site with piles of materials with no value as resources for future buildings.

3 Rebuilt from Remy, Olivier; Verbruggen, Svetlana; Wastels, Jan & Tysmans, Tine. 2011. *Cement Composite Stay-in-Place Formwork: A Concept for Future Building Systems.*

Image 1: Demolition site with piles of downcycled materials with low or no value as resources for future buildings [4]

In present, most of the building's concrete structure is made through in-situ casting. This technique holds negative consequences such as a difficult quality control and high energy demands. However, the biggest issue of this practice is the result of an almost monolithic structure without joints. Concrete is so strong that it is impossible to disassemble two materials or building elements that it holds together. This means that brute force is required to demolish the structure, making it impossible to remove building elements in an efficient way that leaves them undamaged and suitable for reuse. In other words, high-quality reuse of structural concrete elements remains a challenge.

Besides the way in which buildings are currently constructed, the steel reinforcement embedded in concrete structures is another hindrance for reuse. The steel generates corrosion over time. This means that it forms a layer of rust in its boundary surface, which stresses and generates interior cracks in the concrete. For this reason, concrete elements are not suitable for multiple service-lives even when the (dis)assembly has been done efficiently. Therefore, production methods that shift the reinforcement placement should be investigated.

Given the importance that concrete has for the building industry, the ability to optimise the material usage can have a global impact in reducing both pressure from the natural environment and carbon footprint. To fully exploit the potential of concrete in a cost-effective and environmentally sensible way represents one of the greatest challenges posed to building technology today.

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4 Extracted from Jensen, Kasper; Sommer, John; Falk, Niels; Nielsen, Gitte; Hastrup, Annette; Sørensen, Henrik; Merrild, Heidi; Cristensen, Casper; Kristensen, Richard & Gothelf, Stig. 2015. *Building a Circular Future*. KLS Grafisk Hus.

Research Objective

This research is conducted by experimental design. It investigates the engineering of a prefabricated structural concrete slab that optimises the material usage in two manners. First, it comprises material and structural optimisation with the support of digital technologies. The topology of the slab has been evaluated to reduce the amount of concrete needed without affecting the overall functionality of the building element. Correspondingly, a novel production process such as concrete additive manufacture has been considered. The objective of this exploration is to diminish the material waste by avoiding the usage of formwork. The second material optimisation is achieved as the design foresights multiple service-lives of the concrete slab. This means that it can be efficiently demounted and reused to extend its exploitation life. The simplicity of connections for rapid and easy assembly and disassembly (hereafter (dis)assembly) is important in this framework. This translates into additional savings of energy and CO_2 emissions due to a rapid building process. Furthermore, optimisation of the production process and ease of transportation is considered to demonstrate the commercial feasibility of the reusable concrete slab.

Research Limitations

- This research mainly focuses on the reusability potential of the concrete slab. The most important parameter within this framework is the engineering of the slab's connections for easy (dis)assembly. The topology optimisation of the reusable slab is a second priority and therefore it will not be discussed in detail.

- The slab is to be (re)used in housing buildings. Therefore, the structural boundary conditions and loads applied for its design correspond with such building typology. The slab's use for other building typologies (offices, for instance) is not investigated due to time constraints. The time available to do this research has been 7 months. Therefore, it has been decided to focus only on the most needed building typology of the future: housing.

- This research mostly focuses on the engineering of the slab. Business models to make it financially feasible are not in this scope due to time constraints.

- The multifunctionality of the slab is not addressed. Only the structural performance has been evaluated. The inclusion of services within the slab (electricity ducts, drainage holes, etc) has been programmed for future research.

Research Questions

How can a prefabricated structural concrete slab be designed to optimise the use of concrete, minimise material waste and allow for efficient (dis)assembly and reuse to extend its exploitation life?

The main research question has been divided into the following sub-questions to ease an answer:

- What are the structural requirements and material use of a traditional concrete slab?
- How can a traditional concrete slab be topologically optimised to reduce material use?
- What fabrication techniques have the minor ratio of material waste?
- Which of those fabrication techniques are suitable to produce concrete elements?
- Which of those fabrication techniques have potential for large-scale fabrication?
- What are the existing assembly and disassembly methods used by the building industry that aim for quality preservation and element reuse?
- Which of those methods show the best potential to be applied to concrete elements accounting for structural performance needs?
- What is the utility of a multi service-life concrete slab compared to traditional concrete slabs?

Research Methodology

An approach to answering the sub-questions is given in *table 1*. The inclusion of all the answers results in a product that responds to the main research question.

	Question	Approach	Product/Result
1	What are the structural requirements and material use of a traditional concrete slab?	Case-study: • Observation • Measurement • Structural & material calculations	• Architectural features • Dimensions of a traditional concrete slab • Structural boundary conditions • Structural requirements • Actuating forces • Type & amount of material used
2	How can a traditional concrete slab be topologically optimised to reduce material use?	Literature study & Research by Design: • Computational simulations	• Computational model of the optimised concrete slab • Data about reduction of material usage compared to a traditional concrete slab
3	What fabrication techniques have the minor ratio of material waste?	Literature study: • Comparison	• Comparative study of fabrication techniques
4	Which of those fabrication techniques are suitable to produce concrete elements?	Literature study: • Comparison	• Filter of fabrication techniques suitable to produce concrete elements • Comparative study of suitable fabrication techniques • Criteria to assess feasibility of production
5	Which of those fabrication techniques have potential for large-scale fabrication?	Literature study: • Interview • Site visit	• Filter of fabrication techniques suitable for large-scale fabrication • Comparative study of suitable fabrication techniques • Criteria to assess feasibility of production• Selection of fabrication method • Selection of fabrication method
6	What are the existing assembly and disassembly methods used by the building industry that aim for quality preservation and element reuse?	Literature study: • Comparison	• Comparative study of methods • Identification of working principles
7	Which of those methods show the best potential to be applied to concrete elements accounting for structural performance needs?	Research by design: • Computational simulations	• Guidelines for connection design • Guidelines for (dis)assembly process
8	What is the utility of a multi service-life concrete slab compared to traditional concrete slabs?	Literature study: • Interview	• Criteria to assess utility • Comparison to utility of traditional concrete slabs

Table 1: Subquestions with the proposed approach to be answered and a possible product or result.

Before a discussion takes place, it has been necessary to learn about the nature of concrete, understand its behavior and acknowledge the constraints for its production and management. The most significant study within this framework is how the nature of concrete's nature influences the production techniques. A material that turns naturally from a fluid to a solid state has to consider several parameters such as the time required for that transition, workability and buildability of the mixture during that time. The last two parameters are different by definition and they are explained in the literature review. Other knowledge such as the composition of the mixture and its influence extends has been reviewed to a basic level since it is not as relevant for the framework of "Design for Reuse" (hereafter DfR).

Structural requirements and material use of a traditional concrete slab have been researched through literature study in parallel to the review of the concrete's nature. A case-study has eased conclusions in this step. A matrix with the requirements and material use is of relevance due to several reasons: First, it sets the structural boundaries for the engineering of the new reusable concrete slab. Second, it provides the base for the topological optimization of the new building product. Third, it provides with quantitative data to be compared with the new reusable concrete slab.

Principles of the circular economy (CE) have been reviewed through literature study. Special consideration has been put in the principle of DfR as the objective of this research is to enable multi service-lives of the new concrete slab. This inquiry has been important to acknowledge key strategies of DfR, analyze their concept and identify their potential to be applied to concrete elements. Suitable aspects have been identified and applied to the design based on the properties of concrete and fabrication techniques.

Current (dis)assembly methods used in the building industry were reviewed through literature study. This inquiry has been important to learn about their functioning, acknowledge their advantages and challenges and identify their potential of use in concrete structures. Several parameters such as forces acting at the interface of the mechanisms, type of connections, reinforcement and stability of the concrete slab during the connecting process were analysed. Two main objectives were formulated: First, to identify the structural behaviour of the connections. A structural performance study was essential in this phase. This means that special consideration was put on how the forces and deflection of the concrete slab influence the performance and service-life of the demounting mechanism and vice versa. Second, to identify simple connections. The simplicity of connections translates into savings of energy and CO_2 emissions due to a rapid building process. Furthermore, a simple connection means ease of replacement upon damage. The connection must be able to be changed without affecting the whole concrete slab.

The identification of current manufacturing technologies such as concrete casting was carried through

literature study. However, the emphasis was put in the study of novel fabrication methods such as additive manufacture (AM). These techniques are significant because they display the capacity to reduce material waste proper of the production method. This research is necessary to compare the capabilities, acknowledge the potential and future perspectives and identify challenges of AM in concrete. Correspondingly, the properties of concrete in relation to the manufacturing technologies were analysed. This has been relevant to conclude which production methods for concrete elements display more potential to minimise material waste. Additionally, parameters proper of the production process, such as production rate and ease of storage and transportation of the reusable concrete slab are important to demonstrate large-scale fabrication and commercial potential.

Topological optimisation of the reusable concrete slab has been performed once the structural requirements are defined. Digital simulations were carried out to spatially optimize the amount of material needed. This approach is of relevance because it represents the first step towards the reduction in the use of concrete. However, some aspects of the optimisation must be considered. First, the optimisation does not have the most meaningful impact on the overall reduction of material, thus in the reduction of CO_2 emissions. The largest diminutions are achieved with the multiple service-lives of the concrete slab. Second, the optimised geometry must comply with the fabrication process' capabilities. This was an iterative process carried until a good balance between material savings and manufacturing feasibility was achieved. Third, a balance between mass optimisation and thermal performance was reviewed.

To conclude the research, the utility of the reusable concrete slab is studied. The parameters that measure such utility were investigated through literature and with the assessment of experts in circular economy. The results are compared to those of a traditional concrete slab. Hence, conclusions are drawn to assess the relevance of this new approach to reduce concrete consumption, thus energy demands and CO_2 emissions. Economic utility, policies and business models are excluded from this research as they are not the main focus.

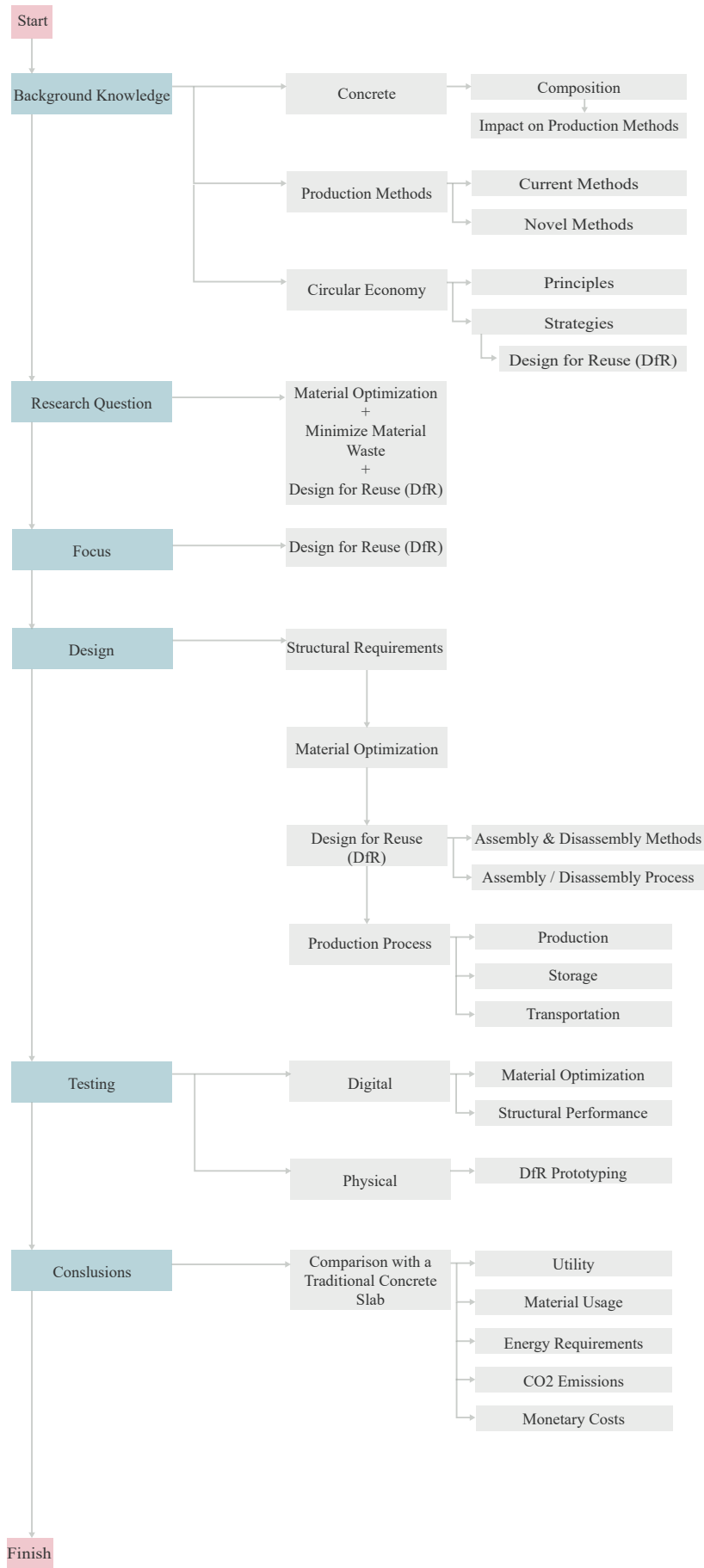*Figure 4* shows the schematic description of the research method.

Figure 4: Schematic description of the research methodology.

Research Structure and Scope

Chapter 1 provides with the introduction to the research. Context information about concrete is given and the problem statement is defined. Consequently, the research objective, limitations and questions are addressed. Furthermore, the research methodology is described.

Chapter 2 addresses general information about concrete. Furthermore, novel production processes are studied and compared. Then, a single production method is selected: 3DCP. Here, the process characteristics are presented and the potential applicability to the production of the reusable 3DCP slab is studied. Furthermore, general information about circular economy is addressed. The focus is on the strategy of DfR. This approach is studied and design parameters are extracted to be applied to the engineering of the reusable 3DCP slab.

Chapter 3 comprises the design of the reusable 3DCP slab. The case study is defined to obtain quantitative data about the material usage. Furthermore, the design process of the slab is described. Geometry approximations for the slab and connections wall-to-slab and slab-to-slab are explored.

Chapter 4 provides with the conclusions of the research and recommendations are made for future investigations.

Chapter 5 presents the reflection about the research. The focus is on the societal and scientific relevance of the topic.

Chapter 2
Concrete, novel production methods and circularity

Concrete

Concrete is a composite material that consists of fine and coarse aggregates bonded together with a fluid cement that hardens over time. A generally known ratio of materials used is one part of cement, two parts of sand, three parts of gravel and water (Witte, 2015). *Image 2* shows the section of a concrete sample that illustrates how the different ingredients of concrete are bonded together.

fine aggregates (sand)

coarse aggregates (gravel)

hardened cement mixture / binding fabric

Image 2: Section of hardened concrete with its visible constituents [5]

The mixture of these materials results in a fluid slurry that is easily poured and moulded into shape. Each material has an important role in the mixture:

The cement is the binder agent that forms the solid mass when it adheres the fine and coarse content (sand and crushed stone, correspondingly). The bonding is achieved when the cement reacts chemically with the water and aggregates to form a durable stone-like material. Forthwith, special consideration must be put in the amount of water used. Too little water causes incomplete bonding and cracking and too much water results in porous concrete. *Image 3* shows the results of these two situations. A generally known water-cement ratio (WCR) is 0,4. This means that one hundred grams of cement need forty grams of water. A higher WCR decreases the reaction time of the mixture and increases the number of capillary pores. Consequently, this decreases the strength of the concrete mixture. The knowledge about hydration levels of the mixture is crucial to determine the production process. In AM layer-extrusion techniques, too much water represents poor buildability of the mixture. This means that the layers deform too much due to a more fluid behaviour of the mixture. Besides difficult quality control, this also represents uncertainty of design tolerances of the reusable concrete slab. On the other hand, too little water causes incomplete bonding of the layers and low workability of the mixture. This means that the period for working with a proper fluid concrete is decreased. *Image 4* presents the results of these two scenarios in AM layer-extrusion processes.

Previous: The smart Slab fabrication process. Retrieved from DBT/ ETH Zürich. 2018. http://dbt.arch.ethz.ch/project/smart-slab/
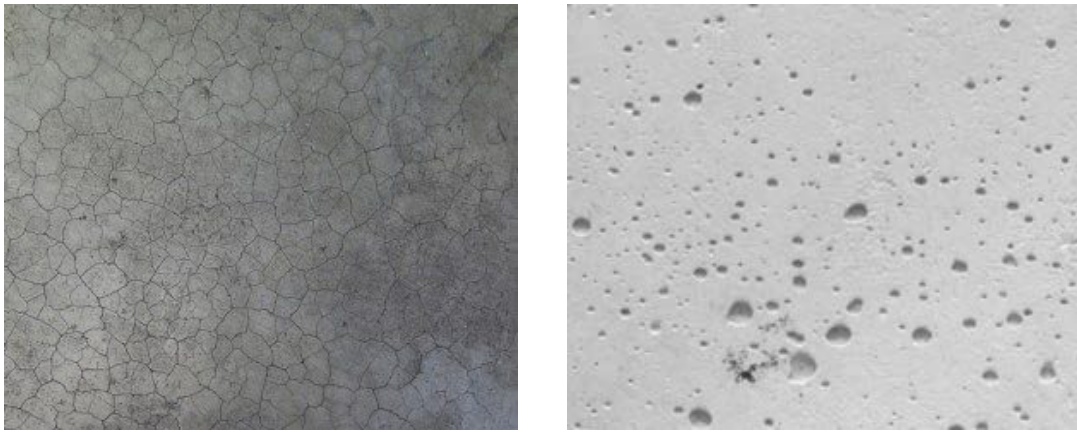5 Extracted from Sing, H. 2017. *Steel fibre reinforced concrete: Behaviour, modeling and design.*

Image 3: Effects of the amount of water in the concrete mixture. Left: cracking of concrete due to insuficient water. Right: Porous concrete due to excess of water [6]

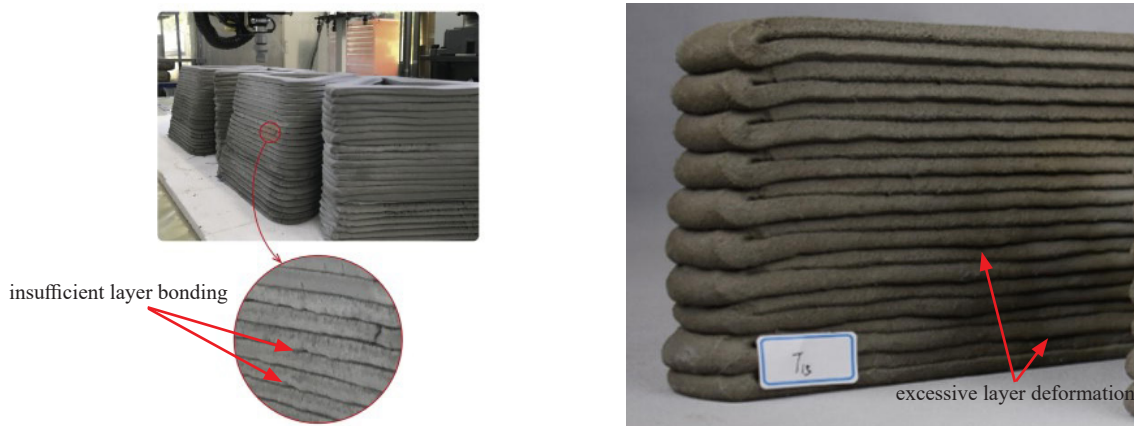

insufficient layer bonding

excessive layer deformation

Image 4: Effects of the amount of water in concrete AM layer-extrusion processes. Left: insufficient layer bonding due to insuficient water. Right: excessive layer deformation caused by the excess of water [7]

The aggregates (sand and gravel) form the body of the concrete mixture. They have different sizes so that the small particles fill the voids between the bigger ones. The comprehension of the effect of the aggregates on the concrete mixture is important to determine the suitability of a production process. In concrete casting this does not represent a challenge. Formwork usually contains the space in which concrete is able to flow almost freely. However, some AM techniques are layer-extrusion based. This means that a filament of concrete comes out of a nozzle. Forthwith, the size of the aggregates must be such to allow a continuous flow without clogging the nozzle. Furthermore, the deposition of aggregates is important to achieve a homogenous strength of the concrete element. As reviewed before, the hardened concrete mainly consists of two components: aggregates and binding fabric. The binding fabric is always uneven due to a non-homogeneous distribution of solids and voids (capillary pores). In a pure cement paste such voids barely influence the mechanical behaviour of concrete. However, this scenario changes completely when aggregates are added to the mixture as it leads to the formation of a thin separation layer between the aggregates and the binding fabric. Such layer is referred to as "interfacial transition zone" (*figure 5*) and is generally weaker than both the aggregates

6 Extracted from Witte, Dennis de. 2015. *Concrete in an AM Process - Freeform Concrete Processing*. Delft, Netherlands: Delft University of Technology.
7 Extracted from Buswell, R.A.; Leal de Silva, W.R.; Jones, S.Z.; Dirrenberger, J. 2018. *3D printing using concrete extrusion: A roadmap for research.* Cement and Concrete Research.

and the binding fabric. This means that this zone has a great influence on the mechanical behaviour of the concrete element and it is the primary source of limiting the strength and Young's modulus of concrete. The comprehension of this principle is important to understand how fractures start in concrete and how they extend until the failure of an element. Cracks usually extend through the binding fabric from one interfacial transition zone to another (*image 5*). This is because the binding fabric is weaker than the stone. Forthwith, it is especially important to maintain a composed mixture where the aggregates are uniformly distributed. Too large areas of binding fabric means that cracks will propagate fast. On the other hand, too packed aggregates lead to easy spread of cracks between interfacial transition zones and to the early mechanical failure of the element. Therefore, a balance between the deposition of aggregates and binding fabric is important. *Figure 6* presents examples of a composed and a decomposed mixture. The result is a homogeneous strength of the concrete element. Translating this information to the research, this represents a challenge for AM layer-extrusion techniques as the deposition of cement paste and aggregates depends on multiple parameters such as the size of the nozzle, size of the hose, capacity of the pump, speed of printing and the thickness of the layers.
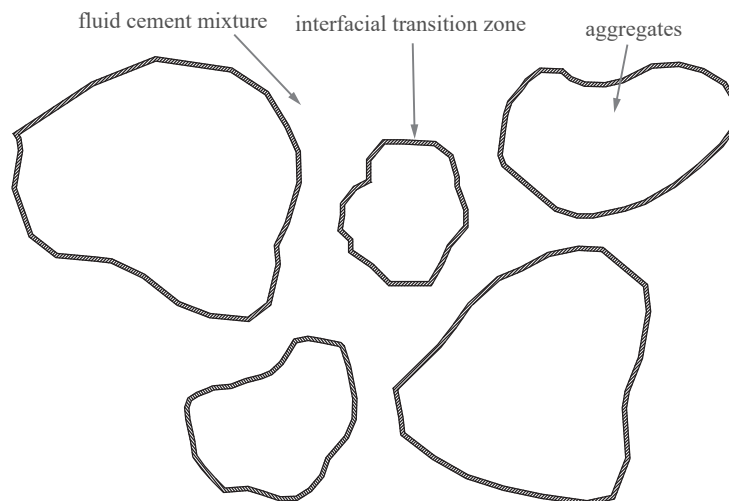

Figure 5: Bonding surface between aggregates and fluid cement mixture.

Image 5: Crack forming from interfacial transition zones [8]

8 Extracted from Sing, H. 2017. *Steel fibre reinforced concrete: Behaviour, modeling and design.*
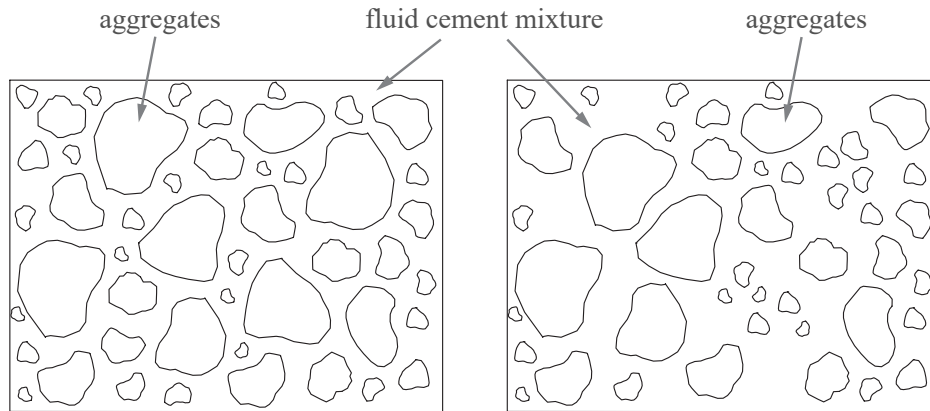
Figure 6: Left: Composed mixture with evenly distributed aggregates. Right: Decomposed mixture with uneven distribution of aggregates.

Concrete is strong in compression but relatively weak in tension. Therefore, steel is generally used as *reinforcement* to provide tensile strength to an element (*image 6*). The comprehension of the effect of reinforcement on the tensile strength is also important to determine the production technique. For most of the AM methods, reinforcement placement is challenging. Its integration in current AM processes represents a big script-mechatronic challenge. On the other hand, doing it in a second production step represents more labour and consumption of energy. Furthermore, conventional steel reinforcement (rebars) shortens the technical-life of concrete elements. This is because eventually, steel rusts and cracks the concrete. Therefore, the element is no longer suitable for structural functions. For this reason, the understanding and exploration of new ways and materials to reinforce concrete elements are essential to extend the technical life of the slab.

Image 6: Steel reinforcement inside a concrete element [9]

9 Extracted from Photos public domain. 2019. *Crumbling concrete with rebar*. http://www.photos-public-domain.com/2011/01/26/crumbling-concrete-with-rusted-rebar/

A basic comprehension of the parameters that affect the quality of the concrete mixture is necessary to understand their impact on parameters proper of the production techniques. The latest parameters are defined by (Chen et al., 2018) as follows:

- *Rheology:* It is the degree of viscosity of the concrete mixture. This parameter is principally affected by the amount of water in the mixture. The rheology determines how the composite flows and how it can be poured. This parameter is relevant if the concrete element will be pumped out from a system or produced using moulds.
- *Extrudability:* Describes the property of the composite that could be quickly and reliably delivered out from the transmission system. Extrudability is crucial when seeking a continuous and uniform extruded mixture. This parameter is affected by the amount and distribution of the aggregates and by the amount of water in the mixture.
- *Workability:* It is the property of concrete that determines the ease and homogeneity with which it can be mixed, placed, compacted and finished. The workability can be determined by conducting a rheological test. This parameter is influenced by the type of cement used and the amount of water in the mixture.
- *Buildability:* It is considered as the ability of fresh concrete to resist deformation under a certain load at a certain open time. Layer settlement and cylinder stability tests are used for determining the buildability of fresh concrete. The buildability of layers is mainly affected by the amount of time passed after mixing (t=0).
- *Open time:* Period for working with fluid concrete with proper workability. Open time is evaluated by the decrease of workability of concrete. This parameter depends on the hydration rate of the mixture.

Conclusions

Due to the importance of concrete for the building industry, the knowledge about its composition, chemical reactions and building characteristics have been well explored. Nevertheless, the processing techniques have hardly evolved if compared to the quality of the mixtures. Next phases of this research focus on the production methods for concrete elements. The aim is to investigate the challenges of current techniques as a possible reason for their stagnation. However, the emphasis is put in the study of novel fabrication methods. The objective is to identify potentials for the fabrication of the reusable concrete slab while minimizing material waste proper of its production. Furthermore, production methods that show potential for novel reinforcement placement are investigated. The former focus allows for the extension of the technical-life of the reusable slab as it avoids the use of conventional steel rebars reinforcement, which is prone to corrosion.

Novel Production Methods

Currently, subtractive manufacturing such as CNC milling has been used to carve moulds on which steel reinforcement is placed and the concrete is poured. *Image 7* shows a wood mould being carved with this fabrication method. This is the most generic strategy to make load-bearing structural components. This fabrication method can be very accurate and create complex forms. However, its main disadvantages rely on the long production time, a considerable amount of post-processing labour (steel reinforcement still needs to be manually placed before casting the concrete) and the excessive material waste product of the milling of the block.

Image 7: Wood mould being carved with a CNC milling machine [10]

Moulds represent roughly 55% of the overall cost of concrete structures (Jipa et al., 2017) and they result in a significant source of waste as they are disposed of sooner or later. Likewise, moulds represent the limiting factor in freedom of shape that architects and engineers face nowadays. Therefore, the absence of moulds in the production process represents an important step towards the reduction of CO_2 emissions in concrete manufacturing. Likewise, if processing concrete without using moulds becomes possible, more 3D designed structures can actually be built the way they were designed.

But what fabrication techniques provide with the flexibility of production without the need for moulds or a reinterpretation of them to reduce material waste? As a future construction trend, AM seems to be one solution to address the challenges of current concrete elements production. According to ASTM (2013), AM is defined as *"a process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing technologies"*. The nature of this production process is material based selective deposition. Thus, optimization of the material usage is possible. This process has been commercially used in other industries such as aerospace and medicine. Therefore, it is worthy to explore the combination of a well-known construction material

10 Extracted from MakerBay. n.d. MakerBay. Accessed 2018. https://www.makerbay.org.

with a novel fabrication technique that has already been applied by other industries.

Numerous attempts of fabrication have been already made with additive manufacture. However, due to the nature of concrete, only some additive manufacture techniques have evolved. Those techniques are generally divided into 3 printing methods: powder-based printing, extrusion-based printing and casting-based printing. The techniques proper of each printing method are explained as follows:

- *D-Shape:* It is a powder-based printing technique. D-shape uses a binder that hardens powder on a powder bed. It constructs an element layer by layer using this approach. This process allows for a high degree of geometric freedom. It is possible to fabricate cantilevered and hollow parts because any unbound raw material that is not used to form the shape may be used as support for the overhanging features. The waste of this technique is minimum as the unbound powder can be reused. However, D-shape presents also some challenges. First, it is a slow process. The small height of the powder layers affects negatively the production time. Second, the final product has a rough surface. The binding deposition process is not very accurate and it determines the level of detail of the concrete element. Third, extra labour is required after the printing of the element. The element needs to be cleaned and powder needs to be removed from the powder bed. Fourth, the introduction of reinforcement remains problematic. This is generally made after the build-up in a complementary process. *Image 8* shows an element being 3D printed using this technique and the end result.

Image 8: Left: Element being 3D printed using the D-Shape technique. Right: Result [11]

- *Contour crafting / 3D Printing:* Layered extrusion is the typical process of extrusion-based printing. This technique in which a digitally controlled nozzle precisely extrudes concrete layer by layer, has been researched extensively by several research institutions and companies over the last decade. Contour crafting presents several advantages. First, a relatively high speed of production. The nozzle follows a 2D pre-set path, which is easy and fast to be programmed. Second, a high-quality surface can be achieved. The trowels located at the sides of the nozzle smoothen the surface. However,

11 Extracted from Promedia Corp. n.d. Promedia Corp. Accessed 2018. https://promediacorp.com.

contour crafting also presents some challenges. First, there is a finite "working time" between layers. A good timing must be calculated so that the deposited layer is dry enough to withstand the layer to be deposited upon, but not too dry as to allow for a strong bonding with the subsequent layer. Second, this process is limited to vertical extrusion as overhangs and voids need support material for stability in the design. Furthermore, the placement of reinforcement remains an open question. Currently, reinforcement is applied after the extrusion in a complementary process. Consequently, the relation between the concrete element and the reinforcement must be rethought to comply with structural codes. *Image 9* shows an element being constructed using this technique.
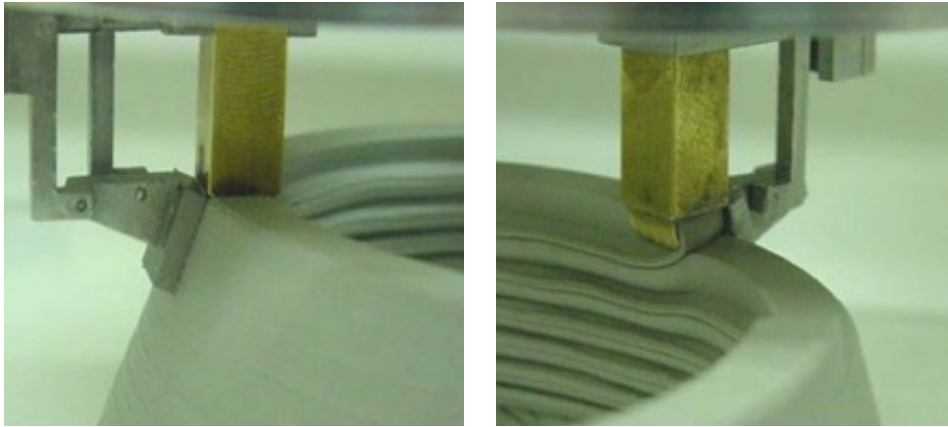

Image 9: Left: Element being 3D printed using the Contour Crafting technique [12]

- *Slipforming:* This can be considered as an evolved extrusion process. It is a single step process in which the concrete is continuously placed into a delimited formwork that moves vertically at a velocity set according to the hydration rate of the concrete. This ensures that the material is self-supporting when released from the formwork. Therefore, the control of the hydration is essential in this technique. The main difference to a typical layered-extrusion process is the use of formwork. This provides with more freedom of shape as the formwork supports the fresh concrete. The continuous nature of this process eliminates layering and cold joints formation. In addition, the formwork can be reused. However, precisely because of the formwork several challenges arise. First, the formwork type will constrain the geometric possibilities of the final element. In that way, the formwork design is essential to the overall process. Second, the slipping process can create friction between the material and the formwork, leading to residual stresses and weakening of the final element. Furthermore, the placement of reinforcement remains an open question. It can be integrated into the robotic process but this represents a big script-mechatronic challenge. Finally, an upscale of the production represents also a challenge. Material properties and process parameters are deeply interlinked. Therefore, an upscale might require substantial changes to both parameters. *Image 10* shows an element being 3D printed with this technique.

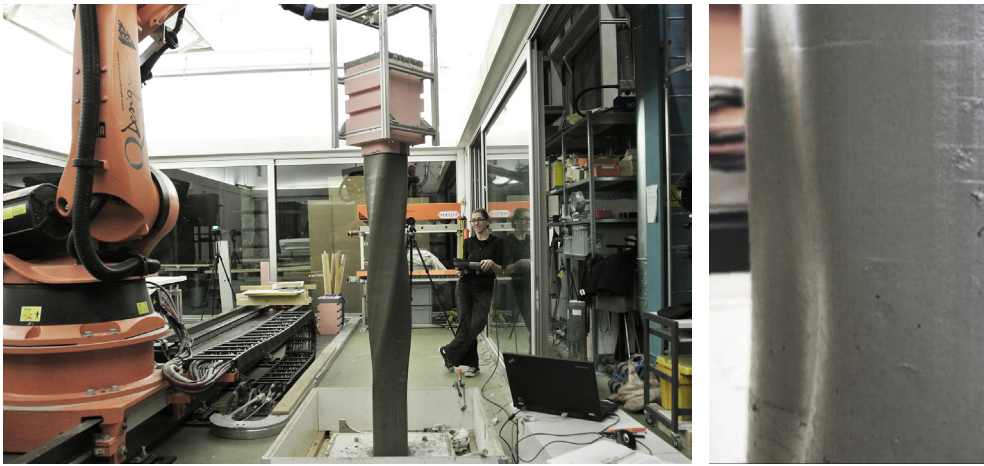12 Extracted from Fabbaloo. n.d. Fabbaloo. Accessed 2018. https://www.fabbaloo.com.

Image 10:Element being 3D printed using the Slipforming technique [13]

- *Flexi-mould:* The Flexi-mould consists of a membrane that is supported and adjusted by CNC controlled actuators. The membrane is flexible enough to form smooth double curved shapes and stiff enough to avoid sagging between the actuators under the load of the concrete. The main advantage of this technique is that the Flexi-mould can be reused. However, achieving high degrees of curvatures is challenging. The main reason is that making a smooth double-curved surface from a planar surface is not realistic. Furthermore, to obtain optimal results a precise timing and control of the viscosity of the concrete is required. This represents a major challenge since it is difficult to precisely quantify the time to shape because the hydration of concrete is sensitive to the smallest environmental changes. *Image 11* shows an element being 3D printed with this technique.

Image 11:Element being 3D printed using the Fleximould technique [14]

- *Mesh mould:* This is a pouring-based technique. The key feature is the unification of the reinforcement and the formwork. A steel mesh is fabricated to function first as the formwork and once the concrete is poured, to function as the reinforcement. Finally, a cover layer is applied and finished. By pouring the concrete in one process the layering issues inherent to other fabrication techniques are reduced. Additionally, activating the mesh as reinforcement renders it as a functional stay-in-

13 Extracted from DBT/ETH Zürich. 2018. Smart Dynamic Casting: Slipforming with Flexible Formwork - Inline Measurement and Control.
14 Extracted from Constanzi, C.; Ahmed, Z.; Schipper, H.R.; Bos, F.; Knaack, U.; Wolfs, R. 2018. *3D Printing Concrete on Temporary Surfaces: The Design and Fabrication of a Concrete Shell Structure.*

place formwork. However, a few challenges have appeared with this technique. First, the opening of the mesh must be carefully thought as big holes might allow the concrete to flow out. Second, extra labour is needed to render a smooth surface of the final element. *Image 12* shows an element being constructed with this technique.

Image 12: Element being constructed using the Mesh mould technique [15]

• *Stay-in-place formwork:* It can be identified as a pouring-based technique. Stay-in-place formwork is the unification of two methods. First, a sand mould is 3D printed using the D-shape technique to later pour the mixture of concrete upon it. During the curing process, the sand mould binds with the concrete mixture, resulting in one structural performing element. This approach explores the synergy between the geometric flexibility of 3D printing sand and the structural capacity of concrete. It allows the production of a composite component with properties superior to either individual material. The advantages of this technique are the practically inexisting material waste and the complexity of forms. By printing the moulds with the D-Shape technique, undercuts, overhangs and voids can be achieved. However, this technique is newly explored and more study is needed about how the concrete and sand interface. *Image 13* shows an element being constructed using this technique and the end result.

A summary of the studied AM concrete technologies is presented in *table 2*.

Image 13: Left: Element being constructed using the Stay-in-Place formwork technique. Right: Result [16]

15 Extracted from Gramazio Kohler Research/ ETH. 2018. *Mesh Mould: Robotically Fabricated Metal Meshes as Concrete Formwork and Reinforcement.*
16 Extracted from DBT/ ETH. 2017. *The Smart Takes From the Strong.*

Type of Process	Casting / Subtractive Manufacture	Powder-bed	Extrusion			Casting		
Example	CNC moulds	D-Shape	Contour Crafting	3D Printing	Fleximould	Slipforming	Mesh mould	Stay-in-place
Processing								
Accuracy	High: CNC milling is accurate to the order of mm	High: The product can be very accurate due to a small layer thickness of the building technique	Medium: It largely depends on the nozzle diameter and rheology of the mixture	Medium: It largely depends on the nozzle diameter and rheology of the mixture	Medium: It largely depends on the nozzle diameter and rheology of the mixture	High: The mould can be accurate below the order of mm	Medium: The size of the steel mesh determines the accuracy of the element as concrete will or will not flow out of it	High: The small layer thickness of the formwork allows an accuracy under the order of mm
Use of material	Waste	Optimum: The unbonded material can be reused	Optimum: no waste material as the extrusion is selectively deposited	Optimum: no waste material as the extrusion is selectively deposited	Optimum: no waste material as the extrusion is selectively deposited	Optimum: no waste material as the mould can be reused	Optimum: No waste material as the mould stays in place as reinforcement	Optimum: no waste material as the formwork stays in place
Use of moulds	Yes	No	No	No	Yes but it can be reused	Yes but it can be reused	Yes but stays in place	Yes but stays in place
Reinforcement	Required in a first step	Unknown or applied externally	Internal: steel fibres or cable External: Post-tension tendons	Internal: steel fibres or cable External: Post-tension tendons	Internal: steel fibres or cable External: Post-tension tendons	Usually steel rebars are placed robotically along with the concrete extrusion	The mesh mould acts as reinforcement upon concrete casting	Not yet studied in depth
Layer thickness	-	4-6 mm	13 mm	6-25 mm	Unknown	-	-	-
Time of processing	Medium: excessive pre and post processing	High: The small layer thickness impacts negatively the building rate	Low-Medium: It depends on the type of reinforcement. No need of material removal after printing	Low-Medium: It depends on the type of reinforcement. No need of material removal after printing	Low-Medium: It depends on the type of reinforcement. The set of the fleximould also increases the processing time. No need of material removal after printing	Low-Medium: It depends on the complexity of the element and internal reinforcement	High: Depending on the geometrical complexity of the element, a robot has to first weld and prepare the steel mesh. Post processing is required to smoothen the surface.	High: The small layer thickness impacts negatively the building rate
Pre/post processing	High: moulds need to be made, reinforcement placed and demoulding is necessary upon mixture hardening	Medium: The unbonded material has to be removed from the built element	It depends on the type of reinforcement. No need of material removal after processing	It depends on the type of reinforcement. No need of material removal after processing	It depends on the type of reinforcement. The setting of the mould need to be done before start printing. No need of material removal after processing	None	High: Depending on the geometrical complexity of the element, a robot has to first weld and prepare the steel mesh. Post processing is required to smoothen the surface.	Medium: The unbonded material has to be removed from the built element
Surface quality	Smooth: A high quality surface can be achieved due to the accuracy of the moulds	Layered	Semi-layered: The trowels smooth the printed layers	Layered	Layered	Smooth	Depends on the post processing	Smooth: the small layer thickness allows to have an almost unperceptible layering
Mechanical Properties								
Compressive Strength	20-50 Mpa	235-242 Mpa	18,6 Mpa	72-110 Mpa	Unknown	Unknown	Unknown	Unknown
Flexural Strength	2-5 Mpa	14-19 Mpa	Unknown	12-13 Mpa	Unknown	Unknown	Unknown	Unknown
Conclusions								
Advantages	• High accuracy • Complex geometries can be achieved	• High degree of geometric freedom • The unbond material can be reused	• High speed of production • Relatively high quality of surface • No waste material • No post-processing is required	• High speed of production • No waste material • No post-processing is required	• High speed of production • No waste material	• More geometrical freedom than layer-extrusion techniques • No cold joints are formed • The formwork can be reused • High quality of surface	• No waste material as the formwork stays in place • No cold joints are formed • High geometrical freedom	• No waste material is produced as the formwork stays in place • No cold joints are formed • High geometrical freedom
Limitations & Challenges	• Waste material • Excessive pre and post processing time	• Slow process • Rough surface • Post-processing is required to remove the unbond material	• Cold joints can be formed between layers • Limited to vertical extrusion • Placement of reinforcement is being studied	• Cold joints can be formed between layers • Limited to vertical extrusion • Placement of reinforcement is being studied	• Cold joints can be formed between layers • Limited to vertical extrusion • Placement of reinforcement is being studied • Pre-processing is necessary to set the mould	• The formwork constrains the geometry of the element to be printed • The slipping process can create friction and generate residual stresses in the element • The placement of reinforcement is a big mechatronic challenge	• The opening of the mesh needs to be carefully studied • Post-processing is required to smoothen the surface	• Slow process • Post-processing is required to remove the unbonded material • Placement of reinforcement is being studied

Table 2: Overview and comparison of the studied AM techniques [17]

17 Extracted from de Witte, D. 2015. *Concrete in an AM process*. Delft University of Technology. and Wangler, T. et al., 2016. *Digital Concrete: Oportunities and challenges.*

Conclusions

Additive manufacturing is a suitable technique for tackling the environmental issue that comes with the waste of material produced by formwork. Its full advantage is when products can be directly produced from the digital model with the minimum or none use of support material. Additionally, topology optimization and finite element analysis can be utilized to generate optimized designs for additive manufactured elements. An optimized element should consume less concrete without strength loss compared to a regularly-shaped element. Combined with topology-optimized structural design methods, additive manufacture becomes a more functional and sustainable fabrication method in practice. However, the printing capability of current additive manufacture techniques for optimized concrete structures is limited. Furthermore, the building industry should be careful since additive manufacture does not represent the general solution for other production challenges. Other methods have been in the market for decades and have been optimized accordingly. It cannot be expected to produce standard concrete elements, such as walls, with these techniques just because of the use of new technology. Furthermore, based on its current production speed, additive manufacture is no competitor for other techniques. This method should be explored for material optimized structures, to fabricate elements that are difficult with other fabrication methods or to complement other fabrication methods.

