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Design for 3D Concrete Printing

Optimisation Through Integrated Workflows

JOSÉ HERNÁNDEZ VARGAS
KTH, Civil and Architectural Engineering

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Abstract

The transition from conventional cast concrete to 3D Concrete Printing (3DCP) marks a paradigm shift by directly depositing fresh concrete layer upon layer according to a digital model without the need for a formwork. This technology offers the possibility of achieving innovative and complex geometries in an automated process. Additionally, the implicit digitalisation introduced by this technology streamlines the interaction among different stakeholders, thereby reducing human errors and augmenting construction quality.

Nevertheless, despite its potential, methods for fully exploiting the design capabilities of 3DCP are still largely underdeveloped. This is primarily due to the assumed separation between the design process and the generation of manufacturing instructions. While the current driver for this technology is linked to increasing productivity and reducing labour costs, its most significant contribution may well be in the manufacturing of material-efficient structures by automatically integrating structural analysis into the design process.

This licentiate thesis aims to extend the design scope for this rapidly maturing technology by investigating its design possibilities, relevant printing parameters, and structural optimisation capabilities within the inherent restrictions of the process. The research focuses on the development of integrated design-to-manufacture workflows for the manipulation, analysis, and optimisation of print paths considering material and process constraints. Additionally, a comprehensive literature review is conducted, with a particular emphasis on the expansive design capabilities of 3DCP.

Experimental studies encompassed the design, manufacturing, and testing of concrete prototypes using a custom-made 3DCP system based on a robotic arm. The results demonstrated that customised material distributions can be successfully programmed and executed, resulting in prototypes with enhanced structural performance. Laboratory tests on topology-optimised unreinforced 3DCP beams revealed a substantial increase in load-bearing capacity per unit weight compared to conventional 3D printing patterns.

The thesis aligns with the broader sustainability goals of the construction industry. Even though the cement content in 3D printed concrete currently tends to be higher compared to conventional methods, the potential of the technology for optimising material use, minimising waste, and incorporating additional functionalities to structures presents significant opportunities for reducing the environmental footprint of concrete construction. By integrating manufacturing constraints into the design process, this study delineates a pathway for extending the design possibilities of 3DCP toward the implementation of material-efficient structures with graded properties. Ultimately, this study contributes to bridging the gap between digital design and digital fabrication methods, thereby advancing concrete construction practices.

Keywords: 3D concrete printing, digital fabrication, concrete structures, additive manufacturing, robotic fabrication, design for manufacturing, structural optimisation, functionally graded concrete, topology optimisation.

Sammanfattning

Övergången från traditionell gjuten betong till 3D-betongutskrift (3D Concrete Printing eller 3DCP) markerar ett paradigmskifte genom att direkt deponera färsk betong lager för lager enligt en digital modell, utan behov av formar. Denna teknik erbjuder möjligheter att uppnå innovativa och komplexa geometrier genom en automatiserad process. Dessutom förenklar digitaliseringen interaktionen mellan olika intressenter, vilket minskar mänskliga fel och ökar byggkvaliteten.

Denna licentiatavhandling syftar till att utvidga designomfånget för denna snabbt växande teknik genom att undersöka dess designmöjligheter, relevanta utskriftsparametrar och kapaciteter för strukturell optimering inom de rådande begränsningarna av processen. Forskningen fokuserar på utvecklingen av integrerade design-till-tillverkning-flöden för styrning, analys och optimering av utskriftsvägar med hänsyn till material- och processbegränsningar. Dessutom genomförs en omfattande litteraturöversikt med särskild betoning på 3DCP:s expansiva designkapacitet.

Experimentella studier omfattade design, tillverkning och testning av betongprototyper med ett skräddarsytt 3DCP-system baserat på en robotarm. Resultaten visade att anpassade materialfördelningar framgångsrikt kan programmeras och genomföras, vilket resulterade i prototyper med förbättrad strukturell prestanda. Laboratorietester på topologioptimerade oarmerade 3DCP-balkar visade en betydande ökning av bärförmåga per enhetsvikt jämfört med konventionella 3D-utskriftsmönster.

Forskningen ligger i linje med byggbranschens övergripande hållbarhetsmål. Även om cementinnehållet i 3D-utskriven betong för närvarande tenderar att vara högre jämfört med konventionella metoder, erbjuder teknologin potential att optimera materialanvändning, minimera spill och lägga till funktionaliteter i konstruktioner, vilket ger möjligheter att minska betongkonstruktioners miljöavtryck. Genom att integrera tillverkningsbegränsningar i designprocessen skisserar denna studie en väg för att utöka designmöjligheterna för 3DCP mot implementering av material-effektiva konstruktioner med varierande egenskaper. Slutligen bidrar denna studie till att överbrygga klyftan mellan digital design och digitala tillverkningsmetoder, och därmed främja betongbyggandets metoder.

Keywords: 3D-betongutskrift, digital tillverkning, betongkonstruktioner, additiv tillverkning, robotstyrd tillverkning, design för tillverkning, strukturell optimering, funktionellt graderad betong, topologioptimering.

Preface

The research presented in this licentiate thesis has been conducted at the KTH Royal Institute of Technology as a collaboration between the Division of Concrete Structures, Department of Civil and Architectural Engineering, and the School of Architecture. The project has been funded by the Hesselmanska Foundation, the Development Fund of the Swedish Construction Industry (SBUF), and the strategic innovation program Smart Built Environment (2020–00257), which is part of the strategic innovation areas initiative funded by Vinnova — the Swedish Innovation Agency, Formas — a Swedish Research Council for Sustainable Development and the Swedish Energy Agency. The premix material for the 3DCP experiments was donated by Sika (Sika Sverige AB). Their significant contributions are sincerely acknowledged and have been vital in enabling this research.

I would like to extend my gratitude to my main supervisor, Professor Johan Silfwerbrand, and my co-supervisor Dr Helena Westerlind for their enduring support, knowledgeable advice, and guidance throughout the tenure of this project. I am also thankful for the collaborative spirit and intellectual generosity of my co-author Dr Andreas Sjölander. I am equally indebted to Docent Richard Malm for his specialised expertise and insightful advice. The members of the reference group have been integral to this process, critical feedback that have significantly enriched the research. A special mention is due to Staffan Hintze who was instrumental in starting the project, and to Christina Claeson-Jonsson for her pivotal role in its continuation. A heartfelt thank you is also due to my colleagues at the Division of Concrete Structures for their advice and expertise, in particular to Docent Annika Gram for reviewing this thesis.

I would like to express my sincere gratitude to Adam Varga, Alexander Sanning, Anna Eklund, and Henrik Stålhandske at the School of Architecture, as well as Viktor Bolund at Civil and Architectural Engineering, for their invaluable hands-on assistance during laboratory work. The expertise of former RISE CBI personnel —Wolfram Oettel, Patrick Rogers, and Gürsel Hakan Tayland— was critical, especially in the early phases of the project. Special acknowledgement to Tobias v. Haslingen and Henrik Ahlberg from

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Furthermore, I am deeply grateful to my friends and colleagues, both at Civil and Architectural Engineering and Architecture departments for providing an enriching and broad research environment. Finally, my deepest gratitude goes to my family and friends, whose unconditional support has been a constant throughout this project.

Stockholm, December 2023
José Hernández Vargas

List of publications

This licentiate thesis presents an introduction and a compendium of the findings presented in three appended papers, encompassing two articles for academic journals and one paper in peer-reviewed conference proceedings. These articles will hereafter be denoted as Paper I—III.

Paper I Hernández Vargas, J., Westerlind, H., & Silfwerbrand, J. (2022). Grading Material Properties in 3D Printed Concrete Structures. Nordic Concrete Research, 66(1), 73–89.

Paper II Hernández Vargas, J., (2023): Spatially Graded Modeling: An Integrated Workflow For 3D Concrete Printing. (in press) XXVII Conference of the Iberoamerican Society of Digital Graphics (SIGraDi 2023) in Punta del Este, Uruguay, Nov. 29 – Dec. 1, 2023.

Paper III Hernández Vargas, J., Sjölander, A., Westerlind, H., & Silfwerbrand, J., (2023). Internal topology optimisation of 3D printed concrete structures: A method for enhanced performance and material efficency. Submitted to an international scientific journal.

In Paper I, the lead author was responsible for the conceptualisation and methodology development, investigation, writing the original draft, review, and editing of the paper. Co-authors contributed by reviewing and editing the manuscript and provided supervision. In Paper III, the first author led the conceptualisation and methodology of the study, developed visualisations, programming, investigation, data curation, as well as writing the original draft, review, and editing of the manuscript. Andreas Sjölander contributed with in the testing and data curation, and he also assisted in reviewing and editing the manuscript. Helena Westerlind and Johan Silfwerbrand's contributions were focused on reviewing and editing the manuscript, as well as providing supervision.

Contents

List of Acronyms

3DCP	3D concrete printing
AEC	Architecture, engineering, and construction
API	Application programming interface
AM	Additive manufacturing
BIM	Building information modelling
CAD	Computer-aided design
CAE	Computer-aided engineering
CAM	Computer-aided manufacturing
CC	Contour crafting
CCS	Carbon capture and storage
CNC	Computer numerical control
DFC	Digital fabrication with concrete
DfD	Design for disassembly
DOF	Degrees of freedom
FA	Fly ash
FDM	Fused deposition modelling
FEA	Finite element analysis
FFF	Fused filament fabrication
FGC	Functionally graded concrete
FGM	Functionally graded materials
GGBS	Ground granulated blast-furnace slag
GH	Grasshopper (Rhinoceros)
KRL	Kuka robotic language

OPC	Ordinary Portland cement
PLC	Programmable logic controller
SC3DP	Shotcrete 3D printing
SCA	Selective cement activation
SCC	Self-compacting concrete
SCM	Supplementary cementitious materials
SDG	Sustainable Development Goals
SF	Silica fume
SLA	Stereolithography
SLS	Selective laser sintering
SPI	Selective paste intrusion
TCP	Tool centre point
TRL	Technology readiness level
TO	Topology optimisation
UHPC	Ultra-high performance concrete
VMA	Viscosity modifying agent
v/v	Volume/Volume percent
w/w	Weight/Weight percent

Chapter 1

Introduction

1.1 Background

Concrete is the most extensively used construction material in the world and has been the foundation of modern architecture, urban development and infrastructure. Although concrete is a relatively inexpensive material with lower embedded carbon emissions than some other common construction materials, its extensive global impact is a consequence of the massive amounts of concrete poured every year. The production of Portland cement, the most widely used binder in concrete, is responsible for approximately 6 — 8 % of global CO_2 emissions [1]. Traditional construction methods are based on pouring fresh concrete into a mould, which is usually a single-use structure that needs to be built and taken apart. This results in a labour-intensive and time-consuming process that leads to high construction costs and material waste. While modularised reusable formwork and prefabrication provide an advantage in terms of efficiency, the possible outcomes are severely limited in flexibility and applications.