One of the goals of this research is to propose a production process for the concrete slab. Consequently, challenges proper of the production methods must be tackled. The major challenge of current additive manufacture is finding suitable reinforcement methods. Therefore, a proper strategy for the integration of this feature must be considered. In this sense, the integration of the formwork as an already performing feature within the concrete element is an attractive approach. This means the unification of formwork and reinforcement into one single construction system. Can a product work first as formwork for concrete casting and furthermore perform mechanically in the final configuration? This is an interesting approach. However, as demonstrated by previous experiments such as D-Shape report (Jakupovic, 2016) and the Smart Slab (ETH Zürich: Digital Building Technologies, 2018), this type of technologies are mainly powder-bed deposition based. They are time-consuming and the implementation of reinforcement is labour-intensive and done in a secondary step, which increases the time required for the fabrication of an element. If the reusable slab is to be produced in mass, ease of fabrication and the time needed for its production are important parameters. For this reason, powder-based technologies are not further implemented in this research.

On the other hand, casting technologies require the fabrication of formwork in the first step. This generates waste material as the formwork is discarded sooner or later. Some techniques, such as slipforming (ETH Zürich: Digital Building Technologies, 2019) propose the utilization of reusable formwork. This would indeed reduce the total cost of the reusable slab. However, this technology

also presents some challenges when applied to this research. First, the formwork to be utilised would have to be at least of equal size to the section of the reusable slab. This means that also the equipment to be used, such as motors to move the formwork along and the actuators to modify the geometry of the formwork, would have to be equally big and powerful. Second, the principle of slipforming is the vertical movement of the formwork. If the movement is horizontal, the geometry to be fabricated is constrained by gravity. If this principle is applied to the fabrication of the reusable slab, it means that the slab would have to be fabricated either on one of its lateral or one of its end sides. Therefore, a system of either 3 meters or 9 meters of height would be needed depending on the base side and printing direction of the reusable slab. Correspondingly, a production warehouse with at least the same height would be necessary. *Figure 7* illustrates such a scheme. The third challenge is that this technology only allows for solid cross-sections of the fabricated elements. Voids and ducts within the geometry of the slab would be difficult to fabricate and this would impact on the material use and weight of the slab. The last criterion is especially important for ease of transportation and on-site assembly of the reusable slab. Based on all the former challenges, casting technologies are not further implemented in this research.
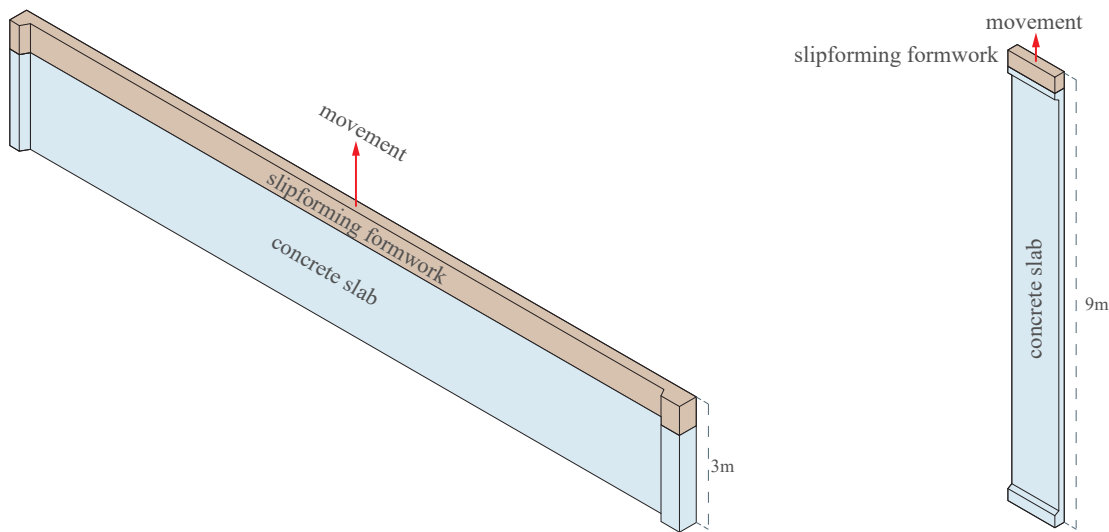

Figure 7: Left: Concrete slab being printed with horizontal slipforming. Right: Concrete slab being printed with vertical slipforming.

Extrusion-based 3D printing methods are the most suitable techniques for this research. Their speed and production rate are relatively high compared to powder-bed based methods and they do not require formwork to produce concrete elements. The basic principle of layer extrusion methods, their advantages and their challenges are further described in the following chapter.

3D Printing Concrete

Digital fabrication is defined as the application of digital technologies to the production of material objects. This disruptive technology includes the so-called 3D printing, which is a sub-technology of AM. 3D printing consists of a digitally controlled nozzle that precisely extrudes material layer by layer (*figure 8*) to fabricate complex structures out of a 3D CAD model. The nozzle follows a 2D pre-set path which is easy and fast to be programmed. This results in a straight-forward and high speed of production. In general, 3D printing has been successful with polymers extruded in a semi-liquid state and hardened naturally upon placement. Consequently, a material usage transition from polymers to concrete seems natural as both materials experience a similar phase transition.
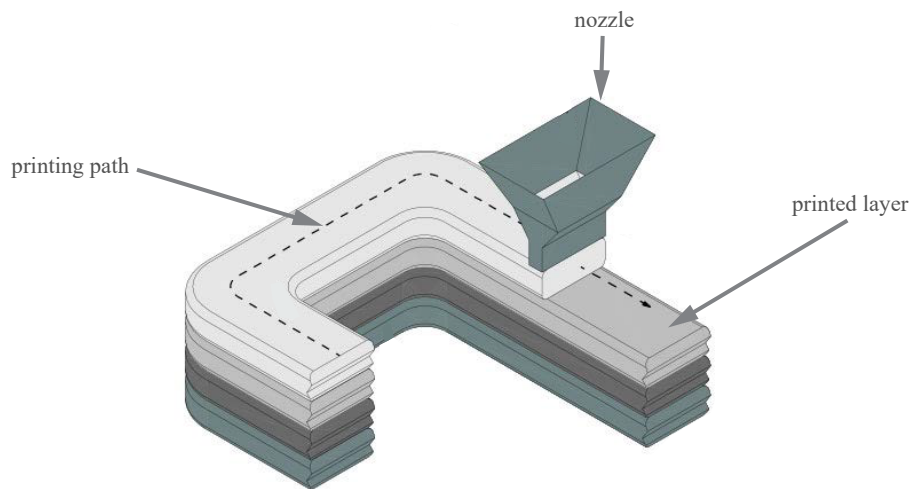
Figure 8: Principle of 3D printing - layer extrusion [18]

However, the nature of concrete makes its 3D printing essentially different from the 3D printing of polymers. The hydration rate of concrete takes a much longer time than the curing of polymers. This means that the extruded concrete layers take more time to develop a proper stiffness to withstand their own weight and the weight of subsequent printed layers. Therefore, special attention needs to be put on the viscosity of the extruded mixture and on the time that occurs between layer deposition. Following chapters explain this concept in more depth. Yield strength, rate of build-up, the formation of cold joints and operation window are the concepts addressed.

Besides the characteristics of the fresh mixture, the properties of the hardened 3D printed concrete (3DCP) are necessary to be studied. Such properties are highly affected by multiple factors such as:

- *Printing path:* Concrete is an anisotropic material. This means that the material properties change with the direction along the object. In 3DCP this behaviour is even more pronounced. The printing path largely determines the mechanical behaviour of the material and of the structural performance of the built element. Therefore, it is highly important to program a printing path in accordance with the

18 Rebuilt from Wangler, T. et al., 2016. *Digital concrete: opportunities and challenges.*

direction and flow of mechanical stresses acting in the built element.

- *Printing speed:* This parameter is directly related to the extrudability of the material. A high speed might break the continuous deposition of the concrete layer if the amount of material coming out of the nozzle is not enough. A high printing speed also influences the interfacial bonding between layers. Local stresses might form at such interface due to excessive friction of the material caused by a high printing speed. On the other hand, a low speed might cause the material to bulge if the printing speed is not in balance with the amount of material coming out of the nozzle. The printing speed determines also the relationship to allow a proper yield strength for building-up and to avoid the formation of cold joints. For these reasons, it is critical to study the close relation between extrudability and printing speed and the effect that these parameters have in the hardened 3DCP.

- *Layer height:* This parameter is partially responsible for the interfacial bonding of layers. A layer with more height means also more weight being applied on lower layers due to gravity. This consequently increases the interfacial stresses and improves the bonding between layers. However, the layer's height needs to be studied as more height might lead to decomposition of the geometry depending on the yield strength developed by the printed mixture. A higher layer also affects the production time and printing speed. Furthermore, the height of the layer also determines the resolution of a printed element. The last parameter is especially important from an architectural perspective.

3DCP presents several advantages: first, the relatively fast speed of production as the 2D nozzle path is straight-forward and easy to be programmed. This production feature is a key parameter within this research as a fast production time means a cheaper production of the reusable slab. This also has a direct impact on the final price of the building product, which increases its commercial attraction. The second advantage of 3DCP is the elimination of the use of formwork, which is an expensive and labour-intensive feature. By avoiding this element, some investigations report a reduction of production times by 50-70 percent and reduction of labour costs by 50-80 percent (Tan, Panda, & Wei Tay, 2016). A formwork-less freeform construction also enhances the production cost as the fabrication of a component is independent of the shape and customisation does not come with exponential costs. This feature is especially important within the architectural field, where form expression can be achieved at low prices.

3DCP presents also several challenges that are necessary to be understood:
- *Yield stress build-up:* This parameter determines the stiffness of the mixture to withstand the own weight of a 3D printed layer and the load of subsequent 3D printed upper layers. The viscosity of the mixture is the main characteristic that determines its structural build-up. A fluid mixture, besides slumping, takes more time to build the sufficient yield stress to withstand subsequent 3D printed

layers. On the other hand, a dry mixture decomposes upon deposition (poor extrudability) and leads to the formation of cold joints as an efficient chemical bonding is not achieved. The comprehension of this behaviour is important to calculate the time necessary to 3D print the reusable slab. A fast printing might result in an improper build-up of the mixture, leading to collapse of the 3D printed layers. On the other hand, a low printing speed might lead to the formation of cold joints between layers. Therefore, a balance between the yield stress of the mixture and the time (speed) of printing should be achieved.

- *Cold joints:* The layered structure of the process allows the formation of cold joints. These generally form when a critical resting time of a layer is exceeded. Therefore, an effective bonding with the subsequent layer is not achieved as the mixture is already to dry. Besides the detriment of the structural capacity of the 3D printed structure, the knowledge about cold joints formation is necessary to evaluate their long-term impact. This is especially important for this research as the extension of the technical-life of the concrete slab is the main objective. Furthermore, a cold joint forms in the weakest point of 3DCP structures: the interlayer bond.

- *Interlayer bond:* The weakest point of 3DCP structures is the interlayer bond. According to (Marchment & Sanjayan, 2019), there are two assumptions as to why such bond is the weakest point of 3DCP structures: First, the interlayer contains voids due to the stiffness of the freshly extruded layers. This means that the material is not malleable enough to penetrate and anchor into surface pores. The second assumption is that the chemical hydration across layers is hindered and compromised. Several approaches have been taken to solve this challenge. Shorter printing periods between printing layers might mean stronger bonds as the mixture would have a more alike hydration rate. However, as previously studied, the printing time has to be balanced with the yield stress of the mixture. The use of reinforcement to form a stronger connection between layers is another option. However, this approach has to be further studied as it might represent a big mechatronic challenge. The understanding of the interlayer bond in 3DCP structures is of importance to evaluate the structural capacity of the structure before delamination.

- *Use of reinforcement:* As previously studied, concrete has a low tensile strength. Therefore, a reinforcement material has to be applied to compensate for such weakness. Steel rebar is used in traditional concrete manufacturing techniques. However, this approach brings two main issues within this research. First, steel rebar corrodes and cracks concrete internally. This means that concrete elements can hardly be reused. Second, the implementation of such reinforcement in 3DCP is a challenge as it constrains the geometry freedom and also represents a mechatronic challenge in order to be incorporated in digital fabrication. Therefore, innovative methods have to be studied. In this sense, fibre reinforced concrete (FRC) emerges as a potential solution as the steel fibres can significantly

improve the structural performance of 3D printed concrete elements. This feature is easy to incorporate in a robotic fabrication process due to the short length of the fibres, which eases their placement and delivery from a transmission system. Furthermore, the use of steel fibres prevents corrosion within the 3DCP element. Even if the fibres corrode, the rusted layer thickness is in accordance with the fibre diameter. This means that the corrosion layer thickness is minimal. Furthermore, the corrosion ends in the fibre edge, which means that the corrosion will not be transferred through fibres. In other words, even if corrosion exists, this is of minimum thickness and confined to the limits of the fibre. Therefore, the affectation to the concrete element is null. This is especially important for the extension of the technical-life of reinforced 3DCP elements as corrosion would be avoided. Therefore, the reuse of the slab would be feasible.

3DCP Process Properties

Yield Stress

Yield stress is the parameter that determines the stiffness of the mixture to withstand both the own weight of a 3D printed layer and the load of subsequent layers. According to Weng et al. (2018) the layer height and the pumping pressure are the factors that determine the yield stress and the plastic viscosity of the concrete mixture. Upon deposition, an increasing resting time decreases the moisture content of the 3DCP mixture. This process is referred to as hydration and is the responsible to build the yield stress of the mixture. *Image 14* displays a mixture with low yield stress versus a mixture with the proper yield stress to form a stable structure.
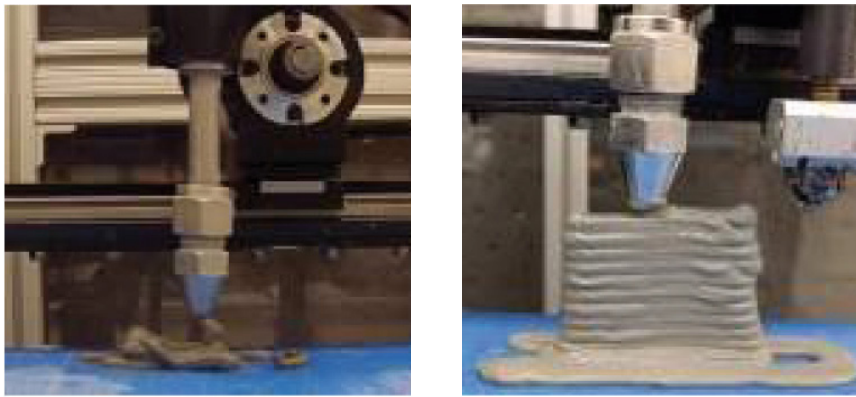
Image 14: Left: 3DCP mixture with insufficient yield stress. Right: 3DCP mixture with proper yield stress. Both scenarios are affected by the factor of time [19]

Right after extrusion, the initial yield stress of the layer ($t_{0,0}$) must be such that it can support its own weight without slumping. This means that the initial yield stress is directly related to the density of the mixture (ρ), the gravity constant (g) and the height of the layer (h). According to (Wangler et al., 2016), the equation to determine the initial yield strength of 3DCP layers is (*equation 1*). In such equation, the printing of the layer is assumed to be done immediately after the mixing of the material (t=0):

$$t_{0,0} = \rho g h / \sqrt{3} \qquad\qquad (eq.\ 1)$$

In 3DCP the rate at which yield stress increases is an important parameter to determine the velocity of printing and the minimum time needed to reach the final layer. Such increase of yield stress (A_{thix}) is described by (Wangler et al., 2016) in (*equation 2*):

$$A_{thix} = \rho g H_m / \sqrt{3} t_{Hm,min} = \rho g h / \sqrt{3} t_{h,min} \qquad\qquad (eq.\ 2)$$

19 Extracted from Jones, S; Bentz, D.; Martys, N.; George, W.; Thomas, A. 2019. *Rheological control of 3D printable cement paste and mortars.*

Where $t_{H,min}$ is the minimum time needed to reach the final layer, producing an element of height H_m and $t_{h,min}$ as the minimum time needed to produce a layer. According to Timothy Wrangler (2016) an upper bound for A_{thix} roughly equals to 2 Pa/s. Therefore, *equation 2* can be rewritten to determine the time required to 3D print an object of a determined height (*equation 3*).

$$t_{h,min} = \rho g h \, / \, (\sqrt{3} \, A_{thix}) \qquad\qquad (eq.\ 3)$$

Applying *equation 3*, the shortest time to 3D print an object of 1 meter height, for instance, cannot be less than 1h40 minutes. This information can be later used to determine the maximum horizontal printing velocity (V). The relation between maximum printing velocity and yield stress of the mixture is described in *equation 4*.

$$V < \sqrt{3} \, L A_{thix} \, / \, (\rho g h) \qquad\qquad (eq.\ 4)$$

Here, L represents the layer length. Therefore, if the same element of 1 meter height, 1 meter long and 1 centimeter layer thickness is to be produced, the maximum printing velocity (V) is of 1,6 cm/s.

The analytical understanding of the yield stress build-up of the 3DCP mixture is further applied in this research to determine the minimum time required to 3D print the reusable slab. Such information is later compared with the average time required to produce a slab by means of conventional methods. Consequently, the relevance of the new design, in terms of production time and cost can be assessed.

Cold joints

Cold joints are formed in the interface between successively printed layers of concrete. This behaviour typically occurs when the critical resting time of a layer is exceeded. Therefore, its level of moisture is too low to form a proper bonding with the subsequent printed layer. *Image 15* shows the effect of a cold joint in 3DCP elements.

Image 15: Formation of a cold joint [20]

20 Extracted from Ahn, J.; Park, J & Jun, H. N.D. *A critical review of the extrusion-based 3D construction printing: technology in the construction industry.*

To avoid this, Timothy Wangler (2016) described the maximum time for a single layer to be produced in *equation 5*.

$$t_{h,max} = \sqrt{((\rho gh)^2 / 12) + (2\mu_p V / h)^2} \, / A_{thix} \qquad (eq.\ 5)$$

In this equation μ_p is the plastic viscosity of the mixture. Several reports average a μ_p of 37 Pa.s. *Equation 5* provides the upper bound of the critical resting time. If such equation is rewritten in terms of printing velocity (V) for a single layer, the minimum linear velocity can be determined. *Equation 6* describes such minimum velocity.

$$V > (\rho gh^2) / 4\,\mu_p \qquad (eq.\ 6)$$

Cold joints undermine the structural capacity of 3DCP elements. Besides such detriment, the knowledge about their formation and how to avoid them is important to evaluate their long term impact. This analysis is important as the main objective of this research is to preserve the technical-life of the reusable slab. If cAold joints are formed in the structure, the slab cannot be reused as its structural capacity will be lowered. To avoid this, the former formulas are applied to the design of the reusable slab. In combination with the minimum yield stress to be reached, the formulas provide with the operation window for the 3D printing the slab.

Operation window

The operation window is the time range for 3D print a single layer. In the lower bound, this parameter allows the mixture to achieve a proper yield stress to withstand loads of subsequent printed layers. In the upper bound, the operation window avoids the formation of cold-joints between the printed layers. *Equations 3* and *5* define the operation window in terms of time to 3D print a single layer. On the other hand, *equations 4 and 6* do the same in terms of the horizontal printing velocity. The last two equations are especially of interest as they can define the minimum length of the 3D printed layer. *Equation 7* provides with this approximation.

$$L > (\sqrt{2/3} \, / \, 8) \, ((\rho g)^2 \, h^3) \, / A_{thix} \, \mu_p \qquad (eq.\ 7)$$

Besides the knowledge of the minimum layer length to be applied on the design of the reusable slab, such length provides the base to determine the linear printing velocity. With this, the estimation of the time necessary to produce a reusable slab can be done. Such time and production rate are of interest to compare with the production time of a conventional concrete slab. Consequently, the relevance of the new design can be assessed.

Interlayer bond

The weakest point of 3DCP structures is the interlayer bond. The main assumption of why such effect happens is that the presence of voids between the layers create weak links in their interface. The voids form due to the stiffness of the freshly extruded layers. This means that the material is not malleable enough to penetrate and anchor into surface pores. *Figure 9* provides an illustration of this effect.
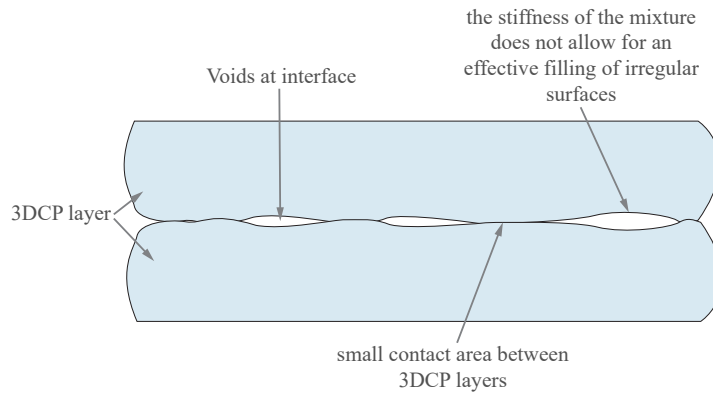

Figure 9: Formation of voids at the 3DCP layers interface

As indicated by Mata-Falcon (2018), the interface bonding strength is directly related to the surface roughness. This is in accordance with the previously reviewed printing speed parameter. If a high printing speed is programmed, the smoother the surface is, which decreases the bonding between layers.

Besides the mixture stiffness, the moisture exchange between the 3D printed layers is also responsible for the formation of voids. The bottom layer becomes dryer as hydration increases. Therefore, it absorbs moisture from the freshly printed layer, which creates air voids between both layers. Here, a faster printing speed might help to partially solve this issue. However, as previously reviewed, a faster speed also means a smoother surface. Therefore, a balance between the surface roughness and hydration level of the 3DCP mixture must be achieved.

A weak interface bonding does not only affect the mechanical behavior of the 3DCP element, but also its durability. Usually, good bonding between layers conveys to a good tensile strength of the printed element. For this reason, it is important to analyse the improvement of such bonding. In this sense, the use of reinforcement or mechanical anchorage to form a stronger connection between layers is an idea worthy to explore. However, some researches reveal that the inclusion of fibers as reinforcement, for instance, increases the porosity between layers in a range of 15-23% due to an increase of the stiffness of the mixture (Nematollahi, et al. 2018). This effect reduces the ability of the freshly printed layers to deform and achieve a seamless interface.

The understanding of the interlayer bond in 3DCP structures is of importance to evaluate the structural capacity of the 3DCP reusable slab before delamination. Next chapter addresses the reinforcement possibilities for both the interlayer and layer mass in 3DCP.

Use of reinforcement

As previously studied, concrete has a low tensile strength. Therefore, a reinforcement material is commonly applied to compensate for such a weakness. Steel rebar is traditionally used in concrete casting techniques. However, the pre-processing is labour-intensive and time-consuming. But the biggest issue with the use of steel rebar in this research is that this type of reinforcement corrodes and causes internal cracks in the concrete elements. This means that after time, the element cannot be reused as its structural capacity is compromised. This leads to investigating novel strategies to provide concrete with tensile strength. Therefore, fibre reinforced concrete (FRC) emerges as a potential solution. The use of steel fibres prevents corrosion from appearing within concrete elements. The reasons for this are mainly two: First, the small fibre diameter does not generate a sufficiently thick corrosion layer. Therefore, even if corrosion generates, the affecting to the concrete mixture can be neglected. Second, if corrosion is generated, it ends in the fibre edge, which means that the corrosion will not be transferred through fibres. This is especially important for the extension of the technical-life of reinforced 3DCP elements as corrosion would be avoided. Therefore, the reuse of the slab would be feasible.

The utilisation of fibres in the 3DCP mixture is gaining interest in recent years. Fibres are usually added to the concrete mixture to modify its viscosity and to enhance its structural properties. When the latest is the main goal, fibres are classified as "structural fibres". The enhance of the 3DCP's structural properties through fibres largely depends on two factors: First, the amount and type of fibres. The structural capacity of a 3DCP element is exponentially increased as the percentage of volume (%vol) of the fibres increases. Second, the properties of the concrete mixture. In relation to the fibres, such properties impact mainly the bond strength fibre-matrix. However, it is important to note that the addition of fibres does not affect the original tensile capacity of the 3DCP mixture. The fibre reinforcement is only activated after microcracking occurs, which is around a tensile stress of 4MPa (Mechtcherine et al. 2019). This means that the addition of fibres has minimum influence on the behaviour of uncracked elements.

The fibres' main contribution is the redistribution of tensile stresses, which limits the widening of formed microcracks and ensures uniform crack patterns. Microcracking occurs before the concrete element reaches its maximum stress. In this mechanical phase, the cracks are usually narrow and a composite behavior still exists between the fibres and the concrete matrix. Such microcracks are

stable as long as they are confined. This phenomenon increases the stability of the 3DCP element as it dissipates energy and avoids the formation of macrocracks. Generally, the arrest of microcracks happens when the developing crack runs into a thougher material. Therefore, when a fibre is in the path of the propagating crack, such crack is stopped. Eventually, the crack crosses the fibre and it is here where crack bridging occurs (*figure 10*).
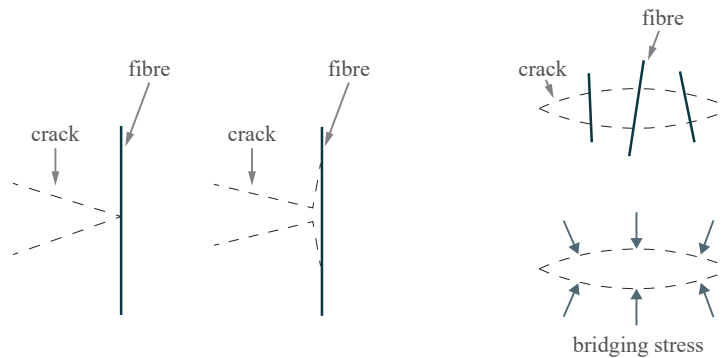

Figure 10: Crack propaation and fibre's influence. Left: crack-tip blunting at fibre. Right: Fibre bridging and crack confinement [21]

This "bridging" is subjected to an extraction force that pulls the fibre off the concrete matrix. Such extraction force is balanced by two mechanisms: First, the bond strength fibre-matrix. This is the force with which the fibre adheres to the concrete. Second, the friction fibre-matrix, which is the force developed by the friction when the fibre is being pulled-off (*figure 11*). The bridging is effectively maintained as long as the fibre does not rupture or pulls-off.
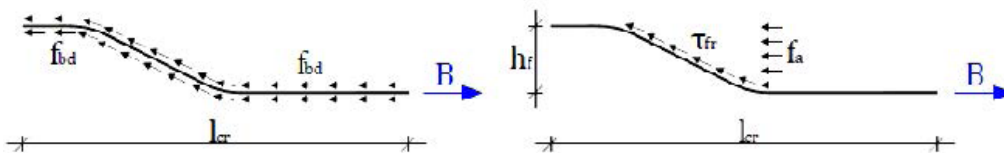
Figure 11: Mechanisms reacting to extraction force (B) for a fibre embedded in concrete Left: bond strength of the fibre-matrix. Right: friction fibre-matrix [22]

Besides increasing the tensile capacity of 3DCP, the addition of fibres provides with more safety to the 3DCP structure. Fibres improve the stability of the structure by possessing a high tensile strength over their strain. Applied to the 3DCP element and compared to plain concrete, this means that the fibres allow for more deformation (or elongation) of the element in the direction of the applied force before failure occurs. The key feature for this behavior is that the resistance forces increase when the fibre is being pulled-off. The result is that the 3DCP element can maintain a constant post-peak load over its strain. This behaviour is known as strain-hardening and it is illustrated in *figure 12*.

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21 Rebuilt from van Mier, J.G.M. 2004. *Cementitious composites with high tensile strength and ductility through hybrid fibres.*
22 Extracted from Vougioukas E. & Papadatou, M. 2017. *A model for the prefiction of the tensile strength of fibre-reinforced concrete members, before and after cracking.*
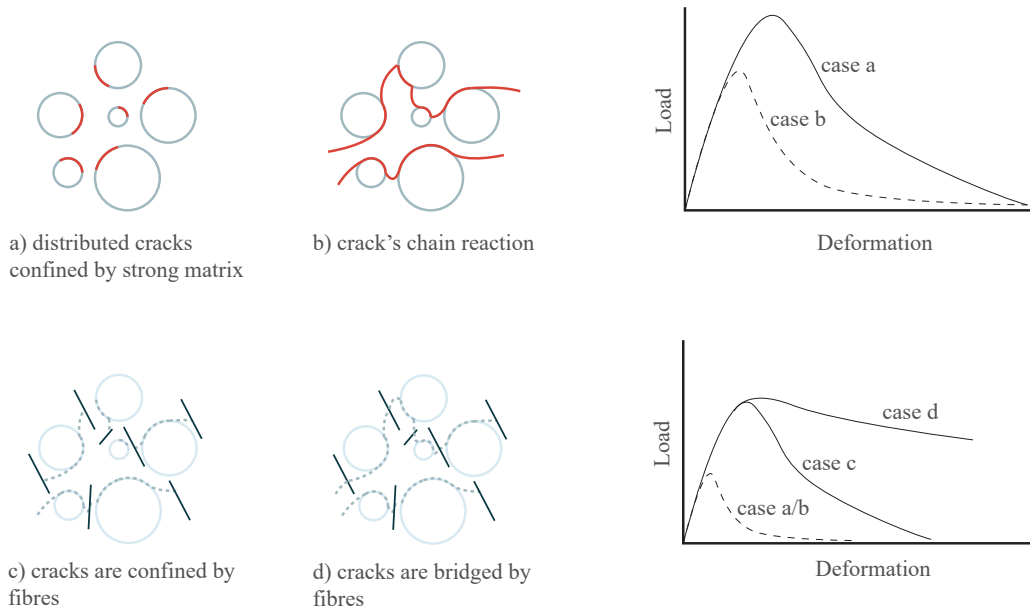
a) distributed cracks confined by strong matrix

b) crack's chain reaction

c) cracks are confined by fibres

d) cracks are bridged by fibres

Figure 12: Failure of concrete elements. Top: Plain concrete behaviour. Bottom: Strain-hardening behaviour of FRC-3DCP elements. [23]

By having the fibre´s strength higher than the pull-out forces, gradual rupture is ensured in the 3DCP element as there is a gradual pull-off defined by a frictional slip force. Consequently, a good failure prediction can be deducted. This is in contrast with plain concrete, which fails abruptly once it reaches its limit tensile strain.

In conclusion and according to Vougioukas and Papadatou (2017), the main considerations to be made when designing FRC-3DCP are:

• The crack-bridging capacity of the fibres must be higher than the crack's strength. This can be ensured by having sufficient fibre content, high fibre's tensile strength and proper fibre-matrix bond strength.

• The fibre-matrix bond strength has to be limited to allow a progressive interfacial debonding of the fibres. This is especially important as the failure by fibres' rupture is not desired as it happens suddenly. This means that it cannot be predicted and consequently, it is a highly unsafe behaviour.

• The fracture toughness of the matrix has to be sufficiently low. The result is the allowance of well-distributed steady microcracks that dissipate the energy. Therefore, the formation of macrocracks is avoided.

However, as further studied, the structural behaviour of FRC-3DCP does not only depend on the previously reviewed parameters. 3DCP largely depends on the orientation of the fibres with respect to the direction of the tensile stresses. One example of this is provided by Mechtcherine (2019) where it compares concrete cast samples with random fibre orientation and concrete printed samples with parallelly oriented fibres. Similarly, Singh (2017) conducted several experiments on this regard. The

23 Rebuilt from van Mier, J.G.M. 2004. *Cementitious composites with high tensile strength and ductility through hybrid fibres.*

results are that having a fibre's inclination of 60°, for instance, contributes as little as 10 % of the case where the fibres are oriented parallel to the tensile forces. Therefore, an optimum structural behaviour is achieved when the fibres are oriented both perpenticular to the loading direction and parallel to the principal tensile forces' direction (*figure 13*).
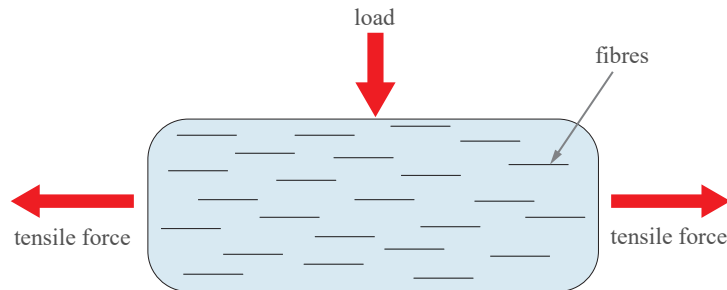

Figure 13: Optimal fibre orientation with respect to the loading and tensile forces direction

With this orientation, fibers are able to bridge the cracks that form due to the tensile forces. To effectively control such orientation several researches have applied magnetic fields that orient the steel fibres parallelly to the magnetic waves. However, it has been demonstrated that fibre orientation is also effectively achieved by means of 3DCP. The diameter-length ratio (d/l) of the fibre is favourable in this situation as it self-orientates longitudinally when the concrete layer is extruded. Therefore, when the layer is deposited, all the fibres that it contains are parallelly oriented to itself (*figure 14*).
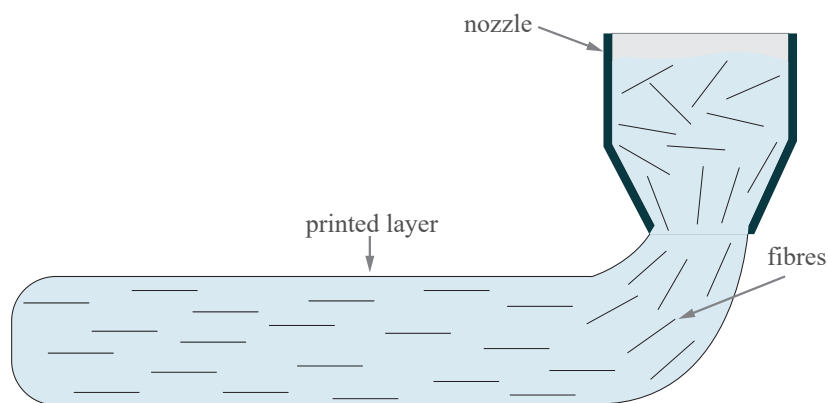
Figure 14: Self-orientation of fibres with layer extrusion (3DCP)

This knowledge is of relevance as it dictates the printing direction of the reusable slab based on the direction of the forces that it withstands. Moreover, a deep link is found between the structural design of the 3DCP reusable slab and the production method. This means that besides the low generation of material waste, 3DCP is a sensible method to achieve the desired structural behaviour based on fibres' orientation while improving the reuse potential of the slab.

Circular Economy

Besides the material aspect, its durability and the production technology, other strategies have to be applied to ensure the reusability of the 3DCP slab. Circular economy is a concept that presents strategies to exploit the full potential and retain the optimal value of the physical environment. This implies an economy in which products and material utilisation are optimised, therefore polluting emissions and waste are reduced as the manufacture of new products is diminished. To achieve this, the circular economy dictates four levels at which the optimal value and resource efficiency of products can be obtained: maintain, *reuse*, remanufacture and recycle. The order of the levels is descending and determined by the amount of energy and raw material needed to retain the value of a useful product. This means that for instance, product reuse is preferred over its recycling. Product reuse is the objective of this research as it allows to exploit one of the most misused advantages of concrete: *its durability.*

The circular economy (CE) is a concept formulated by the Ellen MacArthur Foundation. In the report "Towards the Circular Economy: Economic and Business Rationale for an Accelerated Transition" (2013) CE is presented as an initiative in which products and materials are designed to be reused at their highest utility. This implies an economic and industrial system that is restorative and regenerative by design. By definition, this concept opposes the current "cradle-to-grave" model (*figure 15).*
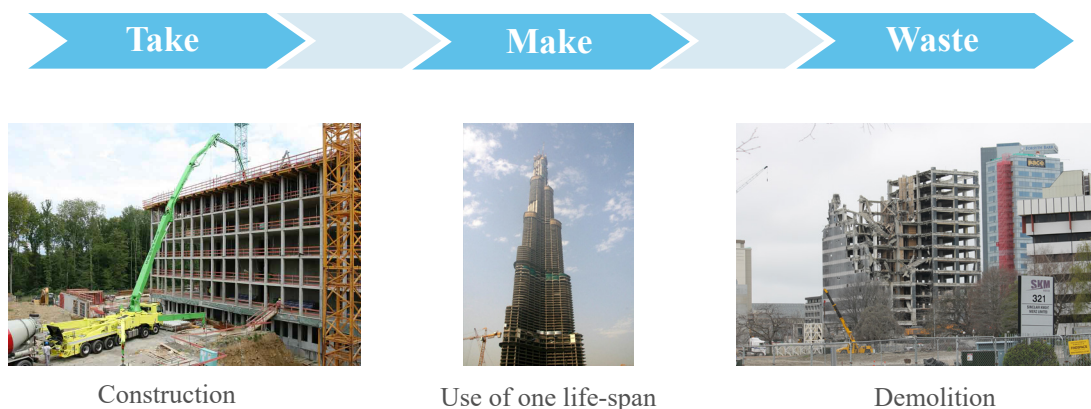

Take	Make	Waste
Construction	Use of one life-span	Demolition

Figure 15: Cradle-to-grave model in the building industry

The main objective of the CE principle is to decouple the economic growth from the extraction and consumption of raw primary materials. The Ellen MacArthur Foundation states that instead of using finite resources, the economic growth should rely on the reuse of materials and products.

The circular economy distinguishes between technical and biological cycles. This research is focused on the technical cycle as it aims to preserve the value of concrete. By definition, material use and its flow fulfil an important role. The Ellen MacArthur Foundation calculated that the circular economy

offers opportunities because, among other things, there are less material extraction and waste processing costs due to reusability of already made products. Here, it is assumed that new revenue models will be added to realise the shift from building products to building services. In other words "it is not the possession of a product but its technical-use that is of importance" (Ellen MacArthur Foundation, 2013).

According to Ellen MacArthur Foundation (2013), there are four main principles to create value in the circular economy (*Figure 16):*
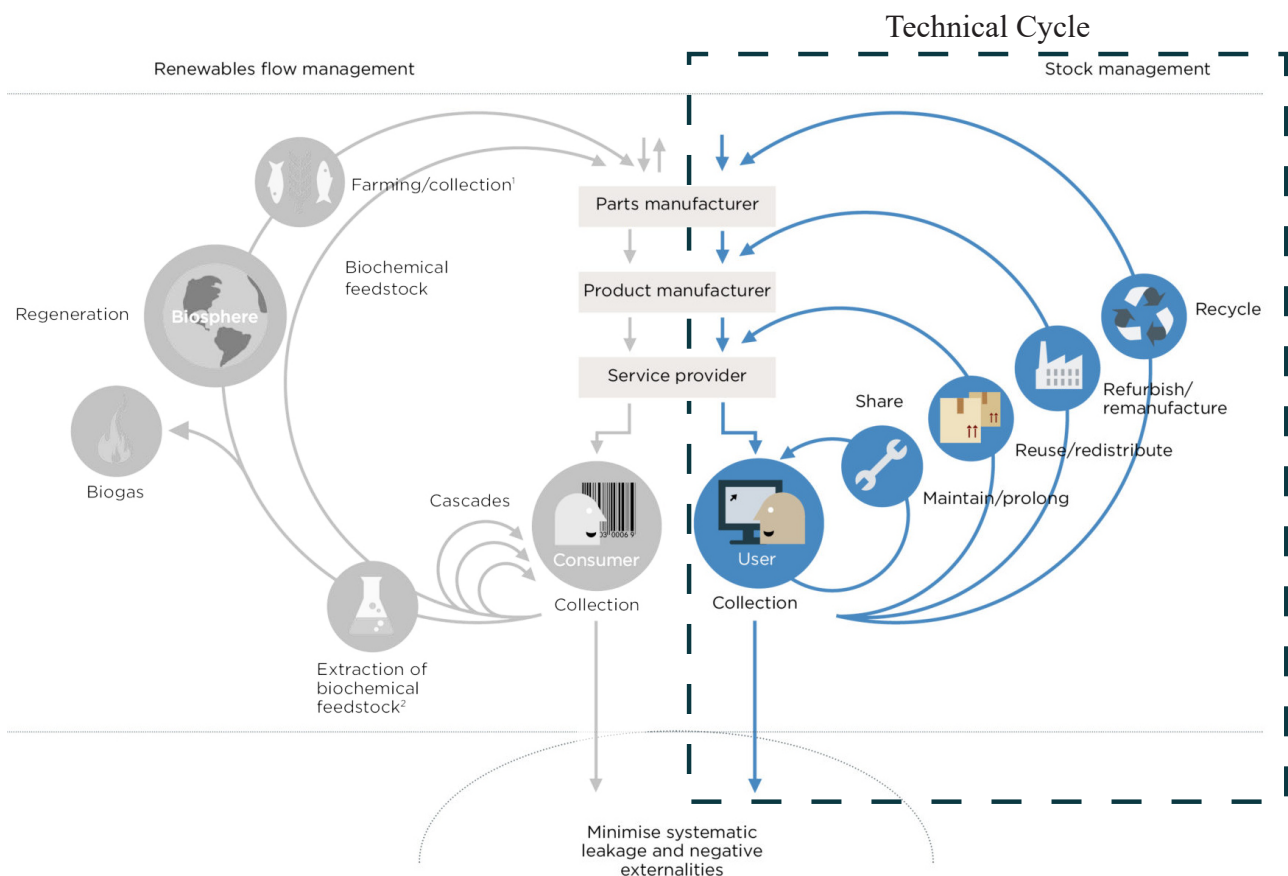
Figure 16: CE butterfly diagram.

- *Power of the inner circle:* the order of circles is maintain/prolong, reuse/redistribute, refurbish/ remanufacture and recycle. The order of the levels is descending and determined by the amount of energy and raw material needed to retain the value of a useful product. This means that for instance, maintenance and reuse preserve more value of the product than remanufacture or recycle. Referring to *figure 16*, the smaller the circle is, the more preference it has within the CE framework.
- *Power of circling longer:* Maintaining the building product within one cycle avoids the need for extra material and energy to create a new product. Hence, value is created by circling longer. By enabling the concrete slab to allow for (dis)assembly and reuse, the technical-life of the product can be extended. This means that its value is also higher.

- *Power of cascaded use:* If a building product cannot be maintained within one circle, the best strategy is to input it in the following circle. For instance, if the reusable slab cannot perform within the "reuse" cycle, refurbish/remanufacture is then preferred. This basically means that when the product cannot perform, its materials can be used for other purposes. Therefore, raw materials are not (partially) needed to create a new product.

- *Power of pure inputs:* Uncontaminated materials are easier to separate. This decreases the amount of energy used and CO_2 emissions, which provides with more value to the building product.

The focus of this research lies in the first two principles: power of the inner circle and power of circling longer. However, the first circle of the first principle (maintenance) is not addressed. The reason is that concrete is already a durable material that requires minimum maintenance. Consequently, this circle can be neglected. As discussed before, the challenge remains in the second circle, which is "reuse". To address this, the Ellen MacArthur Foundation (2013) provides the guidelines reviewed next.

Design for (dis)assembly and reuse (DfR)

One of the measures to avoid the demolition of concrete buildings and waste of their elements is to design them for future disassembly and reuse. Disassembly can be thought of as "the process of demolishing a building but restoring the use of the demolished products" (Ellen MacArthur Foundation, 2013). Design for reuse is an essential principle to close the loop of concrete elements and change the current cradle-to-grave model. This approach can be though as an analogy to the biological metabolism of nature where "waste" is turned into "feed". Applied to this research, this means that it relies on the useful quality of the slab after each service-life so it can be input into the next one. A key aspect to preserve such quality is the assurance of an easy and effective (dis)assembly.

Why designing to reuse?

There is more than one reason that encourages the adoption of designing building products for reuse. An all-embracing opinion is that a sustainable building is a building that:

- Consumes a minimum of energy over its service-life.

- Makes efficient use of environment-friendly, recyclable or low embodied energy materials.

- Generates a minimum amount of waste and pollution over its service-life.

By designing the slab for reuse, the former three concepts are tackled. First, by reusing, the embodied energy of the slabs is preserved. Therefore, the new building saves "raw" energy and by definition, reduces the energy consumed over its service-life. Second, the embodied energy of the reusable slab is optimised so it is divided over its whole technical-life. Therefore, the new building is making use of low embodied energy materials. Third, material waste and pollution are avoided as the slab can be

reused. The result is that the material to landfill is diminished.

It is fair to say that all these reasons consolidate the concept of sustainability. Besides the preservation of the embodied energy, reusing a building reduces the generation of waste caused by demolition. The reduction of the disturbance of the building site and the reduction of landfill areas are a consequence of this approach. Furthermore, Rios et al. (2015) believe that DfR creates job opportunities due to the labour required in the (dis)assembly process. It is important to note that a simple (dis)assembly process does not require skilled labour. This has a positive impact on society as job opportunities are created for unskilled labour. Moreover, DfR stimulates the creation of a brand-new market for salvaged materials.