Extrusion-based 3D concrete printing (3DCP) has become the leading technology for digital fabrication with concrete. Instead of using formwork to shape concrete, 3D printing enables the construction of intricate geometries by directly depositing fresh concrete layer upon layer following a digital model. 3DCP can offer innovative and complex geometries that were previously unthinkable due to formwork constraints. While several studies have focused on the formal flexibility provided by this technology, it remains unclear how beneficial these complex geometries are in terms of minimising the environmental impact of manufactured concrete structures. At present, the main driver behind the adoption of this technology is the increase in productivity and reduction in labour costs. However, its most significant utility arguably lies in the ability to manufacture structures that can deliver the same load-bearing capacity with less material by integrating design and structural analysis. This allows for the creation of optimised elements that use concrete only where required, reducing material consumption and consequently cutting emissions associated with material production. Thus, the design freedom offered by 3D printing can have a major impact on the building industry by allowing custom-made designs to become economically feasible. Although 3DCP technology is expanding rapidly and getting closer to real market conditions, it is still largely operating in a protected research environment and is likely not yet competitive. While several projects have successfully demonstrated the feasibility of 3DCP, the overall development of the technology is still in an early stage, and therefore printing equipment and materials are not yet cost-effective compared with mainstream construction practice.

Moreover, methods for fully harnessing the design potential of the technology remain largely underdeveloped, as most 3DCP processes assume a fundamental separation between the design process and the generation of manufacturing instructions. There is a significant gap in the development of design methods to fully exploit the technical capabilities offered by the technology. As a consequence, the design space is limited to the overall shape of the print and some printing parameters, whereas the printing properties are specified by automated processing that typically occurs outside the control of the designer.

1.2 Aims and scope

The objective of this thesis is to advance the existing design methods for 3D printing with cement-based materials. For this purpose, several workflows to design custom 3D printed concrete elements are evaluated and improved. Furthermore, this research aims to expand the possibilities of 3DCP by incorporating methods for manipulating, analysing and optimising material properties and print parameters within the design environment. Through the exploration of novel design and manufacturing approaches for 3D printed building elements, the overall printing process can be made more efficient. This is investigated through the incorporation of complex internal structures that can improve structural performance while reducing material use. This study aligns with the pressing sustainability goals of the construction industry, creating a path to assimilate the potential of 3DCP to reduce the environmental impact of concrete structures. Although concrete mixes developed for 3D printing have higher cement content than conventional cast concrete, the adoption of 3D printing technology makes it possible to optimise material usage, minimise waste, and create structures with added functionalities that can potentially decrease the footprint of traditional construction methods. Lessons from complex 3D printed structures can be translated into the improvement of manufacturing and design techniques that can be applied to simpler components. The aims and goals are summarised in the following research questions:

RQ 1: *What are the design possibilities afforded by 3DCP?*

RQ 2: *Which design parameters are relevant for 3DCP?*

RQ 3: *How can the freedom of shape offered by 3DCP allow for manufacturing concrete elements with enhanced structural design?*

RQ 4: *How can the structural performance of 3D printed concrete parts be optimised within the bounds of manufacturing constraints?*

1.3 Methods and limitations

The scope of this study is limited to unreinforced 3D printed concrete. The material used in this work is limited to Sikacrete 751–3D [2], a commercially available mono-component dry mix with a maximum aggregate size of 1 mm. Additive manufacturing sessions were carried out at the digital fabrication laboratory at the KTH School of Architecture using a custom-made 3DCP system based on an industrial robotic arm. Mechanical assessment of the printed samples through three-point bending test was conducted at the Institution for Civil and Architectural Engineering at KTH. The focus of this thesis is the digital design of 3D printed concrete structures. For this, an extended CAD environment is used to model, slice, and generate manufacturing instructions. Robotic control is limited to offline programming i.e., the 3DCP system is unable to make adjustments during the printing process.

As presented by Bos et al. [3], 3DCP mainly consists of three expertise areas: digital design and control, robotics and mechanics, and material science. While this was not meant to be a hierarchical description, the suggested order fits well with the focus and expertise of the present research. This licentiate thesis focuses on the digital part i.e., design, generation of printing instructions, and print control. It also features a custom development of a laboratory-scale 3DCP system based on an industrial robotic arm, which relates to mechanical issues. Finally, the material part is restricted to the use of premix mono-component material.

1.4 Outline of the thesis

This thesis is composed of seven chapters encompassing a literature review, experimental procedures, laboratory tests, and three appended papers. Chapter 2 provides an overview of the development of 3D concrete printing. In Chapter 3 the design workflows and tools for 3DCP are presented. Chapter 4, gives a summary of the equipment and methods used in this study. Chapter 5 presents the results of the experiments. Finally, Chapter 6 summarises the main findings and provides points of interest for future research.

Chapter 2

An overview of 3D concrete printing

Over the past two decades, 3D concrete printing (3DCP) has seen significant advancements from preliminary research explorations to a broad range of practical implementations. This dynamic evolution is rooted in synergies across various domains, highlighting the importance of multidisciplinary expertise, which is presented on this chapter as a comprehensive overview of the field. It begins with an exploration of the basic terminologies, the historical development, and the current state-of-the art of 3DCP. Next, Section 2.2 provides an outlook into the diverse configurations and features of 3DCP systems. The distinction between prefabrication and in-situ 3DCP operations, along with their respective challenges, is analysed in Section 2.3. Recent real-world applications of 3DCP are discussed in Section 2.4, focusing on the development of structural members. The chapter then examines the requirements for cementitious materials suitable for 3DCP in Section 2.5, followed by a detailed review of their fresh and hardened properties in Sections 2.6 and 2.7, respectively. Finally, Section 2.8 addresses the critical aspect of sustainability, evaluating the environmental impacts of 3DCP and its potential contributions towards reducing the footprint of concrete construction.

2.1 Development of 3DCP

From its early origins, the development of 3D printing has progressed through several technologies and materials. This scattered evolution has been driven by a vast amount of conceptual and technical frameworks that have shaped and expanded its capabilities.

This section first explores the general definitions and terminologies associated with 3D printing technologies and their evolution over the years. Subsequently, it presents the historical development of 3D concrete printing from early prototypes to full-scale construction. Finally, the advantages and limitations associated with this technology are presented, as well as the anticipated future directions for its coming development in both research and industrial applications.

2.1.1 Process description and terminology

Extrusion-based 3D concrete printing (3DCP) has emerged as the leading technology for digital fabrication with concrete [3–8]. The technology is based on the layered extrusion of fresh concrete through a nozzle following the instructions from a 3D model. This allows to implement a formwork-free process that eliminates several preparatory steps, facilitating the automated manufacture of concrete structures.

Additive manufacturing (AM), also known as 3D printing, is an umbrella term that describes a digital fabrication process based on adding material according to a 3D model. Although AM and 3D printing can be used indistinctively in most contexts, according to the ISO Standard 52900, AM processes are necessarily based on a digital 3D model while 3D printing may not be necessarily [9]. In practice, the term AM is associated with high-precision processes that are commonly linked to the manufacturing industry. Conversely, 3D printing is the preferred term for low-end systems, such as common desktop 3D printers based on thermoplastics. This is also the case for 3D printing with concrete, which uses large-scale systems and comparatively low precision.

The fundamental principle of 3D printing is the layer-by-layer deposition of material to create objects. This technology encompasses a wide variety of different materials and technologies, resulting in a broad spectrum of manufacturing precision and capabilities. Intricate parts, especially those containing hollow features, present significant challenges for conventional manufacturing methods but are relatively easier to manufacture with 3D printing techniques. One notable advantage of 3D printing is that the manufacturing time does not scale with the complexity of components. Furthermore, production costs also do not depend on large production sizes, which made this technology a cost-effective solution for small-scale or customised parts. 3D printing enables new possibilities that enlarge the potential of digital manufacturing, as it allows for almost unlimited variation in the production of each part within the same process, regardless of its complexity.

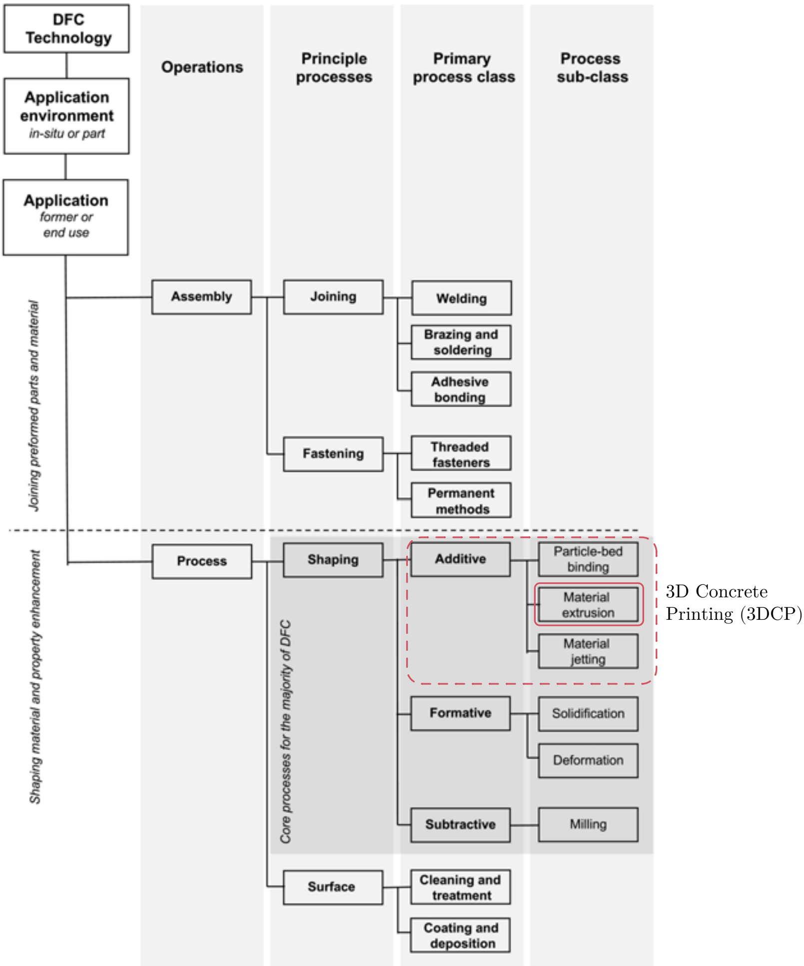

Figure 2.1: RILEM classification for digital fabrication with concrete. Reproduced from [6]

More broadly, digital fabrication with concrete (DFC) encompasses various manufacturing methods, including digitally manufactured formwork and slip forming. Therefore, while several technologies can be classified as DFC and 3D printing processes, they do not necessarily constitute 3D concrete printing as they are not based on cementitious materials. A clear example is the use of 3D printed thin shells as formwork using fast-setting concrete mixes. Within DFC, the field of additive manufacturing with cement-based materials comprehends multiple techniques and systems. Since most of these systems are in a very experimental phase, there is still great variation between different applications based on different types of pumps and extruder devices. According to the RILEM Process Classification Framework for DFC, shaping processes can be classified into additive, formative, and subtractive, which constitute the core primary processes for DFC. In this framework, 3D concrete printing is defined as 'Large-scale, cement-based additive manufacturing processes, often referred to as 3D concrete printing (3DCP)' [6]. In this category, there are three main approaches for additive manufacturing; particle-bed binding, material extrusion, and material jetting. These categories are based on the ISO/ASTM 52900:2021 Standard for additive manufacturing [9].