Furthermore, DfR represents a response to avoid building obsolescence. This means that DfR might be an answer to the continuous change of the users. Elma Durmisevic (2006) reports that transformable buildings that have disassembly potential will be more economical and more sustainable than the ones erected with current building practices (*figure 17*). This is true as an efficient (dis)assembly method shortens the time required to erect the building. Disposal costs can also be avoided as the material waste would be minimum. Furthermore, there is no need to manufacture new building elements as the existing ones could be reduced. All of these aspects lower the investment price of the building even if the transportation costs increase as the products need to be relocated several times.
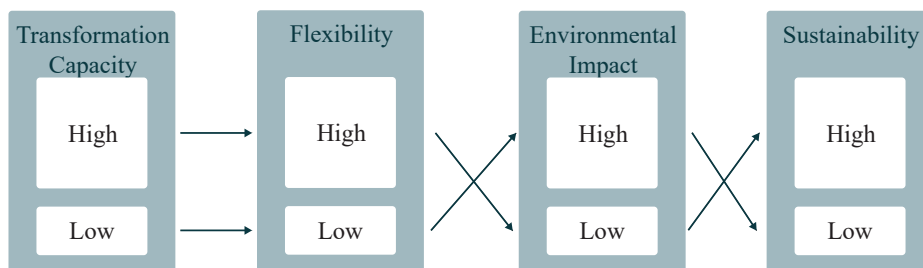
Transformation Capacity	Flexibility	Environmental Impact	Sustainability
High	High	High	High
Low	Low	Low	Low

Figure 17: High transformation capacity of buildings lead to high sustainability [24]

How to design for reuse?

Building Decomposition

Fixed systems are no longer an option as changes of buildings are done almost everyday. Buildings are generally thought of as permanent structures. However, in the long run the buildings constantly change due to changing user demands. The CE concept states that one of the opportunities to achieve an effective DfR model is the development of design strategies that transform inflexible building structures into dynamic and flexible ones (Durmisevic, 2004). Flexible building structures mean that parts can be easily disassembled and reused. *Figure 18* illustrates this according to the technical-life of the building's components. Special attention needs to be put towards the technical-life of the

24 Rebuilt from Durmisevic, Elma. 2010. *Green Design and Assembly of Buildings and Systems.*

building structure. In the current practice, the structure can last up to 300 years.
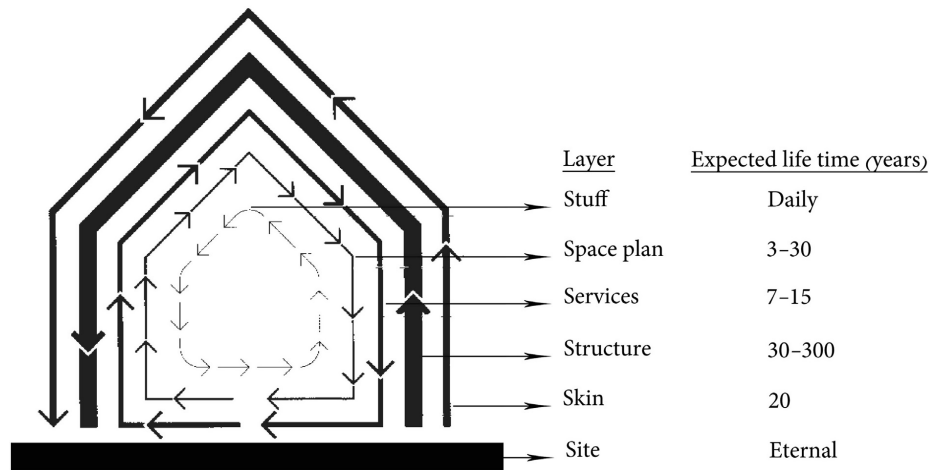

Layer	Expected life time (years)
Stuff	Daily
Space plan	3–30
Services	7–15
Structure	30–300
Skin	20
Site	Eternal

Figure 18: Building decomposition based on the elements's technical life [25]

Building decomposition is not successfully achieved in the current practice. Many building elements are permanently connected even if their technical-life is different. The result is that the building elements with higher technical-life have to be discarded when those of shorter technical-life are obsolete.

To provide a better understanding of the levels of building decomposition that are and that can be achieved, three types of structures can be identified:

• *Fixed structures:* Structures with maximum integration and dependence of its building products. The integration is achieved through the hierarchy of assembly and not related to the product technical-life. This results in the demolition and disposal of the whole building structure despite the remaining potential utilisation of its products.

• *Partly decomposable:* The hierarchy of fixed and flexible products is adjusted accordingly. The flexibility of these structures is restricted to the designed capacity of the fixed elements. This type of structures can be partially reused.

• *Totally decomposable:* These structures can be dismantled at the end of their service-life. They can be relocated or their elements can be rearranged. Modular parts and geometries ease the reconfiguration of products, they can be easily transported and rapidly assembled in-situ as standardized tools are used. The three most important features are: First, there is a clear separation between all the building products. Second, such building products are decoupled in levels according to their technical-life expectancies. Third, the assembly sequence is usually a parallel scheme instead of a sequential one. This results in a faster assembly process as sub-assemblies can be made independently from one another.

25 Extracted from Salama, W. 2017. *Design of concrete buildings for disassembly: An explorative review.*

Elma Durmisevic (2006) identifies three dimensions of transformation that characterize totally decomposable structures (*figure 19)*:

- *Spatial transformation:* ensures continuity in the exploitation of the space through spatial adaptability.
- *Structural transformation:* provides continuity in the exploitation of the building and its elements through replaceability, reuse and recover of building products.
- *Material transformation:* provides continuity in the exploitation of the materials through recycling.
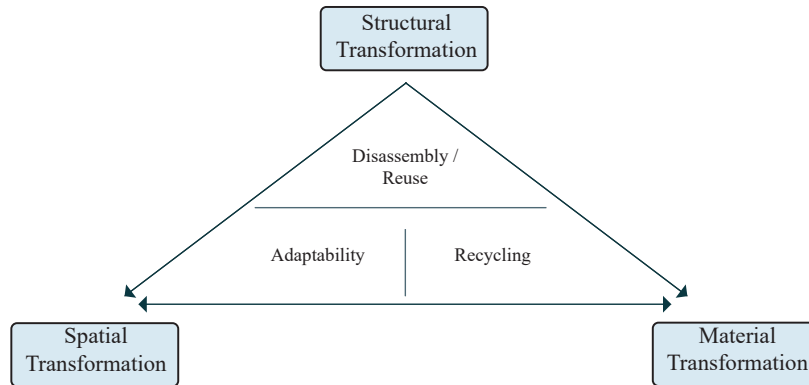
Figure 19: Dimensions of building transformation [26]

From this knowledge, it can be concluded that there are two main factors that affect the level of decomposition of the buildings:

- *Independence of parts*: Also known as the technical (de)composition of the building.

This is the level at which building elements are independent of one another.

- *Configuration design:* Refers to the relation between the building elements. This

feature determines the potential for exchangeability of them.

Independence of parts (technical (de)composition)

Technology and automotive industry provide a good example of what is and how the independence of parts can be achieved. In these industries almost all elements can be disassembled for maintenance or replacement. To facilitate this, manufacturers standardize the parts so they become compatible with many types of vehicles and machines. As the automotive and technology industries, the building industry also consists of components that have different technical-lives. For this reason, Elma Durmisevic (2006) believes that buildings are a "technical (de)composition" that consists of material levels. Elma Durmisevic (2006) identifies five levels in which buildings can be decomposed: b*uilding, systems, components, elements and materials*. In this framework, higher-levels products can be decomposed into lower-level sub-products. However, higher-level products are more valuable than the sum of their parts. This is because every step higher in the hierarchy also means that there is a higher value of labour, energy, material and use of equipment. This is why element reuse has an

26 Rebuilt from Durmisevic, Elma. 2010. *Green Design and Assembly of Buildings and Systems.*

advantage over material reuse. However, separation is appropriate when it is difficult to find suitable applications of higher category products.

To understand better this concept, *figure 20* shows two types of hierarchies within a building system. The current conventional building system with its closed complex hierarchy and a transformable system with its open hierarchy.
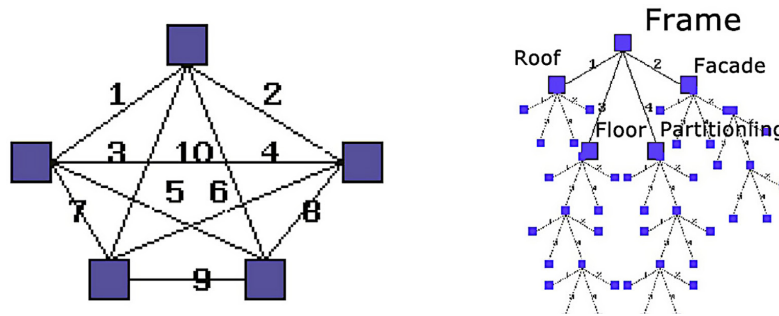

Figure 20: Independence of parts. Closed vs open hierarchy [27]

Nowadays, buildings should be seen as a hierarchy of subassemblies and independence of parts. This should be described at any level of abstraction as: at the highest level (building level) as an overall assembly of systems, at intermediate level (system level) as a composition of components and at the lowest level (component level) as an assembly of elements and materials. *Figure 21* shows the hierarchy of the building decomposition.
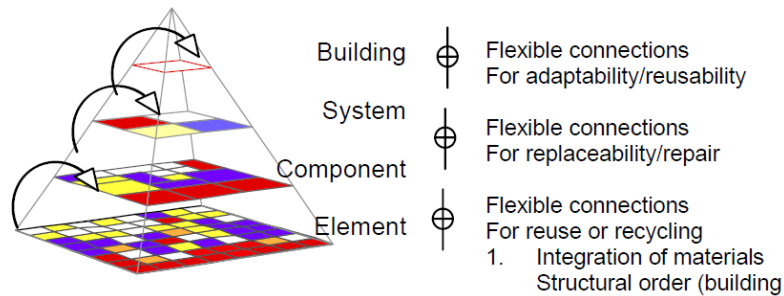
Figure 21: Hierarchy of building decomposition [28]

Based on this diagram, it is important to note that every level within the building has to do with the integration of service and technical-lives of building products. The (de)composition of a building into independent levels is a top-down process.

The evolution of buildings should represent the transformation towards a simplified relational diagram. The first step towards this simplification has to do with the clustering of groups of parts into independent subassemblies. Subassemblies in the building, their functional composition and the

27-28 Extracted from Durmisevic, Elma. 2010. *Green Design and Assembly of Buildings and Systems.*

way in which they are built together determine the behaviour of the total building and its structure. Hereafter, a decision to create a cluster of parts is of essential importance in DfR. The more building parts are integrated into one component, the fewer physical connections are needed on-site.

In this research, the two main aspects to understand the technical (de)composition and important to the technical-life of the reusable concrete slab are: durability of the material and interfaces and arrangements of materials. The interfaces and arrangements are important because according to Elma Durmisevic (2006) the essential aspect of DfR occurs at the junctions where the layers meet. This provides to the building with its adaptability. The junctions allow the independence and exchangeability between assemblies and subassemblies, functions and subfunctions. When this relation of parts happens, the greatest transformation capacity of the building can be obtained.

Configuration design

Based on the DfR principles, the building structure should be designed as a hierarchical arrangement of building elements (technical (de)composition). Furthermore, the relation between those levels and elements is also critical. This relation is referred to as *"configuration design"*. Configuration design deals with the arrangement of building products by defining the relationship between them. Through such relation process, the level of independence and exchangeability of building elements can be defined.

Building elements can be dismantled if they are defined as independent parts of the building structure. This independence means that the interfaces with other elements are demountable, which also allow exchangeability of products.

According to Elma Durmisevic (2006), seven main aspects of configuration design can be extracted by analysing the way in which building products are arranged:

- *Functional decomposition*
- *Clustering / systematisation*
- *Base element specification*
- *Open vs closed hierarchy*
- *Assembly sequences*
- *Interface geometry*
- *Type of the connection*

Functional decomposition

DfR promotes the total separation of the building functions on all levels of the building's structure. The four main building divisions according to the functions are: *supporting, enclosing, servicing*

and partitioning. Due to the nature of the concrete slab, it falls into two partitions: supporting and enclosing. This does not represent an issue as in this case, enclosing is a consequence of supporting. However, the integration of more functions might freeze the reuse potential of the slab
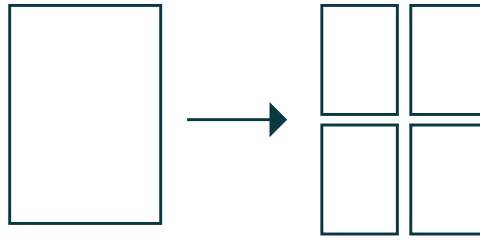
Clustering/ systematisation.

To facilitate the assembly on-site and decrease the time needed, systematisation of building products is required. The systematisation and modulation of building products into sub-products represent a way to achieve more effective building processes. Furthermore it provides with controlled use of raw materials and less labour. To provide independence of elements between clusters, a base element should be defined. Such element is then shared on two levels: to connect elements within clusters and to perform as an intermediary with other clusters.
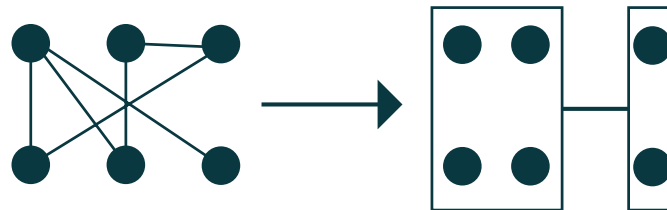
Base element specification

The importance of specifying a base element within a cluster/system lies in that such element links other elements within the group of parts. Furthermore, the base element performs as an intermediary with other clusters.
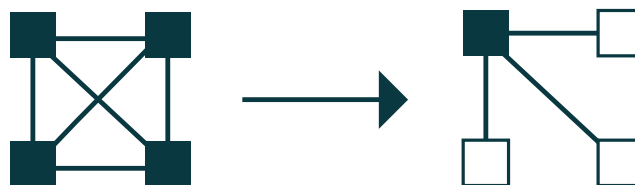
Open vs closed hierarchy

Nowadays, buildings should be seen as a hierarchy of subassemblies and independence of parts. An open hierarchy provides with flexibility as the elements and clusters do not depend on each other to perform their function. An open hierarchy also allows for replacement and exchangeability of parts without affectation to other building elements.
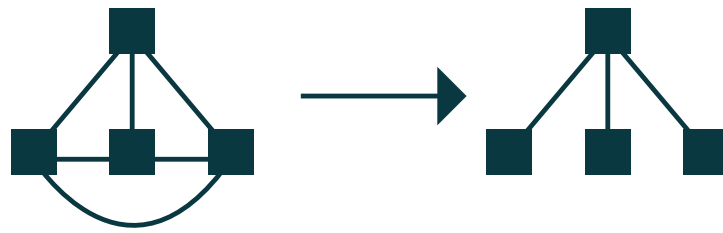
Assembly sequence

Assembly sequence is determined by the functional decomposition of the building and determines the speed at which the building can be erected. Linear assembly sequence determines a logical way of constructing. However, it slows down the process as building steps are always dependent on one another. On the other hand parallel sequence results in a faster assembly process as sub-assemblies can be made independently fom one another.

Interface geometry

According to Elma Durmisevic (2006), three types of element interfaces can be defined:

- *Direct/ integral:* the geometry of the element edges forms a complete connection. The two main types are overlapped and interlocked. Overlapped interface depends on the type of material, assembly sequence, hierarchical position and relation with other components. The interlocked interface is internal and it only allows for sequential assembly.

- *Indirect (accessory):* Additional parts are used to form the connection. The connection possesses the advantages of identical edge shapes to the elements. The dismantling of such connection can be difficult because of the sequential assembly.

- *Filled:* filled with chemical material on site. Disassembly of these connections is often impossible.

Type of connection

The type of connection is closely related to the interface geometry. From here, three types of connections can be identified: Integral, accessory and bonded. The key technical parameters of the type of connections can be defined as the capability of the interface to provide decomposition, re-composition, incorporation and plug-in. Herewith, two main criteria for the design of decomposable connections are:

- All elements should be kept separated avoiding the penetration into another system.
- Dry joining techniques should replace chemical ones.

As reviewed, there are a number of strategies that can be applied to ensure an easy reuse of the 3DCP slab. In the following section, the levels of reused are studied based on two approached: the Ladder of Lansink and the Delft Ladder.

Levels of reuse

Different levels at which reuse can be achieved are defined. The community Strategy of Waste Management describes these levels as:

- *Waste prevention:* This is assured through a proper maintenance cycle of the building element. As a consequence, the technical-life of it is optimised.
- *Reuse:* This is achieved by preserving the technical-life of a building element and reusing it for the same purpose for which it was produced.
- *Recycle:* This is the reprocessing of waste materials into new products, either for the same or different purposes of the original product.

From here, Elma Durmisevic (2006) proposed a hierarchy with sublevels of reuse:
- *Building reuse:*
    On-site: The reuse of the entire building or a significant part of it in the original location. The whole structural system, for instance.
    Relocation: The (de)construction of the building in different sites.
- *Component reuse:*
    On-site the reuse of a group of building components (flooring, for instance) in their original location.
    Relocation: The reuse of a group of building components in different sites.
- *Element reuse:*
    On-site: The reuse of individual elements (core concrete slab, for instance) in the original location.
    Relocation: The reuse of individual elements in different building sites.

For this research, the reuse at the material level is left out of scope. This is because it corresponds more to the recycle level according to the waste hierarchy of both Elma Durmisevic (2006) and the Community Strategy of Waste Management.

The formulation of such waste hierarchy and management was a starting point for governments of the state members of the EU to formulate a more sophisticated and complete matrix of levels. One of the most successful hierarchies is known as the *"Ladder of Lansink"*.

Ladder of Lansink

The ladder of Lansink describes the hierarchy with the *prevention of waste* as the first priority, followed by *element reuse, material reuse, useful application, incineration and landfill*. The issue with this model is that it represents a fixed top-down approach. This means that the first option is always better than the second one and so on.

Some state members, such as Netherlands, introduced a more detailed hierarchy: *prevention, element reuse, material reuse, useful application, incineration with energy recovery, incineration and landfill*. This is a more flexible model, with more waste treatment options. This was a starting point for more detailed models to emerge, such as the *"Delft Ladder"*.

Delft Ladder

The Delft ladder shows different reuse level. This is not a fixed order, but a flexible one. The reuse options are: *Prevention, construction reuse, element reuse, material reuse, reuse of material in a useful application, immobilisation with a useful application, immobilization, combustion with energy recovery, combustion and landfill*. The first option of the Delft ladder tries to prevent the production waste. This step must be considered in the design and building stage. The second option is to renovate old buildings and give them a second life. This can be done with buildings which fulfil certain conditions such as good technical state, good location, economical value or monumental significance. Element reuse is the third option of the Delft ladder. Element reuse is possible after dismantling a building. The main advantage of this approach is that building elements will not be downcycled to secondary raw materials. Herewith, the first thing to do is to establish the building method and matching details. With this information in hand and the knowledge of dismantling techniques it can be determined the success of disassembling the building into elements. This is the essence of DfR and it can be done in 2 ways: by using dismantlable building systems like lego, or by using recyclable or renewable materials which are easy to separate and can be used in their own cycle.

DfR conclusions

DfR is required when the service-life of a building is shorter than the technical-life of its elements. This allows to reuse elements and materials and avoids demolition and material waste.

Reusing elements for the same purpose for which they were fabricated is the most effective strategy

to keep the embodied energy and mantain the value of the product.

Technical (de)composition means dismantling the buildings into elements and components. This is an effective strategy to keep the building elements in their own cycle. The main advantage of this is that buildings as a whole are not downcycled to secondary materials or landfill but into reusable elements and components.

The most important consideration to be made within the DfR framework is in the design phase of a building. This means that considerations of materials durability have to be made in the design of the reusable 3DCP slab.

To start with, some characteristics can be mentioned to effectively design DFR. First, an easy (dis) assembly process has to be thought. The simplicity of connections is of primary attention as it might save time and economic resources. Furthermore, an easy transportation and handling of the reusable 3DCP slab contribute possitively to its potential of being reused. For this, the slab has to be lightweight.

The next characteristic is to effectively separate the 3DCP slab by functions. This means to make independent connections from the slab mass, for instance.

The following characteristic has to do precisely with the connections design. Using low technology connections results in a reduction of energy, material use and time of erection of the building.

The idea of a standard set of parts is another characteristic of successful (dis)assembly. A single design can utilise industrial manufacture proceses to produce the parts. Furthermore, the main characteristic of mass production is illustrated when numerous buildings are made to the same design. This is the potential of the reusable concrete slab as it can be potentially used in all housing buildings. Wasim Salama (2017) supports this argument and recognizes that the manufacture of prefabricated elements for reuse in an industrial scale shows great potential. A floor system, for instance, can be (dis)assembled multiple times with individual and modular concrete slabs industrially produced. This results in low production costs.

Clear and easy (dis)assembly is the next characteristic of a successful DfR building element. This decreases the time needed to erect a building and minimizes the risk of damage to the concrete products.

All these strategies can be applied to the design of the reusable 3DCP slab. However, it is valuable to review the existance of current construction systems that allow for the reuse of their elements. The

next chapter reviews some of the demountable systems in the market.

Existing demountable systems

The government buildings agency performed a research in analysing the existing demountable building systems in the Netherlands. The result is a classification and comparison study of five major precast concrete systems (Van Dijk, et al., 2000).

MXB-5 System

The MXB-5 system (*image 16*) is completely assembled with dry-mounting methods. The columns have steel plates on both ends. The floor elements are provided with anchor bushing, embedded in concrete. The columns and the floor elements are connected through tightening bolts.

- *Standardised floor elements:* 3600 mm x 5400 / 7200 mm
- *Standardised columns:* 200 x 200 mm / 300 x 300 mm
- *Mounting speed:* 800 m2/day
- *Permissible load:* 10 Kn/M2, rib floor
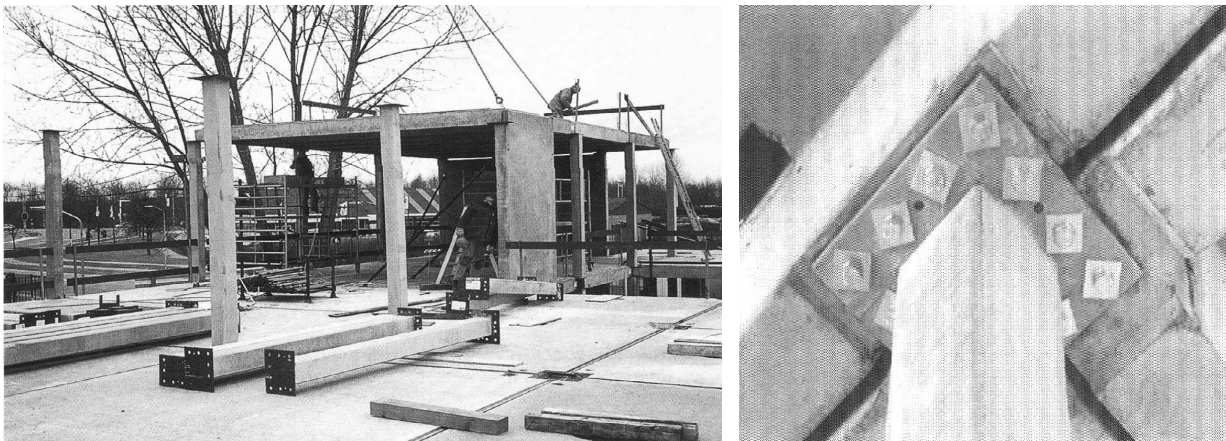
Image 16: MXB-5 System [29]

Bestcon-30 System

The Bestcon-30 system *(image 17)* consists of four threaded ends on the upper side of the columns and openings for grouting in the floor elements form the connection. The structure is dry-mounted at first and the connections are sealed by pouring non-shrink mortar afterwards.

- *Standardized floor elements:* 3600 mm x 5400 / 7200 mm
- *Standardized columns:* 300 x 300 mm
- *Mounting speed:* 500 m2/day
- *Permissible load:* 8 Kn/M2, cassette floor

29 Extracted from Van Dijk, Koen; Boedianto, P; te Dorsthorst, B; Kowalczyk, A. 2000. *State of the art of deconstruction in Netherlands.*

Image 17: Bestcon-30 System [30]

CD-20 System

The CD-20 system *(image 18)* consists of four short pens each on the upper and lower side of the columns and grouting slots in the floor elements form the structural connection. Pouring the grouting slots is needed to provide horizontal stability as well as for fixation of the columns.

- *Standardized floor elements:* 3600 mm x 4800 / 5400 / 6600 / 7200 mm
- *Standardized columns:* 200 x 200 mm / 300 x 300 mm
- *Mounting speed:* 800 m2/day
- *Permissible load:* 4,7 Kn/M2, rib floor

Image 18: CD-20 System [31]

Moducon-2000 System

The Meducon-2000 system *(image 19)* consists of four insert bolts on the upper side of the columns and openings in the floor elements form the structural connection, poured with non-shrink mortar. The following column has four fitting pieces on the lower side, which form connection with previous columns.

- *Standardized floor elements:* 3600 mm x 5400 / 7200 mm

30-31 Extracted from Van Dijk, Koen; Boedianto, P; te Dorsthorst, B; Kowalczyk, A. 2000. *State of the art of deconstruction in Netherlands.*

- *Standardized columns:* 300 x 300 mm
- *Mounting speed:* 400 m2/day
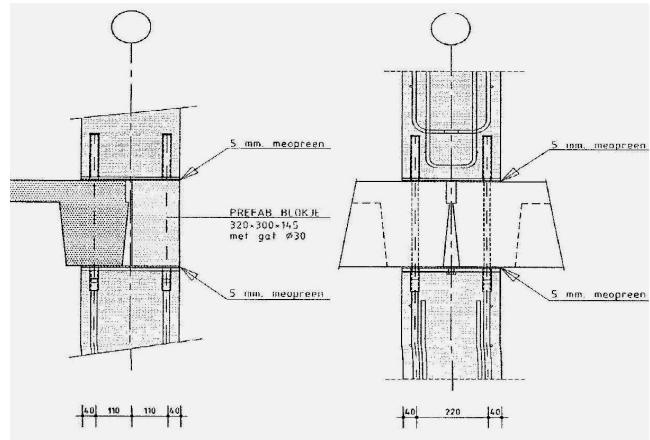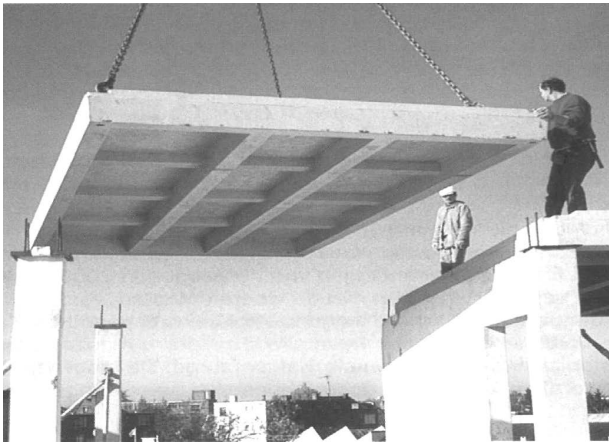- *Permissible load:* 6 Kn/M2, cassette floor

Image 19: Moducon-2000 System [32]

SMT System

Image 20. On the upper and lower side of the columns fitting pieces were casted, in which dowels were inserted. The floor elements with grouting slots are fixed over these dowels and finally poured with non-shrink mortar.

- *Standardized floor elements:* 3600 mm x 5400 / 7200 mm

    3750 mm x 5625 / 7500 mm

- *Standardized columns:* 250 mm x 250 mm
- *Mounting speed:* 500 m2/day
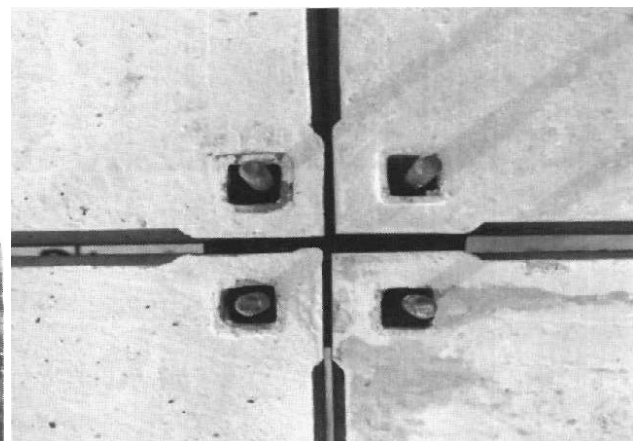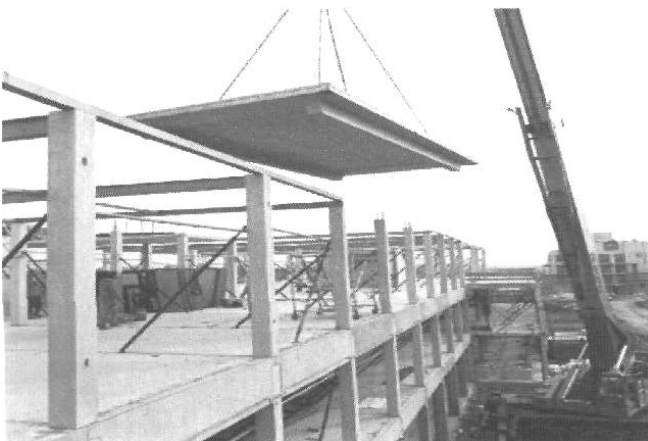- *Permissible load:* 6 Kn/M2, TT- floor

Image 20: SMT System [33]

32-33 Extracted from Van Dijk, Koen; Boedianto, P; te Dorsthorst, B; Kowalczyk, A. 2000. *State of the art of deconstruction in Netherlands.*

Demountable systems: conclusions

The existing demountable systems rely mainly on the dowels of one concrete elements going into ducts of another concrete element. Later, concrete or mortar is poured to compensate the gaps caused by the design tolerances. The bonding of such poured mortar with the concrete is referred to as cold joint. This type of bonding is weaker than a bonding of fresh concrete to frsh concrete. Consequently, it is easy to separate the elements by breaking the cold joint. However, in these cases there still exists a considerable amount of labour involved, which relentices the deconstruction process and makes it expensive. Moreover, it still exists the risk of damage of such connection. If deconstruction is not made carefully, the whole concrete element can be affected.

However, it is important to note that all of the existing systems rely on the use of dowels. A hint is then provided as the dowel provides with a moment connection used to counteract the deflection of the concrete elements. Therefore, the system does not only rely in the weight of its parts but makes use of additional features to balance structural forces. The use of such additional features is therefore a sensible principle to be used in the design of the reusable concrete slab. However, here is important to recall the (de)composition principle of the CE. A decouple of the connections and the concrete elements can provide with more independence and exchangeability between the parts of the system. Therefore, a higher reuse potential can be achieved. Such (de)composition can be based on both functional principles or technical-life spans.

Furthermore, the modular dimensions of the existing systems are reltively big. Here is important to note that the main function of such systems is not to be provide housing. Such systems have a wider range of applications, such as the relatively structural exigent parking lots. Overdimensioned elements are the result of this approach as the concrete elements have to suitable for several applications. In this sense, the reusable concrete slab can be of smaller dimensions as the scope of this research is limited to housing purposes.

Chapter 3
The reusable 3D printed concrete slab

Case-Study: Housing units in Soendalaan Vlaardingen, Netherlands

A case-study of an existing building is necessary to extract the design base of the reusable 3DCP slab. The focus can be defined applying the knowledge gained from the "building (de)composition" concept of the CE. The focus is on housing units at the building level, the structure at the system level and the slab at the component level (*figure 22*).
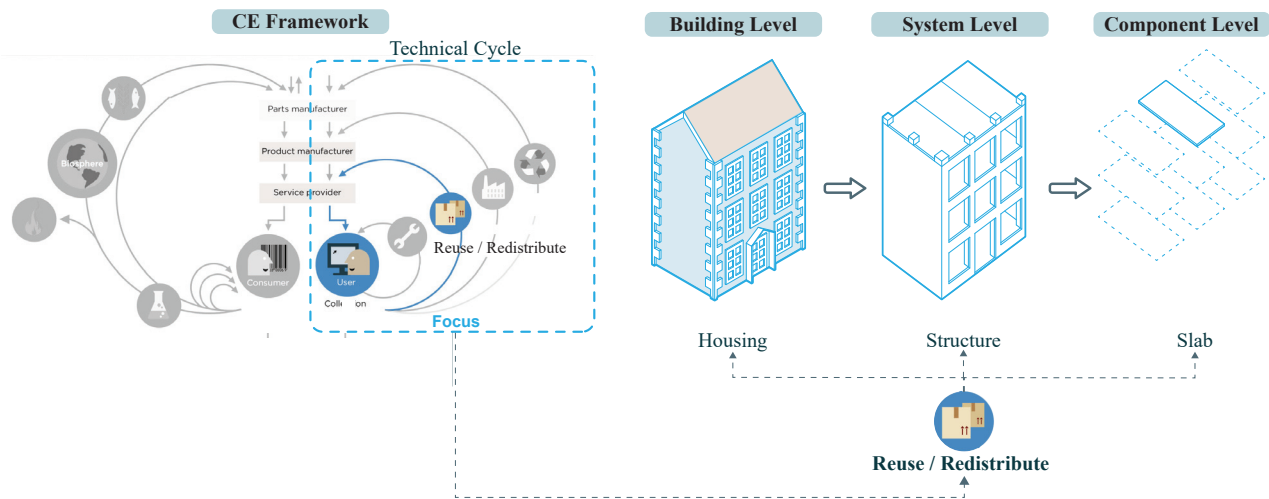

Figure 22: Focus of the research according to CE framework

The housing units studied in this research are located in the Soendalaan neighbourhood of Vlaardingen, Netherlands. *Image 21* shows a perspective of the housing units.

Image 21: Perspective of the housing units in Vlaardingen, Netherlands [34]

Each unit consists of three floor levels with four portico houses per level. The units were built in 1952 as a response to the increasing demand for post-war housing. The Soendalaan housing has been chosen for this research due to several reasons: first, it represents the most common apartment block in Netherlands. According to CBS (2016) in Netherlands 47% of urban inhabitants live in

34 Extracted from Stedenbouw. 2018. Groot onderhoud Indische buurt, Vlaardingen.

apartment blocks with similar layouts and dimensions. As Kasper Jensen's (2016) study projects that 75% of the global population will inhabit urban areas, the focus on this housing topology makes it a sensible knowledge. The second reason is that it was constructed as a response to critical housing demands. The sharing of walls and floors/roofs between stacked houses decreases the cost and time of construction. Thus, it means a fast, reliable and cheap method to provide habitation. This represents a potential solution to the critical housing demand to be faced in the future.

The goal of this case study is to analyse the structure of its slabs. The objective is to obtain information about their size, thickness and consequent material use. This serves as input data for the environmental impact assessment and cost analysis. The results are later compared to the ones of the reusable concrete slab to assess the feasibility and relevance of the new design.

Layout description

Soendalaan housing units consist of three floor levels with four apartments per level. Each apartment has five rooms and covers a floor area of approximately 53,7 m². The most important aspects to analyse from the layout are two: First, a practically free longitudinal span provides with partition freedom to the interior of the apartments. This is important from an architectural perspective as the user is able to modify the dimensions and arrangement of the spaces even when the dimensions of the envelope are fixed. Second, the dimensions of the apartment provide a possible modulation and size of the reusable concrete slab. The length, that is of 9 meters, can hardly be modulated. A partition of the 9 meters (2 slabs of 4,5 meters, for instance) makes the reusable concrete slab easier to handle. However, that also means that more connections need to be made in the construction site. This has a negative impact on the time and related cost of erection of the building. Furthermore, as the connections would be made with a material different than concrete, such as steel, the increase in the number of them means also a linear increase of the overall cost of the reusable concrete slab. On the other hand, the width of the apartment, that is of 7,22 meters can be modulated in 2, 3 or 4 parts. However, as discussed before, more elements mean more connections to be made in the construction site. On the other hand, wider reusable slabs are more difficult to handle and more expensive to transport due to their size. *Image 22* shows the plan of the standardised apartment.
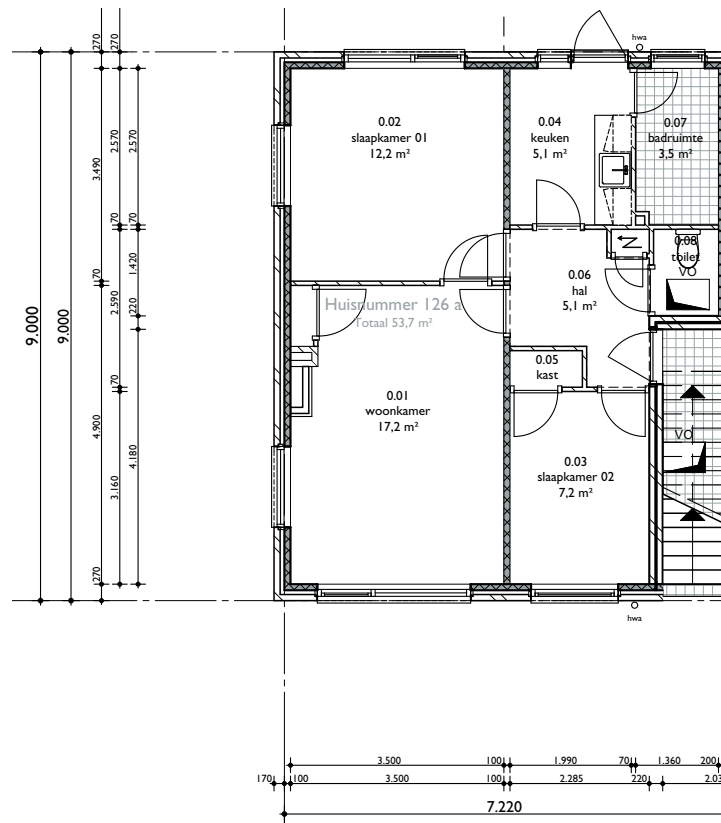
Image 22: Plan of the standardised apartment in Soendalaan

Slab description

The concrete slabs of the Soendalaan apartment units have a thickness of 15 centimetres. *Image 23* shows a detail of the apartment with the concrete slab. This building system generally incorporates steel reinforcement in the concrete elements to provide them with tensile strength. According to Narayan (2016), a generally known ratio of steel reinforcement is 1.5% per cubic metre of concrete. Based on this knowledge and using CES by Granta Design Limited (2018) the following material use and related costs can be calculated per m² of the slab (*table 3*):
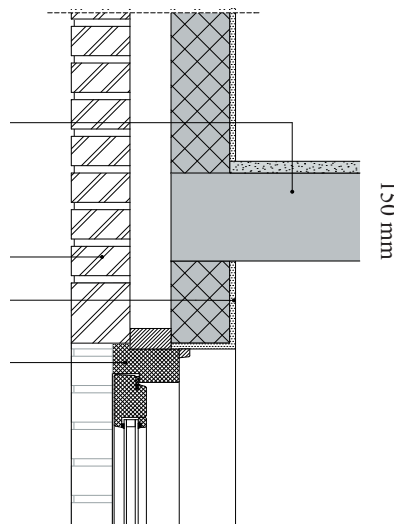

Image 23: Detail of the standardised apartment in Soendalaan

		Case-Study Slab			
		Concrete	Steel	*Total*	*%*
Material Related Costs	**Material Volume** (m3)	0,148	0,002	**0,15**	
	Material Weight (kg)	340,17	17,53	**357,70**	
	Price (€)	17,25	10,53	**27,78**	
	Embodied Energy (MJ)	292,21	594,14	**886,34**	84,91%
	CO2 Emissions (kg)	43,54	43,64	**87,18**	88,37%
Process Related Costs	**Embodied Energy** (MJ)	0,000	73,435	**73,43**	7,03%
	CO2 Emissions (kg)	0,00	5,50	**5,50**	5,58%
Transport Related Costs (50 km)	**Embodied Energy** (MJ)	12	0,620	**12,62**	1,21%
	CO2 Emissions (kg)	0,87	0,05	**0,92**	0,93%
Disposal Related Costs	**Embodied Energy** (MJ)	68	3,500	**71,50**	6,85%
	CO2 Emissions (kg)	4,80	0,25	**5,05**	5,12%
End-of-Life		Landfill	Landfill		
Totals	**Embodied Energy** (MJ)	372,21	671,691	**1043,90**	
	CO2 Emissions (kg)	49,21	49,44	**98,65**	

Table 3: Material use and related costs per m² of the Soendalaan concrete slab [35]

This calculation represents the environmental costs per m² of a 70 years service-life slab. Therefore, the total environmental cost includes the costs related to the material extraction, production processs, transportation of 50 kilimetres and disposal of 1 m² of the concrete slab. All of the environmental costs have been calculated based on the weight of the materials used. The economic cost includes only the material required to produce 1 m² of the Soendalaan concrete slab.

From this analysis several conclusions can be made: First, the use of steel represents an enormous share of the total embodied energy. The mass of this material is roughly 5% of the total mass and contributes to 65% of the total embodied energy. It is important to note that in this case, the steel cannot be recycled as it is embedded in the concrete slab. Therefore, the separation of materials is almost impossible. Forthwith, three approaches can be reviewed: To replace the steel as reinforcement, to decrease the amount of steel reinforcement or to enable the separation of materials so the steel can be recycled. The second conclusion supports the approach of this research as the calculations show that the highest embodied energy and CO2 emissions are proper of the materials. In this sense, the production process for instance, should be a secondary objective as it represents roughly 5% of the total CO_2 emissions. Therefore, the optimisation of such would have a minimum impact. A novel production process should only be considered if it reduces material waste (formwork, for instance), if

35 Extracted from *CES by Granta Design Limited (2018)*

it eases the production of a lighter topologically optimised slab or if it tackles one of the issues related to the material share. Here again, 3DCP emerges as a sensible production process as it tackles the issue related to the steel reinforcement placement and optimisation.

Loads and structural design

The loads applied for the study of the Soendalaan concrete slab have been divided in: the self-weight of the structure (Q_p), weight of additional components (flooring, services, etc) (Q_{padd}) and imposed load (Q_i). Therefore, the resulting loads are as follow:

- Q_p: The self-weight of the slab is *3,57 kN/m²*.
- Q_{padd}: For installations, ceiling and additional components, a permanent load of *0,30 kN/m²* has been assumed.
- Q_i: The value for the imposed load has been extracted from (Wagemans, et al, 2014) specifications for housing use. Such specifications are a simplified representation of the Eurocode. The imposed load applied is *1,75 kN/m²*.

Loads combinations

The load combinations are to verify the Service Limit State (SLS) of the concrete slab. This calculation has been done based on the *equation 8*, which is extracted from the (Wagemans, et al, 2014) specifications. *Table 4* provides an overview of such calculation.

$$G_K + \gamma \cdot Q_{1K} + \sum (\Psi_0 \cdot Q_I) \qquad \text{(Eq. 8)}$$

G_K	=	total permanent load
Q_{1K}	=	characteristic value of the leading variable load
Ψ_0	=	factor for combination of variable load
Q_I	=	characteristic value of variable load
γ	=	load factor

Load Factor γ	Characteristic Value of Variable Load Q_{1K}	Factor for Variable Load Ψ_0	Variable Load Q_I	Total kN/m2
0,4	1,75	1,5	1,75	**3,325**

Table 4: Calculation of load to determine SLS based on the load combinations [36]

The total permanent load has been neglected in this calculation. The reason is that such load depends on the weight of the slab per m². Therefore, this load will have variations as the topological optimisation is performed. The total permanent load will be determined in the simulation software once the weight

36 Extracted from Wagemans, Soons & van Raaij. 2014. *Quick reference of general loads*

of the optimised slab is known.

The case-study has helped to provide a better understanding of how loads are applied according to European codes. However, the values are not to evaluate the SLS of the case-study slab. The values are later applied in the design and verification of the reusable concrete slab.