According to this classification, certain processes that were previously considered additive manufacturing with concrete but today fall outside the formal definition of additive technologies. For example, slip forming is certainly made by progressively adding material according to a digital model, the process is limited to a single continuous extrusion with changing rotation or cross-section [10]. Despite being digital and additive it does not offer the same characteristic formal freedom as 3D printing methods. While slip forming was considered an additive method [11], it has been reclassified as a formative process (cf. [11] and [6]). This example underscores the evolving nature of technology concepts and classifications along with the advancement of the field.

Binder jetting 3D printing is based on the sequential deposition of a thin layer of powder over a solid surface. A computer-controlled inkjet sprays the corresponding cross-section in the form of binder droplets onto the powder bed. The binder rapidly solidifies the powder and provides bonding with the previous layer. After the layer is printed, the powder bed is lowered and a new layer of powder is evenly spread with a roller on top of the previous layer. This layering process is repeated numerous times until the part is fully formed. A major advantage of this technique is that unbound material serves as a support for the following layers. After the completion of the print, the part is left within the binder volume to gain strength. Subsequently, the part is removed from the powder bed and the unbound powder is removed through the application of pressurised air. This process commonly results in very porous structures, that need to be infiltrated to gain full strength.

Binder jetting has been used with various materials, most commonly plaster, quartz-silica sand, and polymers, but also metal and ceramic materials [12]. Adaptations of binder jetting technologies to cement-based materials have been made using different particle sizes and binders. Selective cement activation (SCA) uses a particle bed composed of very fine aggregates (< 1 mm) and cement. In this approach, water is selectively sprayed on specific areas to activate and bind the cement. In Selective Paste Intrusion (SPI), the particle bed consists of larger aggregates, that are selectively bound by the local application of a cement paste. There is a variety of studies applying variations of this method [13].

Although the term used in the ISO classification is binder jetting, it does not accurately apply to techniques such as SCA or SPI. Rather than selectively jetting binder, SCA uses water to activate the binder present in the powder bed. Likewise, the thick cement paste used in SPI elicits a process like a layer extrusion rather than binder jetting, whereas the large size of aggregates does not agree with the definition of powder defined in the ISO standard [6]. Even if binder jetting is listed as a particle bed method for DFC, the 3D printed part yields a lost formwork that is then filled with cast concrete and does not correspond to 3D printing concrete [6]. For this reason, the term particle-bed 3D printing is presented as a more comprehensive term encompassing all the aforementioned techniques [13].

Another approach to 3D printing with concrete material is based on material jetting. In contrast to binder jetting technologies where only the binder is sprayed over a powder bed, in material jetting the part is formed entirely out the material sprayed from the print head. This technology was originally developed as an extension of 2D inkjet printers using wax [12]. When applied to concrete, material jetting is based on sprayed concrete, most commonly known as Shotcrete. This 3D printing technology is referred to as Shotcrete 3D Printing (SC3DP). Shotcrete has had a long development starting from the 1920s, primarily being used in tunnel construction, rock stabilisation, and strengthening of old concrete parts [17]. Like other 3D printing technologies, it employs a layer-by-layer construction methodology based on material jetting. SC3DP offers several advantages when compared with the much more established extrusion-based methods. As sprayed concrete is commonly used in tunnels, this approach is not restricted to the horizontal plane but also allows laminar placement on surfaces with varied orientations. The setting time can be adjusted by introducing an accelerator, a strategy that enables the printing of overhangs up to 90 degrees, allowing greater geometric flexibility and allowing the fabrication of intricate concrete parts [18]. A further advantage of this technique is the enhanced compaction of the concrete layers due to the high kinetic energy of the process that

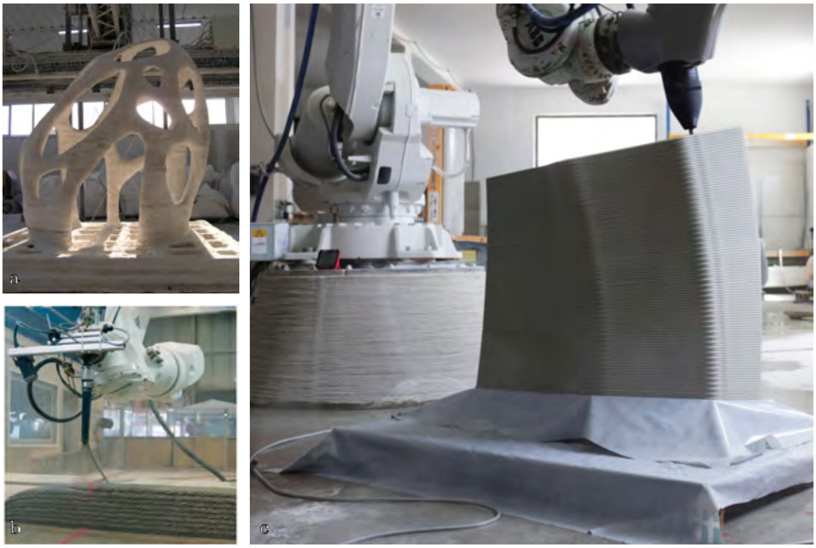

Figure 2.2: Three main technologies for 3D printing with cement-based materials: (a) Particle bed binding (binder jetting) [14], (b) Material Jetting [15], (c) Material extrusion [16].

provides a robust mechanical bond between successive layers [15].

There is, however, a large predominance of material extrusion both in research and in industry applications, and therefore 3DCP most commonly implies the process based on material extrusion [4–6, 8]. The associated terminology presents substantial variability. A great number of correlated terms have been formulated and introduced by many authors, such as Contour Crafting (CC) [19–21], Large-scale rapid prototyping, Additive Manufacturing of cementitious materials (AMoC) [14, 22], Layered extrusion [11, 23, 24], 3D printed concrete (3DPC) [25], and most prominently 3D concrete printing (3DCP). 3DCP has been settled in the literature and industry as the de facto name of the field. In the context of this study, it will refer exclusively to 3DCP.

Still, concrete has not always been the preferred term for the material. Concrete implies an aggregate size of at least 4 mm, the material for 3DCP is often referred to as mortar or micro-concrete [26]. Even when the RILEM classification is widely cited in the literature, many authors define their own terminology. Other authors prefer the term 'cementitious materials' or 'cement-based materials'. The extruded strand of fresh concrete is often called a filament, in reference to the common terminology applied to small-scale 3D printers using spools of thermoplastics. Similarly, the material used for 3DCP can be also referred to as 'ink', completing the analogy to the material used for printing [27].

Although there is currently a wide consensus on the use of the ISO standard to define the different classifications for 3DCP, there are still several studies that list other DFC methods as AM. For example, DFC projects like the smart dynamic casting or mesh mould are listed as AM technologies for construction [28]. Although these technologies are certainly digital and produce concrete parts, they lack the characteristic layered construction and freedom of shape that characterises AM technologies. There is a mismatch with the types of AM listed in the standard. Smart dynamic casting is arguably a shaping process rather than AM.

2.1.2 Historical development of 3D printing technologies

Several technologies can be traced back as precursors leading up to the current state of 3DCP. Ideas that can be today attributed to AM can be traced back as early as the 19th century [29]. Photosculpture was a method introduced by François Willème, a French artist, to produce 3D replicas of objects. His technique involved placing an object in a circular room equipped with 24 equally spaced cameras. Similarly, the layering method was patented by Joseph Blanther in 1892 for creating topological relief maps. This method, still widely used in architecture schools, was based on impressing topological contour lines in wax sheets that were then cut and glued to create scale models of topographies.

The earliest example of a formwork-free concrete shaping process using extrusion has been traced back to the patents by Willian Urschel dating back to the 1930s and 1940s [30]. Urschel described a 'Machine for building walls' that used a telescopic arm rotating around a central point, that creates a wall layer by layer in a cylindrical shape. In the historical extrusion process, these early designs also incorporated a variable wall thickness by locally adjusting the forming plates at the end of the arm. The work was continued by his son, Joe Urschel, and other authors who throughout the 20th century developed a series of derivative patents featuring formwork-free and layered construction of wall extruders. The extrusion process was limited to simple shapes such as circular or spherical structures. Although similar developments have been extensively expanded in the precast industry, the use of extruded concrete is restricted to simple geometries such as in the case of hollow core slabs. However, it is difficult to trace a linear development of extrusion-based 3DCP from these early examples. Whereas the development of extrusion systems

Figure 2.3: François Willème's Photo-sculpture patent from 1864

had a much earlier development of layered deposition of concrete without the use of formwork, the actual development of 3D printing technologies proliferated from other materials and processes.

3D printing technologies have been around for more than 40 years and encompass a range of several technologies with radically different approaches. The precise origins are difficult to define but can be traced back to a series of parallel patents describing a 3D object by selectively adding material layer by layer. The most widely recognised milestone is the Stereolithography (SLA) patent issued by Charles Hull in 1984, which gave rise to 3D systems. Other AM technologies were also presented in the late 1980s including Laminated Object Manufacturing (LOM), Selective Laser Sintering (SLS), and Fusion Deposition Modelling (FDM) [12]. These methods were intended to manufacture prototypes and therefore the new technology was first referred to as Rapid Prototyping (RP) which describes the application of the technology rather than the process itself. This term is largely out of use since the production capabilities improved to the point that the output of the machine is the final product. Other historical terms that applied to 3D printing are automated fabrication, solid free-form fabrication, and layered fabrication [12].

The concept of additive manufacturing was first introduced in opposition to conventional computer-controlled manufacturing methods, which involve the removal of material and have been retroactively referred to as 'subtractive' methods. Subtractive digital manufacturing processes are characterised by computer-controlled removal of material to shape the final part, while in AM the material is incrementally added to form the part in a layered process. These methods tend to be energy-intensive and generate a substantial amount of waste due to the material removal process. On the other hand, the incremental nature of AM limits the amount of material processed to what is required to build the final printed part. Furthermore, the planning process for AM is comparatively simpler than for subtractive techniques. Subtractive methods, such as routing or cutting materials require a cautious process planning due to the forces involved, making it a very sensitive task. By comparison, AM offers much more flexibility in the reliability of the process. While an error in the process planning may lead to a ruined part, the equipment itself is less likely to be damaged. With conventional manufacturing, the material properties are the same as the original stock. With AM, the material properties are highly influenced by the operation itself, resulting in most cases in anisotropic properties determined by the manufacturing orientation.

The first powder-bed technologies were developed in 1986 with the concept use of lasers that selectively sinter metal, plastic, polymer, and ceramic powders into solid objects. This method is known as selective laser sintering (SLS). In 1993, Sachs et al. developed at MIT a 3D printing technique that utilised fluid binders to selectively bind particles in the powder bed. This technology was the first to be known as '3D printing', as former Zprinters sold by Z Corp, which was later acquired by 3D Systems. The technology is based on commercial inkjet printer cartridges to spread binder for each horizontal layer. The typical resolution of these printers was measured in dpi (dots per inch) as it depended on the printing accuracy of the inkjet. Vertical resolution depended on the layer thickness and was usually in the range of 100 μm.