A structural analysis has been made to evaluate the veracity of the structural behaviour of the case-study slab. The portion of the original slab that has been input corresponds to the size concluded in the architectural analysis. This means an slab of 8000x2000 millimetres. *Image 24* shows the results of such calculation made with Karamba for Rhinoceros 6.
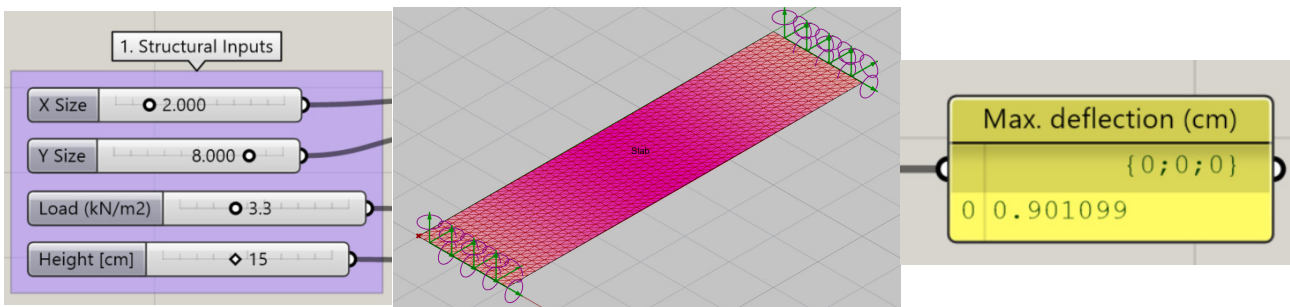
Image 24: Settings and deflection results of the case-study slab [37]

For verification, such results have been compared to the same simulation made with Ansys Workbench 19,1 (*image 25*).
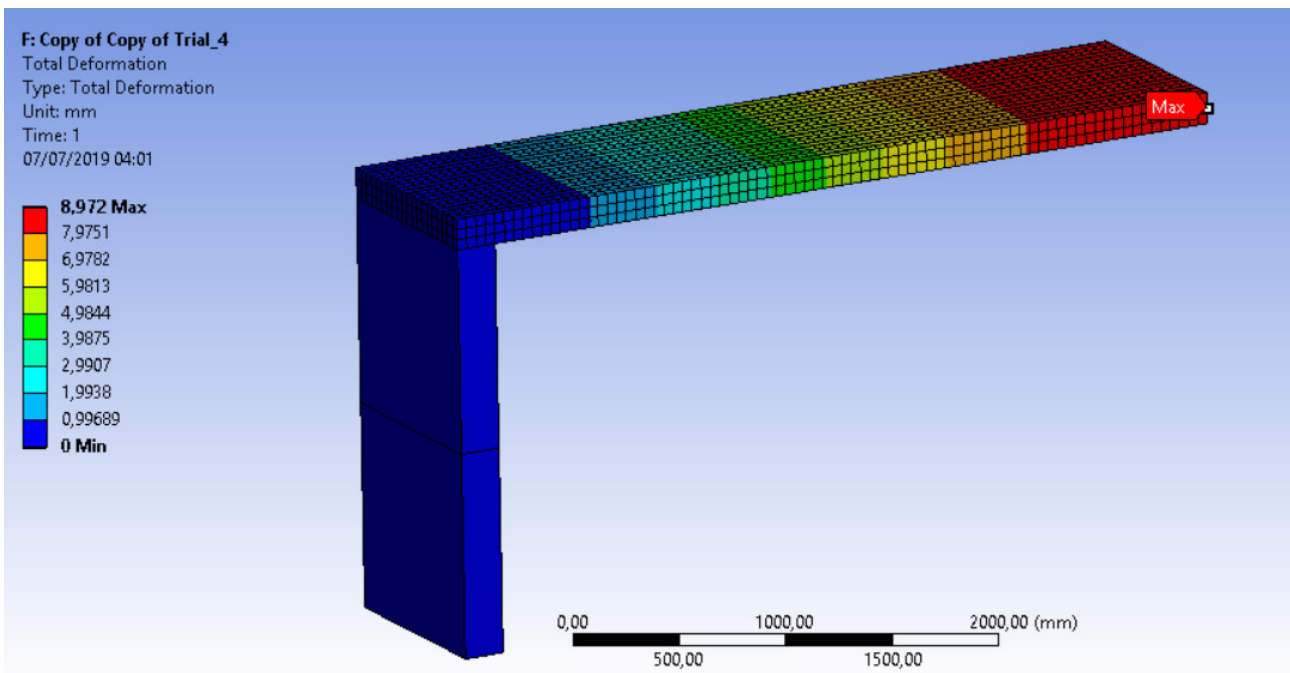

Image 25: Deflection results of the case study-slab made with Ansys Workbench 19,1 [38]

37 Data extracted from Karamba for Rhino 6.
38 Data extracted from Ansys Workbench 19,1

Ansys allows the function of *symmetry*. This means that half of a digital model can be input in the software and a symmetry plane can be applied in either X, Y or Z directions. The symmetry function then recreates the second "virtual" digital half of the model and performs the calculation. The advantage of this function is the reduction in the number of nodes of the model. Consequently, this reduces the calculation time of the software. As a rectangular geometry with a continuous rectangular section is the case of this analysis, ¼ of the model can then be input. Consequently, 2 symmetries have been applied (in x and in y directions). This recreates a full model with the geometry of the reusable slab.

The results of both simulations are consistent with each other. This means that the deflection calculated is correct. Furthermore, according to Aalami (2008) the maximum deflection allowed for roof construction supporting or attached to non-structural elements likely to be damaged by large deflection is *L/480*. This is precisely the scenario of the case-study slab as by having a free span, non-structural partitions are to be made in the interior of the housing units. Therefore 8000/480 = ***16,67 mm of maximum deflection***. The former digital analysis results in a maximum deflection of 9 millimetres. Such deflection remains below the limit allowed by the European norms. Consequently, the case-study slab is veridic both in dimensions, structural behaviour and material use. Therefore, this information can be reliably used for comparison with the reusable 3DCP slab.

Reusable 3DCP slab design

The design of the reusable concrete slab is presented in this chapter. Parameters proper of DfR are the drivers of such design. This means that a light-weight of the reusable slab, separation of functions, ease of connections, standardization of parts, clear (dis)assembly process and functionality are all addressed. The environmental impact of each step in the design is performed to assess the relevance of the approach. Finally, results are compared to the ones of the case-study concrete slab to derive conclusions.

First geometry approximation and structural boundaries

The first step of the design is to determine a proper size for the reusable concrete slab. Referring to the case-study, a floor area of 9m by 7,22 meters is studied. A depth of 9 meters can hardly be modulated as partitions also mean that connections have to be made on site. Furthermore, a partition in the depth of the housing unit means that a structural support is needed in the connection of two slabs. This results in two scenarios: First, a structural frame is needed to support the connection. This conveys multiple issues such as more time of erection of the building, the design of special connections slab-to-slab-to-frame and further research on the composition of such a structural frame. The second scenario is the placement of intermediary columns to support the connections. However, this would have an impact on the free longitudinal span of the housing unit. This means that interior partitions would be conditioned and spatial freedom would be reduced. This is a critical decision from an architectural perspective. Therefore, a free span of 9 meters is a sensible decision to start with.

The width of the apartment is of 7,22 meters. This width can be modulated in 2, 3 or 4 parts. However, as discussed before, more elements mean more connections to be made on site. This has a negative impact on the time and related cost of erection of the building. Furthermore, as the connections are to be made with a material different than concrete, such as steel, the increase of them means also a linear increase in the overall cost of the reusable slab. For this reason, larger widths of the reusable concrete slab are preferred. This decreases the number of slabs needed to cover the required floor area and consequently, the number of connections decreases. However, the width of the slab has to comply with sizes of transportation vehicles to make the research feasible.

According to Larsson (2009) and to the FESS Transport Company (2009) the average width of transportation vehicles in the EU is 2,45 meters. This automatically reduces the width options of the reusable 3DCP slab. Herewith, 2,9 slabs of 2,45 meters are needed to cover the width required. However, a width of 2,45 meters of the slab does not leave space for maneuver once the slabs are in the transportation vehicle. Therefore, a standardized width of 2 meters seems to be a sensible decision.

Larsson (2009) reports that the minimum free length of the transportation vehicles in the EU is of 8 meters and a maximum load capacity of 25 tons. Such transportation vehicles are cataloged as Street Class I. This means that they can circulate in urban streets without special permits as the damage to the road is minimum. The next class of transportation vehicles is Road Class II. These units have a free length of 13,6 meters and they need special requirements to transit in urban streets. Therefore, a sensible decision seems to shorten the length of the reusable concrete slab from 9 to 8 meters. This length allows the reusable concrete slab to be transported in Street Class I vehicles. This results in an ease of transportation as no special permits would be needed by the carrying vehicle. Furthermore, smaller vehicles also mean less fuel consumption or vehicles powered by electricity in the short future. This is healthy for the environment.

However, shortening the length of the slab also means that the housing units are shorter, which reduces the floor area. On the other hand, such loss of floor area is compensated by an increase of the housing units width from 7,22 to 8 meters. 8 meters width is the result of installing 4 reusable concrete slabs of 2 meters. Therefore, with such dimensions of the slabs and requiring 4 slabs per housing unit, the resulting floor area is 64 m² versus the 65 m² of the original design. The decrease of 1 m2 in the floor area is compensated by the advantages of modulating the reusable slabs to be best suitable for transportation and handling.

Based on the load capacity of the Street Class I transportation and referring to the weight of the case study slab (358 kg/m²), 4 slabs can be transported at once. *Figure 23* shows the scheme of this first geometrical approximation. *Figure 24* shows the described dimensions of the reusable 3DCP slab.
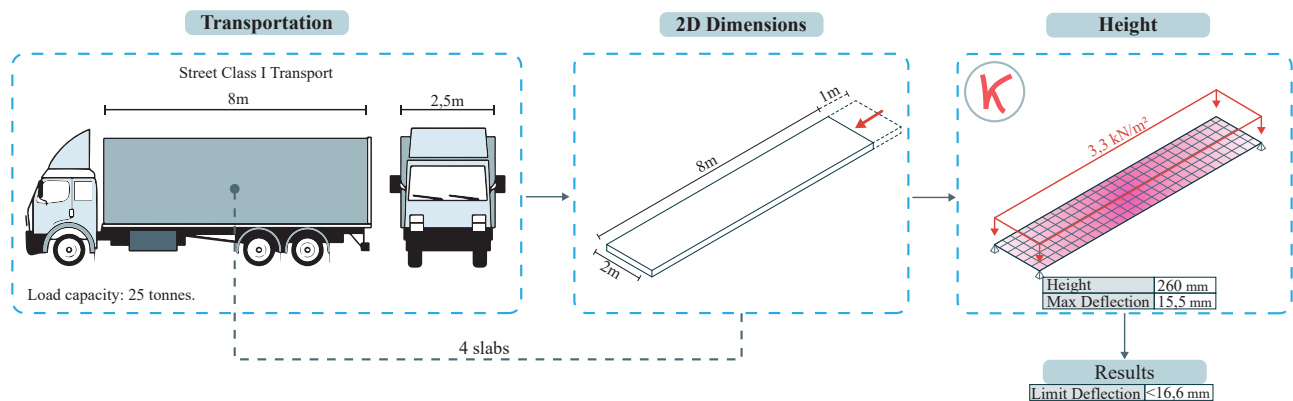

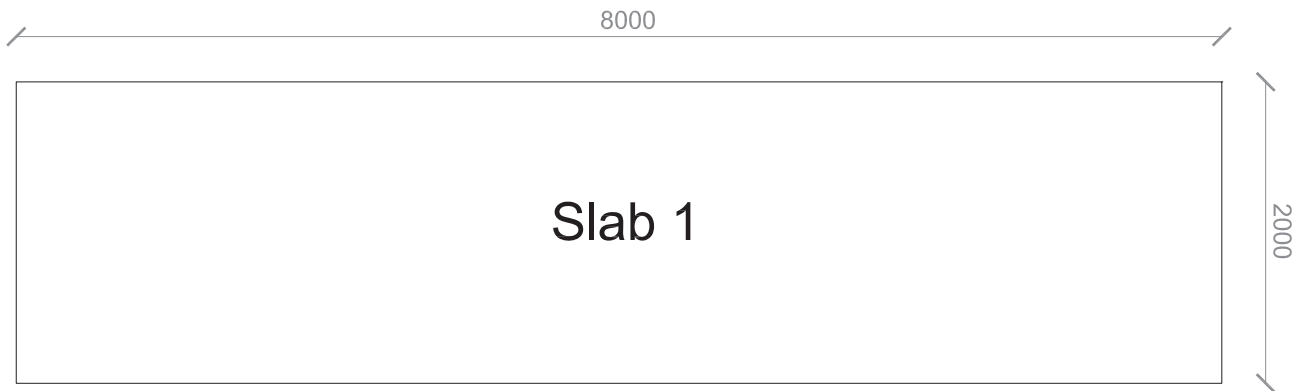*Figure 23: Scheme of the first geometrical approximation*

Figure 24: 2D dimensions of the reusable 3DCP slab

Thickness of the reusable 3DCP slab

The first approximation to determine the proper thickness of the slab was made using Karamba for Rhino grasshopper, a digital plug in to perform simple structural calculations. Here on, the loads applied for the assessments are the same explained in the case-study loads. The load combinations are to verify the Service Limit State (SLS) of the reusable 3DCP slab. *Table 4* shows the live loads to be applied. *Image 26* shows the results of the calculation made with Karamba.
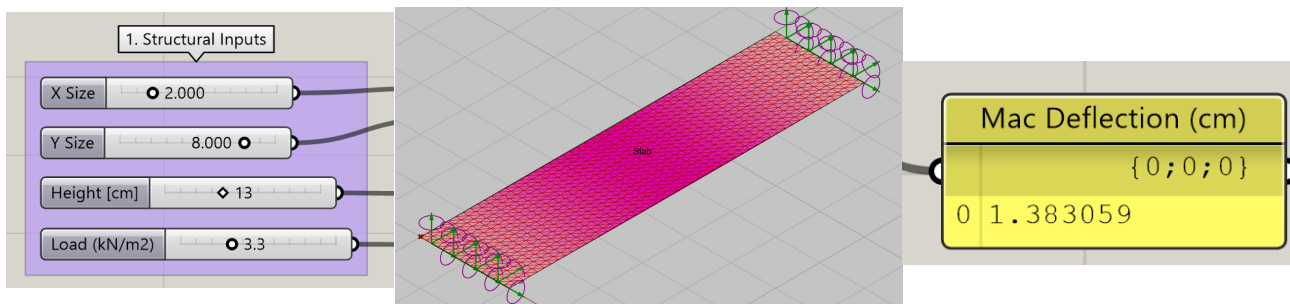

Image 26: Settings and deflection results of the case-study slab [39]

This first analysis indicates that even a slab heigh of 13 centimetres has enough stiffness to withstand a deflection lower than the one allowed by the norms (16,67 mm). However, the interpretation of these results is dangerous. The type of support used in the calculation is a fixed support. This means that even if the rotation of the reusable slab is allowed, its displacement in all directions is fixed. This condition would be accurate if the reusable 3DCP slab were joined to the wall by traditional methods, such as mortar pouring. However, as reviewed before, the main principle of reuse is the ability to effectively separate building products. Therefore, a contact support is needed instead of a fixed one for an accurate calculation of the SLS of the reusable slab. Contact support means that only friction between the components is present. This type of support cannot be simulated in Karamba. Therefore, the software use is not of relevance anymore for future calculations. On the other hand, the software and simulation have been helpful for a better understanding of the structural principle and behaviour

39 Data extracted from Karamba for Rhino 6.

of the interface slab-to-wall.

From here on, simulations and analysis have been performed with Ansys. The software allows to simulate contact supports and takes a user input friction coefficient between the materials. This is precisely the support condition of the reusable slab as it exists a friction coefficient between the materials of the slab and of the wall.

Second geometry approximation

The second geometry approximation has started with a rectangular geometry with a continuous rectangular section of 150mm. This starting point is provided by the case-study slab. The loads applied for the assessment of the SLS and deflection of the reusable slab are the same as the first geometry approximation.

Properties of the material can be input in Ansys Workbench. Such properties are also verified with CES edupack 2018. The reason for this verification is that the values for the environmental impact are extracted from CES Edupack. Therefore, a correspondence of the material properties must exist in both software. This makes the environmental impact data consistent with the structural calculations and material use. The material properties of concrete input in the calculation are shown in *table 5*.

	Density (kg/m3)	Young's Modulus (Mpa)	Poisson's Ratio	Tensile Strength (Mpa)	Friction Coefficient Concrete-to-Concrete
Concrete	2300	30000	0,14	1,2	0,4

Table 5: Material properties of concrete input for the structural calculations [40]

The following information was input in Ansys Workbench to perform the structural analysis:
- Both the slab and the support wall are of concrete.
- The function of symmetry was input in the model in x and in y directions.
- A friction contact between the slab and the wall with a value of 0,4 has been input.
- The mesh size of the support wall is of 1.250mm as this geometry is not of interest and it does not influence the deflection value of the slab.
- The mesh size of the slab is of 50mm as this is the geometry of importance in the analysis. The slab thickness is of 150mm. Therefore, 50mm has been decided so the geometry has the mesh cells size to properly show tension and compression zone and a mesh cell to connect both of the former cells. This approach gives accurate results.
- The standard earth gravity has been input as an inertial force.
- The total live load has been input as a distributed pressure force on the top surface of the slab (red surface in *image 27*.

40 Data extracted from CES Edupack 2018

- A fixed support has been input at the bottom of the support wall (letter "c" in *image 27*). This support is only used so the model runs the structural simulation. If no support is specified, a "free motion body" error is specified by the software and the analysis cannot be done.

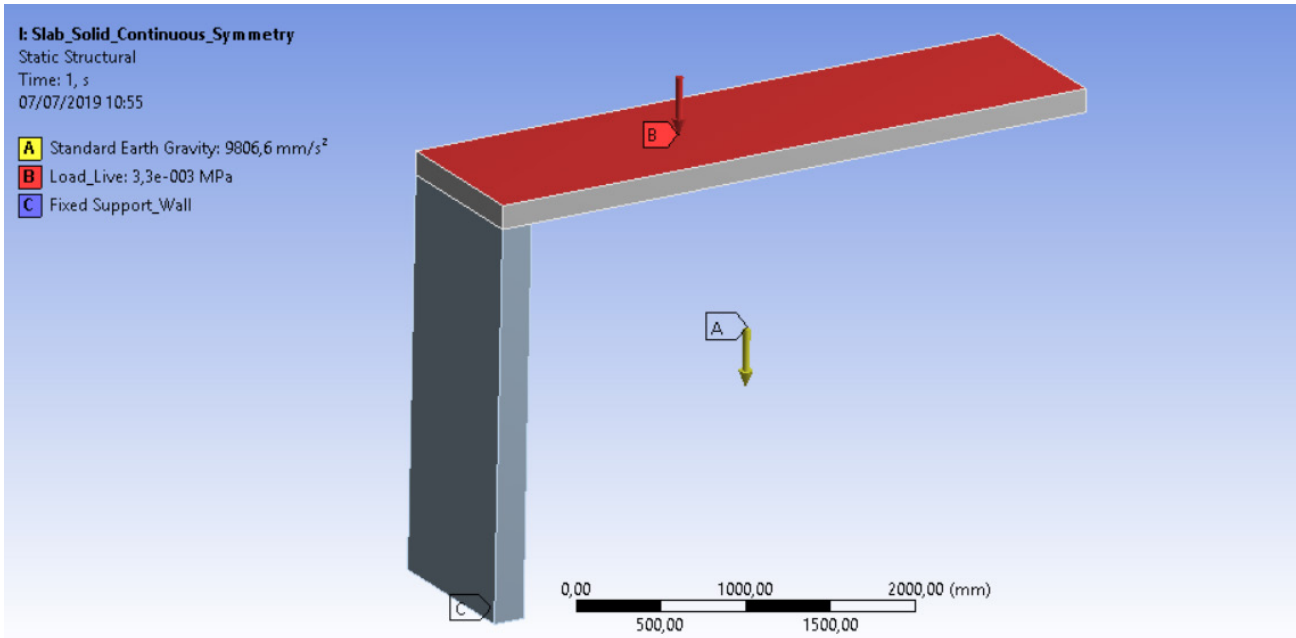*Image 28* shows the results of the structural analysis.

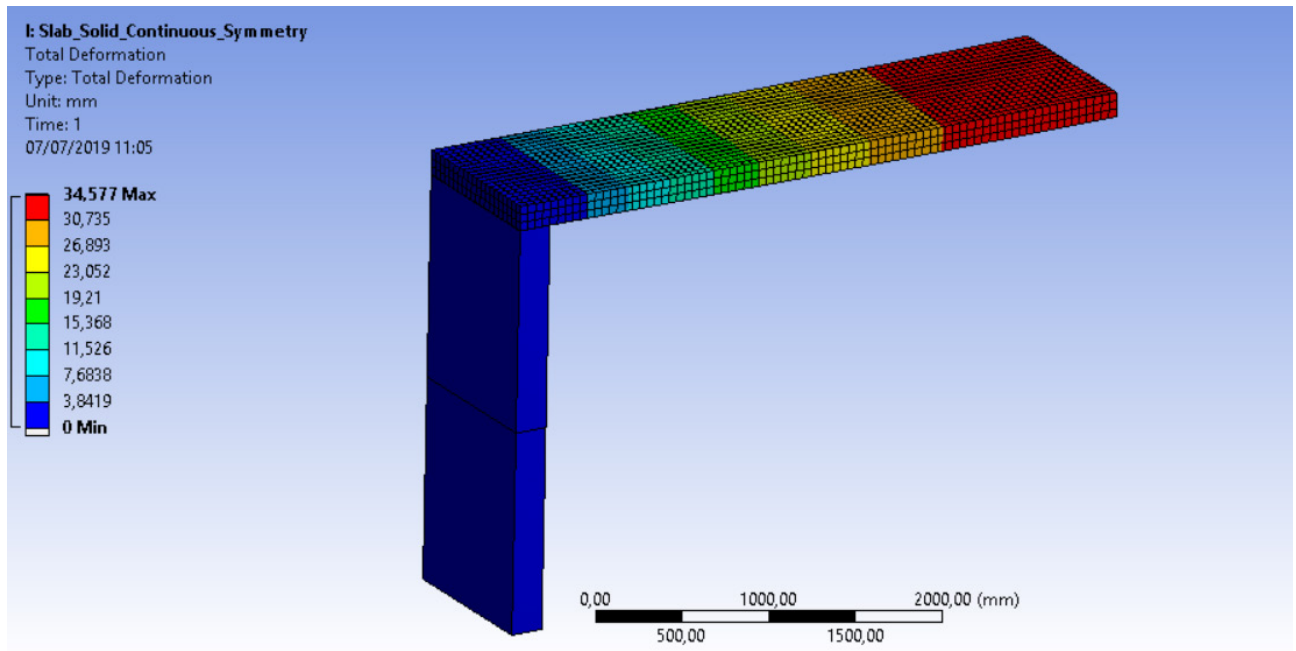*Image 27: Visual inputs of the structural analysis [41]*

Image 28: Deflection of the slab [42]
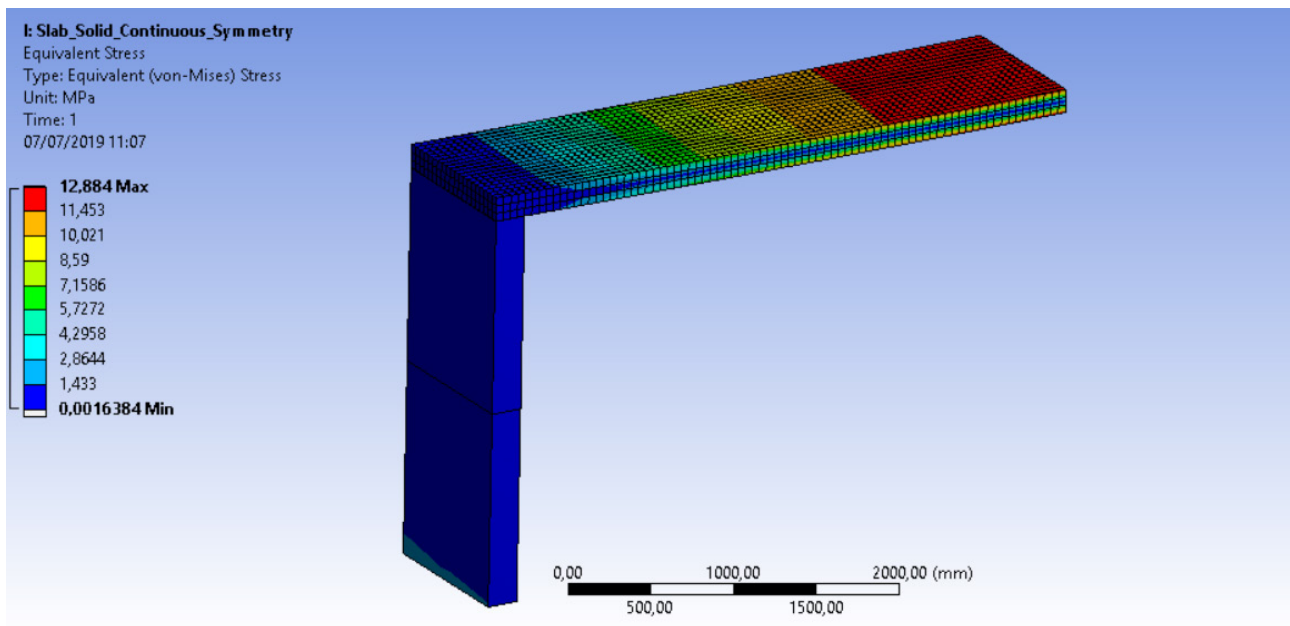
41-42 Data extracted from Ansys Workbench 19,1

Image 28: Equivalent stress of the slab [42]

It is important to note that the self-weight of the slab is taken into account by inputting the gravity load. Therefore, the results correspond to a full SLS load combination.

The accuracy of the symmetry function of Ansys workbench has been corroborated. This has been done through inputting and simulating a full geometry to compare the results. The comparison indicates that the geometry function works properly and it is reliable.

The results indicate a maximum deflection of *34,6* millimetres at the middle of the slab. The deflection is beyond than the maximum deflection of *16,67* mm allowed by the norm. It is important to note that this deflection corresponds to only a contact support situation. However, the application of dry mechanical connections seems to be sensible to connect the reusable slab to the wall. This limits the displacement of the slab and the maximum deformation is decreased. Forthwith, the design and simulation of mechanical dry connections are needed to acknowledge their impact on the reduction of the deformation of the slab.

The equivalent stress of the slab shows a maximum value of *12,9* MPa. In compression this is not an issue as the compression strength of concrete is well above such number. On the other hand, the tension value is also within the limits of FRC-3DCP as reviewed further in the research.

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41 -42 Data extracted from Ansys Workbench 19,1

First connections' design

DfR principles promote the separation of functions to ease the disassembly of building products. Therefore, a connection that is independent of the geometry of both the slab and wall seems a sensible approach. The connections are the parts of the slab that will carry high-stress values. This might potentially crack them, deform them or limit their technical-life based on the stress and the number of cycles they can perform under such stress. The separation of connections and concrete elements also facilitates the replacement of the connections upon damage. This results in less value loss as the overall slab does not have to be replaced or repaired.

Under the technical decomposition scheme of DfR, the connections fall into the element level. Based on the DfR concepts, the following strategies have been applied (*figure 25).*
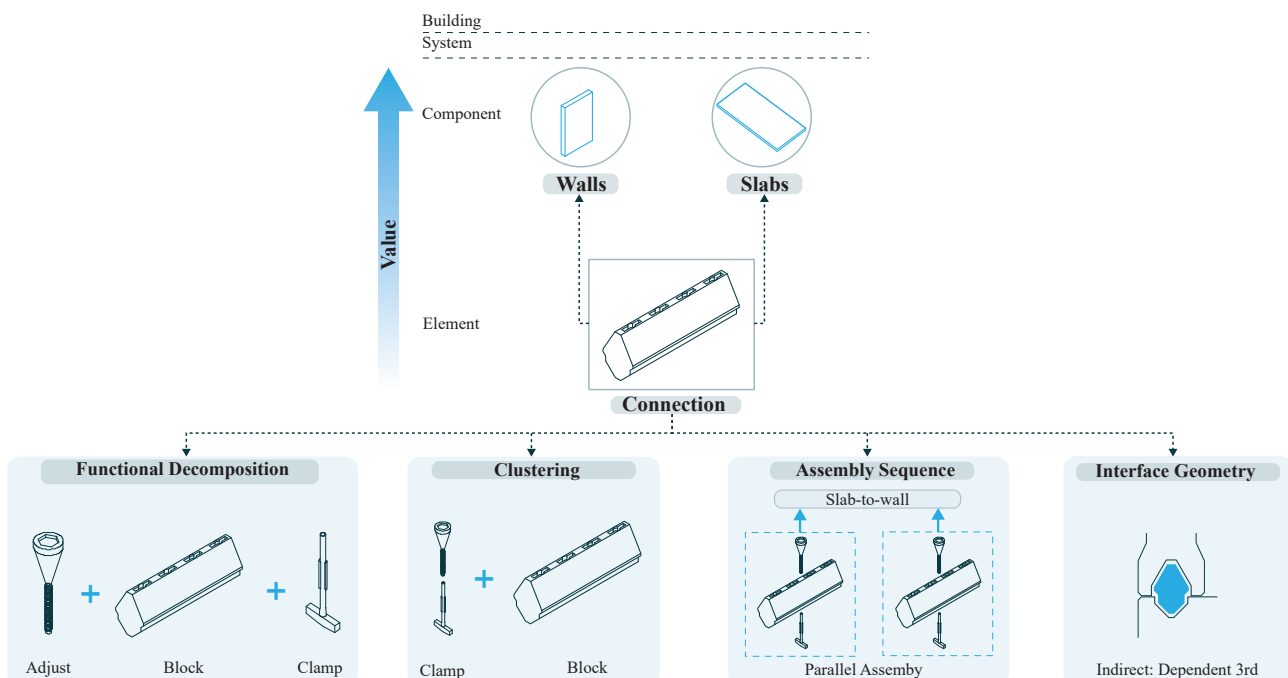

Figure 25: DfR strategies applied to the connection design

- *Functional (de)composition:* When the concept of functional (de)composition is applied, the connection are divided according to the function of a subelement. In this research, to adjust, to block and to clamp are the primary sub-functions of the connections. Each function is subjected to different structural requirements and therefore, to different damage potential. By dividing the connections by function, the replacement or maintenance can be done to each element independenty and without affectation to the others.
- *Clustering:* to facilitate the assembly on site and decrease the time needed, clustering of the connections can be performed. This means that the connection is already a sub-system previously assembled and only installed to connect the slabs on site. Clustering also means that the connection

can be further disassembled into sub-elements. This can be done according to the specific function of the sub-element. Length adjustment and displacement prevention are some of such functions. However, a fine balance needs to be achieved. Too many sub-elements complicate the clustering and too few sub-elements minimize the level of decomposition of the connection. This might result in a whole connection replacement even if only the length adjuster is damaged, for instance.

- *Assembly sequence:* If the open hierarchy is applied to this approach, the independence of connections in relation to their assembly sequence is critical. This reduces the time required on site as the connections' assembly is not linear. Therefore, multiple connections can be assembled at the same time. Furthermore, This might result in a whole connection replacement even if only the length adjuster is damaged, for instance.

- *Interface geometry:* The type of connection proposed is an integral-indirect connection. This means that additional parts are used to perform a complete connection. This connection possesses the advantage of identical edge shaes to the elements. Furthermore, internal connections are divided in overlapped and interlocked. The proposal of this research is to perform an interlock connection which is internal and allows for sequential assembly.

The connections provide with independence to other clusters at element level. This means that walls are independent of slabs. However, they are linked by the connection. In this sense, the connection can be identified as the base element to connect other clusters of sub-elements.

Design tolerances

Tolerance is defined as "the permitted variation from a given dimension or quantity" (Construction, n.d.). The immediate reason to specify tolerances is to ease the construction without the need of later modifying building elements to fit together. A more long-range reason is to ensure that the structure will perform as designed, particularly with respects to safety. Therefore, a critical aspect of the design of the connections is the knowledge about design tolerances. This becomes more critical as two production systems need to meet at such interface. As reviewed in the production methods, the 3D printing of the concrete slab and the potential casting of the concrete walls contemplate different tolerances by nature.

According to (Construction, n.d.) the design tolerance for precast concrete elements is +- *5 millimetres*. Such design tolerance value is formulated by the American Concrete Institute (ACI). The variations from the original design are minimal as the process of casting has been optimised accordingly. Furthermore, many precast concrete manufacturers utilise steel moulds. This allows them to be more accurate than using a wood mould. A disadvantage of this approach is the high embodied energy of the steel mould. The information about the design tolerances of precast concrete was corroborated in a site visit to Betonfabriek Vrijeban in Delft. Here, tolerances of even 2 millimetres can be achieved.

However, this has an impact on the price of the final precast product. Lower tolerances mean more labour involved in the creation of the moulds and stricter quality control, which makes the process more expensive. Therefore, it is decided to design with tolerances of 5 millimetres to keep the price of the process low.

3D printing concrete (3DCP) tolerances are higher than the ones required for concrete casting. However, there is relatively little information about standard 3DCP tolerances. The reason for this is that the production method is not yet standardised. Therefore, multiple 3DCP companies and research groups work with their own tolerances. However, a site visit to the Technical University of Eindhoven was useful to learn about their tolerances, which are up to 10 millimetres. The Technical University of Eindhoven is relevant as is one of the pioneer institutions to work with 3DCP. Furthermore, the value of such tolerances was corroborated in a visit to the company Witteven + Bos, a company that just starts working with 3DCP for multiple projects. Even if this area is relatively new for them, they have set their design tolerances to 10 millimetres as well. Therefore, the same value of +-10 millimetres is taken as the design tolerance for the 3DCP of the reusable slab.

The reason for such high tolerances is the fluid nature of concrete. As 3DCP does not utilise moulds, the concrete is able to expand almost freely. This is what Chen et al. (2018) describe as the buildability degree of concrete, which is the ability of fresh concrete to resist deformation under a certain load. The load can be only the self-weight of the layer caused by gravity or by the action of a layer that lies upon. *Figure 26* illustrates this principle.
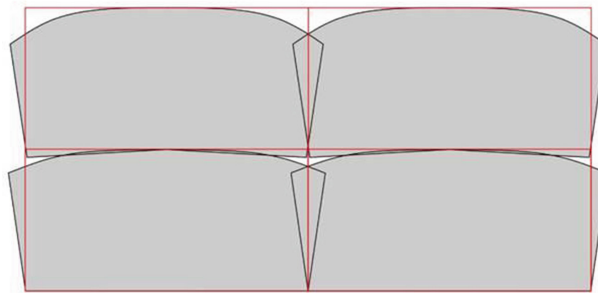

Figure 26: Deformation of concrete layers created by 3DCP techniques [43]

Connection design

Based on the principles of DfR and design tolerances, the first design of the connection was made. This connection consists of a steel block that is inserted by gravity into pockets in the precast walls *(figure 27)*.

43 Extracted from Chen, Yu; Veer, Fred; Copuroglu, Oguzhan & Schlangen, Erik. 2019. *Feasibility of using low CO2 concrete alternatives in extrusion-based 3D concrete printing.*
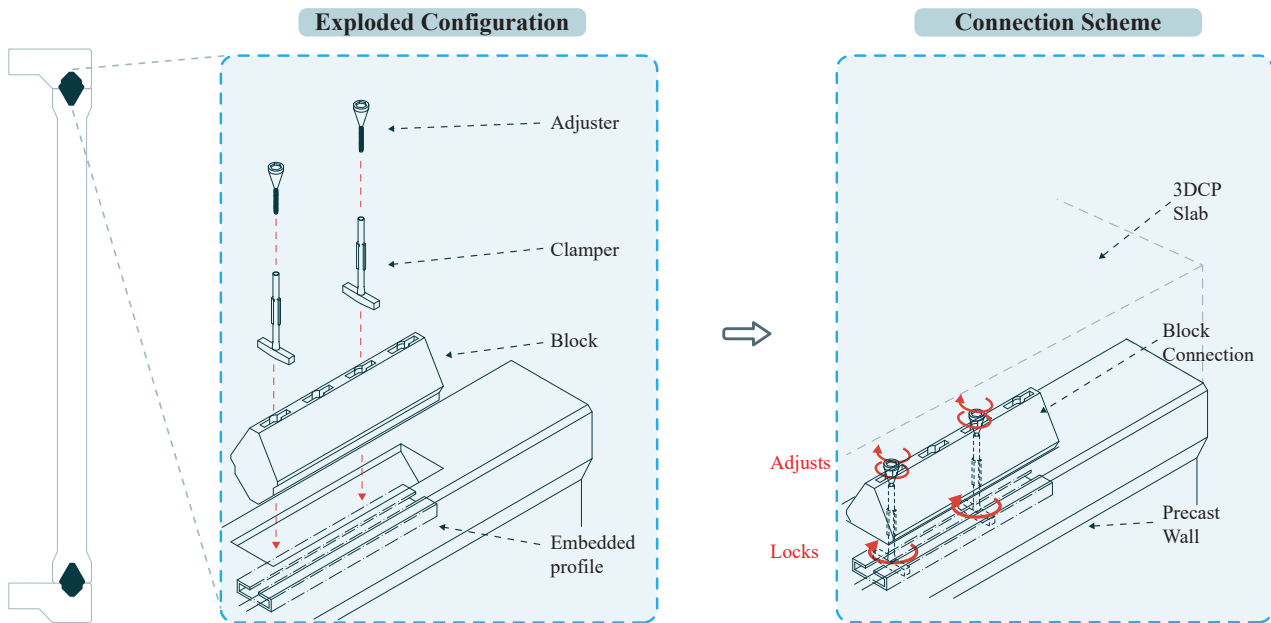
Figure 27: Conceptual design and assembly of the block connection

The vertical displacement of the block is restricted by insert bars. The insert bars are tightened to the steel block and precast wall with the help of adjusters. The First ½ rotation secures the bottom part of the insert bar to a steel profile embedded in the precast wall. Subsequent rotations tight and push the steel insert down until it achieves a good fit. The main advantage of this connection is that minimum rotations are needed. This translates in less time required to assemble the connection. Two steel inserts are placed per wall. In this way, the precast walls and slab can have a shifted arrangement, which increases the stability of the whole building structure.

Once the inserts are in place, the slab rests on the wall and inserts. The insert blocks prevent the horizontal displacement of the slab. In this instance, three inserts are placed to secure the wall to be installed on top of the slab.

The result of this design is a hidden connection. However, this connection has two main disadvantages: first, once the structure assembly is made, there is no way of checking the state of the connections. This means that if a connection gets damaged in the process of assembly, it will not be noticeable until the structure is disassembled again (potentially in 70 years). Second, it utilises an enormous amount of steel. Manual calculations suggest that around 20 kilograms of steel are needed per block. This translates into high embodied energy and costs. Furthermore, a heavy connection difficults the assembly on site.

Performance validation

The slab geometry, loads and material properties of concrete set for this validation are the same as

the ones input for the validation of the first geometry approximation of the slab. However, material properties of stainless steel have to be set for the block insert. Such properties are displayed in *table 6*.

	Density (kg/m3)	Young's Modulus (Mpa)	Poisson's Ratio	Tensile Strength (Mpa)
Stainless Steel	7750	200000	0,31	725

Table 6: Material properties of concrete input for the structural calculations [44]

The properties of the material correspond to stainless steel. The material has been selected based on the following criteria:

• *Resistance to fresh and salt water:* The material has to be resistant to oxidation as it will be exposed to a semi-open environment and it might be assembled under rainy conditions. Furthermore, the reusable 3DCP slab might be as well located in areas near the sea. Therefore, the material needs to resist oxidation due to salt particles suspended in the environment.

• *Resistance to acids:* The material might be exposed to acids located in the construction site and before the assembly is performed. Therefore, an acceptable resistance to acids is desired in the material properties. This eases the logistics of transportation and storage as practically all the pieces of the connection would remain in a proper state to be used.

• *Resistance against UV radiation:* The assembly process might take time to be performed. In this case, the connections would be exposed to direct sunrays and consequently, UV radiation. Therefore, a good resistance to this condition is desired.

• *Recyclability:* If this condition is met, the connections can be recycled upon damage and when unsuitable for reuse. This, besides saving a portion of the embodied energy, avoids production of material waste.

• *Non-flammable:* One of the main hindrances for the reuse of building elements within the CE framework is their relatively high risk to burn. Therefore, a non-flammable material is desired for safety reasons. Moreover, as the connection is a vital part of the structure, the delay of thermal failure in case of fire is a sensible criteria.

When such characteristics of the material are input in CES Edupack, only metals and alloys are left. However, an important consideration to be made is the price of the material against its structural properties, such as the Young's modulus, yield and tensile strength. Therefore, a chart is made to plot such parameters (*figure 28, 29 and 30 respectively*).
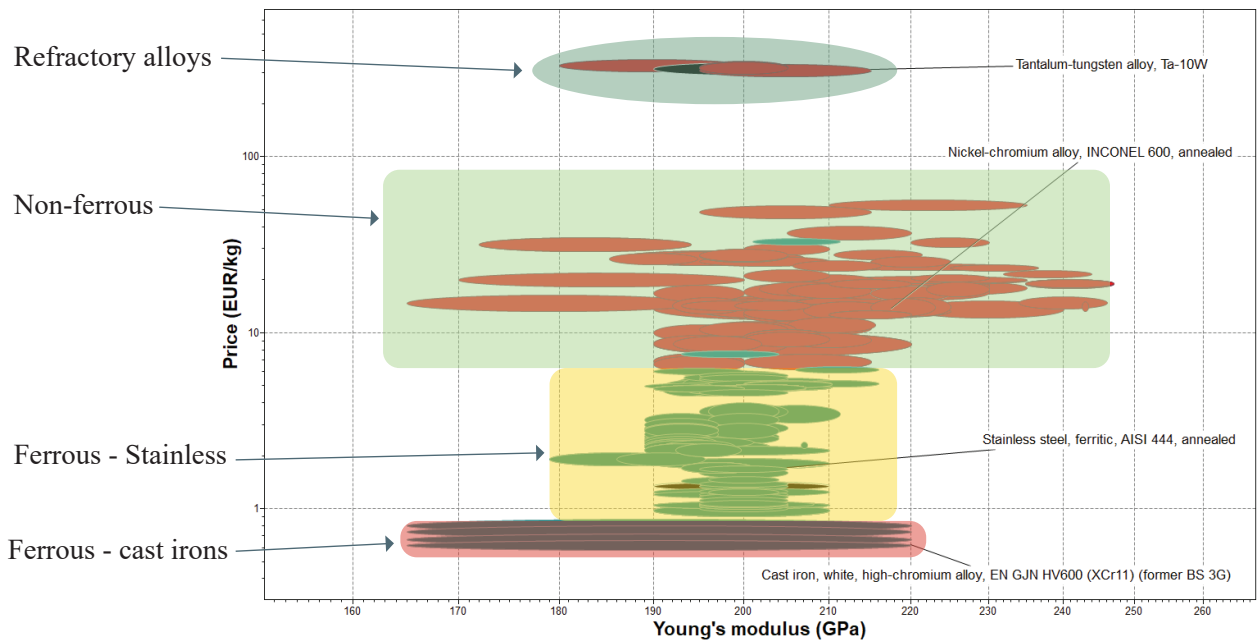
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44 Data extracted from CES Edupack 2018

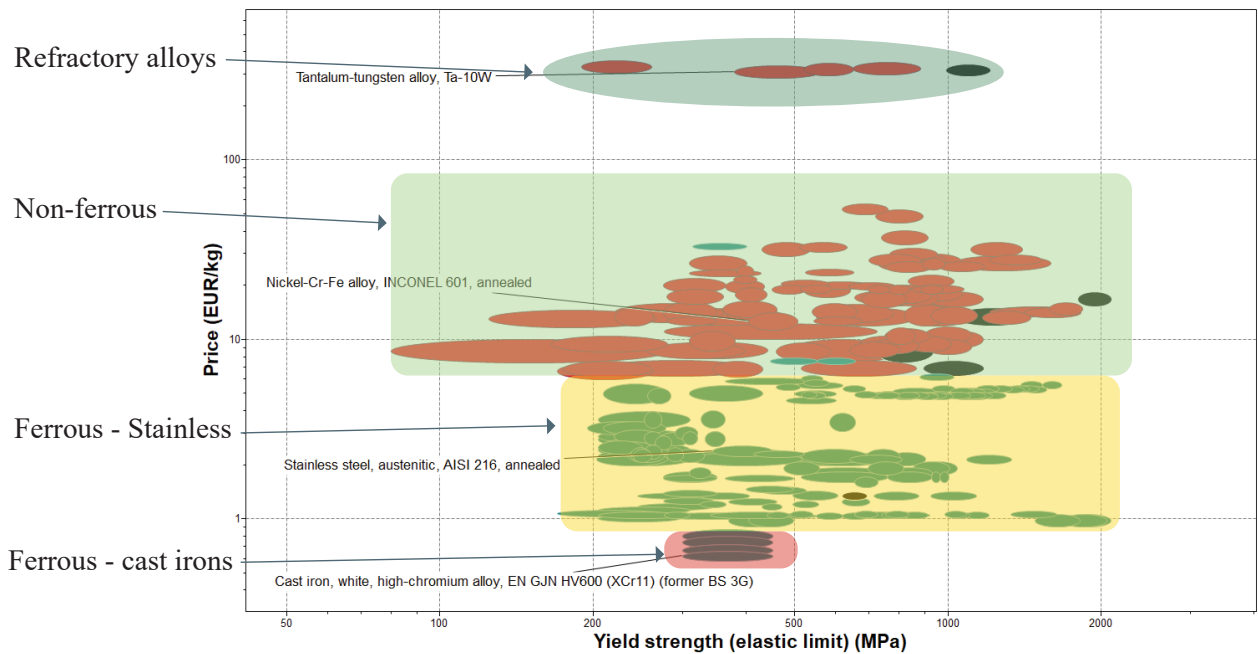*Figure 28: Price vs Young's modulus comparison of materials [45]*

Figure 29: Price vs Yield strength comparison of materials [46]

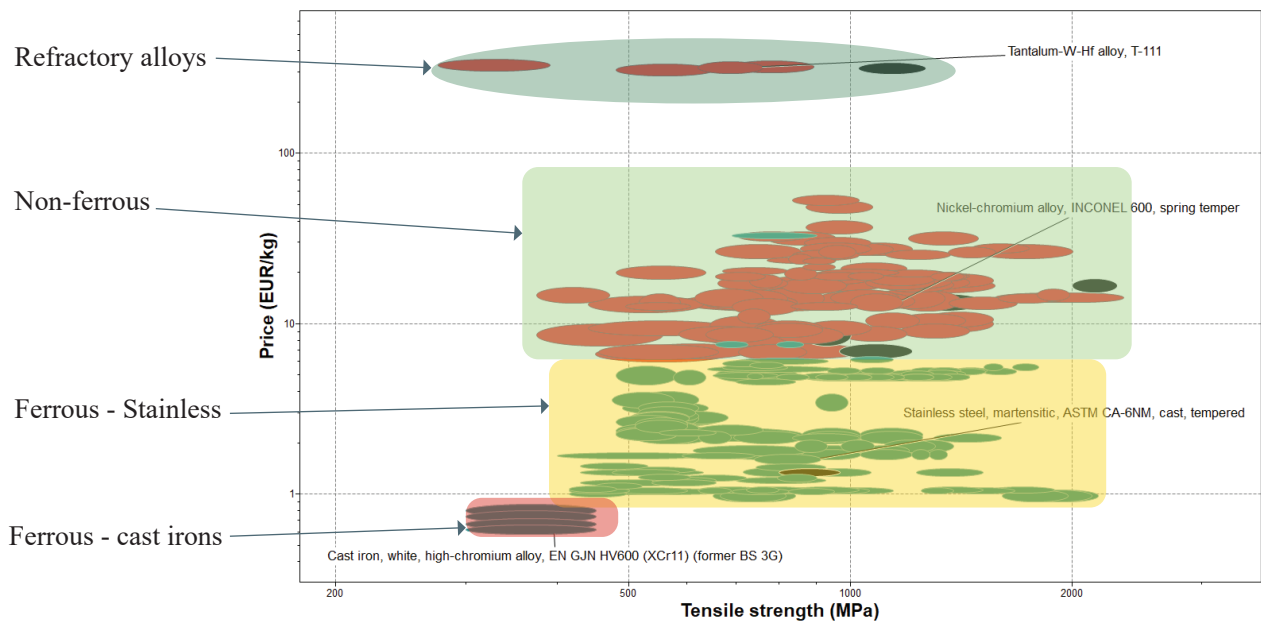45-46 Data extracted from CES Edupack 2018

Figure 30: Price vs Tensile strength comparison of materials [47]

In *figure 28* it can be observed that the materials left are roughly grouped in four areas based on their price range. They are going from cast irons as the cheapest group to refractory alloys as the most expensive group. Based on their young's modulus, all the materials remain in the same order of magnitude. However, they exhibit considerable differences in their structural values. In this sense, further knowledge is necessary to decide for a material with proper structural capacity. Therefore, a comparison price versus yield strength is necessary (*figure 29*). It is important to remark that even when the materials remain in the same order of magnitude based on their young's modulus, their price have considerable differences. At this point no material is discarded. However, refractory allows and non-ferrous materials start to slide out of the comparison as they are considerably more expensive. If the reusable 3DCP slab aims to demonstrate feasibility of production and implementation, the cheapest it becomes, the more possibilities it has to achieve such objective.