The first conceptualisation of 3D printing using concrete was proposed by Pegna in 1995 [31,32]. In this proposal, Pegna introduced a layer-by-layer selective deposition utilising Portland cement. These elements were made by placing a layer of sand which was selectively covered by cement that was then activated by applying water vapour after rolling each layer. The first materialisation of this technology into large-scale 3D printing was developed in 2007 with D-shape by Erico Dini. D-shape is based on the same working principle as the Zprinters, but scaled up using larger particles and a cement-based compounds for the reaction. One of the main limitations of using this approach is the presence of reactive powders that are sensitive to moisture. As a result, this method was only suitable for indoor spaces with controlled moisture.

What is now classified as a type of material extrusion 3D printing, was first envisioned in 1989 by Scott Crump who patented the Fused Deposition Modeling (FDM). In this process, a heated nozzle is used to melt a polymer material supplied in the form of a filament and then extruded to form the printed part layer by layer [33]. The thermoplastic properties of the polymer filament are critical for this process. When heated, the filament can be fused together and then solidifies as it cools down, forming a printed layer. This layering process has a great influence on the mechanical properties of the final part, which depends primarily on printing parameters such as layer height, width, and infill orientation. Unlike binder jetting technologies, the material is extruded just in the region defining the printed part, and further layers need to be supported by the layer below. Support can be created by printing a scaffolding with a lower density that allows for easy removal after print. Some systems print support using a secondary filament with a different material, usually water-solvable.

An analogous principle of material extrusion was pioneered by Khoshnevis under the name of Contour Crafting (CC) in the late 1990s [19], being the first extrusion-based 3D printing method. While the early publications described a wider spectrum of materials, subsequent developments moved towards cement-based mortars [19, 20, 34, 35]. In this process, a fresh cement-based paste was extruded against a trowel to provide a smooth surface finish and which was described as a key feature of the technology. This technology included several process-specific developments for automated construction that range from material grading to automated plumbing and tiling [20]. In the late 2010s, another extrusion-based process with concrete was developed at the Loughborough University under the name ‘concrete printing’. Unlike the application-specific developments characteristic of CC, concrete printing focused on the formal freedom achievable with the technology. This new form of concrete printing also eliminated the use of trowels to flatten the surfaces. Although there are several former publications carefully explaining the differences between CC and concrete printing [21], most authors today recognise the CC technology as a predecessor of large-scale 3D printing by material extrusion i.e., 3DCP [14, 36, 37]. Similarly, it is not uncommon to find literature that classifies 3DCP or other material extrusion processes as FDM [14]. While both 3DCP and FDM are 3D printing technologies based on material extrusion, FDM refers specifically to the technology based on thermoplastic polymers.

One substantial milestone in the development of 3D printing was the expiration of the patent for Fusion Deposition Modelling (FDM) 3D printers in 2009 owned by Stratasys. FDM 3D printers are mechanically simple and do not require complex components. This movement was led by the RepRap project which impulsed the development of affordable 3D printers that made them available to the public. The RepRap movement was initiated in 2005 by Adrian Bowyer as an open-source project for building a self-replicating 3D printer. Since FDM is also a trademark owned by Stratasys, the

RepRap movement coined the term Fused Filament Fabrication (FFF) as an open-source alternative [38]. RepRap served as the foundation for several companies that democratised access to 3D printers. In the following years, the number of actors in the 3D printing market increased dramatically and the price for 3D printers decreased accordingly.

Similar to what happened with computers in the 1980s, 3D printers moved from being expensive and confined equipment in research areas to becoming affordable desktop devices available for home use. The extended impact of 3D printing technologies is already evident through the proliferation of 3D printed products and services available to the public. Today, the technology has widespread adoption in a wide variety of fields, where 3D printed products have surpassed conventional manufacturing techniques in specific applications requiring complex geometries, especially in high-added-value industries. In contrast to its application in other industries, which have moved from fabrication towards manufacturing, the old concept of rapid prototyping remains highly suited in the context of highly customisation requirements of the architecture, engineering, and construction (AEC) industry [39]. Virtually every building requires a manufacturing approach analogous to prototyping due to the unique local conditions and site-specific challenges. As the technology continues to expand and mature, it is expected to also play a major role in reshaping the AEC industry. The increased digitalisation of the sector has led to a remarkable boost in productivity and resource efficiency. In this context, the spread of 3DCP is expected to continue to surge, as the technology is entering a highly experimental phase with research and practitioners exploring different applications and pushing the boundaries.

2.1.3 State-of-the-art of 3DCP

3DCP has gained significant attention as a technology capable of enhancing productivity, decreasing labour, minimising material waste, and reducing the environmental impact of concrete construction [3]. Publication trends show sustained exponential growth, especially from the year 2015 [8, 40]. The development of 3DCP has demonstrated notable advancements in both its technical capabilities and the robustness of the process, leading to increased market deployment. Several narratives support the current advancement of technology and its expansion into mainstream construction. This section reviews the introduction chapters of the most relevant papers on 3DCP as the conveyors of the main drivers for the development of the technology. From these narratives, this section also discusses the current advantages and limitations of the technology, and its expected future prospection. In contrast with these narratives presented in the scientific literature, media coverage centres primarily on the ability of the technology to create complex geometries and intricate textures. Similarly, older narratives describing the increased urbanisation and the shortages in the housing market have now adopted an increasingly environmental perspective. Unlike other materials and processes, the unique properties of concrete make it a viable candidate for expanding to large-scale construction. 3DCP not only can automate the production of concrete elements but also extensively expand the range of what is achievable with the material.

Global environmental impact of concrete construction A common introduction to the sustainability challenges with concrete is to mention the massive amounts of concrete used globally each year and their associated environmental impact [1,23,41–46]. The adoption of 3DCP facilitates the use of structural optimisation techniques that can considerably reduce material consumption. However, this argument is contradicted by the fact that 3DCP typically involves a considerably higher environmental footprint per unit volume than ordinary concrete [45]. Some articles also focus on the savings related to the mould, although these savings are mostly monetary rather than environmental [46]. The ability to digitally control the internal distribution of concrete allows for the placement of material only where it is structurally required [23]. Optimised concrete elements with tailor-made shapes can reduce material requirements, reduce transport and lifting weight, replace additional building components, and increase energy efficiency in buildings. The environmental impact of conventional concrete construction varies based on the complexity and the number of times that the formwork can be reused. In contrast, 3DCP typically maintains a more consistent environmental impact, regardless of complexity. While the production of formwork adds extra environmental costs, these can be reduced for repetitive components where formwork can be reused multiple times. For instance, studies have shown that 3DCP offers significant environmental benefits in structures with higher complexity [47]. However, this advantage decreases as the number of parts that can be produced with the same formwork increases.

Productivity of concrete construction The construction industry is currently facing an urgent need for new advanced construction methods to address the low efficiency of the sector in comparison to almost any other industry [5, 36, 48, 49]. The efficiency of concrete construction has stagnated or even declined over the last 50 years [5]. It is often stated that the construction industry is conservative and risk-adverse [50], as well as its heavy reliance on low-tech and manual labour, which often result in poor performance and quality [48]. There is a strong contrast when compared with the technological development of other industries such as manufacturing or aerospace. While other sectors have embraced automation, digitalisation, and additive manufacturing, the construction sector has been slower to embrace and integrate new technologies [48]. Industries such as manufacturing are already actively discussing and implementing concepts of ‘industry 4.0’, which involves the deep integration of cyber-physical systems and human-robot collaboration, the construction industry has not yet implemented the ‘industry 3.0’ [17]. The construction industry has been relying on the same principles for centuries, especially in the case of concrete which was invented by Romans about 2100 years ago and is still largely dependent on manual labour [51]. This argument is in direct contrast with the remarkable advancement in the strength of concrete used in construction, which has leaped from low-strength concrete in the 1960s to ultra-high performance concrete (UHPC) of the last decade (100-120 MPa) [52]. Also, there have been significant improvements in reducing the carbon footprint of concrete by introducing SCMs, the development of self-compacting concrete, fibre-reinforced concrete, low-density concretes, grading concrete properties, and concrete at sub-freezing temperatures are some examples of the advancements of concrete technology. As a result, despite the significant advancements in concrete material science, the actual construction processes associated with concrete remain largely unchanged. The conventional casting process still encompasses several operations that require human guidance and physical work. Although prefabrication has demonstrated improving efficiency, it emerges from industrialisation of manual work instead of a completely new technology.

Labour shortage and worker safety Early development of 3DCP was driven by the challenges of the industry in terms of low labour efficiency, high accident rates and low-quality control [5, 20, 49, 53]. Although it has mostly been associated with the previous narrative of the low efficiency of the industry, labour shortages are one of the main problems for the construction industry. The shortage of skilled labour poses a critical challenge to the industry’s ability to advance and adopt more sustainable practices and innovative technologies. This affects not only the construction sector but also its key role in the overall economy of any country [48] Furthermore, the scarcity of skilled labour is associated with worker migration and occupational health risks due to workplace environmental conditions [49]. 3D concrete printing is therefore proposed as a way of compensating for the lack of skilled labour while offering more attractive jobs.

Advantages of 3DCP Several studies have noted the potential of the technology to provide a wide range of benefits for the construction industry.

One of the most prominent advantages of 3DCP resides in the elimination of the need for moulds, which entails the fabrication, preparation, casting, and subsequent removal of the formwork. The formwork process is time-consuming and constitutes a significant portion of the overall construction expenses. It is estimated that the material and labour expenses of formwork account for approximately 50% of the total construction costs, while this percentage could increase to up to 90% when non-standard and single-use moulds are required for complex shapes [54]. In a 3DCP process, these expenses can be significantly reduced or eliminated, leading to potential cost savings and increased efficiency in the construction industry. The absence of formwork is also highlighted as a significant reduction in material waste. This is especially relevant in the case of custom-made formworks for non-conventional uses. Reduction in material use is, in comparison with massive cast concrete, an important advantage of 3DCP.

Beyond the elimination of formwork, the advantages of 3DCP are a consequence of the digitalisation of the design-to-manufacturing workflow. The automated process of turning digital 3D models into physical objects reduces many intermediate steps in the construction process and enables the further integration of the building with its digital counterpart. The introduction of digital workflows in 3DCP allows for seamless integration between the digital design and the physical manufacturing, which alleviates the logistic burden of information transfer between different actors involved in the construction process [48]. This also minimises the reliance on manual labour and therefore reduces the likelihood of human errors, leading to higher-quality construction.

The higher productivity of 3DCP is primarily attributed to its faster construction process and reduced labour. Research suggests that 3DCP can shorten the construction time to a quarter of the time compared to conventional construction methods [40], which is a significant driving force behind the current interest in the technology. This significant comparative advantage of 3DCP becomes most relevant in scenarios that require the rapid deployment of housing in emergencies or situations where remoteness and hostile environments make traditional methods inoperable. Therefore, use cases have also been argued in the context of natural disasters, war conditions, and even extraterrestrial settlements, where it presents the biggest competitive advantage [55]. Still, very few cases have demonstrated these contexts as effective use cases of 3DCP technology. In opposition to this focus on the rapid deployment of housing in emergencies or the further development of non-conventional geometries, the steady development of 3DCP has been progressively coming closer to mainstream construction.

Limitations and current challenges Despite the ever-increasing number of 3DCP structures being showcased, the technology still faces significant challenges at the material and processing levels. In a recent study, Ma et al. [8] presented a comprehensive assessment of the Technology Readiness Level (TRL) for 3DCP to be between 6 and 7, i.e., that the technology has been demonstrated in a relevant environment(TRL 6) and an operational environment (TRL 7), respectively. This study highlights four developmental frontiers for 3DCP: materials, process, software, and building integration. Primary drivers for advancing 3DCP are maximising the robustness and automation of the process while minimising costs and environmental impact. Nevertheless, both materials and processing equipment for 3DCP need to be improved in terms of robustness and reliability.

Although expanding rapidly, the reach of the 3DCP technology is still in an experimental phase, where equipment and materials are not widely available. The reported printing time and material costs do not reflect the current state of development of the technology. While several studies report impressive figures of heavily reduced construction times, they often report the actual printing time while not considering all the preparation and indirect costs of the printing procedure [56]. One of the challenges for the field is to move fabrication, which implies one-off production, to manufacturing, which entails routine production at scale [6]. 3DCP systems can be broadly divided into two opposed application scenarios: prefabrication and in-situ construction, presenting very different types of equipment and application possibilities.

To date, the main industrial applications of 3DCP have been focused on two key use cases related to reducing labour [56]. The first is the use of 3DCP as a substitute for formwork labour when printing stay-in-place formwork. This not only eliminates the labor-intensive tasks associated with traditional formwork assembly but also removes the need for its removal after the concrete has been poured and cured. The second use case is the replacement of masonry labour when 3D printed concrete is used as a replacement for unreinforced masonry. Correlating unreinforced 3DCP with unreinforced masonry is also used for regulation purposes [3]. This is because the implementation of reinforcement is still the most fundamental question that remains unsolved [5, 7, 45, 57]. Nevertheless, research is moving toward the manufacturing of structural elements.

Despite the rapid advancement of 3DCP from research environments to real market conditions, it is still far from being competitive against well-established conventional construction practices [3]. Several successful projects demonstrated the potential of 3DCP, however, the technology remains in the early stages of development with print materials and equipment still not able to reach the cost-effectiveness and robustness needed to challenge mainstream construction practices. Another major challenge is the limited range of printable construction materials. Although there is plenty of research providing high-performance and high-durability concrete materials, a small fraction of them are compatible with the rheological requirements of the 3DCP process [50].

Finally, the sustainability aspects represent the main challenge for the future development of the construction sector. While increased efficiency and automation are certainly drivers for the advancement of the technology, reducing the environmental impact has converged as the main goal for research. As time passes, insufficient action on this global issue makes climate targets progressively more challenging. In this context, mitigation and adaptation measures are becoming a necessary reality where concrete technology is expected to play a role [58]. Sustainability concerns extend far beyond the CO_2-equivalent calculations that have been in focus for the industry [59].

Given the wide spectrum of different technologies involved, it is clear that the successful development of 3DCP technology requires a broad set of specialisations, encompassing chemistry, rheology, material science, mechanics, and robotics, among others. This is on top of architects, civil engineers, and other parts of the AEC industry. Therefore it has been remarked on the need to include multi-disciplinary training in digital construction, or more specifically 3D printing, into the curricula of educational institutions [3].

2.2 3D concrete printing systems

As in other 3D printing processes, 3DCP is based on the controlled deposition of material following a 3D model. A 3D printing system for concrete can be divided into three main components: (i) the material processing system, (ii) the manipulator, and (iii) the digital control system. To ensure a uniform material deposition, the material delivery system must be able to provide a stable and sustained flow of fresh concrete in coordination with the computer-controlled movement of the robotic system. In this regard, the common use of the term 'robot' can be misleading. In its technical definition, a robot refers to a programmed actuated mechanism with a degree of autonomy [60], which includes manipulators, mobile platforms, and wearable equipment. Contrarily, in common speech, the term robot often refers in particular to articulated industrial robot arms, which are a specific type of manipulator with rotary joints mounted in series that are capable of performing a wide range of tasks. Here it is important to remark that the term robot comprises both the manipulator and the control system but not the end-effector. Therefore, in the case of 3DCP, the extruder nozzle should be considered as part of the material processing system. This section provides an overview of the development of printing systems for cement-based materials, as well as their technical requirements in terms of material processing, robotic manipulators, and control systems.

2.2.1 Material processing and delivery systems

A stable flow of fresh concrete material is a fundamental prerequisite for any successful printing operation. Material processing encompasses all the different steps from the elementary constituents of concrete to the deposition of fresh material. The development of reliable and robust material processing systems is, together with the implementation of reinforcement, the primary challenge to make 3DCP a viable solution for mainstream construction [56]. While the focus of this section centres on the equipment parts and their specific requirements, Section 2.6 will provide a more comprehensive perspective on rheology and the mechanics associated with freshly deposited material.

Currently, 3DCP technologies can be divided into two main approaches depending on the type of concrete mix used. Initial developments relied on concrete mixes with thickening agents to ensure a high yield stress after the deposition. More recent developments of concrete mixes used retardant to prevent the setting of the fresh material during the pumping process, in combination with accelerators that counteract the retardant effect and induce faster setting times [61]. This second approach is applied to 3DCP by using a material based on two different parts: a heavily retarded mix and an accelerated cement paste, which are delivered separately and mixed in a secondary mixing process that takes place at the nozzle. Originally developed for advanced casting processes the approach was termed 'set-on-demand' [23, 62–64], 'accelerated mixes' [53], mono and bi-component [46], or more recently, 1K and 2K, respectively [45, 56]. Although other systems also used bi-component approaches in relatively early developments of 3DCP, they were not explicitly addressed as a separate category [65]. As 3DCP systems and materials are already commercially available, the use of mono and bi-component systems sets apart their corresponding printing equipment and materials. Section 2.5.2 offers an extended revision of this topic.

The production of self-supporting 3D printed concrete material comprises a sequential array of operations. While these steps have been discussed from a material perspective [53, 56], the steps in this processing chain are here examined from the perspective of printing equipment. It is worth noting that these steps may involve radically different equipment depending on different types of materials and additives.

Mix proportioning: In most cases, this is done by pre-dosing materials. Today, several companies offer premix material specially developed for 3DCP. These mixes can be fed into the next step as batches of different sizes. Larger systems use a silo of dry material that provides material as a continuous flow.

Primary mixing: This involves the addition of water to the dry materials to initiate the hydration process. Mixing can be done by batch mixing, but several 3DCP systems are moving towards continuous mixers. Continuous mixers are often integrated into a single unit with the pumping system [14].

Transport: Large-scale 3DCP systems are predominantly based on concrete pumps for moving the material to the printing nozzle, where progressive cavity pumps are the most popular choice, although positive displacement piston pumps have also been used [53]. The rotational speed of the pump's motor and the material flow rate generally follow a linear relationship [66]. There are some examples of progressive cavity pumps being used as extruders when mounted directly on the manipulator. In the case of small-scale systems, most commonly found in laboratories, material transport may be done by manually feeding fresh material from the primary mixing to the second mixing.

Secondary mixing: Systems may include a secondary mixing prior to the extrusion nozzle, that responds to different purposes depending on the type of system. For mono-component systems using a screw extruder to extrude the material, secondary mixing is used mainly to keep the material in a flowable state to allow the extrusion. In the case of bi-component systems (2K), secondary mixing entails the injection of an additive at the printhead with the aim of modulating material stiffness and the development of material strength. This step may also include the addition of fibres or other materials to grade the material properties of the concrete being extruded [22, 67–69]. This approach is discussed in more depth in Section 3.4 and in Paper I.

Extrusion: The extrusion of fresh material from the print head is the most critical step for 3DCP. Some systems use a passive nozzle that is directly coupled to the pumping system. In this case, the extrusion is a consequence of the force exerted by the concrete delivery system. Other systems use screw extruders that allow for the controlled deposition of concrete. Ram extruders are most commonly used in laboratory setups for studying the extrusion flow, characterise rheological properties, and examining the extrudability of materials. In this configuration, a barrel is filled with concrete that is then extruded by pressing a ram that pushes the material through a die on the opposite end. A major drawback is the need for refilling which makes them unsuitable for larger prints. Screw extruders in their simplest form feature an open hopper with a feeder screw that extrudes the material directly. While this hopper can be fed manually in laboratory setups, larger systems use a pump that feeds material continuously to the extruder. The deposition rate increases linearly with the rotational speed of the screw [70], which allows simple and precise control of the extrusion flow. The relationship of nozzle sizes and the efficiency of 3DCP is further discussed in Section 2.8.

Post-processing: As in other digital fabrication processes, geometric validation of the printed part is essential for quality control [71]. Some 3DCP systems include post-processing steps such as a secondary milling operation to improve the surface quality but also to extend the levels of detail hitherto unachievable with only additive processes. This step is nevertheless outside what is defined as the 3D printing process [6], corresponding for example to a hybrid process that incorporates subtractive manufacturing techniques for surface finishing.

Curing: The curing phase is indispensable for achieving what is termed 'buildability', given that an insufficient development of material strength could lead to structural failure of the printed structure during the printing process [56]. This emphasises the necessity of ensuring that the printing speed does not exceedes the maximum vertical build rate of the material. In terms of equipment, active moisture control is used by several projects to avoid excessive plastic shrinkage and eventual cracking of the printed parts [3]. For off-site printing systems, the relative humidity at the facilities is artificially kept above 65%, while in the case of on-site printing systems the use of water sprinkles and protective foil are employed as protective measures [44].

2.2.2 Manipulators

Precise positioning is one of the key components of every 3D printing process. This is achieved by the use of various robotic systems that allow to achieve high precision and repeatability for the computer-controlled movement of the printhead. Robot manipulators comprise mechanical assemblies of links interconnected by joints. The system capabilities are expressed by the concept of degrees of freedom (DOF) that defines the range of possible independent movements. These DOF are parameters that describe the spatial orientation of a rigid body and are divided into translational and rotational movements.

Advancements in mechatronics offer a great variety of manipulators that can be used for 3D printing concrete. Different types of manipulators present distinct technical capabilities which can be advantageous for certain applications. Akin to other extrusion-based 3D printing processes, 3DCP most commonly relies on planar, evenly-spaced slices that simplify both the file preparation and the hardware requirements for the printing system. Although 3DCP systems are most often built as 3-axis systems, there are multiple examples of the use of manipulators with a higher number of DOF for what is referred to as non-planar 3D printing, where the print paths are not parallel sections.

Gantry systems Cartesian robotic manipulators, commonly referred to as gantry robots, feature three orthogonal linear axes that form a Cartesian coordinate system (X, Y, Z). As a parallel configuration, Cartesian manipulators offer a simplified kinematic model where the movement of the motor(s) on each axis can be mapped directly to the movement on each axis. The workspace is therefore limited as a prismatic volume defined by the maximum range of motion on each axis. Gantry manipulators are a cost-effective solution that has made them the most prevalent configuration for 3DCP systems, especially in large-scale systems for on-site printing [72]. Being mechanically simpler than robotic arms, this configuration is also the most common for computer numerical control (CNC) milling machines and desktop FFF 3D printers. Compared to CNC routers, the fabrication of an equivalent gantry system has lower power requirements for additive manufacturing, as the process does not need to exert extra forces as part of the operation. As in most 3D printing processes, the vertical axis is only engaged when transitioning between layers, hence they are sometimes described as '2.5D'. While this is an inherent restriction of the printing process, for several Cartesian manipulators the mechanical capabilities for vertical movement are also restricted by hardware. For example, in several gantry systems, the vertical axis has counterweights and the motors driving vertical movement are often designed with lower power specifications.