A similar pattern arises when comparing the price versus the yield strength of the materials. Here again, four groups are formed based on their price range. All the materials remain in the same order of magnitude based on their yield strength. However, they exhibit considerable differences in the former value. Furthermore, it can be appreciated that ferrous-stainless steel have roughly the same yield strength as non-ferrous materials but at a much cheaper price. From here, it can be almost concluded that refractory alloys and non-ferrous materials are discarded as they are much more expensive than ferrous stainless steel and cast irons.

The yield strength value is important because it describes the capacity of the material to resist a permanent deformation. Applied to the research, this means that the more yield strength the material

47 Data extracted from CES Edupack 2018

has, the more chances it has to remain geometrically as designed. This is important as permanent deformations also come with a change in the structural behaviour of the material. Therefore, if a material deforms, its structural capacity changes. If the connections of the reusable 3DCP slab are deformed they have to be changed as their structural capacity cannot be predicted. Besides the structural performance, this has a direct impact in the feasibility of the design. A periodical change of the connections represents a hindrance for the feasibility of the reusable 3DCP slab as it means more labour involved and a higher price.

Figure 30 displays the comparison based on the price and the tensile strength of the materials. The most important scenario to notice is that here again, stainless steel has the same range of tensile strength as non-ferrous materials but at a much cheaper price. Furthermore, cast-irons fall behind in such structural capacity and therefore, they can also be discarded.

The tensile strength value is important because it describes the capacity of the material to remain uncracked or or without break. This is such an important parameter for the design as the ability of the material to withstand relatively high stresses without breaking is essential.

Based on the criteria presented previously, stainless steel is selected to be the material of the connections and its properties have been applied in all the further structural analysis.

Besides the information input in Ansys Workbench in the previous analysis and the information of the connections' material, information about the type of contacts between the block connections and the concrete elements are input. Such information is as follows:

- Frictional contact concete-to-concrete (slab-to-wall) with a value of 0,4.
- Rough contact steel-to-concrete (insert block-to-wall)
- Frictional contact steel-to-concrete (insert block-to-slab) with a value of 0,6

The selection of a rough contact is due to the assumption of a high tightness between the insert block and the precast wall achieved by torque. The use of the insert adjustment bars explained before help achieving this behaviour.

The symmetry feature is once again input in Ansys Workbench to perform the structural analysis. The following results are obtained by the simmulation (*image 29*).
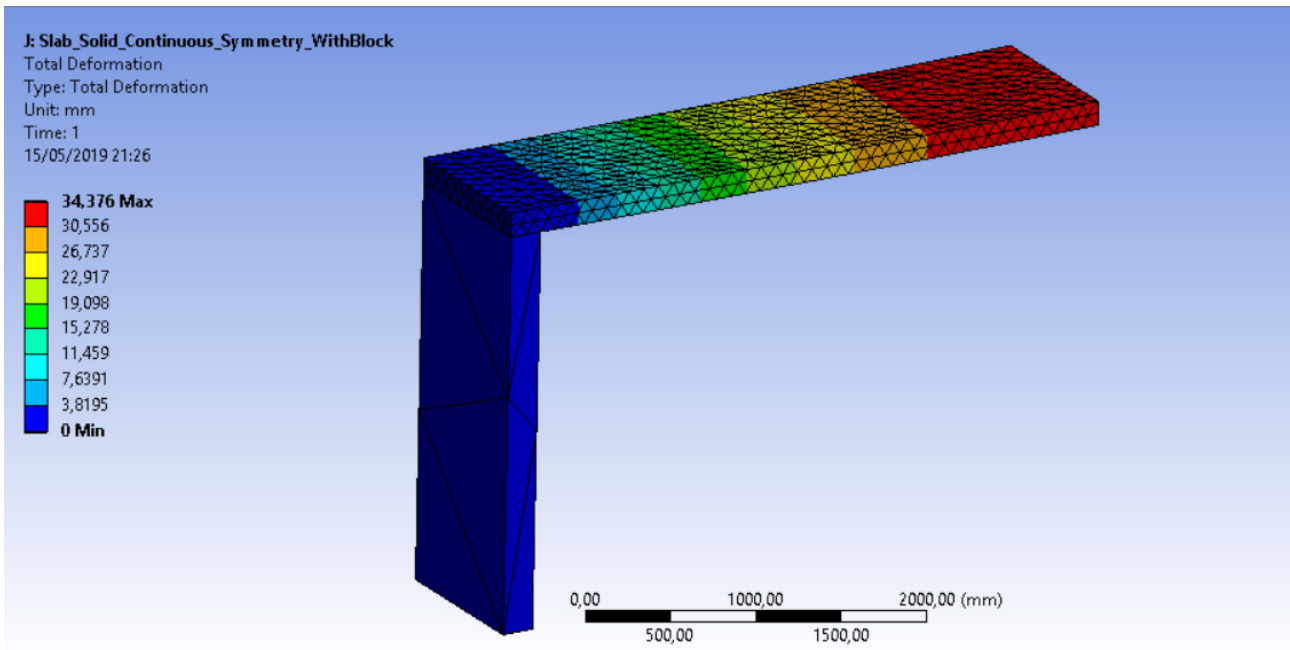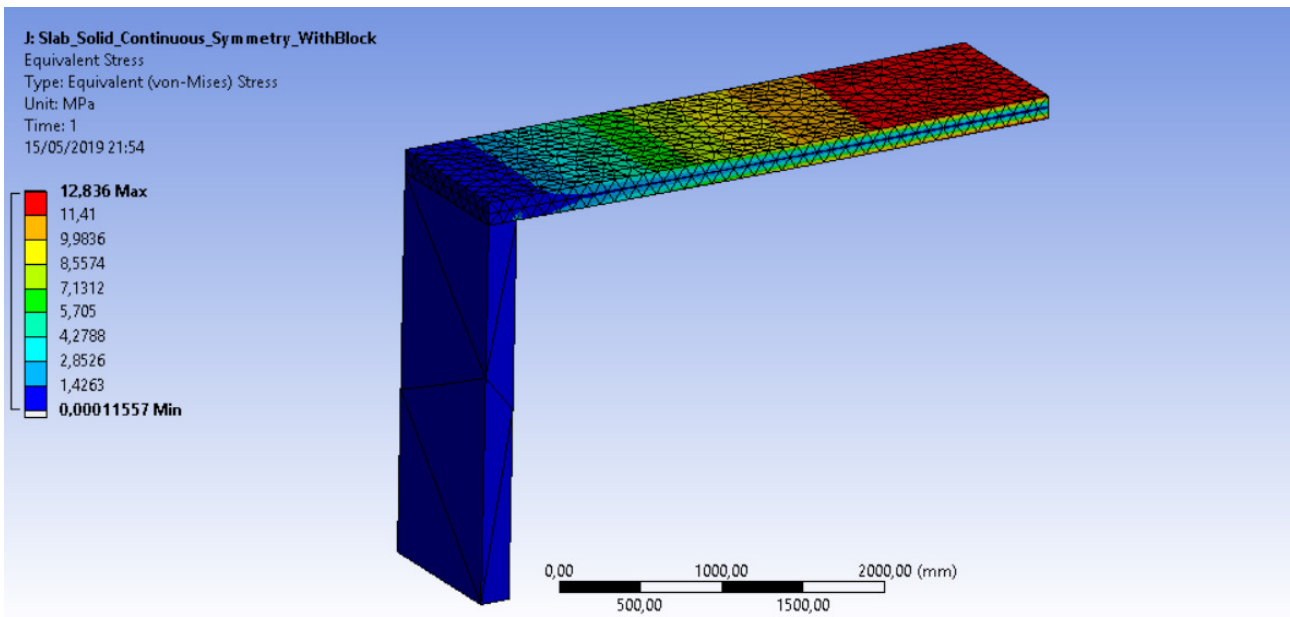
Image 29: Deflection of the slab [48]

Image 29: Equivalent stress of the slab [48]

The results indicate a maximum deflection of 34,38 millimetres at the middle of the slab. This represents a very minimal difference compared to the calculation without mechanical connections. The difference is barely 0,2 millimetres. The maximum stress is also barely decreased compared to the first calculations. Such results are obtained because the tolerances set for the 3DCP reusable slab and consequently to the design of the connections, are set to 10 millimetres. This represents the gap between the steel insert blocks and the pockets of the concrete elements. Therefore, even when moment-rotation is achieved by the slab, the pocket's boundaries do not make full contact with the

48 Data extracted from Ansys Workbench 19,1

steel insert blocks due to such 10 millimetres tolerance. *Image 30* shows the behaviour described.
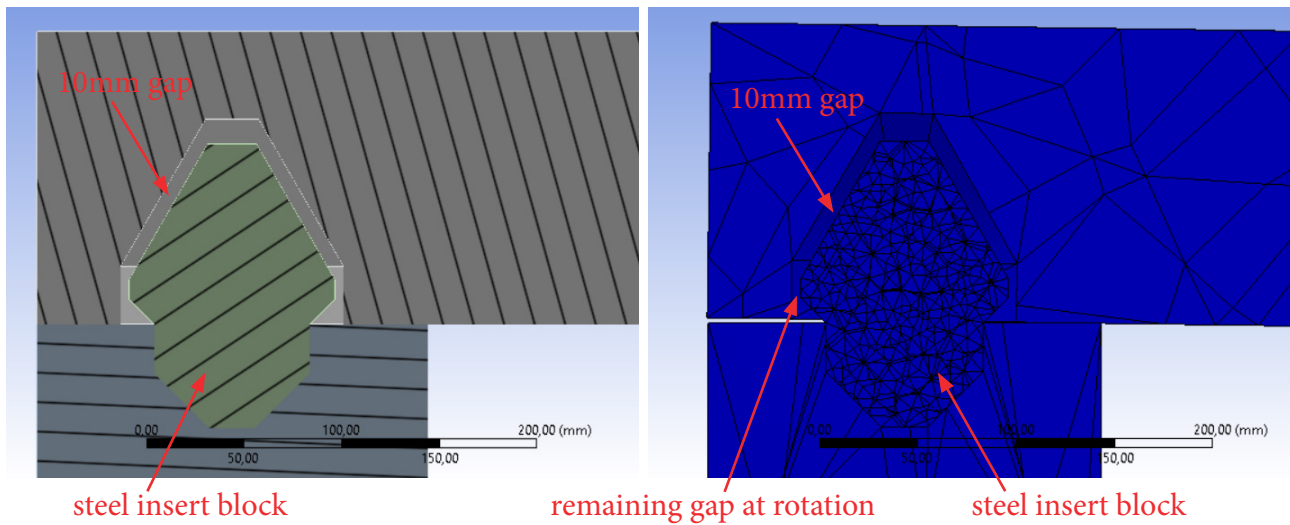
Image 30: Left: Original state of the connection without applied loads.
Right: Connection behaviour with the application of loads [49]

Two approaches can be taken from here: to reduce the tolerances to close the gaps or to design moment connections as the ones reviewed in the existing demountable systems.

Reducing the tolerances is not adequate as this would impact the feasibility of the production process and its capabilities. This results in an unrealistic approach.

Therefore, the need to design moment connections is obvious. The net horizontal displacement of the slab due to load can be neglected as it is almost inexistent. The load application results in the rotation of the slab that uses the corner edge of the precast wall as a pivot. Therefore, the highest displacement to restrict is a rotation displacement. As reviewed in the existing cases, the use of dowels is a common practice.

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49 Data extracted from Ansys Workbench 19,1

Second connections' design

Just as the first design of the dry connections, the separation of functions to ease the disassembly of the building elements is crucial in the design of the moment connection. To facilitate the assembly on site and decrease the time needed, clustering of the moment connections is to be performed. This means that the connection is already a sub-system previously assembled at the manufacture warehouse and only installed to connect the slabs on site. Clustering also means that the connection can be further disassembled into sub-elements. This can be done according to the specific function of the sub-element. Length adjustment, centers of the geometry to reduce the effects of tolerances and connection of dowels are some of those functions. However, a fine balance needs to be achieved. Too many sub-elements complicate the clustering and too few sub-elements minimize the level of decomposition of the connection.

Connection design

Based on the principles of DfR and design tolerances previously reviewed, the design of the moment connection was made. This connection consists of two stainless steel "T" dowels connected by stainless steel cylinders that allow for adjustment in the length of the "T" inserts. The "T" inserts then are tightened to stainless steel profiles cast in the precast wall and in the 3DCP reusable slab. A schematic representation is shown in *figure 31*.
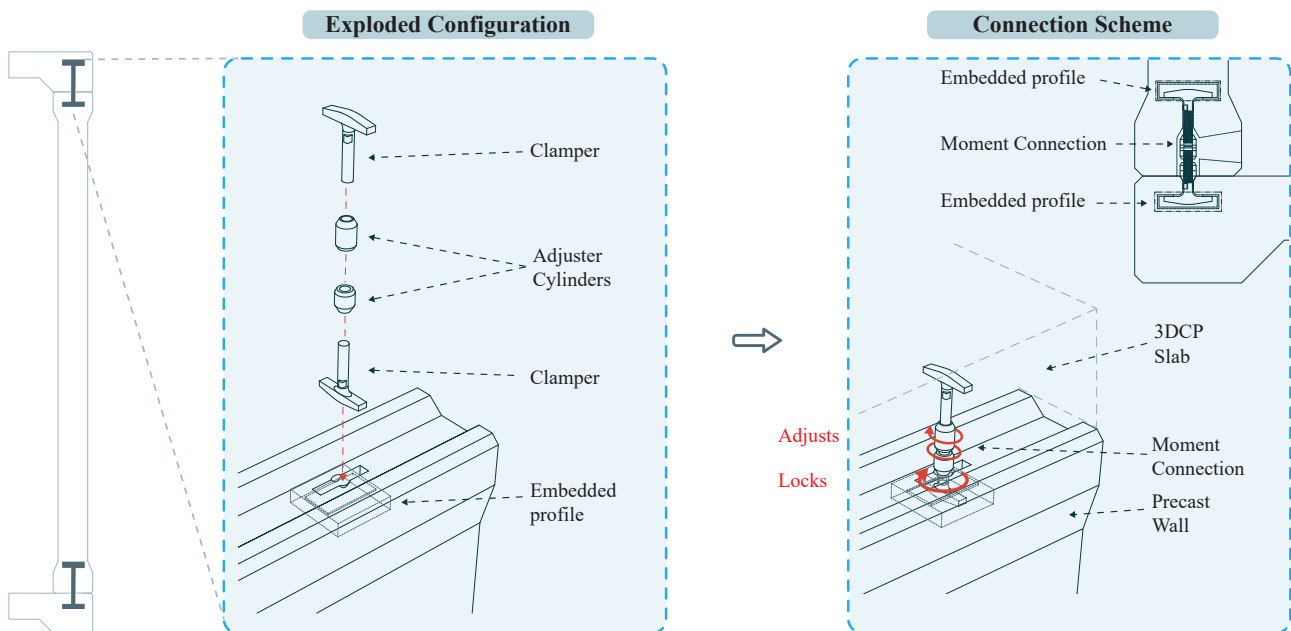
Figure 31: Conceptual design and assembly of the moment connection

"T" dowels are inserted in parallel to the front face of the precast wall. Later, a clockwise rotation of 90° fixes them to the steel plate embedded in the precast wall. Subsequent rotations will tighten the cylinder and the "T" insert. This will pull the "T" inserts up and the cylinders down. In this way, a proper fixation to the precast wall is achieved with only a few rotations.

The installation is completed once the slab is supported on the wall. Here, access to the connection is needed to tighten the top "T" dowel to the slab. The principle of tightening is the same as in the bottom "T" dowel. A clockwise rotation of 90° fixes the top "T" dowel to the steel plate embedded in the 3DCP slab. Subsequent rotations tighten the cylinder and the "T" insert. This pulls the "T" inserts down and the cylinders up. In this way, a proper fixation is achieved between the precast wall, the moment connections and the reusable concrete slab.

The result of this design is a semi-hidden connection. The advantages compared to the previous design are several: First, utilises much less amount of material (stainless steel), which lowers the cost of the connection. Second, there are fewer connections to be made on-site, which eases the assembly process. Third, the "T" dowels are a simple and unique design. Applying the DfR principles, this means that the dowels can be placed in any arrangement. Furthermore, the orientation of their installation does not impact their structural performance.

Moreover, the cylinders are of the same radius (15 millimetres). This means that the no change of tools is needed to tighten both of them. The difference however, lies in their length. The bottom cylinder is shorter and its tread is uni-directional. This means that the rotation will always have the same effect on the insert. The top cylinder is a little longer as it connects the two "T" dowels. A difference in length also helps the building workers to differentiate it from the bottom cylinder, which due to its function is different in thread. The top cylinder has two threaded cavities with opposite directions in the tread. This is because it has to pull both "T" dowels together. This means that the direction of tightening is opposite by nature. Therefore, either one of the "T" dowels has a "negative thread" or the cylinder has two opposite threads. The decision has been made for the cylinder to have two opposite treads. This keeps the number of different parts low. Furthermore, the orientation in which the top cylinder is installed does not affect the connection procedure. Having two opposite threads means that such threads will always be correct for any of the "T" dowels at top and at the bottom. The cylinders' geometry help with centering the dowels and keep them vertical during the assembly process. This makes it easier for the building workers as no further action is needed to keep the connections vertical when the concrete elements are being put in place. Furthermore, the geometry of the cylinders help to counteract the tolerances. The wider the pockets are, the lower the cylinders are installed; the smaller the pockets are, the higher the cylinders are installed. This then means that horizontal differences of the pockets are compensated by vertical placement of the cylinders. The dimensions presented also take this into account.tical placement of the cylinder. The wider the pockets are, the lower the cylinders.

Figure 32 shows the general scheme of the connection.
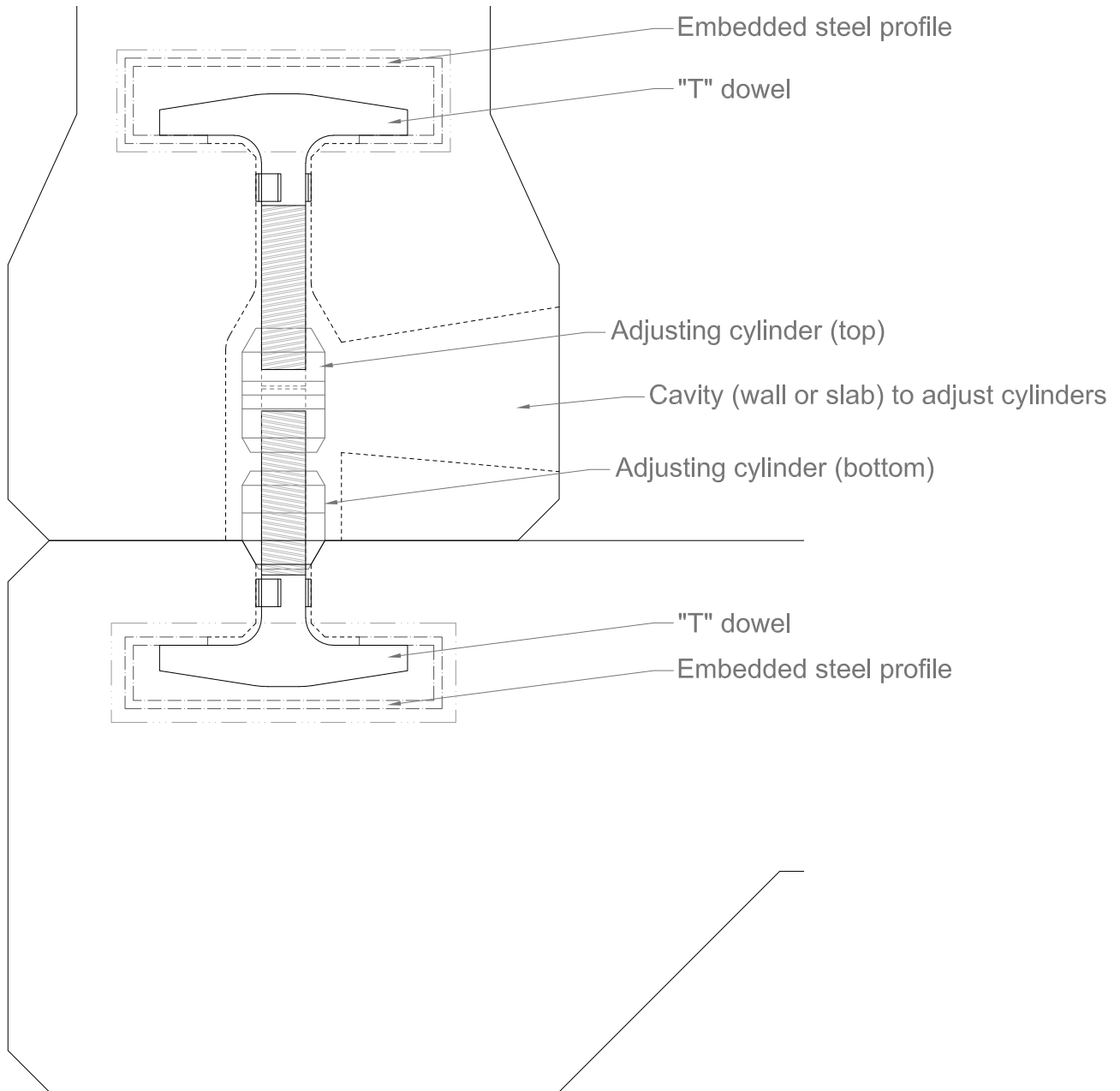*Figure 33* shows general measures of the connection.

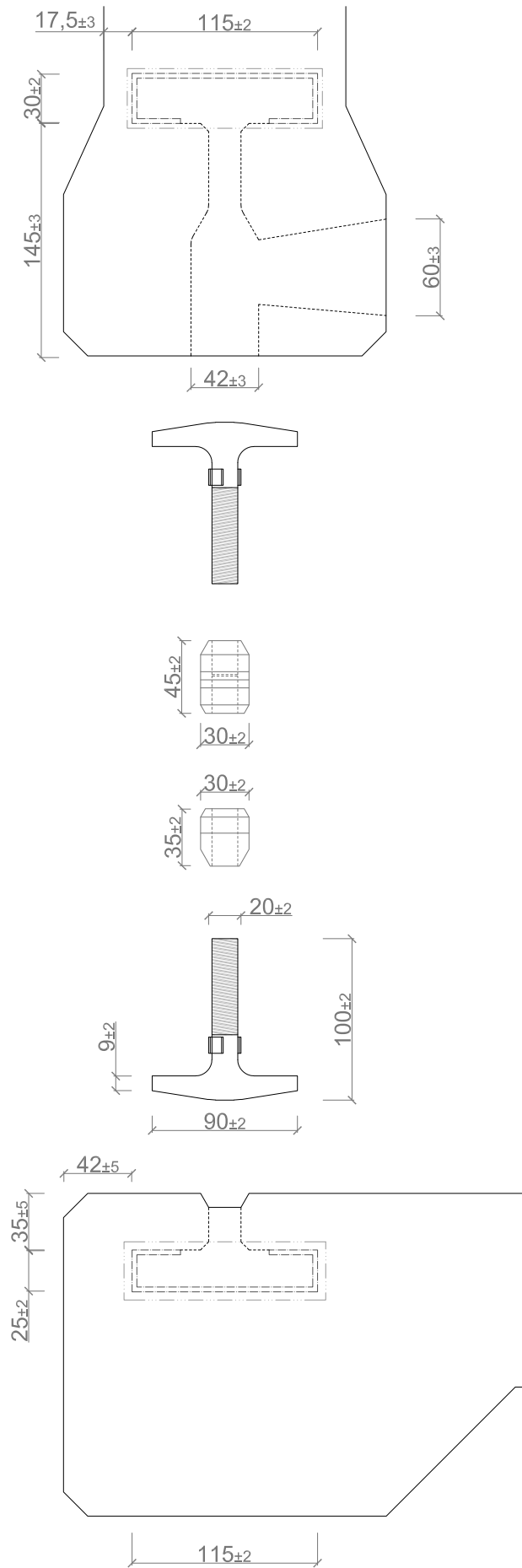*Figure 32: General scheme of the connection*

*Figure 33: General dimensions (in mm) of the moment connection*

Thedimensions of the moment connection take into account the design tolerances for precast concrete and for the 3DCP concrete slab. The dimensions given then are mechanically proper even in the worst-case scenario. This means that the dimensions allow for a proper mechanical performance even when the tolerances are the largest allowed both in size and position of the moment connection elements.

The proper fit of the connection has been checked with a 3D model built in Rhinoceros. The impact of such connection in the final deflection of the slab has been checked with Ansys Workbench 19.1.

Performance validation

A performance validation of the moment connection has been made using the same parameters applied in the former structural analysis.

For this validation, a simplified geometry of the connection is made. Here, the use of cylinders is neglected and replaced by a continuous piece "T" dowel. This still represents the basic principle of the moment connection but reduces the amount of nodes to calculate. Therefore, the time of calculation is also reduced. The following results are obtained by the simulation (*image 31*).
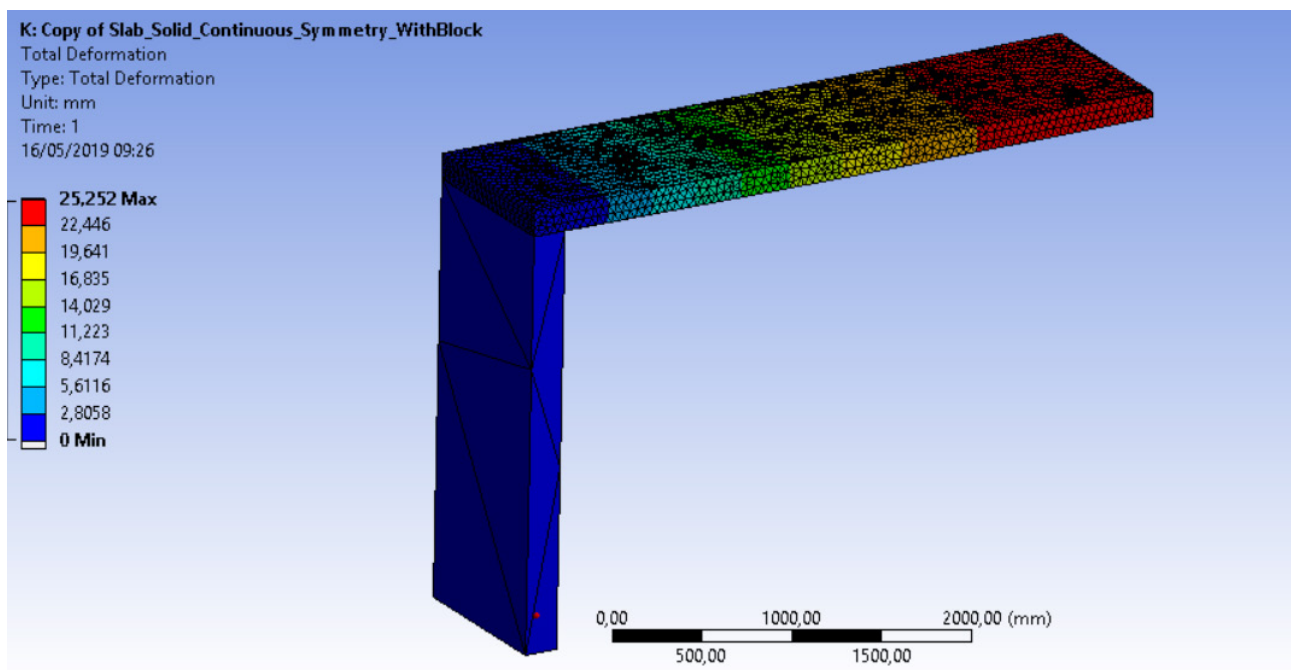
Image 31: Deflection of the slab [50]

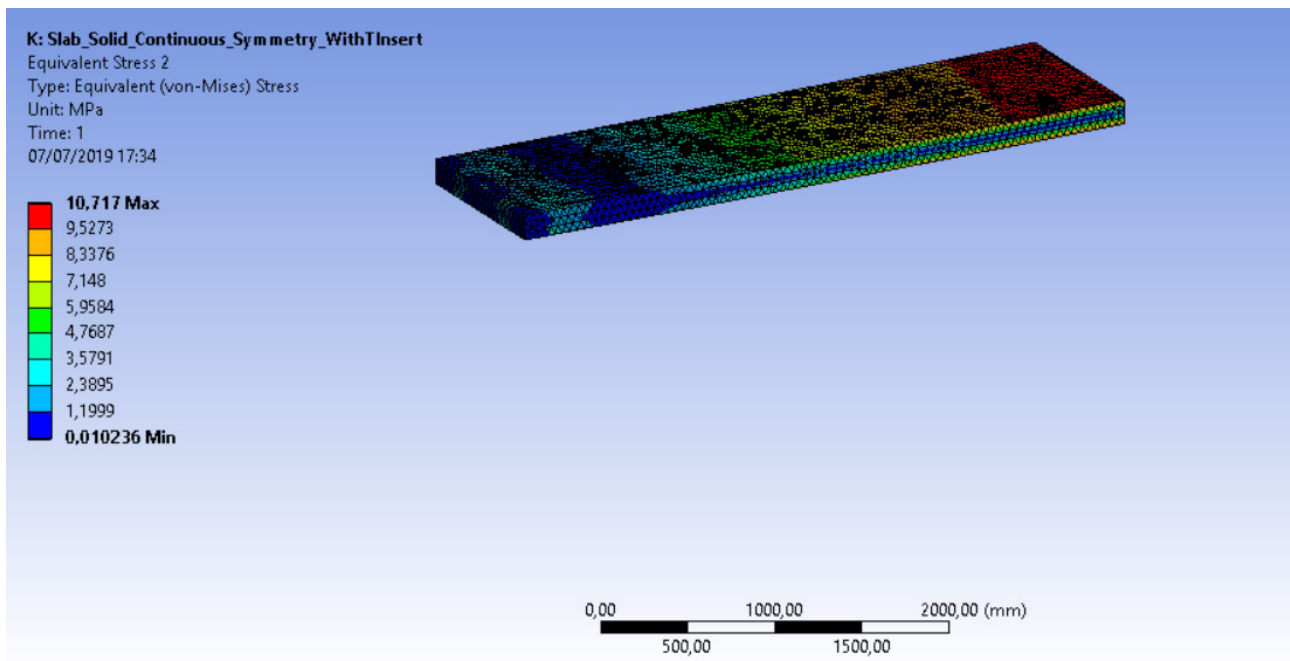50 Data extracted from Ansys Workbench 19,1

Image 31: Equivalent stress of the slab [50]

The results indicate a maximum deflection of 25,25 millimetres at the middle of the slab. This already represents a considerable difference compared to the calculation of the block connection. The difference is of 9,15 millimetres. This demonstrates the correct performance of the designed moment connection of limiting the maximum deflection of the slab. However, the deflection calculated is still higher than the maximum deflection allowed by norm. From here, two approaches can be taken: First, to increase the volume of the connection. This consequently would increase the strength. However, by increasing the connection, the most expensive material of the reusable 3DCP slab is also being increased: *the stainless steel.* The second approach to be taken is to increase the mass of the slab. The increase of its cross-section also increases its stiffness. Moreover, the increase is in the cheaper and less contaminant material of the reusable 3DCP slab: *the concrete*.

Based on this analysis, a geometry exploration of the concrete slab is done to reduce the current deflection. Such geometry exploration is shown further in tis research.

Third geometry approximation of the slab

The third geometry exploration is focused on reducing the maximum deflection of the reusable concrete slab below 16,67 millimetres. From here, two scenarios can be explored: First, reduce the thickness of the slab. This results in the reduction of its self-weight. However, this also results in the reduction of the stiffness of the whole slab due to a smaller second moment of area. The last parameter has a major impact in the final deflection value. Therefore, it is decided to increase the cross-section of the slab to achieve a major second moment of area.

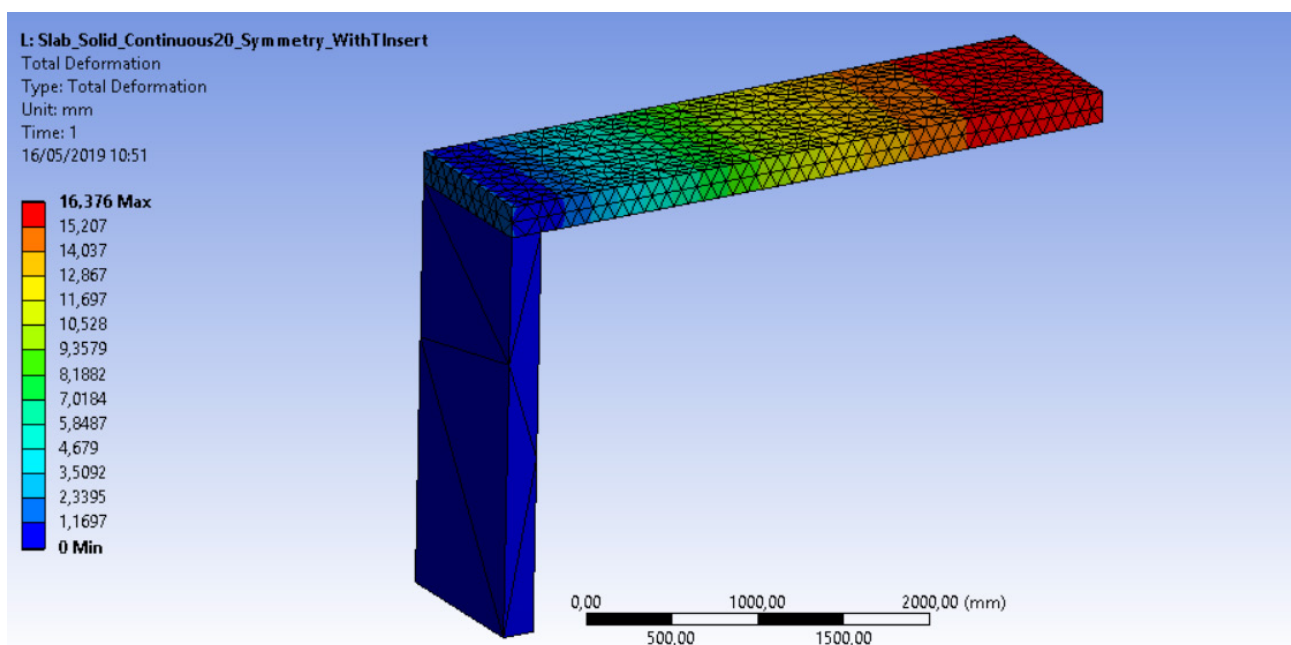50 Data extracted from Ansys Workbench 19,1

An automatic topology optimisation to achieve a proper distribution of mass is not possible in this approach. The reason is that computational calculations rely in linear stress and mass behaviour. However, the frictional contact on which the dry connections rely, results in a non-linear stress behaviour of the slab. This means that the frictional contact causes first a linear stress increase, but once the coefficient of friction is surpassed, the slab experiences displacement, which reduces the stress values. This is then a cyclic behaviour that gets interrupted only when the friction coefficient is not surpassed. For this reason it is not possible to perform an automatic topological optimisation. It is important to remember that topological optimisation is not the main goal of this research. Therefore, the relevance of the research is not affected by the lacking of this feature. The geometry exploration has been done manually.

The first step then has been in the increase of the thickness of the slab. This has been done in steps of 10 millimetres until a deformation under 16,67 millimetres is achieved. *Table 7* presents the results of each step of increase.

Slab Thickness (mm)	Maximum Deflection (mm)
150	25,25
160	22,84
170	20,31
180	18,19
190	16,37

Table 7: Maximum deformation of the reusable 3DCP slab with different thickness [51]

Based on these calculations, a slab with a thickness of 190 millimetres presents a deformation within the structural limits set by the norms. *Image 32* shows the results of the structural simulation.
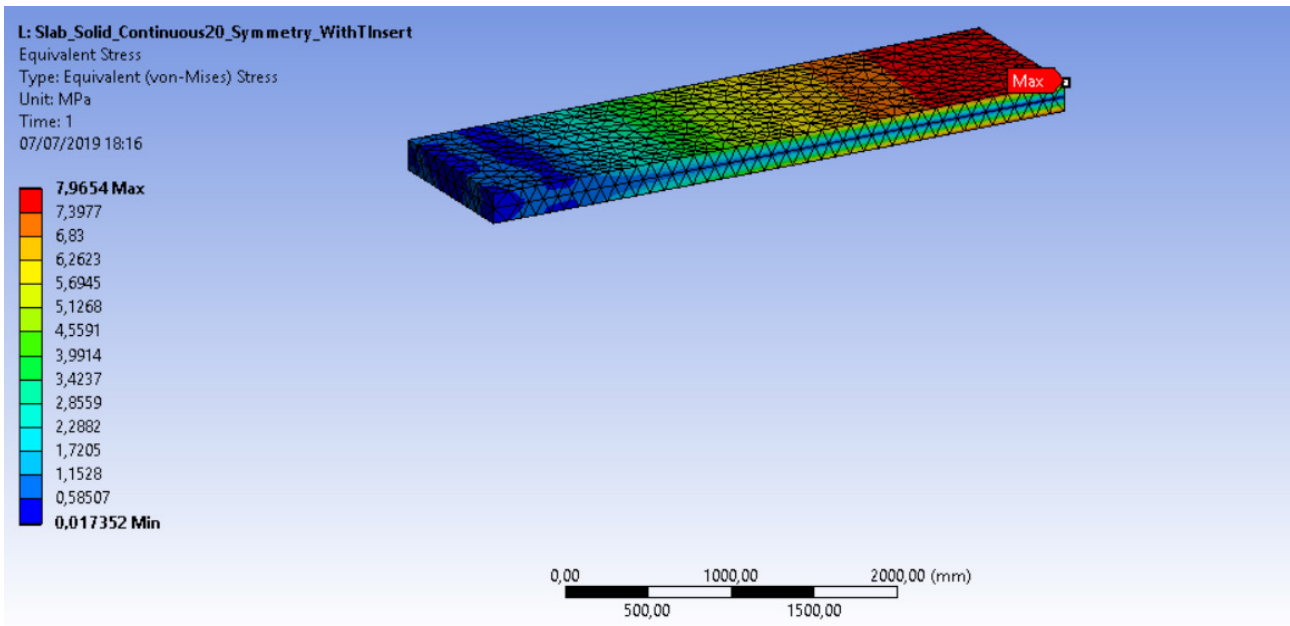

Image 32: Deflection of the slab [52]

51-52 Data extracted from Ansys Workbench 19,1

L: Slab_Solid_Continuous20_Symmetry_WithTInsert
Equivalent Stress
Type: Equivalent (von-Mises) Stress
Unit: MPa
Time: 1
07/07/2019 18:16

7,9654 Max
7,3977
6,83
6,2623
5,6945
5,1268
4,5591
3,9914
3,4237
2,8559
2,2882
1,7205
1,1528
0,58507
0,017352 Min

Image 32: Equivalent stress of the slab [52]

However, this reusable 3DCP slab is heavier and with more material utilisation per m² compared to the slab of the case-study. A comparison between both slabs is presented in *table 8*:

		Case-Study Slab			Reusable 3DCP slab (190mm)		
		Concrete	Steel	*Total*	Concrete	Steel	*Total*
Material Related Costs	**Material Volume** (m3)	0,148	0,002	**0,15**	0,187	0,003	**0,19**
	Material Weight (kg)	340,17	17,53	**357,70**	430,88	22,20	**453,08**
	Price (€)	17,25	10,53	**27,78**	21,85	13,34	**35,19**
	Embodied Energy (MJ)	292,21	594,14	**886,34**	370,13	752,57	**1122,70**
	CO2 Emissions (kg)	43,54	43,64	**87,18**	55,15	55,28	**110,43**
Process Related Costs	**Embodied Energy** (MJ)	0,000	73,435	**73,43**	0,000	110,000	**110,00**
	CO2 Emissions (kg)	0,00	5,50	**5,50**	0,00	8,30	**8,30**
Transport Related Costs (50 km)	**Embodied Energy** (MJ)	12	0,620	**12,62**	15	0,790	**15,79**
	CO2 Emissions (kg)	0,87	0,05	**0,92**	1,10	0,06	**1,16**
Disposal Related Costs	**Embodied Energy** (MJ)	68	3,500	**71,50**	86	4,400	**90,40**
	CO2 Emissions (kg)	4,80	0,25	**5,05**	6,00	0,31	**6,31**
End-of-Life		Landfill	Landfill		Reuse	Reuse	
Totals	**Embodied Energy** (MJ)	372,21	671,691	**1043,90**	471,13	867,763	**1338,89**
	CO2 Emissions (kg)	49,21	49,44	**98,65**	62,25	63,94	**126,20**

Table 8: Comparison of material use and related costs per m² of the concrete slabs [53]

In this step, it can be concluded that dry connections lead to more material use. This is because a larger second moment of area is needed to decrease the deflection experienced by the slab. More material use consequently leads to more environmental impact in the form of CO_2 emissions and embodied energy of the reusable concrete slab.