Since Cartesian manipulators are defined by three linear axes, they offer three translational DOF. Many systems include an extra rotatory axis to orient the nozzle to the print direction. In particular, 3DCP systems using a rectangular nozzle require this extra rotary axis to maintain the nozzle oriented to the print direction to prevent the twisting of the filament when changing direction [14]. Therefore, they become 4-axis systems, with three translational and one rotational axis. For circular nozzles, this extra axis is not necessary as they are symmetrical in all directions, as displayed in Figure 2.4. Some gantry systems are equipped with extra axes that allow orienting the nozzle for printing on non-planar surfaces. From an economic

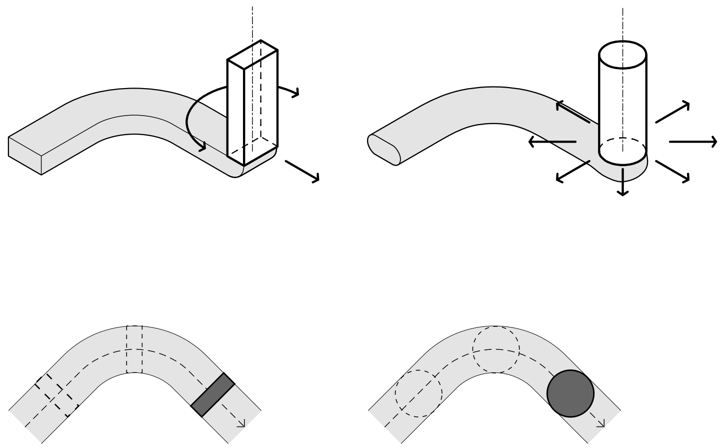

Figure 2.4: Different nozzle configurations. Left: rectangular nozzles require an extra rotational axis to maintain the orientation relative to the printing direction. Right: Circular nozzles are inherently symmetric and therefore can be used with systems with just 3 DOF

perspective, gantry systems can be more cost-effective for large-scale projects.

For large-scale systems, such as those used for printing on-site, the main challenge is the scaling up of the system. Several manufacturers offer comprehensive industrial solutions for 3DCP. Nevertheless, this approach presents several limitations. Despite the extensive build volume offered by large-scale gantry systems, the printer is must be even larger than the structures they construct. Also, the large footprint of these systems can be a limiting factor in constrained construction environments. Deploying the machine on-site is also a critical step that poses particular requirements, being mostly circumscribed to new constructions on empty plots.

Industrial robotic arms Robotic arms provide a versatile option for a wide variety of industrial tasks due to their high degrees of freedom, which are widely used in manufacturing [73]. Due to their relatively small size and high repeatability, industrial robots are a popular choice as manipulators for 3DCP systems. Robotic arms offer a flexible alternative as they are capable of a broader range of movements, which makes them suitable for intricate designs or complex spatial configurations. The main disadvantage of industrial robots is their limited reach. Therefore, robotic systems are often mounted on linear tracks that provide an extra degree of freedom. Another method to extend the reach of a robotic arm is the use of a printing front end mounted on the flange of the robot [49]. This acts as an extended arm on the sixth axis of the robot that takes advantage of the rotation to increase the reach of the robotic arm but increases the load applied to the robot.

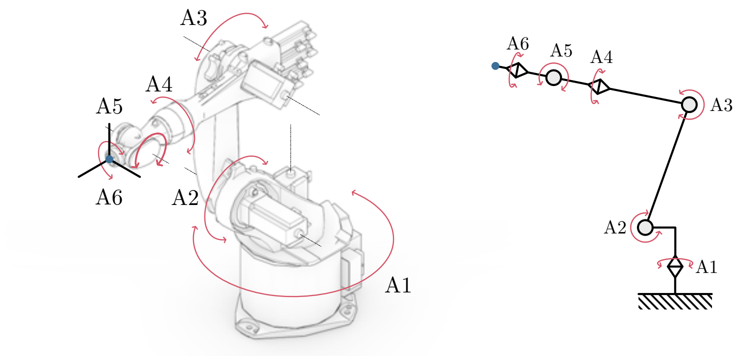

Figure 2.5: Industrial robotic manipulators are serial rotary joints that give them 6 DOF

Robots can be also mounted on large-scale gantry systems or transverse cranes to extend the limited reach of stationary robotic arms [23]. While these can potentially be used as an integrated kinematic system, the role of the gantry or crane is in most cases to reposition the robot between different printing tasks, improving accuracy and simplifying the control system. Mobile robotic platforms are another technical solution to extend the range of motion to allow the robot to navigate in a more flexible and dynamic manner. Unlike linear tracks, mobile platforms for robotics can move freely in four DOF i.e., three translational axes and rotation. Zhang et al. demonstrated the feasibility on a mobile platform, for extended range of motion [74]. This topic is further discussed in Section 2.3.2 An interesting approach to distributed 3D printing systems was developed in 2014 at the IAAC in Barcelona. This model relies on the distributed collaborative work of several small-scale robots. Unlike large printing system, these mobile robots use the printed part as support for the building process.

Other manipulator types In addition to gantry systems and articulated robotic arms, a variety of other manipulators have been used as alternatives to 3DCP. While less common than the aforementioned types, they may have certain advantages. One of the first commercially available 3DCP systems was a polar manipulator developed by Apis Cor [3]. Polar robots, also called cylindrical robots, are based on two rotary joints and one prismatic joint (linear axis).Cable-driven robots use a system of tensioned cables for positioning control. The use of tensioned cables requires the positioning of anchor points [75]. While cable-drive manipulators are more often found in indoors environments, a large-scale on-site proposal based on cable-driven robotics is presented under the name of Sky Big Area Additive Manufacturing (SkyBAAM) [76]. Unlike indoor implementations, this approach uses a crane for vertical anchoring plus two active and two passive anchor points on the ground.

2.2.3 Printing control

Most commonly, control systems are integrated with the manipulator in robotic systems. However, precise control of the material delivery is also required to synchronise the rate of extrusion of the filament with the movement of the manipulator. Whereas many 3DCP systems do not have direct control over the material deposition [23, 77], they all rely on implicit coordination between the travelling speed of the nozzle and the material extrusion speed. Control systems in 3DCP are central to operationalise the printing procedure. These systems are typically based on general-purpose Programmable Logic Controllers (PLCs), like robotic control systems, that are specially adapted for the requirements of 3DCP applications.

Most printing systems rely on an open-loop control system, where the printing system executes the instructions contained in the print file without any feedback mechanism. Various models have been formulated to predict the rheological behaviour of fresh concrete and introduce offline compensatory adjustments for expected deformations [78]. However, unexpected variations in the material flow or uncontrolled parameters within the printing system can yield inconsistent results, For example, Wolfs et al. implemented a linear measurement system for monitoring the nozzle height during the printing process [79]. This parameter is critical for assuring the quality of the printing, especially when printing using the infinite brick deposition regime, where variations in the extrusion or travelling speeds can lead to tearing or buckling of the filament [80]. Yuan et al. developed a real-time control system to enhance the printing quality and dimension consistency when printing with variable-width filament [66]. Also, computer vision systems have been developed for real-time feedback of the extruded filament [81], compensating for variations in the material rheology.

Gantry systems are most commonly based on CNC controllers adapted for 3D printing, akin to the control boards used in smaller-scale 3D printers, but with higher safety and reliability standards. They typically use stepper or servo motors to drive the print head with precision. Most of these controllers use G-code to control the movements of the machine, which is the industry standard language for programming CNC machines. Unlike gantry systems, robotic arms most commonly use their proprietary programming languages. While these systems offer extended automation capabilities, such as the definition of variables and programmable logical sequences, the development relies on closed-source environments that require specialised research and development. An extended explanation of the programming procedures for 3DCP is provided in Section 3.1.

2.3 Prefabrication vs. on-site printing

From its early origins, the development of 3DCP has been driven by two distinct approaches defined by the construction environment: prefabrication and on-site construction. Prefabrication involves the printing of elements off-site, which are subsequently transported to the construction site for assembly. This transportation requirement limits the maximum size of each element. Conversely, on-site construction requires the deployment of the 3DCP system directly on the construction site. This approach demands a printer that is capable of printing the entire volume of the structure. The printing environment is strongly correlated to the type of 3DCP system in use, where robotic arms are mostly used in factories i.e., under a controlled environment which is also beneficial for the material. Conversely, gantry systems are mostly used in on-site printing operations. In a quantitative analysis of 42 3DCP projects, Huang et al. found that 28 of them (67%) were printed on-site [72]. This section compares the advantages and disadvantages of each approach, as well as some examples of the use of prefabricated elements in on-site printing operations.

2.3.1 Prefabrication

The use of prefabrication in the concrete industry is a well-established production method. Off-site manufacturing enables a high degree of quality control, increased productivity, and significantly reduced construction waste, leading to potential cost savings and shorter project lead times [5]. Analogous to conventional prefabrication techniques, off-site 3DCP encompasses a series of operational phases including relocation, storage, hoisting, and installation. Although ‘precast’ is a term commonly used for denoting prefabrication with concrete, the term implies a casting process that is normally associated with conventional casting on a mould, and is therefore not applicable for 3DCP. Prefabrication schemas also imply the necessary sectioning of the building components into parts. This division is dictated either by the build volume capacity of the printing system or by the constraints imposed by the transportation and lifting of the prefabricated elements.

Figure 2.6: Examples of 3DCP projects printed as prefabricated elements and assembled on-site. Top: Fibonacci House, Canada. Middle: Striatus Bridge, Venice. Bottom: Milestone project, Eindhoven.

Prefabricated 3D printed concrete can benefit from the increased precision and processing control of factory environments to produce structural elements, significantly enhancing the quality and consistency of the parts produced. Unlike on-site 3DCP, which centres on producing walls with constrained geometries [23], prefabrication allows a wider range of options as it can take advantage of printing orientations other than the intended position of the element. A longer discussion on the advantages of different printing orientations is examined in Paper III.

Given the controlled environment, waste can be significantly reduced thus improving the material efficiency. Another important advantage of prefabricated 3DCP is the ability to control environmental conditions like temperature and relative humidity, allowing for more predictable and consistent results. These parameters have a direct influence on processes like curing times, which are critical for structural integrity. By artificially controlling the humidity, the curing process can be regulated to avoid excessive shrinkage of the printed concrete. This has been done for the Milestone project and the Striatus bridge, where the environmental humidity was kept above 65% and 70% respectively [3]. Similarly, factory conditions allow better control over the manufacturing process and allow inspection routines that would otherwise collide with the building schedule on-site. Inspection is a critical factor for quality assurance in the manufacturing industry [82].

An interesting case is the introduction of hybrid processes [6]. These methods are based on combining different operations, such as integrating 3DCP with subtractive methods for surface finishing [75]. In terms of surface planarity and precision, hybrid methods greatly surpass the current capabilities of 3DCP. Further refinement in this area can achieve or even exceed the performance of conventional moulding techniques [71]. These methods have so far only been reported in prefabrication setups.

Industrial robotic arms are most prevalent in off-site printing operations [3], where their 6 DOF capabilities are used to produce advanced print paths, such as the use of multi-planar or non-planar print paths. There is a clear gap in terms of geometric complexity and diversity of printed structures when comparing prefabricated and in-situ printed concrete structures. This gap results from the higher DOF offered by robotic arms, but even when restricted to planar printing using only 3 DOF, the superior acceleration capabilities due to their lower mass allow achieving sharper corners and details when compared with large-scale gantry systems. Nevertheless, the application of these advanced print path strategies requires the corresponding development of slicing algorithms.

Salet et al. identify the movement towards prefabrication as a promising development for improving the quality of concrete construction [83]. This increased freedom of shape combined with the production of structural elements promotes the production of more sustainable concrete production through material-efficient shapes [7,23]. Therefore, while on-site construction holds appeal, prefabrication offers the greatest potential for innovative construction methods [5]. Furthermore, the modular nature of prefabricated components allows for easier disassembly and reuse, thus contributing to a more circular economy in the construction sector [84]. This approach is further discussed in Section 2.8.

2.3.2 On-site printing

On-site, or in-situ, building operations are the prevailing mode of construction. This approach offers the advantage of mitigating transportation costs, simplifying or removing the need for assembly, and has the potential to print an entire building in a single operation [72]. Given the current developments in mobile equipment, the adaptation of deployable gantry systems and robotic arms has significantly propelled the capabilities of on-site printing systems. Most on-site 3DCP projects use large-scale gantry systems that most commonly exceed the dimensions of the building which is achieved by modular scalable equipment solutions. Conversely, the potential of robotic arms has yet to be realised due to limitations posed by varying site conditions. Although the vast majority of on-site printers are based on large-scale gantry systems, there are notable cases of the use of robots on-site. In the case of the Dubai office building [3], Apis Cor used a cylindrical robot that was relocated in different positions to cover all the reach. The 3D printed farmhouse in Wujizhuang displayed an extensive robot deployment on site [49], as displayed in Figure 2.8a. Apis Cor was one of the first companies to offer 3DCP services commercially, based on a cylindrical printer with 3.1 m radial reach [3, 48].

The main advantage of the use of robotic arms for on-site construction resides in the possibility of parallelising the printing process [86]. Although robots have a limited reach, their smaller size allows the use of collaborative or parallel operations. The scalability of 3D printing systems on building sites depends on the total printing volume as well as the potential for parallelisation of the printing operations. One of the main challenges with parallelised on-site robotic operations is material delivery. One scenario is the use of parallel material processing and delivery systems, but this approach means doubling the printing equipment. Material supply can be performed continuously or batch-wise and the mixing can be done centrally or distributed [86]. The deployment of on-site operations has been proposed as a potential solution for humanitarian assistance and disaster response [87].

Figure 2.7: Examples of 3DCP projects with on-site printing. Left: Beckum House [44]. Centre: Municipal building in Dubai [85]. Right: Data centre in Heidelberg.

2.3.3 On-site prefabrication

While a sharp line is often marked between prefabrication and on-site printing, some projects have combined both approaches. On-site prefabrication or on-site preprint represents an interesting middle ground between conventional prefabrication and on-site 3DCP. The main advantage of this approach is enabling the possibility of printing using orientations other than the direct printing of the building part on its final location. This is noticeable in the case of the Beckum House in Germany (Figure 2.7a), where the entrance features a 3D printed component that was pre-printed on-site and lifted to its final position, allowing a cantilever that would be unfeasible due to the support requirements of the printing [3, 44]. The Wujizhuang farmhouse further extends this approach, where all arched and flat roofs were produced on-site and then lifted to place [49] (Figure 2.8). Similarly, the 3dpod by Obayashi features a ribbed slab made of preprinted stay-in-place formwork that is placed and cast on-site [88], as shown in Figure 2.11.

2.4 Applications

The development of 3DCP technologies has rapidly transitioned from research environments to industry applications and is expanding at an accelerated pace. Especially in the last five years, the quantity, and complexity of 3DCP projects have sustained a surging growth, noticeable in the number

Figure 2.8: The Wujizhuang farmhouse featured three tracks for the deployment of the 3DCP system based on robotic arms. The different orientations used for printing roofs are visible in the ribbed surface of the structure. Reproduced from [89]

of scientific publications, commercial patents, industrial practitioners, and completed projects [8]. In line with the objectives of this thesis, a special focus is given to 3D printed structural members. However, the sustained proliferation of new projects renders a comprehensive review increasingly challenging. For a more extensive review, interested readers are directed to the following reviews [3, 6, 7, 72, 90]. This section aims to give an overview of prominent instances of 3DCP applications, illustrating the potential of this growing technology in real-world scenarios.

2.4.1 Buildings

Residential buildings constitute one of the main focuses in the development of 3DCP technology and account for a significant portion of its applications [7, 72]. The common method involves fabricating walls through continuous monolithic printing, or assembly of off-site or on-site produced concrete panels, linked via conventional steel connection systems. Using curved walls or surface patterns can introduce architectural variation while having a marginal impact in terms of material use or printing time, setting 3DCP apart from traditional cast concrete methods. Rather than being solid, 3DCP elements commonly exhibit a defined contour and an infill pattern, representing the intended shape while potentially offering material efficiency and aesthetic diversity compared to conventional cast concrete structures.

The production of buildings by 3DCP primarily focuses on the production of walls with straight-extruded geometries. From a structural standpoint, these buildings correspond to unreinforced masonry, with certain scenarios allowing design focused solely on compression, eliminating the need for reinforcement [7]. Despite the advantages of the technology in terms of automation, the use of 3DCP to print such structures is questionable due to the high environmental impact of printable materials [23]. Unlike other projects based on adapting structural principles of unreinforced masonry, Project Milestone (Figure 2.7c)features 3D printed walls that support the full weight of the roof without any structural cast RC for vertical load-bearing [3]. The first completed house in 2021, comprises approximately 94 m^2 with various 3D printed concrete wall elements. All walls were fabricated off-site and transported to the site on trucks.

Given the inherent difficulty of printing spans and cantilevers due to the support required by fresh deposited material, the construction of roofs relies on different solutions to circumvent this problem. Three common approaches exist for constructing roofs in 3DCP houses: firstly, creating wooden or steel frames on top of 3D printed walls for roof panel installation, removing the load-bearing role of 3DCP walls [49]. Secondly, assembling precast concrete slabs, while efficient, this approach requires substantial formwork, especially for houses with irregular plans as customised formwork is needed. This method, while versatile, necessitates more on-site labour and procedures compared to the precast concrete slab approach. Lastly, roofs can be constructed by manually placing formworks and rebars before casting or spraying concrete. Each approach reflects a balance between aesthetic, environmental, local material availability, and cost considerations, with few examples being realised entirely through 3D printing.

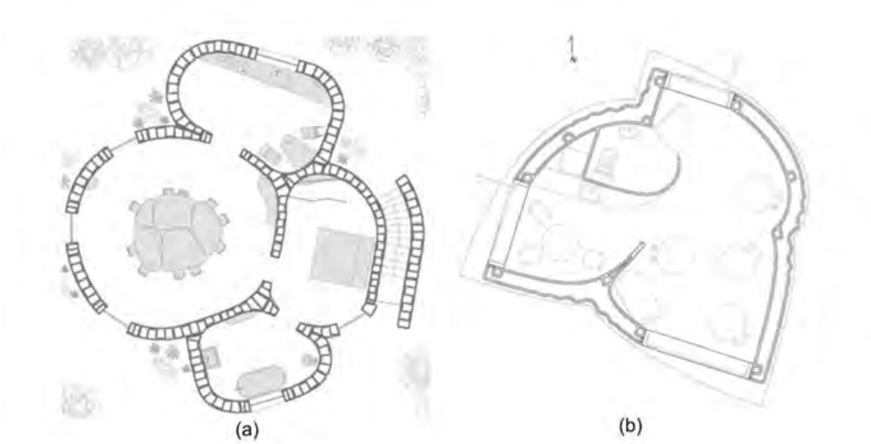

Figure 2.9: Architectural plans of 3DCP residential projects. (a) 3D Housing 05 by ARUP/CLS Architetti and printed by Cybe. (b) The BOD by 3D Printhuset (today COBOD). Reproduced from [7]

Several commercial implementations use an internal infill pattern to maximise the stability of the part during the printing process. This printing pattern has been used from the early developments of 3DCP, and provides the maximum moment of inertia while minimising material use [91]. This zigzag pattern can be observed in multiple projects, where two main extreme versions can be distinguished. The use of a triangulated pattern based on straight lines allows for the minimal amount of material, but implies high accelerations when changing direction (cf. the TRUSS pattern used in Paper III). Depending on the mechanical limitations of the 3DCP system, a print path describing a perfect triangular infill in practice will be rounded proportionally to the maximum acceleration allowed by the controller. The other option is the use of a sine wave that minimises the accelerations of the printing nozzle but has a larger material footprint. An extreme version is the use of an infill resembling a square wave, that provides an increased cross-section, for example in Figure 2.9a. Contrarily, some commercial applications opt for a hollow wall, which despite reducing the stability of the print facilitates the installation of systems inside the walls, as seen in Figure 2.9b.

Figure 2.10: A 24 m^2 house demonstrator project was the first 3D printed building in Sweden by ConcretePrint [92].

In Sweden, the first 3D printed building was a 24 m^3 cottage (referred to as an 'Attefallhus' in Swedish) completed in 2021 by ConcretePrint in Tumba, a suburb near Stockholm [92]. The project was printed using a 50 mm nozzle and was completed in 28 hours of printing time spread over 13 days [93]. As with other 3DCP projects, the construction featured double walls for integrated insulation and systems installations. Steel bars were added between layers to form reinforced lintels above the doors and window openings. Notably, the entire structure was lifted and placed on a site next to the printing facility. The project was completed with windows and door frames 3D printed in biocomposite materials mixed with wood fibres, including the curved window shown in Figure 2.10.