52 Data extracted from Ansys Workbench 19,1
53 Data extracted from CES Edupack 2018

However, its possible that not all the material is needed across the cross section of the slab. If material reduce is accomplished then also the environmental impacts are lower. For this, a topology optimisation is performed. Again, an automatic topological optimisation is not possible due to the non-linear stress behaviour of the reusable slab. Therefore, a manual optimisation is made based on the principle of the functioning of T-beams (*image 33*).
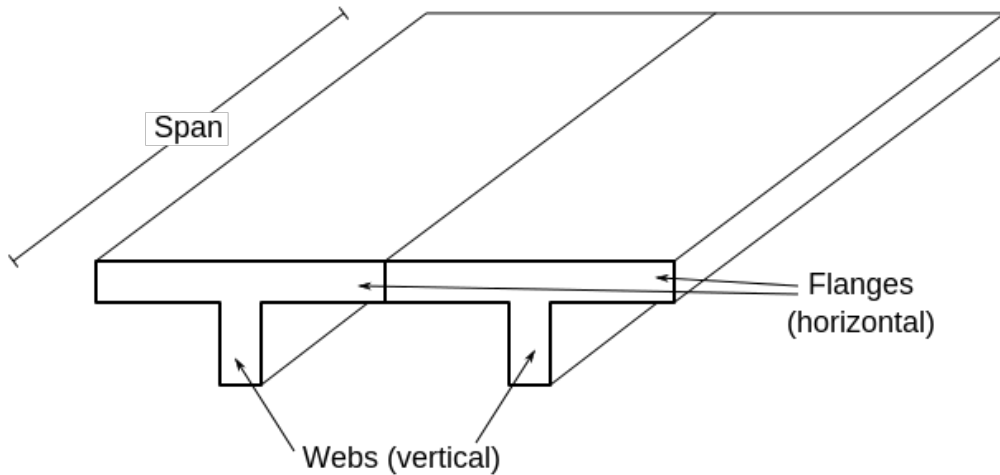

Image 33: T-Beam

The T-beam bases its principle in the increase of bending stiffness due to the increase of the second moment of area. This is achieved through the use of two intersecting geometries that give form to a "T" shape. The top (horizontal) cross section works as a compression member to resist the compression stresses. The vertical section resists shear stresses and provides greater stiffness for the bending forces. The following geometry exploration of the reusable 3DCP slab is based on this principle.

Fourth geometry approximation of the slab

A manual optimisation has been made based on the T-Beam principle. Therefore, the start is to leave the central axis of the reusable slab with a height of 190 millimetres and decrease the height progressively towards the longitudinal edges. A scheme of this principle is shown in *figure 34*.
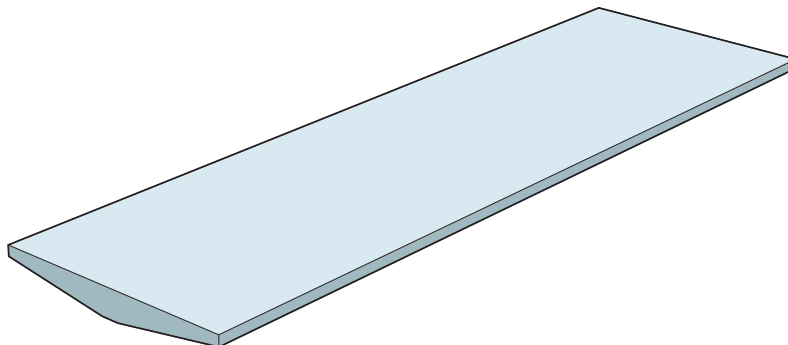

Figure 34: T-Beam principle applied to the reusable slab

This design approach seems to be a sensibl solution to economise the material of the reusable 3DCP slab. However, there are a couple of noticeable issues at first glance. First, the geometry difficults the transportation as the whole slab would only rest on its central axis. This might lead to a balancing of the slab while being transported as the longitudinal edges do not make contact with any other element. The second issue is that such "T" geometry is also needed in the wall to allow an effective connection. This already complicates the production of both of the concrete elements as a special geometry is needed.

Consequently, the decision is made to leave the contact areas with a continuous section of 190 millimetres of height and explore the "T" shape geometry only in the free span of the reusable concrete slab. A scheme of this approach is shown in *figure 35*.
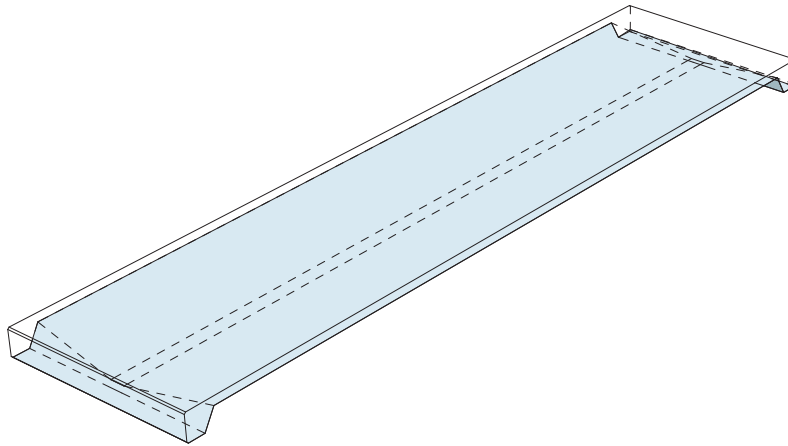

Figure 35: Reusable 3DCP slab T-shape with continuous section in the connection area

The connection remain as originally with this approach. Furthermore, the transportation is eased as both ends of the slab are flat. Therefore, slabs can easily be stacked on-top. However, this scenario presents an issue. There is not enough space below the slab to insert and maniuver tools for the tightening of the dry moment connections. Therefore, it is decided to create also a slope of 6 centimetres in the central axis. This space will be increasing towards the longitudinal edges. Therefore, according to the position of the tools-insert pocket, there will always be space for a building worker to properly maniuver the tools. *Figure 36* presents the scheme of this approach. Figure 37 illustrates the overall concept of this geometry exploration.

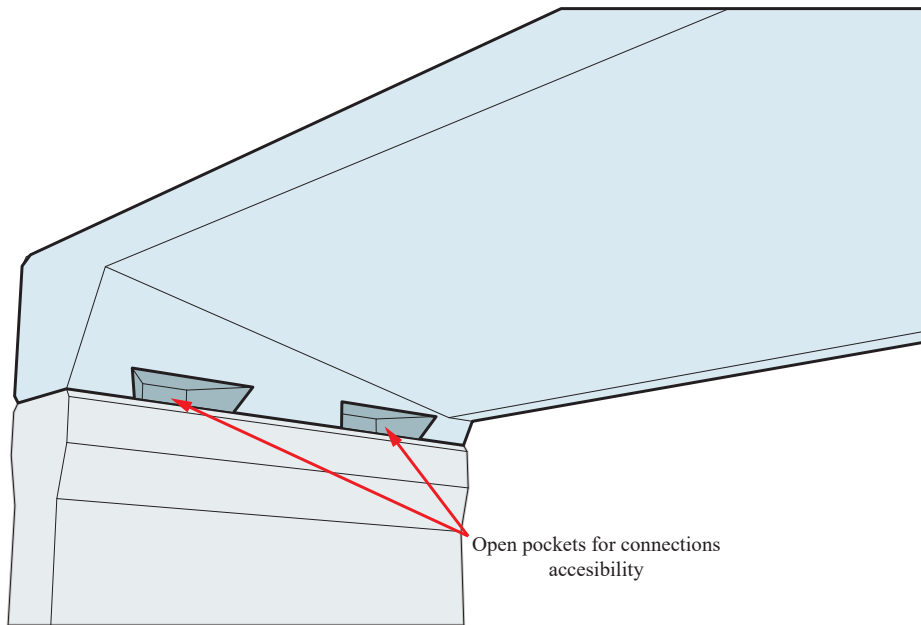Open pockets for connections
accesibility

Figure 36: Perspective from below the reusable 3DCP slab. Pockets location for tightening of the moment connections
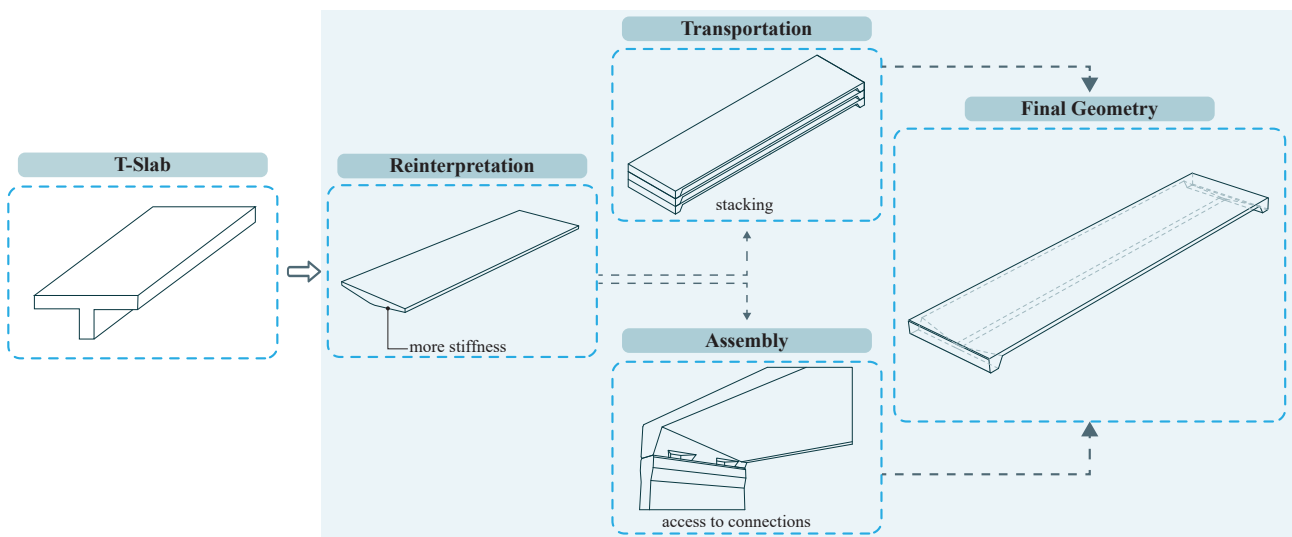

Figure 37: General approach for the design of the T-slab

From this point, multiple configurations of geometry have been explored. The principal parameters have been the height and thickness of the central axis and the thickness of the longitudinal edge of the slab. The conlusions after these configurations are several: First, the height of the central axis is the most influencial parameter to control the deflection of the reusable slab. This is because this part provides the central stability to the geometry. A minor change in its height results in large deflection differences. Second, the differences of thickness of the central axis are not as relevant to control the deflection of the reusable slab. The thickness can fall in a range, between 100 and 150 millimetres in which the difference practically does not affect the deflection value of the reusable 3DCP slab. Third, the height of the longitudinal edges plays a secondary role. This means that it affects the deflection value of the slab but it is not as relevant as the height of the central axis. This is because the slope between the central axis and the longitudinal edges provides with stiffness to the longitudinal edges. Therefore, the bending forces are transmited along such slope to the central axis of the reusable slab.

Table 9 provides an overview of the results of such explorations. An optimal geometry has been found. The sizes of the reusable slab are highlighted in green. An schematic representation of such sizes is given in *figure 38*.

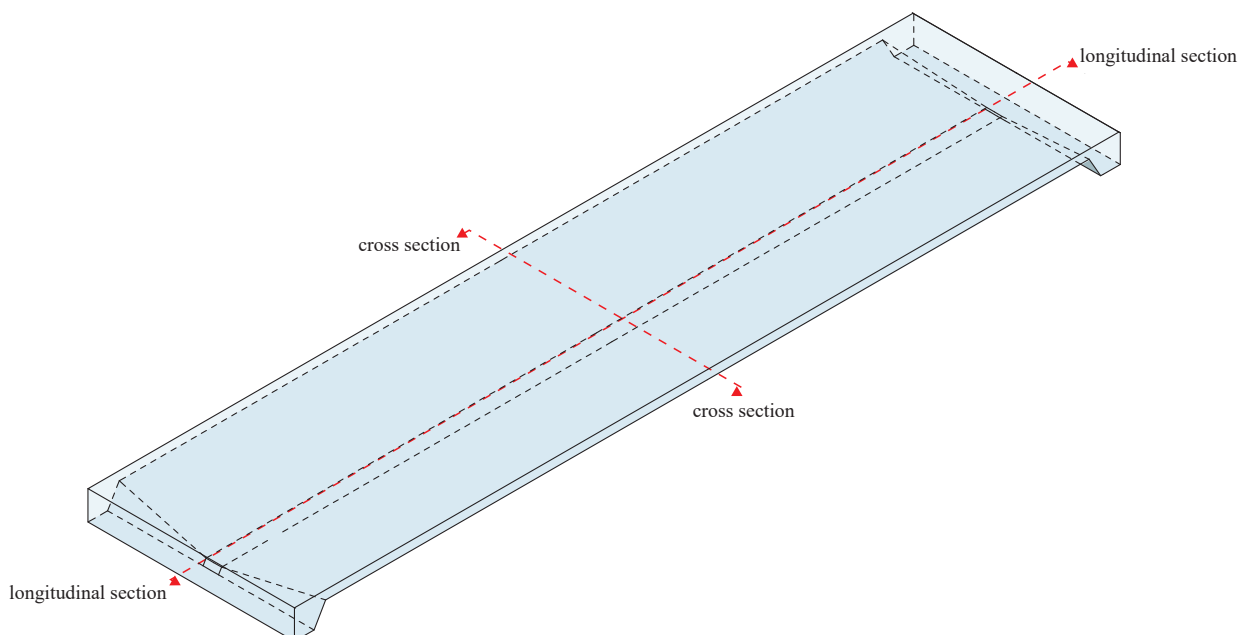| Exploration	Beam Height (mm)	Beam Width (mm)	Connection Height (mm)	Mass (t)	Deflection (mm)	Stress (MPa)
0	150	200	85	1,15	50,81	21,83
1	160	200	85	1,2	44,12	20,42
2	170	200	85	1,25	38,56	19,11
3	180	200	85	1,31	33,88	17,91
4	190	200	85	1,36	29,94	16,79
5	200	200	85	1,41	26,61	15,78
6	210	200	85	1,47	23,76	14,86
7	220	200	85	1,52	21,32	14,02
8	230	200	85	1,57	19,21	13,24

Table 9: Comparison of T-Slab geometries [54]

Figure 38: General dimensions of the reusable 3DCP slab

54 Data extracted from Ansys Workbench 19,1
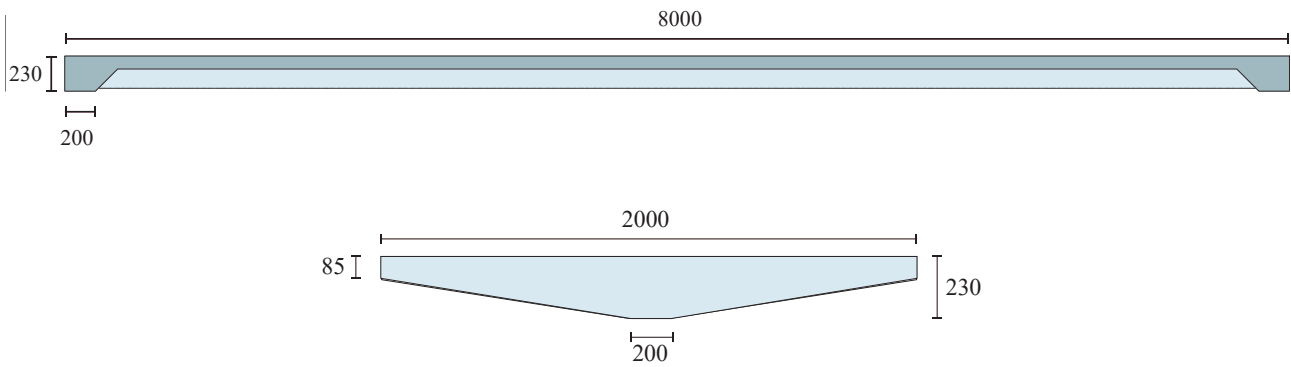
Figure 38: General dimensions of the reusable 3DCP slab

Performance Validation

A strutural validation has been made to assess the feasibility of this geometry. The material properties of concrete, loads and contact coefficients used for this validation have the same values as in the former geometry validations. It is important to note that this validation has been made without connections' contacts. An average of 3 millimetres of deflection disminution was noted with the use of connections. Therefore it was decided to perform the validations without such geometries to decrease the time of calculation and with a rough expectation of 19 millimetres of deformation. *Image 34* shows the results of the structural analysis.

Image 34: Deflection of the slab [55]

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55 Data extracted from Ansys Workbench 19,1

Image 34: Equivalent stress of the slab [55]

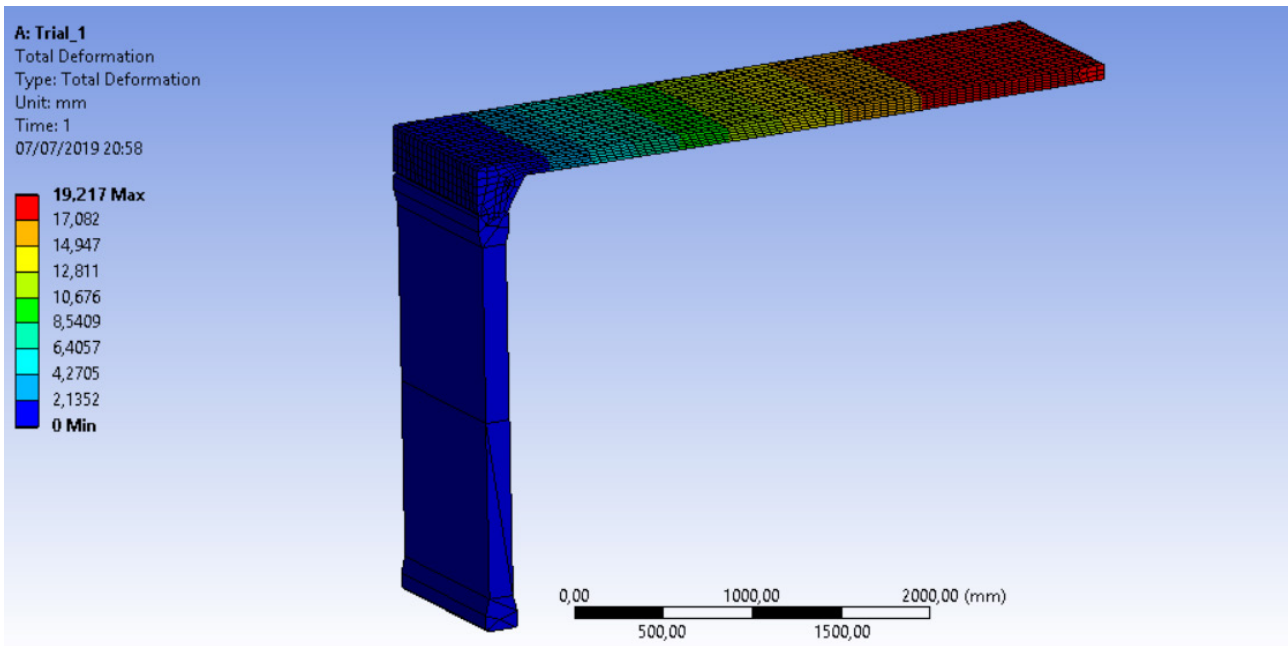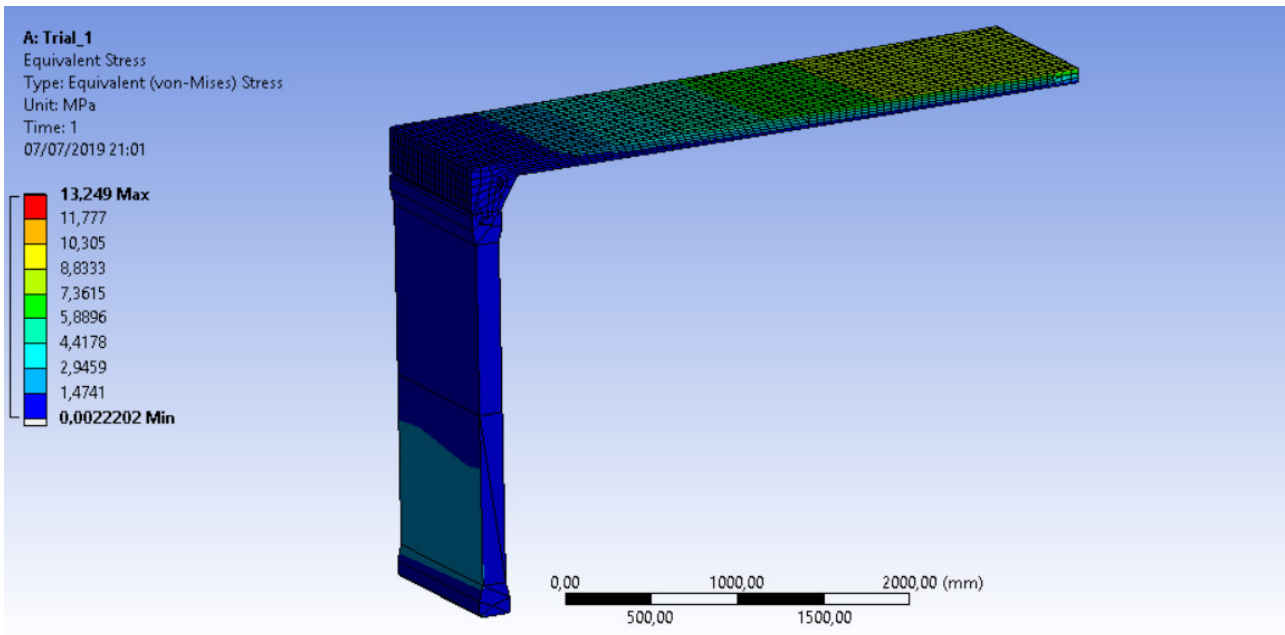From this simmulation, it can be assumed that a deflection within the norm limits will exists if the dry connections are applied. The deflection results with connections will be shown later in this research. Reviewing the results within the structural limits, the material use and environmental impact per m² can be calculated. The results are later compared to the cost and environmental impact of the case-study slab. A weight of 392,5 kg/m² is extracted from Ansys. This means that if a continuous cross section is considered, the height would be of 170,6 millimetres. *Table 10* shows such comparison.

		Case-Study Slab			Reusable 3DCP slab T-Shape		
		Concrete	Steel	*Total*	Concrete	Steel	*Total*
Material Related Costs	**Material Volume (m3)**	0,148	0,002	**0,15**	0,168	0,003	**0,17**
	Material Weight (kg)	340,17	17,53	**357,70**	386,89	19,93	**406,82**
	Price (€)	17,25	10,53	**27,78**	19,62	11,98	**31,59**
	Embodied Energy (MJ)	292,21	594,14	**886,34**	332,34	675,73	**1008,07**
	CO2 Emissions (kg)	43,54	43,64	**87,18**	49,52	49,63	**99,15**
Process Related Costs	**Embodied Energy (MJ)**	0,000	73,435	**73,43**	0,000	100,000	**100,00**
	CO2 Emissions (kg)	0,00	5,50	**5,50**	0,00	7,50	**7,50**
Transport Related Costs (50 km)	**Embodied Energy (MJ)**	12	0,620	**12,62**	14	0,710	**14,71**
	CO2 Emissions (kg)	0,87	0,05	**0,92**	0,99	0,05	**1,04**
Disposal Related Costs	**Embodied Energy (MJ)**	68	3,500	**71,50**	77	4,000	**81,00**
	CO2 Emissions (kg)	4,80	0,25	**5,05**	5,40	0,28	**5,68**
End-of-Life		Landfill	Landfill		Reuse	Reuse	
Totals	**Embodied Energy (MJ)**	372,21	671,691	**1043,90**	423,34	780,441	**1203,78**
	CO2 Emissions (kg)	49,21	49,44	**98,65**	55,91	57,46	**113,38**

Table 10: Comparison of material use and related costs per m² of the concrete slabs [56]

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55 Data extracted from Ansys Workbench 19,1
56 Data extracted from CES Edupack 2018

The comparison shows that the reusable concrete slab is still heavier, with more material use and with a higher environmental impact than the case-study slab. This is because more material is needed to provide with more bending stiffness to the reusable slab as the connection to the wall does not perform as a solid bonding. Thus, a thiner section means also a higher displacement of the slab. However, even if the environmental impact is higher, the reusable concrete slab can perform during more time and during multiple service-lives. Thus, the environmental impact and cost decrease exponentially throught the number of service-lives. For instance, two conventional slabs are needed to perform two service-lives. On the other hand, one reusable slab can perform two service-lives. Therefore, the environmental impact and costs are almost half the ones of the conventional slab.

However, if the comparison is made with the previous geometry approximation (continuous slab section of 190 mm) an improvement has been made in material use. This consequently, has an impact on the CO_2 emissions and embodied energy of the reusable 3DCP slab.

Fifth geometry approximation of the slab

The fourth geometry aproximation of the concrete slab is based on the principle of stiffness of honeycomb structures (*image 35*). This type of structure minimises the amount of material required. This consequently reduces the weight according to where the honeycomb structure is placed. The nature of this structure provides a relatively high compression properties and shear properties. The approach for the application of the honeycomb structure to the reusable concrete slab is as a sandwich element. This means that it is built of two "plates" (thin layers) to provide strength in tension and limit the maximum deflection of the reusable concrete slab. The honeycomb structure is placed in the core of the element to reduce the self-weight of the slab at its center without compromising the structural properties. *Figure 39* shows the scheme of the honeycomb geometry applied to the reusable concrete slab.
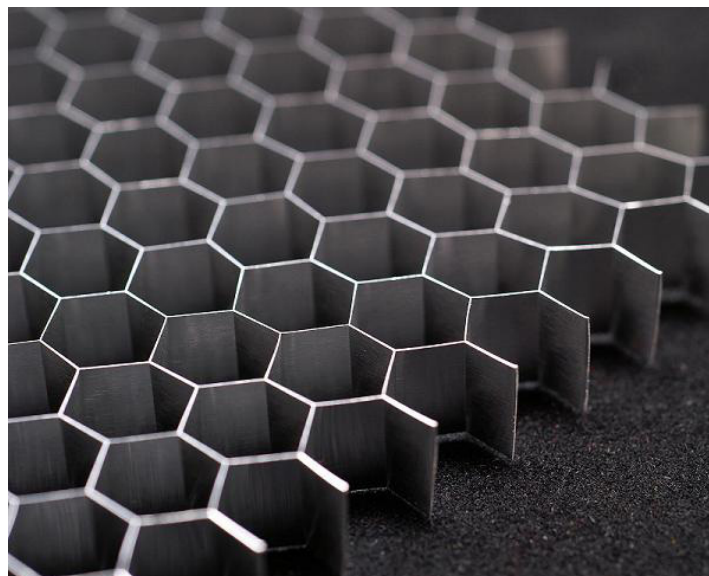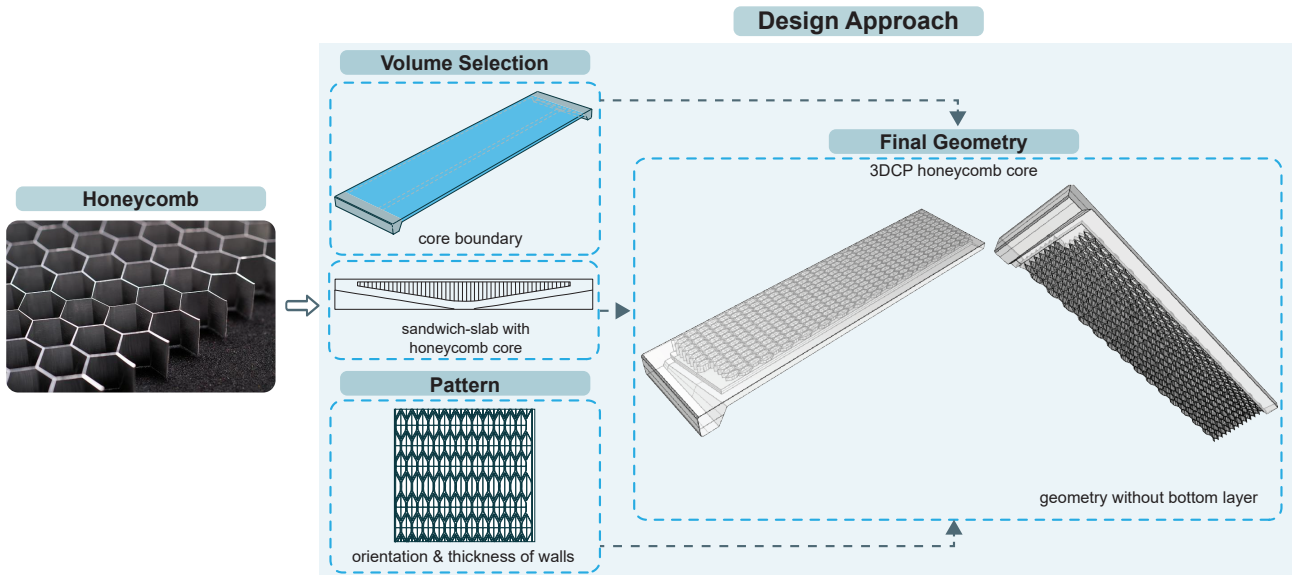

Image 35: Honeycomb structure

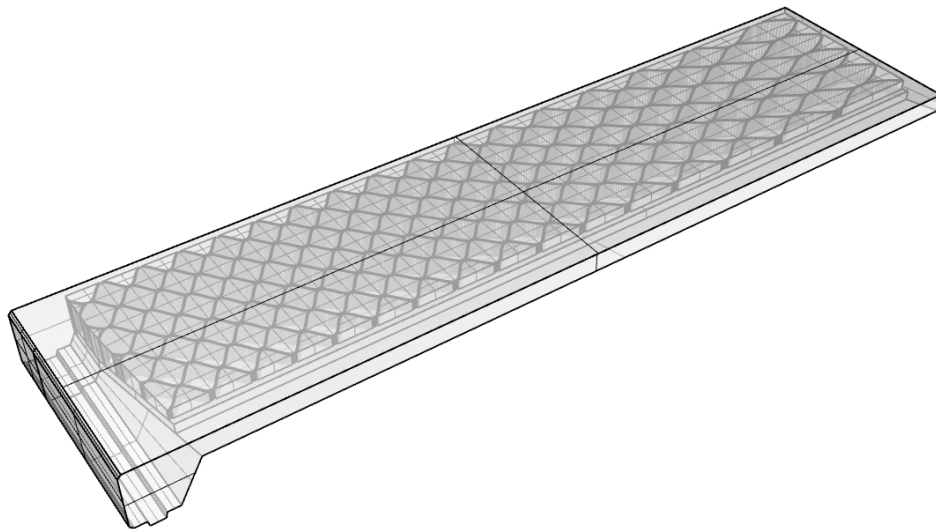*Conceptual application of honeycomb structure to the reusable 3DCP slab*

Figure 39: Honeycomb structure applied to the reusable 3DCP slab. Isometric view
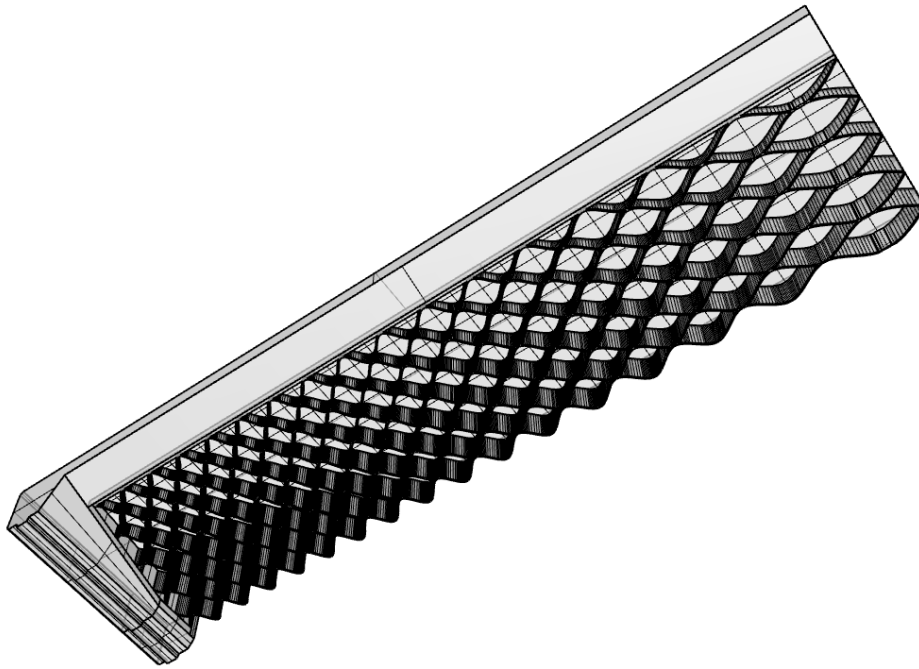
Figure 39: Honeycomb structure applied to the reusable 3DCP slab. View from bottom without bottom layer

It can be observed that the honeycomb structure is not present in the whole geometry of the reusable 3DCP slab. This is because solid material is needed in determinated areas to be able to connect to other structural elements. In the cross width, mass is needed to perform a friction connection with the precast wall. The overall system relies in gravity for its stability, therefore more mass is applied in such area. This results in more weight transferred to the precast wall and in higher stability of the reusable concrete slab against moment rotation and displacement. On the longitudinal length, mass is required to connect to other slabs.

Furthermore, the concrete honeycomb structure is built in-between two layers. This creates a sandwich-slab that provides with more stability to the element. The concrete layers distribute the tensile forces along their area. Consequently, this reduces the stress forces on the honeycomb structure. On the other hand, the concrete honeycomb structure connects the two layers. In this sense, it also distributes the forces between the two concrete plates. A cross section of the reusable slab is shown in *figure 40*.
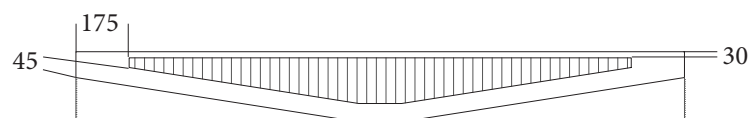

Figure 40: Cross section of the reusable 3DCP slab with the honeycomb structure in the core

The honeycomb structure has been designed as the topology optimisation of the reusable slab geometry. This means a manual approach of reviewing the radius of the ovals, the thickness of the walls, the height of the cells and the height of the plates. From this exploration, several conclusions have been derived: First, the bottom plate plays an important role for limiting the deflection of the reusable slab. This is because the bottom is where the tensile forces are the highest. Consequently, a change in the thickness of the bottom plate results in significant changes in the deflection of the reusable slab. Secondly, the orientation of the honeycomb cells also determines the final deflection of the reusable slab. A cross arrangement results in a weak element. The reason for this behaviour is that the forces are not transmitted continuously from one honeycomb cell to another, which causes stress peaks on the shared-walls of the honeycomb cells. Third, the top plate has a secondary role in the final deflection of the slab. This is because, as specified before, the largest tensile forces are in the bottom of the reusable slab. Therefore, the affectance to the top plate is not as meaningful. Based on this criteria, the following parameters of the honeycomb structure have been defined (*table 11*) The final dimensions are highlighted in green.

Geometry	Wave Amp	Frequency	Number of Waves	Thickness of wave (mm)	Mass (t)	Deflection (mm)	Stress (MPa)	Top Layer (mm)	Bottom Layer (mm)
0	36	2,5	50	20	1,03	21,48	17,86	4	3
1	36	2,5	50	20	1,03	20,33	13	3	4
2	36	2,5	50	20	1,06	19,16	11,62	3	4,5
3	36	2,5	50	20	1,03	20,4	12,48	2,5	4,5
4	36	2,5	50	20	1,03	20,93	12,1	2	50

Table 11: Honeycomb structure parameters

According to literature, a regular layer thickness of th 3DCP filament is 20 millimetres. Therefore, such thickness is also applied to the design of the reusable 3DCP slab. Furthermore, a minimum radius of 30 millimetres has been defined in the waves. This ensures the feasibiity of the honeycomb design based on production parameters of 3DCP concrete. Such parameters have been extracted from meetings with personnel at the Technical University of Eindhoven.

Performance Validation

A strutural validation has been made to assess the feasibility of the concrete honeycomb structure. The material properties of concrete, loads and contact coefficients used for this validation have the same values as in the former geometry validations. It is important to note that this validation has also been made without the connections. An average of 3 millimetres of deflection disminution was noted with the use of connections. Therefore it was decided to perform the validation without such geometrie. This decreases the time of calculation. There is a rough expectation of 19 millimetres of deformation. *Image 36* shows the results of the structural validation.

57 Data extracted from Ansys Workbench 19,1
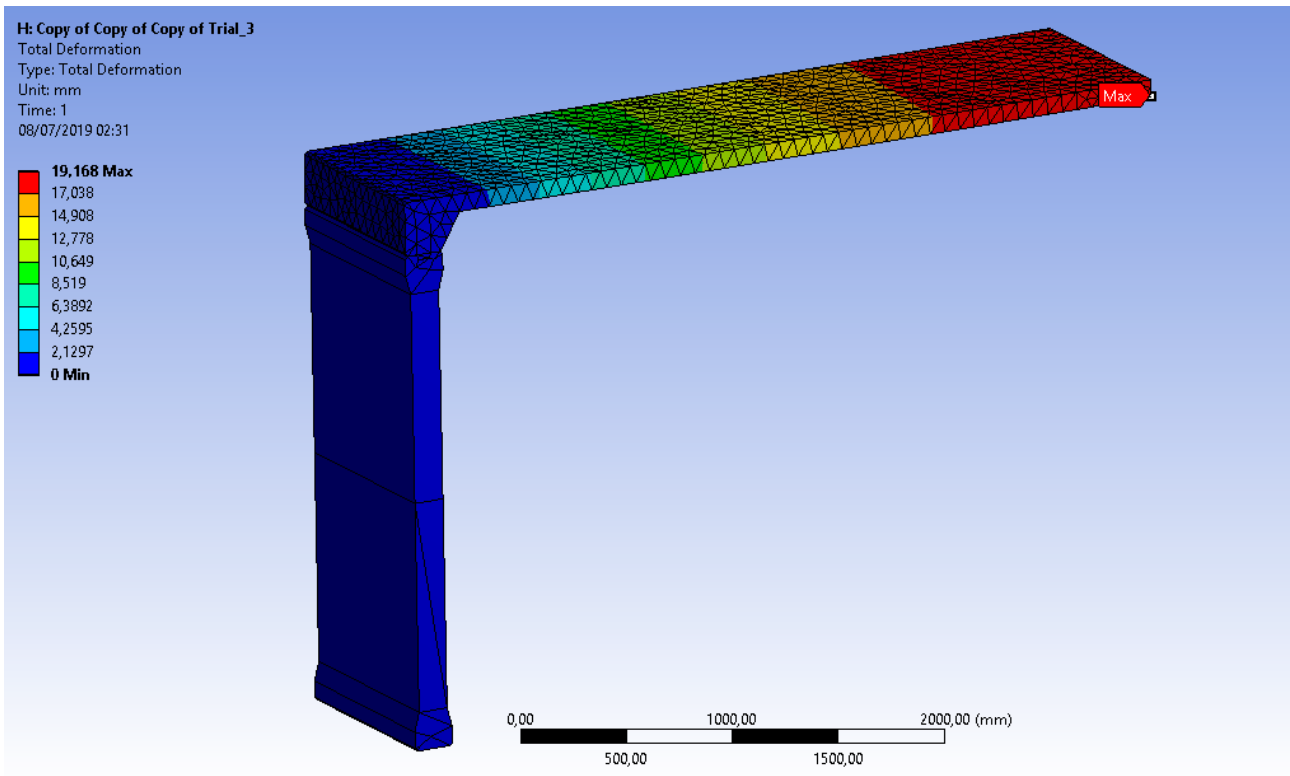
Image 36: Deflection of the slab [57]
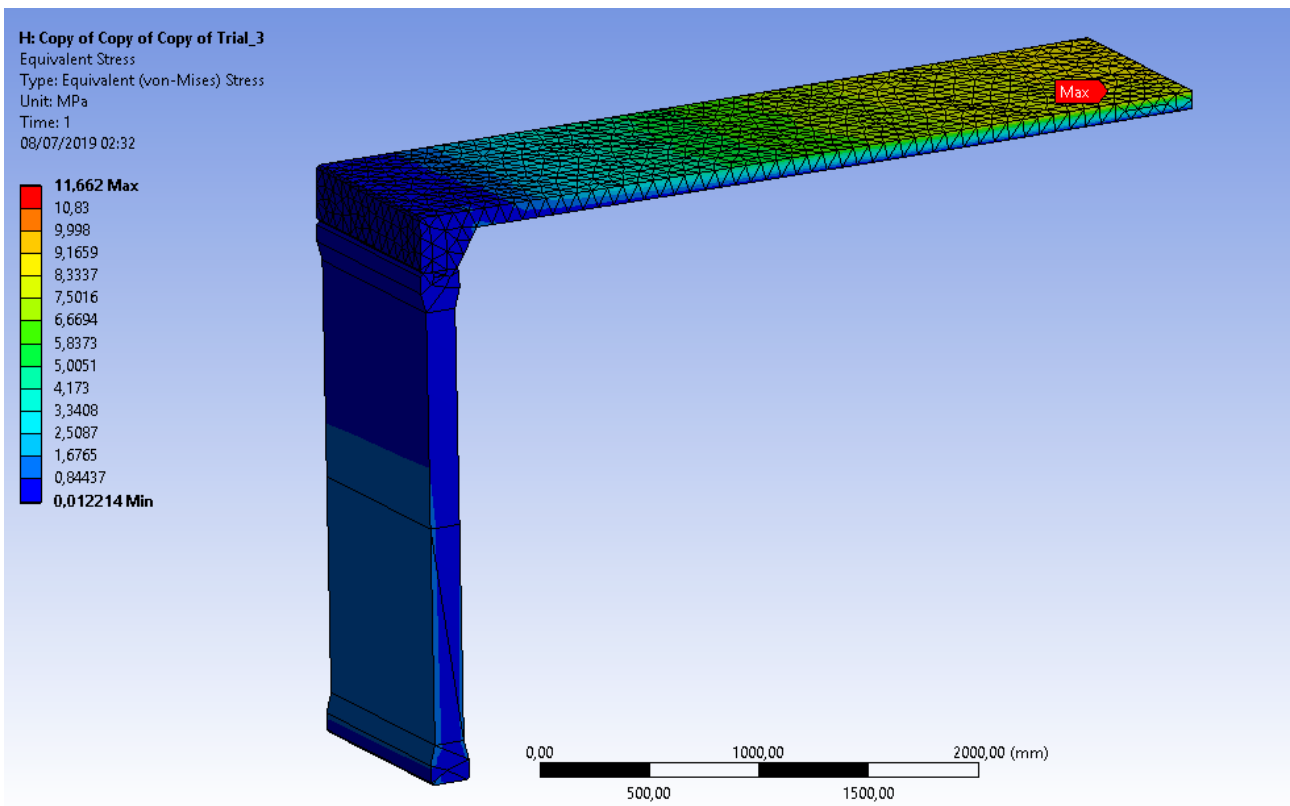
Image 36: Equivalent stress of the slab [57]

57-58 Data extracted from Ansys Workbench 19,1
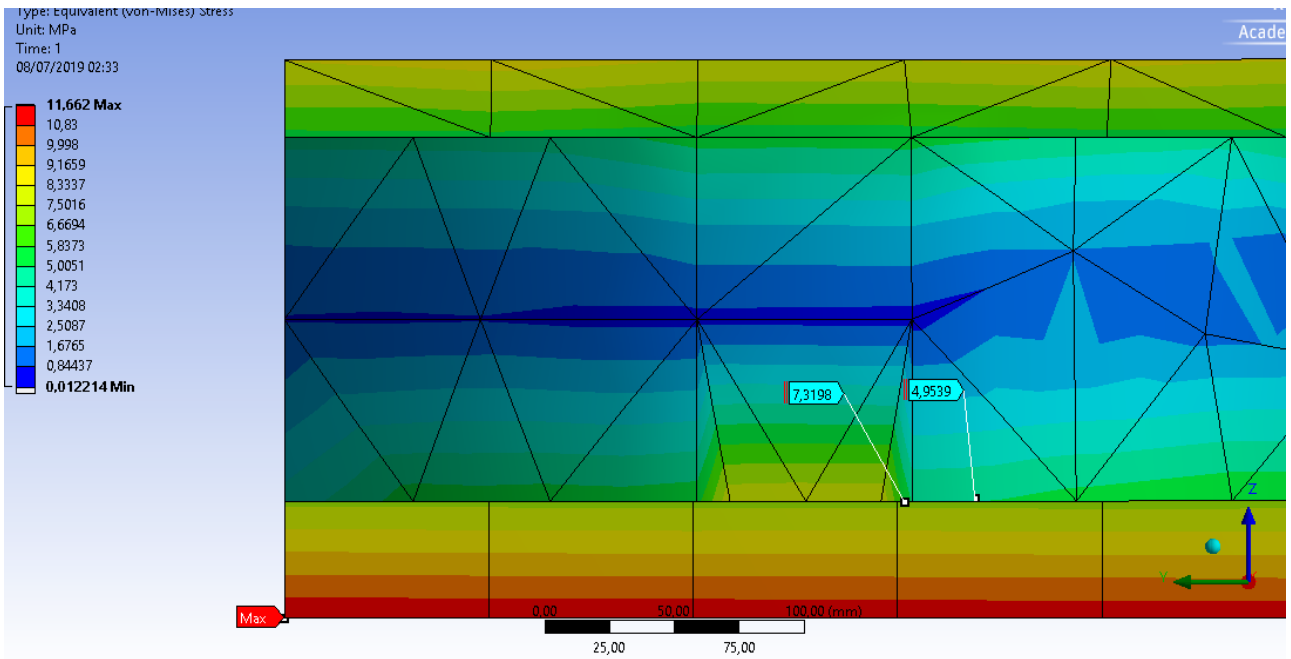
Image 37: Equivalent stress in the honeycomb structure [58]
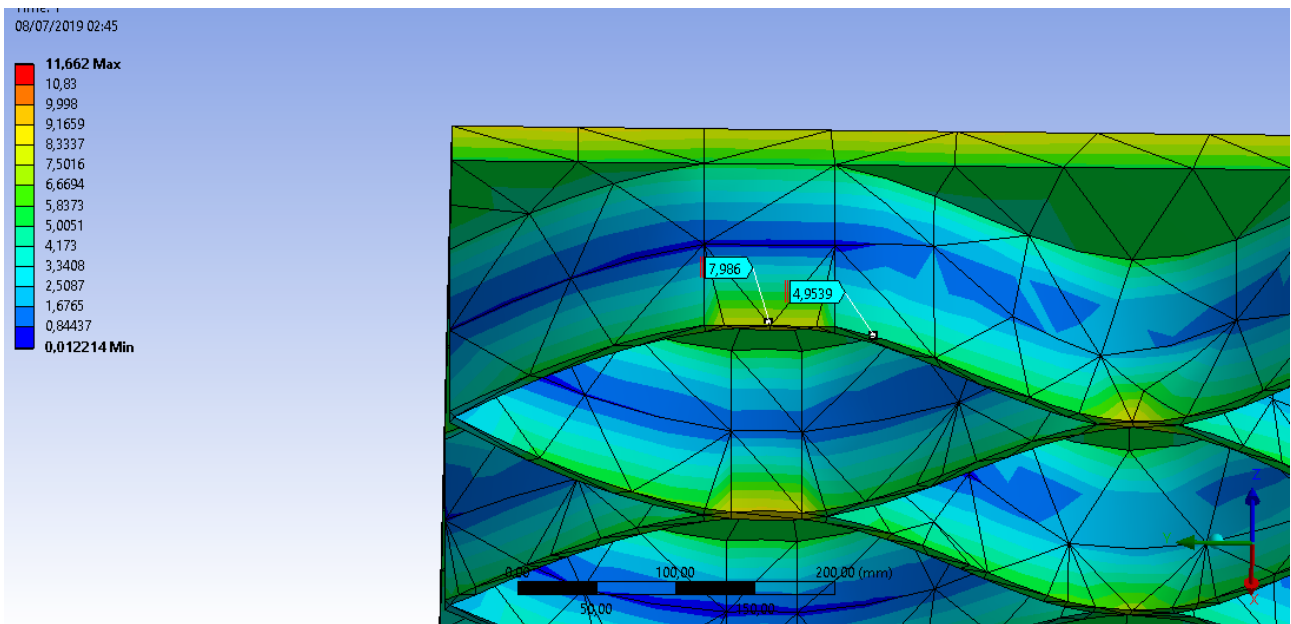
Image 37: Equivalent stress in the honeycomb structure [58]

From this simmulation, it can be assumed that a deflection within the norm limits will exists if the dry connections are applied. The deflection results with connections will be shown later in this research.

However, as shown in *image 37,* there is an abrupt change of stress value in the interface of the honeycomb structure and slab plates. This is caused due to the relatively small area of contact between both geometries. This is precisely one of the main disadvantages of honeycomb panels. Some actions can be done to decrease the stress values of such interface. The first option is to increase the wall

58 Data extracted from Ansys Workbench 19,1

thickness. However, this leads to an increase of material use and self-weight of the slab. The second option is to increase only the contact area without increasing the thickness at the middle of the the cells' height. This means a funnel shape from the top plate towards the middle of the honeycomb cells and an inverted funnel shape from the middle of the cells towards the bottom plate. This requires a deeper topological optimisation of the honeycomb structure. However, the remaining time for this research does not allow to complete such exploration.

Reviewing the results within the structural limits, the material use and environmental impact per m² can be calculated. The results are compared to the cost and environmental impact of the case-study slab. A weight of 222,5 kg/m² is extracted from Ansys. This means that if a continuous cross section is considered, the height would be of 97 millimetres. Ta*ble 12* shows the results of such comparison.

		Case-Study Slab			Reusable 3DCP slab T-Shape with Honeycomb		
		Concrete	Steel	*Total*	Concrete	Steel	*Total*
Material Related Costs	**Material Volume** (m3)	0,148	0,002	**0,15**	0,096	0,001	**0,10**
	Material Weight (kg)	340,17	17,53	**357,70**	219,98	11,33	**231,31**
	Price (€)	17,25	10,53	**27,78**	11,15	6,81	**17,96**
	Embodied Energy (MJ)	292,21	594,14	**886,34**	188,96	384,21	**573,17**
	CO2 Emissions (kg)	43,54	43,64	**87,18**	28,16	28,22	**56,38**
Process Related Costs	**Embodied Energy** (MJ)	0,000	73,435	**73,43**	0,000	57,000	**57,00**
	CO2 Emissions (kg)	0,00	5,50	**5,50**	0,00	4,30	**4,30**
Transport Related Costs (50 km)	**Embodied Energy** (MJ)	12	0,620	**12,62**	8	0,400	**8,20**
	CO2 Emissions (kg)	0,87	0,05	**0,92**	0,56	0,03	**0,59**
Disposal Related Costs	**Embodied Energy** (MJ)	68	3,500	**71,50**	44	2,300	**46,30**
	CO2 Emissions (kg)	4,80	0,25	**5,05**	3,10	0,16	**3,26**
End-of-Life		Landfill	Landfill		Reuse	Reuse	
Totals	**Embodied Energy** (MJ)	372,21	671,691	**1043,90**	240,76	443,908	**684,67**
	CO2 Emissions (kg)	49,21	49,44	**98,65**	31,82	32,71	**64,53**

Table 12: Comparison of material use and related costs per m² of the concrete slabs [59]

The comparison shows that the reusable concrete slab is lighter than the slab of the case-study due to a core optimisation. Consequently, this leads to less material use and less environmental impact. The average reduction in costs, embodied energy and CO_2 emissions is *33%*. Furthermore, it is important to notice that these calculations correspond to one service-life of the elements. This means that the reusable concrete slab's reductions are even higher if multiple service-lives are accounted. The environmental impact and cost decrease exponentially throught the number of service-lives. For instance, two conventional slabs are needed to perform two service-lives. On the other hand, one reusable slab can perform two service-lives. Therefore, the environmental impact and costs are almost half the ones of the conventional slab added to the reductions of these calculations.

[59] Data extracted from CES Edupack 2018

Slab-to-slab connections

The feasibility of this research also relies on how the reusable slab is connected to other slabs. This exploration is necessary for two reasons: First, to achieve a structural behaviour similar to the case-study slab. Most of the conventional concrete slabs have a "diaphragm behaviour". Its function is basically to provide lateral load distribution to other slabs. This behaviour is necessary to transmit seismic, wind and/or out-of-plane loads. Second, this exploration is important to evaluate the (dis) assembly process of the reusable slab. For instance, if a flat connection is designed. then some measure has to be taken on-site to achieve the diaphragm behaviour. This might potentially mean the use of bonding elements/products between to slabs (such is the case of mortar). If additional elements are used to connect the reusable slabs, more time is required for their installation and more elements have to be transported.

Based on these considerations, the most logical solution seems to be a connection that is already part of the concrete slab. This means that it cannot be removed or replaced. According to DfR principles, a fixed connection is not recommended due to its low flexiblity for (dis)assembly. However, as reviewed in the DfR, (dis)assembly time is a considerable hindrance for the development of the circular economy principles. Therefore, it is decided to lower the (dis)assembly potential of the reusable slab in light of easying the building process and decreasing the building time. Furthermore, the reusable slab is already connected mechanically to the precast walls. This means that the lateral forces to be distributed are relatively low. Forthwith, the damage suffered by the slab-to-slab connections due to diaphragm behaviour is almost inexistent.

The proposed slab-to-slab connection works by interlocking the longitudinal edges of the reusable slabs. According to DfD principles, this means an integral connection made by the geometry of the elements. This results in an efficient transmision of forces from element to element. However, one of the disadvantages for this type of connections is that only their sequential assemby is possible. This means that each element is fixed by a newly assembled one. Therefore, linear dependency is stablished and it is proportional to the number of assembled elements. *Figure 41* shows the schematic principle of the interlock connection. *Figure 42* provides the proposed dimensions.

Design Approach

Interlocking

low forces

0,4 - 0,49 MPa

low frictional stresses in the interface

Heat Keeper

Diaphragm Behaviour

Intregal connection:
efficient transmission of forces

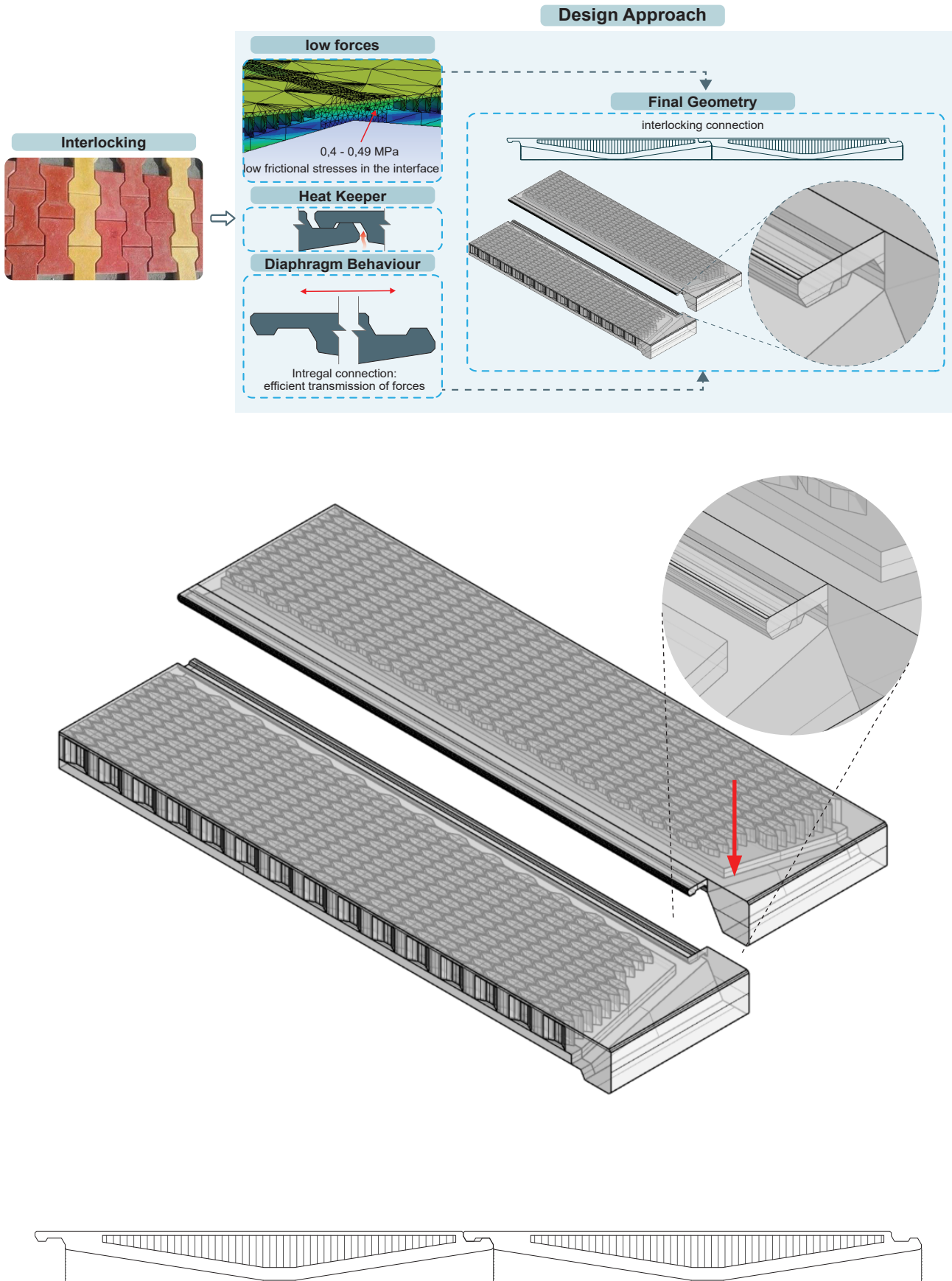**Final Geometry**

interlocking connection

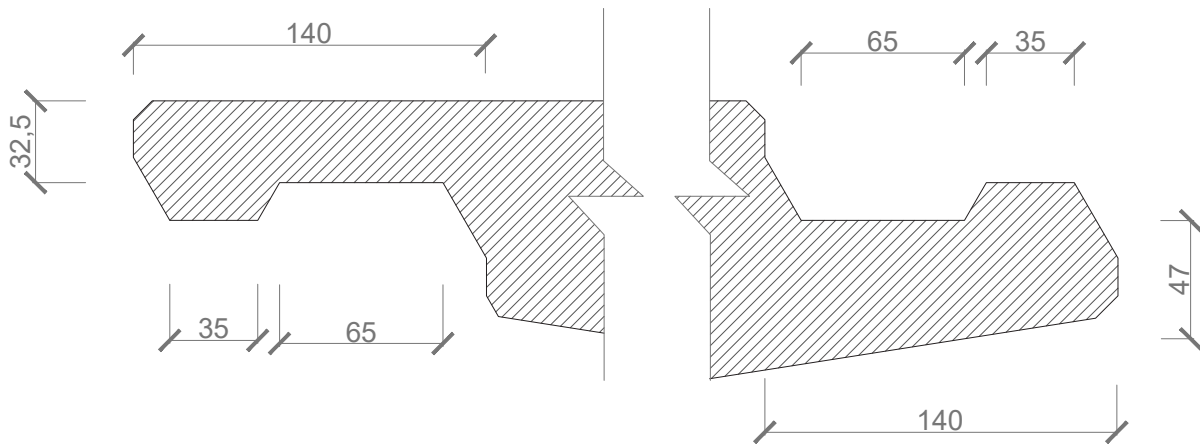*Figure 41: Schematic design of the slab-to-slab connections*

Figure 42: proposed dimensions of the slab-to-slab connections

Performance Validation

A structural validation has been made to assess the feasibility of the interlock connection. The material properties of concrete and loads used for this validation have the same values as in the former geometry validations. Furthermore, a concrete-to-concrete friction coefficient of 0,4 has been input to simmulate the contact connection between the slabs. It is important to note that this validation has also been made without the connections. An average of 3 millimetres of deflection disminution was noted with the use of connections. The main objectives for this simmulation are to identify the maximum deflection of the reusable slabs when they are connected and to assess the frictional stress values at the interface of the connections. *Image 38* shows the results of the structural validation. *Image 39* shows the values of frictional stress at the interface of the connection.
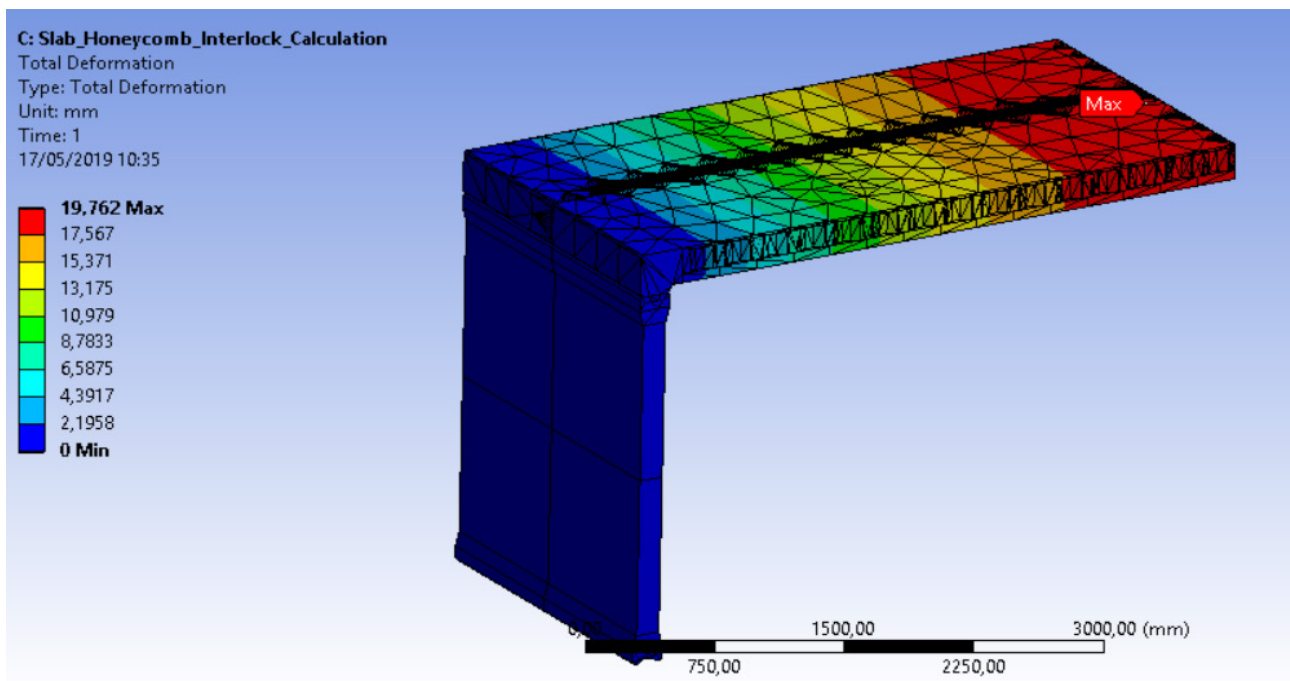
Image 38: Top: Maximum deflection under SLS load combination [60]

60 Data extracted from Ansys Workbench 19,1

C: Slab_Honeycomb_Interlock_Calculation
Equivalent Stress
Type: Equivalent (von-Mises) Stress
Unit: MPa
Time: 1
17/05/2019 10:36

12,991 Max
11,549
10,106
8,6642
7,222
5,7798
4,3376
2,8953
1,4531
0,010887 Min
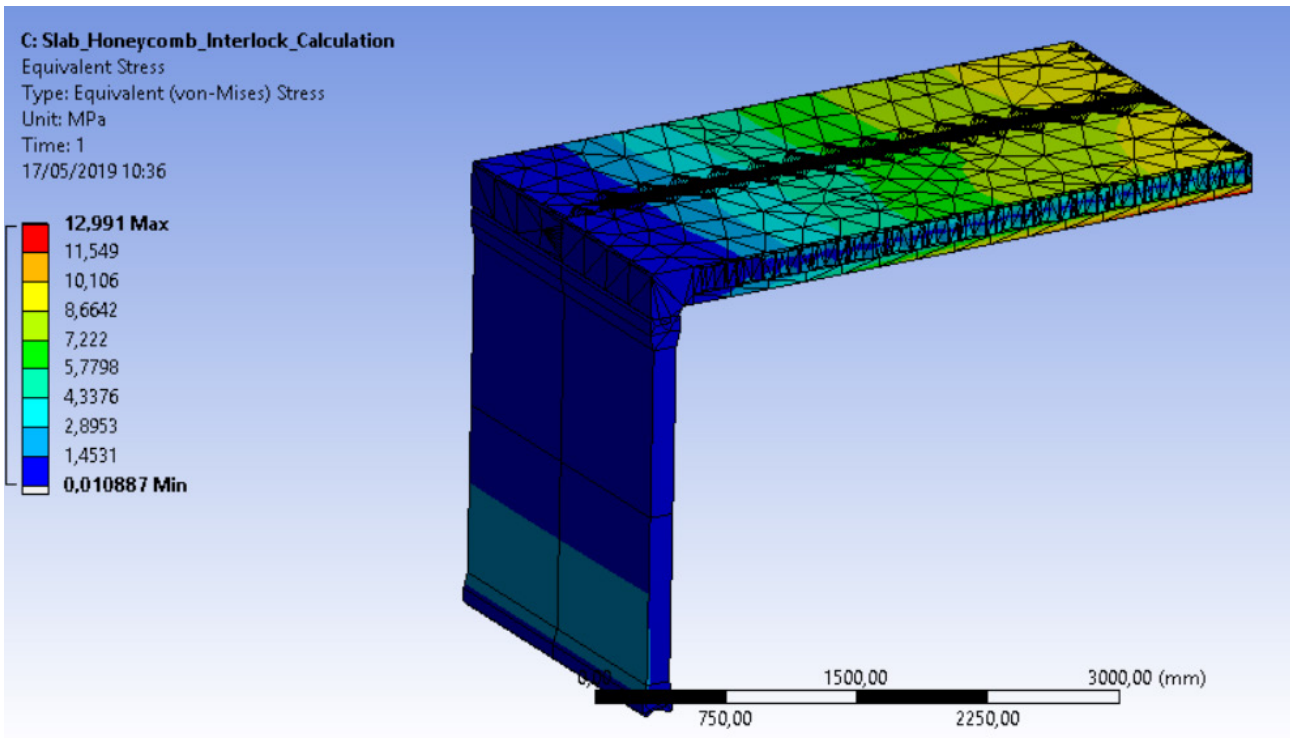
Image 38: Bottom: Maximum stress under SLS load combination [60]

Image 39: Stress at interface [61]

60-61 Data extracted from Ansys Workbench 19,1
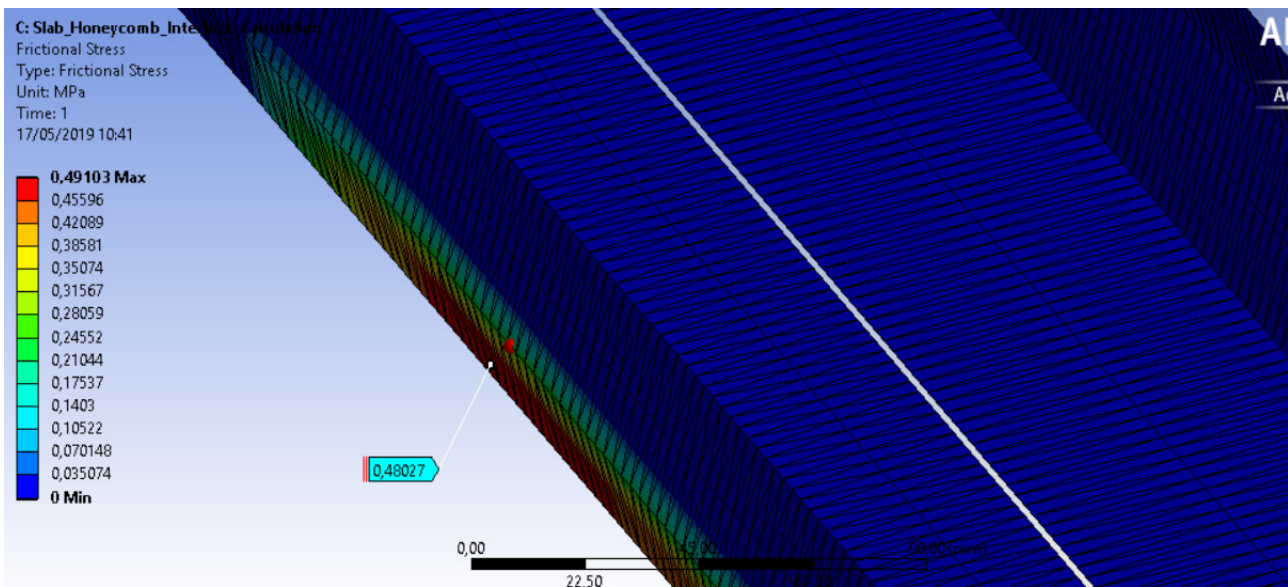
Image 39: Stress at interface [61]

It can be observed in *image 38* that the maximum deflection of the connected slabs is slightly lower than the deflection of an individual slab. This is because an individual slab is relatively slender, which causes a larger deflection at the middle due its proportions. This scenario can be compared to a beam behaviour. However, when to slabs are connected, the behaviour is similar to a plate element which is wider. Therefore, the geometry (width dimension) is increased and the maximum deflection is decreased as a consequence. It is important to remember however, than the most influencial fact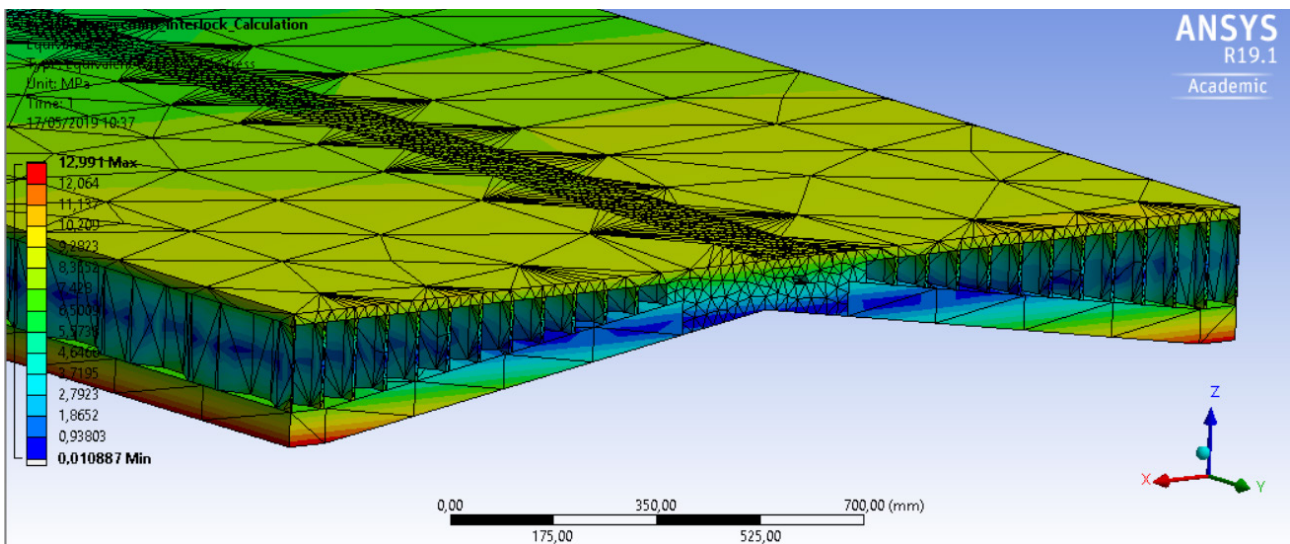or that affects the maximum deflection is the height of the slab. This is why even if the width has been increased by connecting two slab, the reduction in the final deflection is minimal.

Image 39 corroborates that the frictional stress occurring at the interface of the reusable slabs is minimal. This supports the assumption previously made about the effectiveness of an interlock connection and the low affectance of the friction forces.

Overall design validation

The previous structural validations of the geometry have been made without connections. It was assumed that a decrease of around 3 millimetres would occur with the use of them. The neglection of the connections in tthe previous scenarios was to reduce the calculating time of Ansys. This chapter presents the results of the structural validation accounting the performance of the steel connections.

The material properties of concrete and loads are the same as in previous validations. However, a rough contact is set in the T-dowel-to-plate interface. A rough contact is due to the assumption of a high tightness between the steel elements due to the torque applied by the building workers on site.

61 Data extracted from Ansys Workbench 19,1

Table 13 presents the material properties input for the calculation.

	Density (kg/m3)	Young's Modulus (Mpa)	Poisson's Ratio	Tensile Strength (Mpa)	Friction Coefficient Concrete-to-Concrete
Concrete	2300	30000	0,14	1,2	0,4
Stainless Steel	7750	193000	0,31		

Table 13: Material properties used for the calculation.

For this validation, a simplified geometry of the connection is made. Here, the use of cylinders is neglected and replaced by a continuous- 1 piece "T" dowel. This still represents the basic principle of the moment connection but reduces the amount of nodes to calculate. Therefore, the time of calculation is also reduced. *Image 40* presents the results of the structural validation.
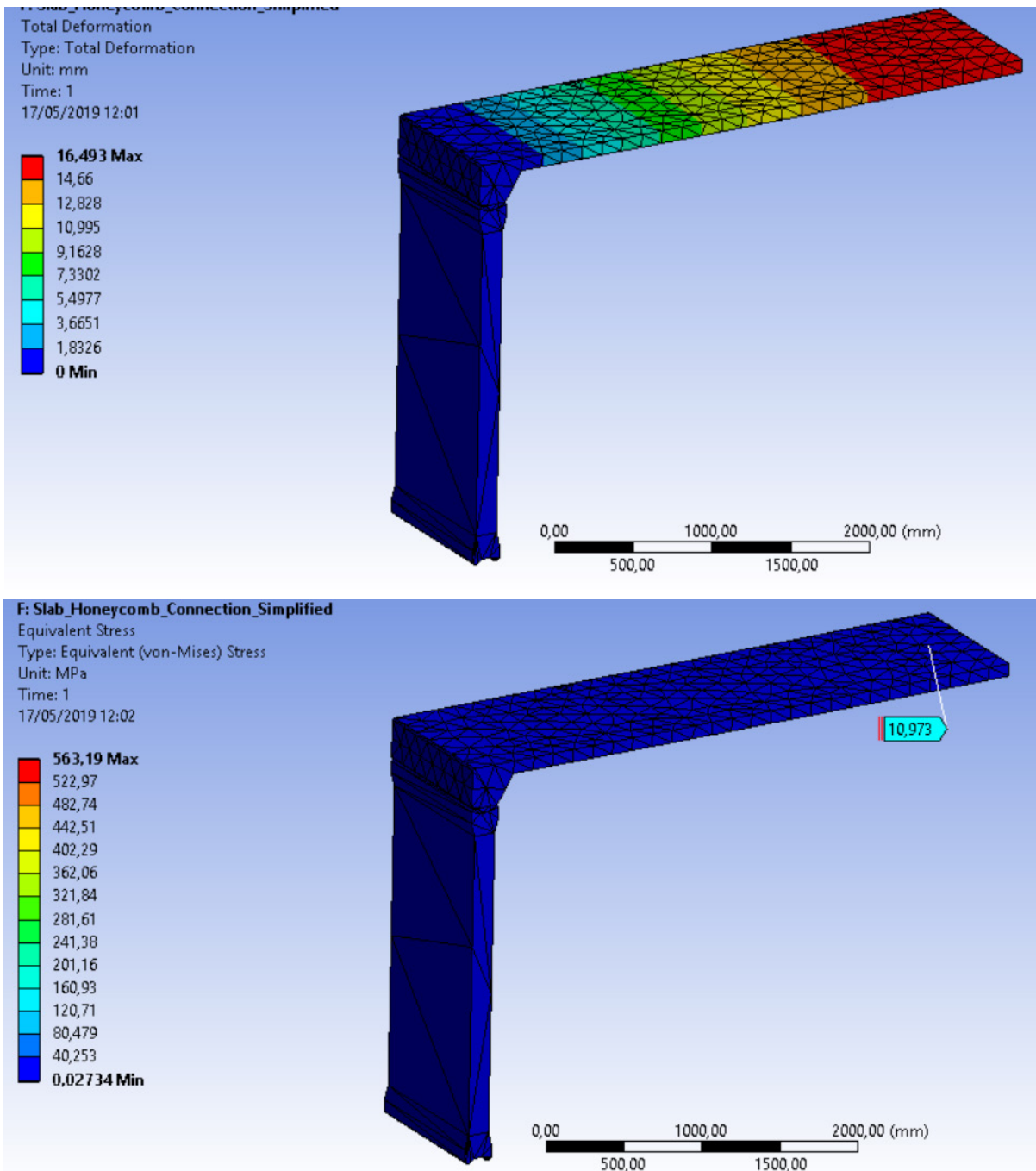

Image 40: Top: Deflection of the reusable 3DCP slab. Bottom: Maximum stress of the reusable concrete slab [62]

62 Data extracted from Ansys Workbench 19,1

The structural validation supports the assumption made previously. A calculation with the dry connections effectively decreases the maximum deflection of the slab by 3 millimetres. Therefore, the maximum deflection experienced by the reusable slab is within the limits set by the norms. This confirms the validity of the design not only under structural principles but also in the lower impact to the natural environment compared to a traditional slab.

The case-study is an appartment building of 3 levels. To effectively validate the design of the reusable slab is necessary to compare its performance in a multi-level arrangement. Some scenarios can be predicted from the validation: First, the maximum deflection of the slab located in the first level will be smaller than the deflection obtained in the former calculations. The reason for this is that the weight of the upper concrete elements (such as the precast walls) will be added to the connection area of the slab. Consequenly, this load will limit the moment rotation of the slab, which lowers the maximum deflection. The second scenario is that the precast walls will have a small moment rotation towards the center of the slab. This is caused because the SLS loads on the slab cause its moment rotation in the connection area. This rotation is consequently transmitted to the precast wall. However, the moment rotation of the second slab causes an outward displacement of the precast wall. which is partially cancelled by the moment rotation experienced from the bottom slab. This is a chain reaction of all the concrete members in a multi-level arrangement. Stress values experienced by the concrete elements are the focus of atention in this scenario.

The material properties of concrete, loads and contact parameters are the same as in the validation of one level. *Image 41* presents the results of this structural validation.
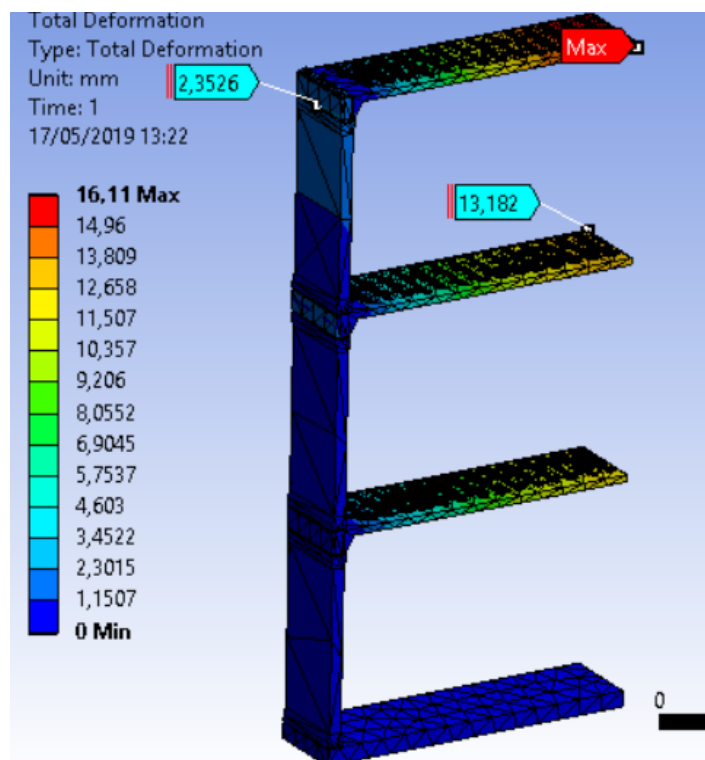

Image 41: Maximum deflection of a multi-level arrangement of the reusable slabs under SLS load combination

This validation confirms the revious assumption about the decrease of the maximum deflection experienced by the reusable slab. The most critical point is the top slab as it has no loads from the precast wall to restrict its moment rotation. Even, such slab's deflection is within the structural limits. Furthermore, this scenario is valid for a building with flat roof. This is not the scenario of the case-study as the Soendalaan building has a gable roof. If applied to the validation scenario, this means that a precast wall is located ontop of the connection area of the reusable slab. Therefore the maximum deflection of such slab is 13,2 millimetres. In a gable roof scenario, the top slab does not exists. However, the validation was made for the most critical scenario.

Connection Validation

The validation of the connection is needed to assess its proper functioning. This means that it will not crack or achieve a permanent deformation due the tensile stresses. According to the previous simmulation (flat roof), the connections that experience highest tensile stresses are the ones located at the top. This is due to a largest moment rotation of the slab. Therefore, it can be assumed that in the case of a gable roof, the connections tensile stress will decrease.

The material properties of the steel are the same as in the previous calculations with connections. The results of the validation are displayed in *image 42*.
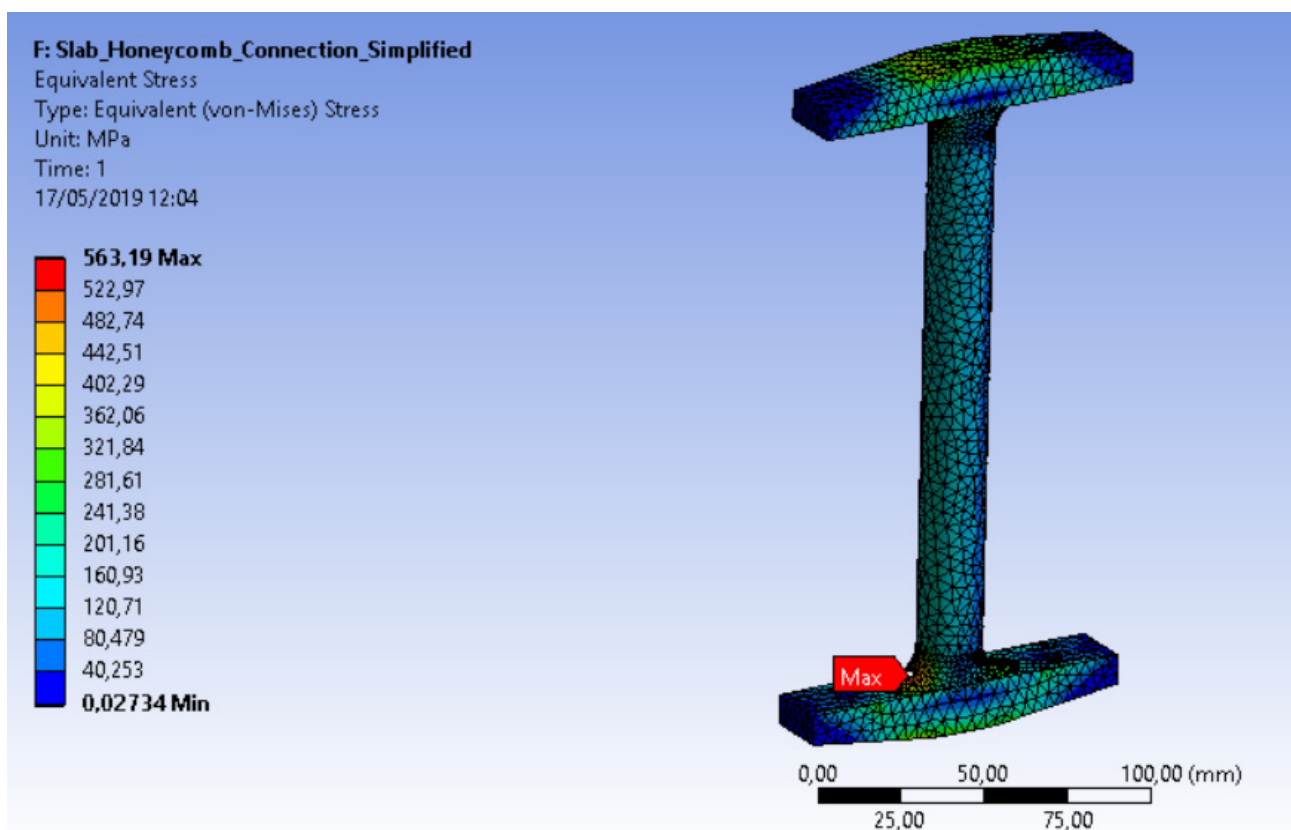

Image 42: Tensile stresses in the steel connection [63]

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63 Data extracted from Ansys Workbench 19,1
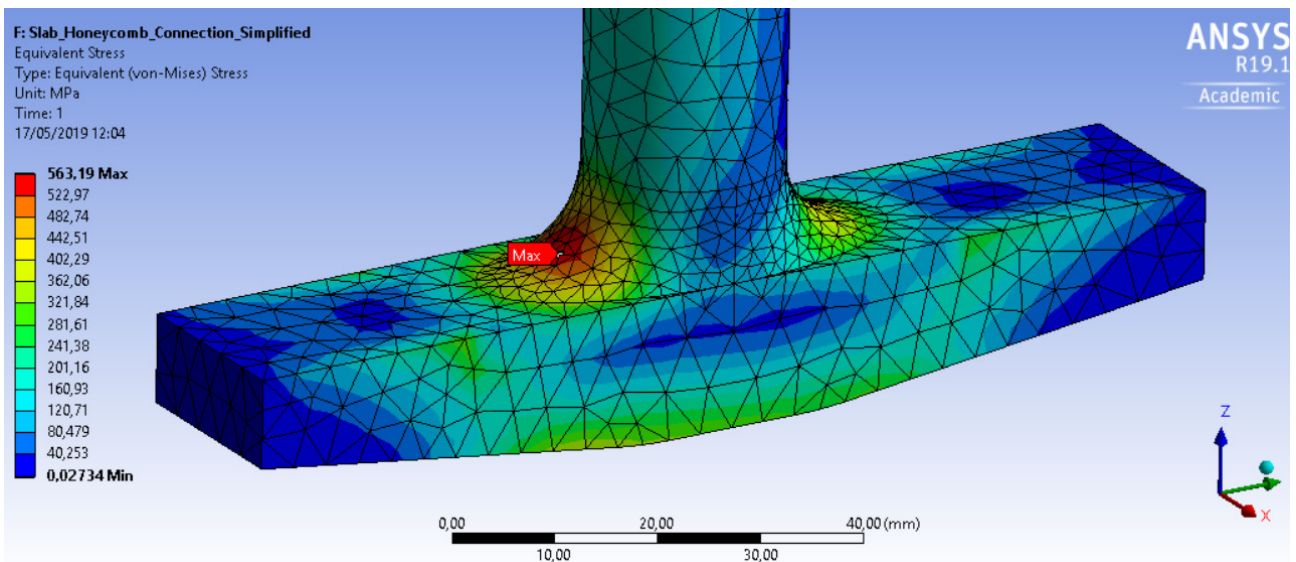
Image 42: Tensile stresses in the steel connection [63]

According to the validation, the maximum tensile stress value experienced by the steel connection is 563,19 MPa. The yield strength of the stainless steel according to CES Edupack 2018 is 700 MPa. This is the stress at which the material first suffers permanent deformation. Furthermore, the tensile stress required to break the material is 750 MPa (CES Edupack, 2018). Based on this information, it can be concluded that the connection will resist the tensile forces imposed without permanently deforming or breaking.

As seen in *image 42* the weakest point of the steel connection is in the fillet of the vertical and horizontal geomeries. Even if the tensile stress is lower than the minimum required to deform or break the material, it is important to know how many cycles such point will withstand. This means to assess the number of cyclic load required to break the connection due to the fatigue of the material. For this, a damage study has been made in Ansys based on the stress values experienced by the connection. The type of loading has been set to *"zero-based"*. This means that the loading will only be applied possitively (in direction to the concrete slab) as the deflection works only in one direction. The results of the damage study are shown in *image 43*.

Image 43: Tensile stresses in the steel connection [64]

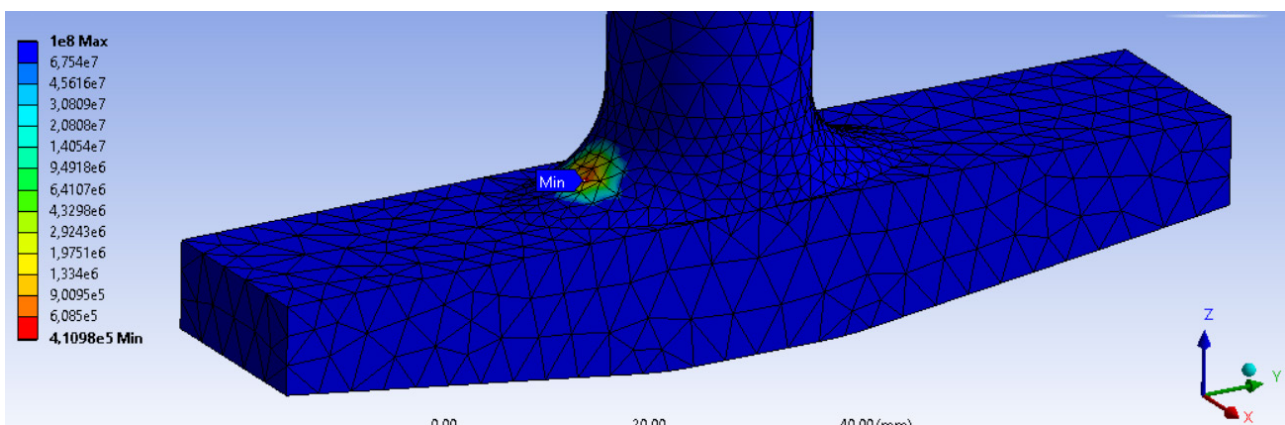63-64 Data extracted from Ansys Workbench 19,1

From this validation is seen that the minimum cycles that the connection can withstand before breaking is 410.980. This means that if the load is applied everyday (due to maintenance, for instance), the connection will perform during 1.141 years. It is important to note that this value is only based on the cyclic tensile forces of the connection. Other parameters, such as creep deformation are not studied.

Interior walls connection design

The current design contemplates a planar surface in the bottom of the slab. This provides with the flexibility to modulate the interior space of the appartments. However, by leaving complete freedom to the user in this regard, the structural behaviour of the slab might be compromised. For instance, the user might start drilling holes in the slab to create such partitions. Therefore, to provide features ready to connect interior walls seems to be a sensible approach. Such features are to be prefabricated along with the slab. The principle of pluging and turning is kept as the T-dowels used in the wall-to-slab connection can be used for interior connections as well.

The fifth geometry approximation is therefore to provide such facilities. The planar bottom of the slab is formed by slopes. Therefore, the installation of interior walls is challenging as the slope has to be known everytime the wall geometry is being prepared. Besides the required knowledge, this takes time and consequently, it is more expensive. Therefore, this geometry exploration starts by defining planar-straight channels so the installation of interior partitions is easy. Each planar channel has a separation of 0,5 meters from each other in the transversal direction and 1 meter in the longitudinal direction. This grid contributes to the easy modulation of the interior spaces. *Figure 43* illustrates the geometry with such channels and the schematic view of the slab's bottom.
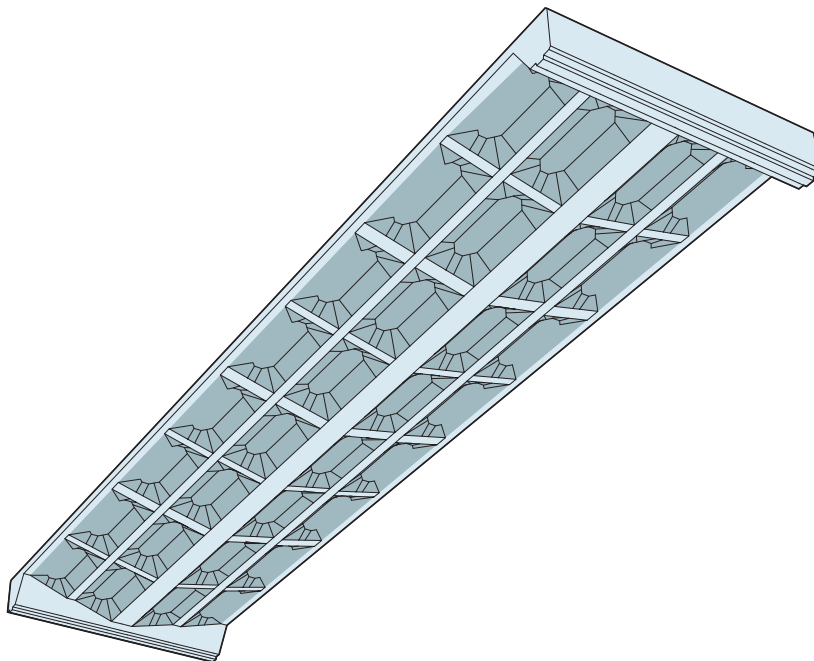
Figure 43: Slab with channels to accomodate interior partitions

From the image, it can be noted that the channels act as structural beams as well for the reusable 3DCP slab. This is an interesting finding as the slab maintain its structural behaviour while functional features are given as well as material usage is minimised. However, the important aspect to analyse is the tensile stress that the central beam has to withstand. As previously reviewed, one of the hindrances of concrete is its restricted tensile strength. Therefore, it is necessary to know the stress acting at such geometry to evaluate the structural feasibility of the material and of the reusable 3DCP slab. *Image 44* shows the results of the structural analysis. It is important to note that the following analysis has been made without connections. However, a similar behaviour of the former analysis is observed. Therefore, it can be concluded that the addition of connections into the calculation will lead to a maximum deflection below the maximum allowed by norms.
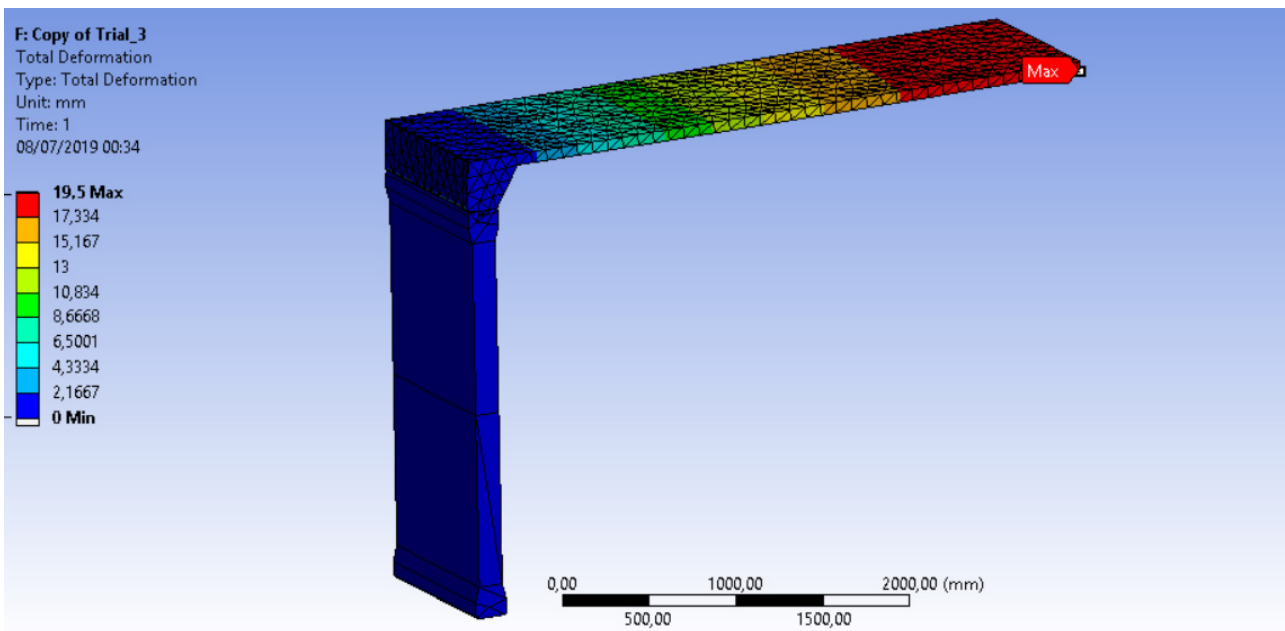
Image 44: Deflection of the slab [65]
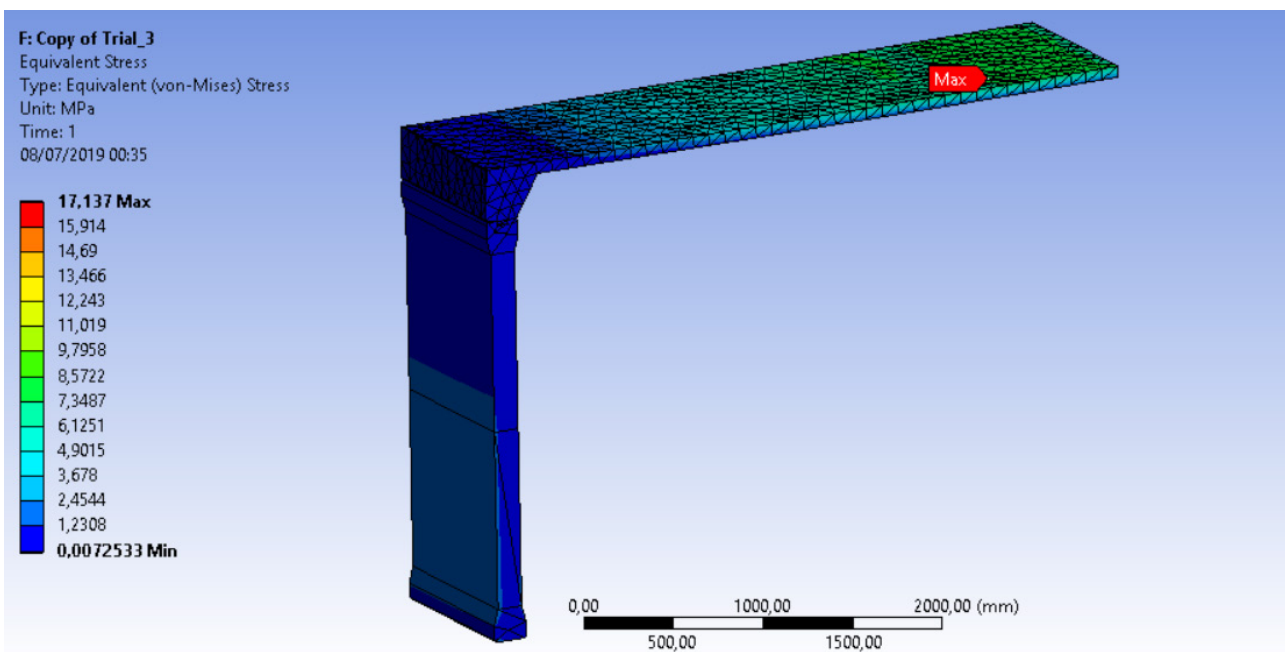
Image 44: Equivalent stress of the slab [65]

65 Data extracted from Ansys Workbench 19,1

From this analysis is can be appreciated that the structural behaviour of the reusable 3DCP remains the same. However, there is a reasonable increase of tensile stress in the bottom of the slab.

The following material comparison is made between the case-study slab and the reusable 3DCP slab (*table 14*). The objective is again to compare the environmental impact of each slab. According to Ansys Workbench, the weight of the reusable 3DCP is of 207 kg/m². This means that if a continuous cross section is considered, the height of the slab is of 90 millimetres.

		Case-Study Slab			Reusable 3DCP slab T-Shape with Honeycomb and channels		
		Concrete	Steel	*Total*	Concrete	Steel	*Total*
Material Related Costs	Material Volume (m3)	0,148	0,002	**0,15**	0,089	0,001	**0,09**
	Material Weight (kg)	340,17	17,53	**357,70**	204,10	10,52	**214,62**
	Price (€)	17,25	10,53	**27,78**	10,35	6,32	**16,67**
	Embodied Energy (MJ)	292,21	594,14	**886,34**	175,32	356,48	**531,81**
	CO2 Emissions (kg)	43,54	43,64	**87,18**	26,13	26,18	**52,31**
Process Related Costs	Embodied Energy (MJ)	0,000	73,435	**73,43**	0,000	53,000	**53,00**
	CO2 Emissions (kg)	0,00	5,50	**5,50**	0,00	3,90	**3,90**
Transport Related Costs (50 km)	Embodied Energy (MJ)	12	0,620	**12,62**	7	0,370	**7,57**
	CO2 Emissions (kg)	0,87	0,05	**0,92**	0,52	0,03	**0,55**
Disposal Related Costs	Embodied Energy (MJ)	68	3,500	**71,50**	41	2,100	**43,10**
	CO2 Emissions (kg)	4,80	0,25	**5,05**	2,90	0,15	**3,05**
End-of-Life		Landfill	Landfill		Reuse	Reuse	
Totals	Embodied Energy (MJ)	372,21	671,691	**1043,90**	223,52	411,952	**635,48**
	CO2 Emissions (kg)	49,21	49,44	**98,65**	29,55	30,26	**59,81**

Table 14: Comparison of material use and related costs per m² of the concrete slabs [66]

It can be concluded that the design of the slab leads to an important crease of material usage. Consequently, a reduction of embodied energy and CO2 are achieved. Furthermore, the current case is only evaluating the results of one service-life of the slab, when in theory it can be reused many times. Consequently, such values of CO2 emissions and embodied energy reduce exponentially as the slab is reused over and over again.

The structural analysis shows a maximum tensile strength of 17,13 Mpa. This value is considerably higher than the one of the previous slab design without channels. Literature reports that steel fibre reinforced concrete (SFRC) with a %vol of 2% leads to a tensile strength of 15,5 MPa. This value falls short compared to the required tensile strength. Therefore, for the purpose of providing stability to the reusable 3DCP slab and due to time constraints, a value %vol of fibres proposed is of 2,5%. Following this numbers, the final material comparison between the reusable 3DCP slab and the case-study slab is provided in *table 15*.

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66 Data extracted from CES Edupack 2018

		Case-Study Slab			Reusable 3DCP slab T-Shape with Honeycomb and channels				
		Concrete	Steel	*Total*	Concrete	Steel	*Total*	Steel connections (4x Slab)	
Material Related Costs	Material Volume (m3)	0,148	0,002	**0,15**	0,089	0,002	**0,09**	0,0003	
	Material Weight (kg)	340,17	17,53	**357,70**	204,10	17,53	**221,63**	2,37	
	Price (€)	17,25	10,53	**27,78**	10,35	10,53	**20,88**	1,42	
	Embodied Energy (MJ)	292,21	594,14	**886,34**	175,32	594,14	**769,46**	80,34	
	CO2 Emissions (kg)	43,54	43,64	**87,18**	26,13	43,64	**69,77**	5,90	
Process Related Costs	Embodied Energy (MJ)	0,000	73,435	**73,43**	0,000	88,000	**88,00**	12,000	
	CO2 Emissions (kg)	0,00	5,50	**5,50**	0,00	6,60	**6,60**	0,89	
Transport Related Costs (50 km)	Embodied Energy (MJ)	12	0,620	**12,62**	7	0,620	**7,82**	0,084	
	CO2 Emissions (kg)	0,87	0,05	**0,92**	0,52	0,57	**1,09**	0,01	
Disposal Related Costs	Embodied Energy (MJ)	68	3,500	**71,50**	41	3,500	**44,50**	0,470	
	CO2 Emissions (kg)	4,80	0,25	**5,05**	2,90	0,25	**3,15**	0,03	
End-of-Life		Landfill	Landfill		Reuse	Reuse		Reuse	
Totals	Embodied Energy (MJ)	372,21	671,691	**1043,90**	223,52	686,256	**909,78**	92,897	1002,677103
	CO2 Emissions (kg)	49,21	49,44	**98,65**	29,55	51,06	**80,61**	6,83	87,4355695

Table 15: Final comparison of material use and related costs per m² of the concrete slabs [67]

The final comparison shows that the reusable 3DCP slab is slightly less polluting than the case-study slab. Even if the reusable 3DCP slab has much less concrete volume compared to the case-study, the stainless steel connections contribute to the increase of embodied energy and CO_2 emissions. However, it is important to remember that such values are still for a slab that can be reused multiple times, compared to the case-study that can only be used one service-life.

67 Data extracted from CES Edupack 2018

Conclusions

This report explores the design of a reusable concrete slab for housing buildings. The conceptual design is based on the Design for Reuse approach of the circular economy. This concept, among other principles, dictates the effective separation of the building's elements according to their function and technical-life. This type of separation results in the possibility of the elements to be replaced. The main advantage of this approach is that if an element is damaged or at the end of its tehnical-life, it can be replaced without affecting the overall composition of the building. This enables to keep exploiting the technical-life of the undamaged elements. The application of this DfR approach to the design of the reusable slab lies in the separation of the connections and core of the slab. An effective separation is achieved thorugh the design of interlocking interfaces. This means that they can be disassembled as no chemical bond is achieved between the reusable slab and the wall.

The design tolerances play a crucial role in the design of the connections. They become more relevant when the elements to connect have been made by two different production proccesses. This means that the tolerances are also different and the design of the connection has to account for both of them. Moreover, the production processes selected for this research have a considerable variation of tolerances. Precast tolerances are +-5 millimetres while 3DCP are +-10 millimetres. An effective solution to cover such tolerances is with the use of slopes and angles in the connection geometry. The angles assure a good fit even when the tolerances are too big. However, an important consideration is to design also the length of the connection. This is because the horizontal tolerance of the element will be covered by the vertical displacement of the connection. Therefore, the length of the connection has to be proper to account for such vertical displacements. A topology optimisation of the connection T-dowel is therefore adviced for future research. This would reduce the steel use which as seen, has a major impact in the cost and environmental impact of the reusable slab.

Dry connections require a thicker cross section of the slab. This increases the second moment of area and restrict the maximum deflection of the slab. However, an increase of the cross section of the slab also means the increase of the self-weight. An effective method to minimize the self-weight of the slab while manteining the stifness of a thick cross section is the use of honeycomb structures. This research explores the effectiveness of a 3DCP honeycoms tructure that minimizes the material weight in certain areas and keeps the stiffness of the slab. The feasibility of this approach has been validated with Ansys and the results are positive as the maximum deflection of the slab is within the structural limits set by norm. Furthermore, the decrease in material use also means a decrease in the weight of the slab. This is a possitive feature as their transportation could be done without heavy vehicles and their installation can be eased as well. The utilisation of the 3DCP honeycomb also reduces the environmental impact caused by material utilisation. However, abrupt changes of stress forces have

been noticed in the interface of the 3DCP honeycomb and the concrete plates.

It has been noticed that the strutural behaviour of FRC largely depends on the orientation of its fibres. Here, 3DCP seems a sensible solution as it has been observed that the fibres orient parallel to the deposition of the concrete layer. If this strategy is applied, this means that a printing path can be programmed and, the fibres will orient accordingly. Therefore, 3DCP techniques not only contributes to material waste diminish, but also to achieve certain structural performance based on the printing path.

The exact gain from the improved durability of the reusable 3DCP slab is difficult to estimate. Physical testing data is missing in this research and therefore, only approximations can be applied. The gain is also explored to a basic level due to time constraints.

The ugly appearance of old concrete elements might improve significantly with the use of FRC. Here, the corrosion caused by steel rebars is avoided and therefore, the overall look of the concrete slab will remain the same. This is critical to change the mind-set that new is always better than reused. This logic is most of the times supported by how the product looks.

The design process of current concrete elemens is the main challenge to overcome in the DfR framework. This stage usually neglects the end-of-life of the product.

An easy (dis)assembly is critical for the success of DfR. If the time it takes to (dis)assemle a building is longer compared to demolition, the second method will be preferred. According to Salama (2017), the time required for disassembly vary between 3 to 8 times that of mechanical demolition. The design of an easy and straight-forward (dis)assembly process is therefore critical to overcome this challenge.

Size and weight of the concrete elements are important in the DfR framework. The lighter and smaller the product is, the easier is to (dis)assemble it. This can be overcome if advanced manufacturing techniques such as 3DCP, are used to produce a topologically optimised element.

There is a lack of assesing methods for measuring the benefits of DfR. This might be due to the limited number of projects that have successfully applied this strategy. Therefore, more data is required. This might become possible as DfR becomes a common practice in the built environment.

Recommendations for future research

Physical testing of the production process is missing in this research. The 3DCP production method is propossed and the design of the slab has been done accordingly. However, to evaluate its complete feasibility physical studies need to be made.

The bonding strength of the layers' interface has not been studied. Assumptions have been made with regards to the structural capacity. However, a proper physical testing is also required here to evaluate the feasibility of the slab design based on the layers' interface strength.

The perpenticular bonding between layers needs also to be validated. This is currently one of the main challenges of 3DCP techniques. An option might be to accomodae manually series of anchors that will be embedded later in the layers through the AM process. This approach requires extra labour but it might be still less labour than the one needed in current production techniques.

The impact of cold joints in the durability of the slab needs revision. Cold joints might not affct immediately the structural capacity of the slab. However, after time such joints might weaken the structure leading to failure. A proper revision of cold joints, their impact and the time that it would take for such impact is a point of attention.

The slab does not integrate space for services. Here, electrical conduits or drainage holes might be designed and input into an overall production process. Therefore, the user would not neet to make holes in the slab to fix housing features. If this is achieved, the reusability potential of the slab would increase as the user would not have the need to modify the slab. Therefore, the original design of the slab would and its structural capacity would remain.

A multi-porpuse slab might be designed from here. The current research is only focused on housing usage. However, the slab can be designed to function for a wider range of uses with similar structural requirements. This might increase the reuse potential of the slab as its reuse options would increase.

Structural calculations and force transfer might be done with advanced software. Then, a printing path can be programmed to achieve the structural requirements of the 3DCP slab based on fibres orientation. Based on the printing path, a printing time can be calculated and compared to that of a conventional concrete slab.

Digital algorithms can be scripted to introduce stress constraints to the material properties. Therefore,

optimal shapes can be generated and then produced through AM methods.

Research reflection

Position of the Graduation Topic in the Studio

The graduation studio of the Building Technology (BT) master track is referred to as "sustainable graduation studio". Hence, sustainability plays a central role in every course offered within the BT master track. This research has a clear focus on sustainability as it investigates how to optimize the usage of the most consumed material in the built environment: concrete. Given the significant share that concrete has in the building industry, the ability to optimize the composite use represents a global impact in reducing both pressure from the environment and carbon footprint.

A merge between the fields of material science and circularity drive this research. Material science is aknowledge offered within the BT track. On the other hand, education on circularity is not offered widely enough. This has represented a challenge because the knowledge has been new and has to be acquired in a relatively short period. The combination of these two fields results in the understanding of the material properties of concrete and alternatives to fully exploit its potential in a cost-effective and environmentally friendly way. This represents one of the greatest challenges posed to building technology today.

Relation of Research and Design

This research is conducted by experimental design. It investigates the engineering of a prefabricated structural concrete slab that optimizes the composite use in two manners. First, comprises material and structural optimization with the support of digital technologies. Topology optimization will be evaluated to reduce the amount of concrete without affecting the functionality of the slab. Correspondingly, a production system that minimizes material waste, such as formwork, must be considered. Second, the design will foresight multiple lifespans of the concrete slab. This means that it can be efficiently demounted and reused to extend its exploitation life before being remanufactured. The simplicity of connections for rapid and easy assembly/disassembly is important in this framework. This translates into additional savings of energy and CO_2 emissions due to a rapid building process. Prototypes of the reusable concrete slab should be fabricated to evaluate this new approach.

Societal Relevance

The success of maintaining the sustainability of our natural environment largely depends on our ability to optimize our resources. This research offers a new approach to the usage optimization of the most globally used building material: concrete. In this exploration the use of concrete is reduced by increasing the life-span of a structural element. The structural element can be reused multiple times. Therefore, it is not necessary to build new elements. This reduces the intensive depletion of raw

materials in our natural environment. Furthermore, it offers a shift towards rethinking buildings as material banks to use in the future. The ability to optimize the use of concrete is necessary to maintain and sustain many of the resources that our planet offers. After all, Earth is our only Earth.

Furthermore, this research has also an economic relevance as the monetary costs for producing new buildings would greatly be reduced. Investments for the fabrication of new components would be avoided, leaving only logistics and transportation expenses.

Scientific Relevance

The information gathered in this research can disclose new ways of constructing our buildings to optimize the use of materials. Design for reuse is a practice that has been recently applied to the built environment. However, its focus has been mainly on façade systems and interior components. The practice has left aside the most expensive, labour intensive and energy consuming segment of the building: the structure. In this sense, every piece of information on how the strategy of design for reuse can be applied to structural concrete elements, with all its advantages, represents a step towards a more sustainable use of our resources.

Bibliography

Aalami, B. (2008). Deflection of Concrete Floor Systems for Serviceability. ADAPT Technical Note, TN292(650), 1-38.

Aghaei-Meibodi, M., Bernhard, M., Jipa, A., & Dillenburger, B. (2017). The Smart Takes from the Strong. ETH Zürich, Zürich, Switzerland.

Allwood, Jullian, M., & Cullen, J. (2009). Steel, Aluminium and Carbon: Alternative Strategies for Meeting the 2050 Carbon Emission Targets.

A Model for the Prediction of the Tensile Strength of Fiber-Reinforced Concrete Members, Before and After Cracking. (2017, 7 28). Fibers, 5(3), 27.

Aninthaneni, P., & Dhakal, R. (2017). Demountable Precast Concrete Frame–Building System for Seismic Regions: Conceptual Development. Journal of Architectural Engineering, 23(4), 04017024.

Aninthaneni, P., Dhakal, R., Marshall, J., & Bothara, J. (2018). Nonlinear Cyclic Behaviour of Precast Concrete Frame Sub-Assemblies With "Dry " End Plate Connection. Structures, 14(March), 124-136.

Araújo, D., Prado, L., Silva, E., & El Debs, M. (2018). Temporary beam-to-column connection for precast concrete frame assembly. Engineering Structures, 171, 529-544.

Asprone, D., Menna, C., Bos, F., Salet, T., Mata-Falcón, J., & Kaufmann, W. (2018, 10 1). Rethinking reinforcement for digital fabrication with concrete. Cement and Concrete Research, 112, 111-121. Elsevier Ltd.

Bao, Y., Xu, M., Soltan, D., Xia, T., Shih, A., Clack, H., & Li, V. (2019). Three-dimensional printing multifunctional engineered cementitious composites (ECC) for structural elements. In Y. Bao, M. Xu, D. Soltan, T. Xia, A. Shih, H. Clack, & V. Li, RILEM Bookseries (Vol. 19, pp. 115-128). Springer Netherlands.

Boogaard, W., & Reinhardt, H. (2019). Demountable and Remountable Concrete Structures for Renovation.

Borg Costanzi, C., Ahmed, Z., Schipper, H., Bos, F., Knaack, U., & Wolfs, R. (2018). 3D Printing Concrete on Temporary Surfaces: The Design and Fabrication of a Concrete Shell Structure. Automation in Construction, 94(May), 395-404.

Bos, F., Ahmed, Z., Jutinov, E., & Salet, T. (2017, 11 16). Experimental exploration of metal cable as reinforcement in 3D printed concrete. Materials, 10(11).

Bos, F., Ahmed, Z., Wolfs, R., & Salet, T. (2017). 3D printing concrete with reinforcement. High Tech Concrete: Where Technology and Engineering Meet - Proceedings of the 2017 fib Symposium (pp. 2484-2493). Springer International Publishing.

Bos, F., Bosco, E., & Salet, T. (2019, 4 3). Ductility of 3D printed concrete reinforced with short straight steel fibers. Virtual and Physical Prototyping, 14(2), 160-174.

Bos, F., Wolfs, R., Ahmed, Z., & Salet, T. (2019). Large scale testing of digitally fabricated concrete (DFC) elements. In F. Bos, R. Wolfs, Z. Ahmed, & T. Salet, RILEM Bookseries (Vol. 19, pp. 129-147). Springer Netherlands.

Braendstrup, C. (2017). Conceptual Design of a Demountable, Reusable Composite Flooring System. Delft University of Technology, Faculty of Civil Engineering and Geoscience.

Browell, R., & Hancq, A. (2006). Ansys: Calculating and Displaying Fatigue Results. Ansys Technical Support. Ansys Technical Support.

Buswell, R., Leal de Silva, W., Jones, S., & Dirrenberger, J. (2018, 10 1). 3D printing using concrete extrusion: A roadmap for research. Cement and Concrete Research, 112, 37-49. Elsevier Ltd.

CD20 Building Systems. (n.d.). CD20 Building Systems. Retrieved from https://www.cd20.nl/en/elements/Loadbearingfassades.php#.XFwdflxKhPY

Chen, Y., Veer, F., & Copuroglu, O. (2017). A Critical Review of 3D Concrete Printing as a Low CO2 Concrete Approach. Delft University of Technology, Delft, Netherlands.

Chen, Y., Veer, F., Copuroglu, O., & Schlangen, E. (2018). Feasibility of Using Low CO Concrete Alternatives in Extrusion-based 3D Concrete Printing. Delft University of Technology, Delft, The Netherlands.

Choumanidis, D., Badogiannis, E., Nomikos, P., & Sofianos, A. (2016, 12 30). The effect of different fibres on the flexural behaviour of concrete exposed to normal and elevated temperatures. Construction and Building Materials, 129, 266-277.

Citation Weng, Y., Qian, S., He, L., Li, M., & Tan, M. (2018). 3D printable high performance fiber reinforced cementitious composites for large-scale printing. Pro-AM, 19-24.
Co, A. (n.d.). Tolerances in concrete construction. 27-31.

Core77. (n.d.). The Ultimate Wood Joint: Visual Reference Guide. Retrieved from https://www.core77.com/posts/43001/Reference-The-Ultimate-Wood-Joint-Visual-Reference-Guide

Curosu, I., Liebscher, M., Mechtcherine, V., Bellmann, C., & Michel, S. (2017, 8 1). Tensile behavior of high-strength strain-hardening cement-based composites (HS-SHCC) made with high-performance polyethylene, aramid and PBO fibers. Cement and Concrete Research, 98, 71-81.

Crowther, P. (1999). Design for Disassembly: An Architectural Strategy. Queensland University of Technology, Brisbane, Australia.

Dal Lago, B., Negro, P., & Dal Lago, A. (2018). Seismic Design and Performance of Dry-Assembled Precast Structures with Adaptable Joints. Soil Dynamics and Earthquake Engineering, 106(July 2017), 182-195.

Dean, J. (1986). PERFORMANCE OF A DUCTILE MOMENT RESISTING CONNECTION BETWEEN A PRECAST CONCRETE COLUMN AND A TIMBER BEAM. Bulletin of the New Zealand National Society for Earthquake Engineering, 19(2), 111-122.

Dhakal, R. (2014). Conceptual Development: Low Loss Precast Concrete Frame Building System with Steel Connections. University of Canterbury, Christchurch, New Zealand.

Di Prisco, M., Plizzari, G., & Vandewalle, L. (2009). Fibre reinforced concrete: New design perspectives. Materials and Structures/Materiaux et Constructions, 42, pp. 1261-1281.

Ding, T., Xiao, J., Zhang, Q., & Akbarnezhad, A. (2018). Experimental and numerical studies on design for deconstruction concrete connections: An overview. Advances in Structural Engineering, 21(14), 2198-2214.

Duballet, R., Baverel, O., & Dirrenberger, J. (2018). Space Truss Masonry Walls with Robotic Mortar Extrusion. Structures(September), 1-7.

Durmisevic, E., & Brouwer, J. (2006). Design Aspects of Decomposable Building Structures. Proceedings of the CIB Task Group 39-Deconstruction Meeting(January), 2-24.

Edition, F. (1999). Manual for Quality Control for Structural Precast Concrete Products.

Ellen MacArthur Foundation. (2013). Engineering the Circular Economy: A Field Manual for Re-designing a Regenerative Economy - The Art of Design for Disassembly. Ellen MacArthur Foundation - Rethink the Future(September), 1-5.

Ellen MacArthur Foundation. (2013). Towards the Circular Economy: Economic and Business Rationale for an Accelerated Transition. Journal of Industrial Ecology.

Erkelens, P. (2002). Extending Service Life Of Buildings And Building Components Through Re-Use. 1-5.

EUROCODE 3. (2011). Simple Joints to Eurocode 3 Joints in steel construction :.
European Comission. (2011). Roadmap to a Resource Efficient Europe. European Comission, Brussels.

Ferrara, L., Ozyurt, N., & Di Prisco, M. (2011, 1). High mechanical performance of fibre reinforced cementitious composites: The role of "casting-flow induced" fibre orientation. Materials and Structures/Materiaux et Constructions, 44(1), 109-128.

Gassel, F. (2014). Experiences with the Design and Production of an Industrial, Flexible, and Demountable (IFD) Building System. Eindhoven University of Technology, Eindhoven, Netherlands.

Ghayeb, H., Razak, H., & Sulong, N. (2017). Development and Testing of Hybrid Precast Concrete Beam-to-Column Connections under Cyclic Loading. Construction and Building Materials, 151, 258-278.

Glabbeek, L. (2019). Development of an Innovative Demountable Floor System. Delft University of Technology, Faculty of Civil Engineering and Geoscience.

Gosselin, C., Duballet, R., Roux, P., Gaudillière, N., Dirrenberger, J., & Morel, P. (2016, 6 15). Large-scale 3D printing of ultra-high performance concrete - a new processing route for architects and builders. Materials and Design, 100, 102-109.

Granta Design Limited. (2018). CES EduPack 2018. Cambridge, UK.

Gritsenko, A. (n.d.). Towards a Demountable Composite Slab Floor System. Delft University of Technology, Faculty of Civil Engineering.

Hack, N., Lauer, W., Gramazio, F., & Kohler, M. (2015). Mesh Mould: Robotically Fabricated Metal Meshes as Concrete Formwork and Reinforcement. ResearchGate(June).

Hack, N., Wangler, T., Mata-Falcón, J., Dörfler, K., Kumar, N., Walzer, A., . . . Kohler, M. (2018). Mesh Mould: An on Site, Robotically Fabricated, Functional Formwork. ETH Zürich, Zürich, Switzerland.

Hambach, M., & Volkmer, D. (2017, 5 1). Properties of 3D-printed fiber-reinforced Portland cement paste. Cement and Concrete Composites, 79, 62-70.

Holschemacher, K., Mueller, T., & Ribakov, Y. (2010, 5). Effect of steel fibres on mechanical properties of high-strength concrete. Materials and Design, 31(5), 2604-2615.

Huuhka, S., Kaasalainen, T., Hakanen, J., & Lahdensivu, J. (2015). Reusing Concrete Panels from Buildings for Building. Tampere University of Technology, Tampere, Finland.

IGUS Headquarters by Grimshaw. (n.d.). Retrieved from https://www.youtube.com/watch?v=p1XpZGS6niE

IS 456. (2005). Plain and Reinforced Concrete: Code of Practice.

Jensen, K., Sommer, J., & GXN. (2016). Building A Circular Future. 284. Copenhagen, Denmark.

Jipa, A., Bernhard, M., Dillenburger, B., Ruffray, N., Wangler, T., & Flatt, R. (2017). skelETHon Formwork 3D Printed Plastic Formwork for Load-Bearing Concrete Structures. XXI Congreso de la Sociedad Ibero-americana de Gráfica Digital(November), 345-352.

Jipa, A., Bernhard, M., Meibodi, M., & Dillenburger, B. (2016). 3D-Printed Stay-in-Place Formwork for Topologically Optimized Concrete Slabs. ETH Zürich, Zürich, Switzerland.

Jones, S., Bentz, D., Martys, N., George, W., & Thomas, A. (2019). Rheological control of 3D printable cement paste and mortars. In S. Jones, D. Bentz, N. Martys, W. George, & A. Thomas, RILEM Bookseries (Vol. 19, pp. 70-80). Springer Netherlands.

Kristinsson, J., Hendriks, C., Kowalczyk, T., & te Dorsthorst, B. (2001). Reuse of Secondary Elements: Utopia or Reality. Delft University of Technology, Delft, Netherlands.

Lakusic, S. (2016, 9 21). Preliminarno istraživanje utjecaja orijentacije vlakana u mikroarmiranim mortovima. Journal of the Croatian Association of Civil Engineers, 68(08), 645-655.

Larsson, S. (2009). Weight and Dimensions of Commercial Vehicles: Directive 96 / 53 / EC and the European Modular System (EMS). ACEA, Brussels, Belgium.

Lloret Fritschi, E., Reiter, L., Wangler, T., Gramazio, F., Kohler, M., & Flatt, R. (2018). Smart Dynamic Casting: Slipforming with Flexible Formwork - Inline Measurement and Control. ETH Zürich, Zürich, Switzerland.

Lloret, E., Shahab, A., Linus, M., Flatt, R., Gramazio, F., Kohler, M., & Langenberg, S. (2015). Complex Concrete Structures: Merging Existing Casting Techniques with Digital Fabrication. CAD Computer Aided Design, 60, 40-49.

Maheninggalih, G. (2016). A Demountable Structural System of Multi-storey Building Case Study of Car Park Building. Delft University of Technology, Faculty of Civil Engineering and Geoscience, Delft, Netherlands.

Mangat, P. (1976). Tensile strength of steel fiber reinforced concrete. Cement and Concrete Research, 6(2), 245-252.

Marchment, T., & Sanjayan, J. (2019). Method of enhancing interlayer bond strength in 3D concrete printing. In T. Marchment, & J. Sanjayan, RILEM Bookseries (Vol. 19, pp. 148-156). Springer Netherlands.

Martens, P., Mathot, M., Bos, F., & Coenders, J. (2017). Optimising 3D printed concrete structures using topology optimisation. High Tech Concrete: Where Technology and Engineering Meet - Proceedings of the 2017 fib Symposium (pp. 301-309). Springer International Publishing.

Mata-Falcón, J., Bischof, P., & Kaufmann, W. (2019). Exploiting the potential of digital fabrication for sustainable and economic concrete structures. In J. Mata-Falcón, P. Bischof, & W. Kaufmann, RILEM Bookseries (Vol. 19, pp. 157-166). Springer Netherlands.

Metelli, G., & Riva, P. (2008). Behaviour of a Beam to Column "Dry" Joint for Precast Concrete Elements. The 14th World Conference on Earthquake Engineering, (pp. 1-8). Beijing, China.

Mechtcherine, V., Nerella, V., Ogura, H., Grafe, J., Spaniol, E., Hertel, M., & Füssel, U. (2019). Alternative reinforcements for digital concrete construction. In V. Mechtcherine, V. Nerella, H. Ogura, J. Grafe, E. Spaniol, M. Hertel, & U. Füssel, RILEM Bookseries (Vol. 19, pp. 167-175). Springer Netherlands.

Ministry of Insfrastructure and the Environment, & Ministry of Economic Affairs. (2016). A Circular Economy in the Netherlands by 2050. 1-72.

Mitchell, J. (2008). The Concrete Conundrum. Chemistry World(March), 62-66.

Naaman, A. (2003). Engineered Steel Fibers with Optimal Properties for Reinforcement of Cement Composites. Journal of Advanced Concrete Technology, 1(3), 241-252.

Nematollahi, B., Xia, M., Sanjayan, J., & Vijay, P. (2018, 11 20). Effect of Type of Fiber on Inter-Layer Bond and Flexural Strengths of Extrusion-Based 3D Printed Geopolymer. Materials Science Forum, 939, 155-162.

Nzabonimpa, J., Hong, W., & Park, S. (2017). Experimental Investigation of Precast Concrete Based Dry Mechanical Column–Column Joints for Precast Concrete Frames. Structural Design of Tall and Special Buildings, 26(5), 1-19.

Nzabonimpa, J., Hong, W.-K., & Park, S.-C. (2017). Experimental Investigation of Precast Concrete Based Dry Mechanical Column–column Joints for POrecast Concrete Frames. Structural Design of Tall and Special Buildings, 26(5), 1-19.

Panda, B., Chandra Paul, S., & Jen Tan, M. (2017, 12 15). Anisotropic mechanical performance of 3D printed fiber reinforced sustainable construction material. Materials Letters, 209, 146-149.

Panda, B., Noor Mohamed, N., Tay, Y., & Tan, M. (2019). Bond strength in 3D printed geopolymer mortar. In B. Panda, N. Noor Mohamed, Y. Tay, & M. Tan, RILEM Bookseries (Vol. 19, pp. 200-206). Springer Netherlands.

Paus, T. (n.d.). STEEL FIBRE REINFORCED CONCRETE IN FLAT SLABS.

PCI. (n.d.). Design for Seismic: Precast Protection Against Earthquakes. Retrieved from https://www.pci.org/DesignForSeismic

Petek Gursel, A., Masanet, E., Horvath, A., & Stadel, A. (2014). Life-Cycle Inventory Analysis of Concrete roduction: A Critical Review. Cement and Concrete Composites, 51(August 2014), 38-48.

Pfändler, P., Wangler, T., Mata-Falcón, J., Flatt, R., & Kaufmann, W. (2019). Potentials of steel fibres for mesh mould elements. In P. Pfändler, T. Wangler, J. Mata-Falcón, R. Flatt, & W. Kaufmann, RILEM Bookseries (Vol. 19, pp. 207-216). Springer Netherlands.

Precast Concrete Institute. (n.d.). Connections for Architectural Precast Concrete. (Precast Concrete Institute, Ed.) Chicago, Illinois: Precast Concrete Institute.

Reinhardt, W. (2019). Demountable and remountable concrete structures for renovation.

Residential Structural Design Guide. (1999). Design Loads for Residential Buildings.

Rios, F., Chong, W., & Grau, D. (2015). Design for Disassembly and Deconstruction - Challenges and Opportunities. Procedia Engineering, 118, 1296-1304.

Ruffray, N., Bernhard, M., Jipa, A., Aghaei-Meibodi, M., Montague de Taisne, N., Stutz, F., . . . Dillenburger, B. (2017). Complex Architectural Elements from HPFRC and 3D Printed Sandstone. RILEM Symposium on Ultra-High Performance Fibre-Reinforced Concrete(1), 1-11.

Salama, W. (2017). Design of concrete buildings for disassembly: An explorative review. International Journal of Sustainable Built Environment, 6(2), 617-635.

Salet, T., Ahmed, Z., Bos, F., & Laagland, H. (2018, 7 3). Design of a 3D printed concrete bridge by testing*. Virtual and Physical Prototyping, 13(3), 222-236.

Schut, E., Crielaard, M., & Mesman, M. (2015). Circular Economy in the Dutch Construction Sector. National Institute for Public Health and the Environment(December), 1-58.

Simple, I. (n.d.). Joints 5.1. In I. Simple.

Singh, H. (n.d.). Springer Transactions in Civil and Environmental Engineering Steel Fiber Reinforced Concrete Behavior, Modelling and Design.

Sorensen, C., Berge, E., Saga, P., & Østvold, A. (2013, 5 30). Factors Affecting the Efficiency of Fibers in Concrete on Crack Reduction. Open Journal of Civil Engineering, 03(02), 80-85.

Soutsos, M., Le, T., & Lampropoulos, A. (2012, 11). Flexural performance of fibre reinforced concrete made with steel and synthetic fibres. Construction and Building Materials, 36, 704-710.

Stefanoni, M., Angst, U., & Elsener, B. (2019). Corrosion challenges and opportunities in digital fabrication of reinforced concrete. In M. Stefanoni, U. Angst, & B. Elsener, RILEM Bookseries (Vol. 19, pp. 225-233). Springer Netherlands.

Taher, S. (2007). Wet vs. Dry Techniques in Connecting Piecewise Precast Reinforced Concrete Beam-Column Elements In Moment Resisting Frames. Tanta University.

Tan, M., Panda, B., & Wei Tay, Y. (2016). Current Challenges and Future Perspectives of 3D Concrete Printing. 2nd International Conference on Progress in Additive Manufacturing(May), 16-19.

te Dorsthorst, B., & Kowalczyk, A. (2000). State of the art deconstruction in the Netherlands. Delft University of Technology, Delft, Netherlands.

Thaddeus, D., & Arbes, D. (2016). Structure of the Everyday: Structural Steel Connections. (pp. 1-45). Charlotte, North Carolina: University of North Carolina.

The Economist. (2019). The Trump Show. 2, 47-48.

The European Parliament and the Council of the European Union. (2008). Directive 2008/98/EC. November.

Van Der Putten, J., De Schutter, G., & Van Tittelboom, K. (2019). The effect of print parameters on the (micro)structure of 3D printed cementitious materials. In J. Van Der Putten, G. De Schutter, & K. Van Tittelboom, RILEM Bookseries (Vol. 19, pp. 234-244). Springer Netherlands.

van Dijk, K., Boedianto, P., te Dorsthorst, B., & Kowalczyk, A. (n.d.). State of the Art Deconstruction in the Netherlands: Chapter 6. Delft University of Technnology, Delft, Netherlands.

van Gurchom, H., & Damen, T. (n.d.). IFD Building in Europe: A Blueprint for Production and Delivery of Costumer Satisfaction Oriented Buildings. Eindhoven University of Technology, Eindhoven, Netherlands.

Van Mier, J. (n.d.). CEMENTITIOUS COMPOSITES WITH HIGH TENSILE STRENGTH AND DUCTILITY THROUGH HYBRID FIBRES.

Vander, M., & Walker, H. (1976). Tolerances for Precast Concrete Structure. PCI Journal(4), 44-57.

Vantyghem, G., Boel, V., De Corte, W., & Steeman, M. (2019). Compliance, stress-based and multi-physics topology optimization for 3D-printed concrete structures. In G. Vantyghem, V. Boel, W. De Corte, & M. Steeman, RILEM Bookseries (Vol. 19, pp. 323-332). Springer Netherlands.

Wagemans, L., Soons, F., & Van Raaij, B. (2014). Quick Reference of General Loads. In L. Wagemans, F. Soons, & B. Van Raaij. Delft, Netherlands: Delft University of Technology.

Walraven, J. (2013). Connections Between Precast Elements : Types, Design & Application. Delft University of Technology, Delft, The Netherlands.
Wangler, T., Lloret, E., Reiter, L., Hack, N., Gramazio, F., Kohler, M., . . . Flatt, R. (2016). Digital Concrete: Opportunities and Challenges. RILEM Technical Letters, 1, 67.

Wijffels, M., Wolfs, R., Suiker, A., & Salet, T. (2017, 7 1). Magnetic orientation of steel fibres in self-compacting concrete beams: Effect on failure behaviour. Cement and Concrete Composites, 80, 342-355.

Witte, D. (2015). Concrete in an AM Process - Freeform Concrete Processing. Delft University of Technology, Faculty of Architecture and the Built Environment.

Witzany, J., Zigler, R., & Polák, A. (2016). Precast reinforced concrete demountable system ofmulti-storey buildings. Insights and Innovations in Structural Engineering, Mechanics and Computation - Proceedings of the 6th International Conference on Structural Engineering, Mechanics and Computation, SEMC 2016.

Yu, J., & Leung, C. (2019). Impact of 3D printing direction on mechanical performance of strain-hardening cementitious composite (SHCC). In J. Yu, & C. Leung, RILEM Bookseries (Vol. 19, pp. 255-265). Springer Netherlands.

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Delft University of Technology
Faculty of Architecture and the Built Environment
Master Track Building Technology