The '3dpod' project by the Obayashi corporation (Figure 2.11) represents a significant advancement of 3DCP towards real-world applications [88]. Completed in 2023, the 34 m^2 demonstration project was the first 3D printed building to attain certification under the building standards in Japan. From an architectural perspective, the project makes use of the freedom of form enabled by 3DCP to create a very distinctive aesthetic, blending numerous architectural elements into a curved shell that differentiates strongly from other more conventional projects. The multi-layered walls also feature an integrated ventilation system and an insulating layer filled with particulate

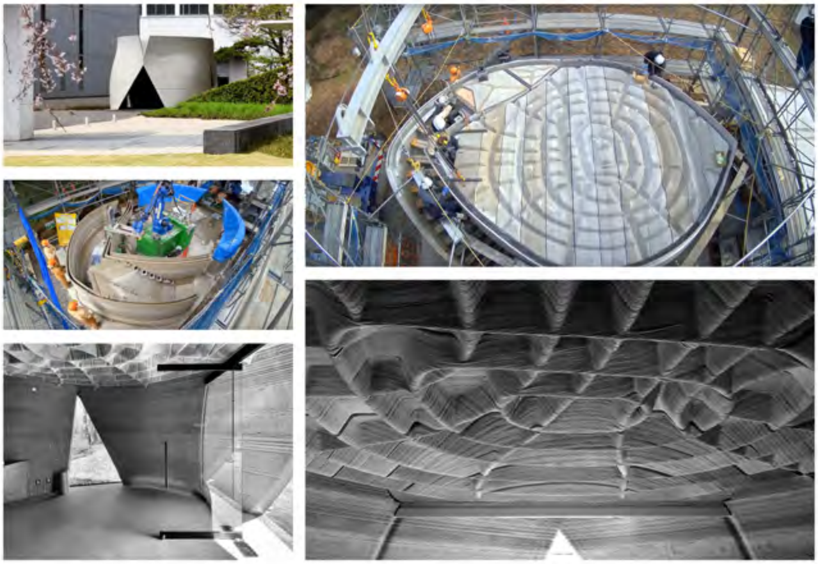

Figure 2.11: The 3dpod is a 34 m^2 demonstration building completed in March 2023 in Kiyose, Japan. Structurally, the Slab is made of 3DCP stay-in-place formwork which is later cast with fibre-reinforced SCC. Multi-layered walls are also filled with SCC and include a ventilation system and insulation layer. Images from [88].

material. From a structural standpoint, the building is printed as a lost formwork which is subsequentially filled with SLIM-crete. Developed by the Obayashi, SLIM-crete is a proprietary steel-fibre-reinforced self-compacting concrete (SCC) that is rated at 180 MPa in compressive strength and 8.8 MPa in tensile strength [88]. The slab is printed in sections creating a ribbed surface that is then mounted and cast with SLIM-crete without using rebars.

Non-residential buildings are less common than residential projects but contain interesting developments. Notable cases include the 640 m^2 two-storey administrative building for the Dubai Municipality printed on-site by Apis Cor [3]. Also, a reception centre in Nanjing featured a series of 3DCP facade elements combined with in-situ cast concrete beams and walls. As presented in Section 2.3, the farmhouse in Wujizhuang demonstrated the feasibility of deploying industrial robotic arms on site and combining in-situ printing with preprinted flat and arched roof elements that are then lifted to place [49]. This project parallelised the printing operations using three robotic arms and reported a 47.6% reduction in person-hours (hour/m^2) when compared with common 3DCP approaches, and a total 62.4% when compared with a conventional reinforced concrete structure.

2.4.2 Structural elements

The range of structural elements that can be produced through 3DCP is mostly limited by the type of reinforcement approach. Reinforcement in concrete construction is a well-acknowledged requirement in the domain, given the relatively low tensile strength of concrete, which is roughly 10% of its compressive strength with a high degree of variability. Consequently, the tensile strength of concrete is most often disregarded in structural design, rendering the incorporation of reinforcement crucial for the load-bearing capacity of structural concrete [94]. Beyond merely enhancing tensile strength, reinforcement is also key for preventing brittle failures, ensuring ductile behaviour for stress redistribution, and limiting deformations and crack widths. However, reinforcement techniques compatible with the automation expected from a 3DCP project is one of the main challenges for the development of the technology [7, 45, 57, 94]. Conventional reinforcement techniques were developed with traditional casting methods and are unsuitable to be applied to digital fabrication methods, both in terms of performance and compatibility with the process [95]. Initial projects mainly tackled this issue by using 3D printed concrete as stay-in-place formwork that was then reinforced and cast with conventional methods. Alternatively, other early examples relied on the use of mesh reinforcement between layers and the incorporation of post-tensioning to the printed element [57]. Given its unique properties, concrete is predominantly favoured as a structural material, and the use of 3DCP to optimise its use is higher when the enhanced capabilities of 3DCP are harnessed to deliver material-efficient structures. The use of 3DCP to manufacture structural elements enables the potential for structurally demanding designs with novel aesthetics, which would otherwise entail substantial expense and material wastage [23]. Moreover, prefabrication in 3D Concrete Printing (3DCP) allows for the discretization of geometries, which can be printed in orientations favourable to manufacturability without compromising mechanical performance.

Vertical elements Most of the vertical structures produced by 3DCP correspond to wall elements printed in situ. Beyond examples related to buildings, some particular developments of 3DCP columns deserve particular attention. Printing columns poses a significant challenge for the development of 3DCP materials, as the vertical building rate is higher for elements with a small footprint. A well-known example of the manufacturing of complex structures is the intricate design of the 4 m high truss-shaped pillar developed by XtreeE in Aix-en-Provence, France [96]. The structure is printed in four sections of 3DCP formwork, that are filled with ultra-high performance concrete (UHPC) and are then assembled on site. Void sections are filled with material that serves as support and is then removed after casting. Despite the successful demonstration of this complex structure, using concrete support material is rarely used in 3DCP structures given the extra material and labour cost of printing and removal. Anton et al. developed a robotic fabrication platform for the design and manufacturing of customised 3DCP columns [23].

Alabassi et al. developed a methodology for the development of a topology-optimised 3D printed column [97]. Considering only axial loading would yield a column with a uniform cross-section, with reinforcement to account for possible eccentricities in the load. Contrarily, the study also took into consideration reinforcement as part of the boundary conditions for the design. Like the previous example, the structure is based on a lost formwork using conventional steel reinforcement and cast with SCC. The study considered a 1:1 printed column as well as scale models at 1:2 and 1:3 respectively. As the full-size model failed due to the hydrostatic pressure of fresh concrete, the tests were performed on the 1:3 scale model, as shown in Figure 2.12. The study reported a 40% material savings, 38% reduction of labour, and half the construction time when compared with conventional construction methods [97]. Nevertheless, the feasibility of filling 3DCP moulds with SCC has been demonstrated in earlier research. A recent pilot study provided practical insights into the implementation of this technique, demonstrating that 3DCP moulds could sustain the pressure of casting without cracking or leakage [98]. The bond strength between the 3DCP formwork and SCC was found to be comparable with typical concrete-to-concrete adhesion. The combination of 3DCP and SCC reveals a pragmatic application for 3DCP technology, which enables the manufacturing of structural elements that meet current building standards.

Horizontal elements Recent research efforts have focused on the analysis and development of horizontal building elements, such as beams, girders, and bridges, as portrayed in Figure 2.13. Gehbard et al presented an experimental investigation of 3DCP beams printed on their cross section with different reinforcement strategies [101]. The authors added interlayer cables and fibres as shear reinforcement, which is combined with unbounded post-tensioned bars or conventional bounded reinforcement. Besides these advancements in material reinforcement, there has been a growing emphasis on structural optimisation methods specifically tailored for 3DCP. Vantyghem et al. utilized TO for the development of a 3DCP post-tensioned girder [102].

Figure 2.12: Some examples of 3DCP columns. Left: Truss-shaped pillar by XtreeE [99], Centre: Prefabricated columns printed at ETH Zürich [100], Topology optimised column prototype testing [97]

However, as the TO problem was defined in 2D, the results required interpretation and adjustment to be translated into 3D volume, which was printed in sections taking into account material and process constraints. A follow-up iteration of this work was presented by Ooms et al. [103], expanded upon the initial design based on the same 2D optimization result but in the form of a topology-optimized bridge with a wider top surface and longer span.

Similarly, Breseghello and Naboni introduced an optimisation method based on a printpaths for 3DCP beams printed on their longitudinal section,

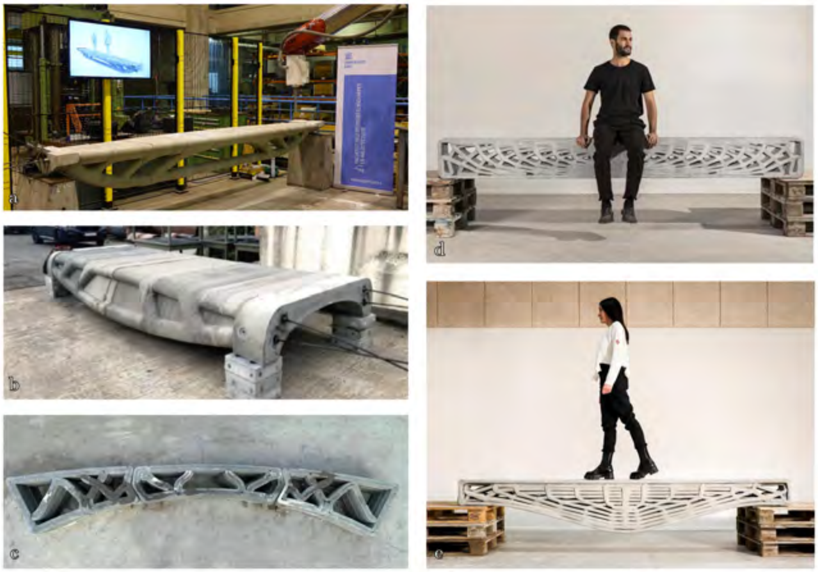

Figure 2.13: Examples of horizontal structural members manufactured by 3DCP: (a) Topology optimised Girder [102], (b) Topology optimised bridge [104], (c) Topology optimised Arch [105], (d) Stress-based optimised beam [77], (e) Shape-optimised beam [106].

following the principal stress lines obtained from finite element analysis (FEA) [77]. In a further iteration of this work, Breseghello et al. [106] presented an extended framework that includes shape optimisation and a subsequent FEA mode for infill-optimised reinforced 3DCP beams. A detailed review of optimised horizontal 3DCP structures is provided in Paper III.

An important milestone for the development of 3DCP was the printing, testing, and installation of a post-tensioned 3DCP bicycle bridge in Gemert, Netherlands [83]. This methodology of design by testing was further applied in a subsequent bridge structure composed of five girders and four pairs of columns, with a total length of 29 metres [107]. Unlike the aforementioned post-tensioned approaches, the Striatus bridge is composed of 53 unique 3DCP segments that form a compression arch. This temporary footbridge, constructed in 2021 for display at the Venice Biennale, features a maximum span of 15.1 m and a height of 3.5 m, as presented in Figure 2.14. Functioning primarily as masonry blocks, these elements operate under compression, thus obviating the necessity for tensile reinforcement or shear keys. The project was designed in collaboration between the Block Research Group at ETH and Zaha Hadid Architects [108]. All parts were printed individually by Incremental 3D in Innsbruck and then transported to Venice where they were assembled without the use of wet connections. The design of infill paths for these parts was designed to respond both to structural demands and process-related considerations, such as varying layer thickness, print path continuity, and filament stacking [3].

Figure 2.14: The manufacturing, transport, and assembly of the Striatus Bridge. Images from [16]

2.5 Printable concrete materials

When casting concrete, the material only needs to provide strength in its hardened state. This is because the formwork holds the shape of fresh concrete, provided that it has sufficient resistance to hold its hydrostatic pressure, until it gains sufficient strength to stand independently. This is not the case for 3DCP, where the fresh material needs to provide sufficient load-bearing capacity to hold its own weight and limit deformation during the printing process. Since it is a progressive layer-by-layer procedure, several interfaces and time differences between materials with evolving properties affect the properties of the printed object.

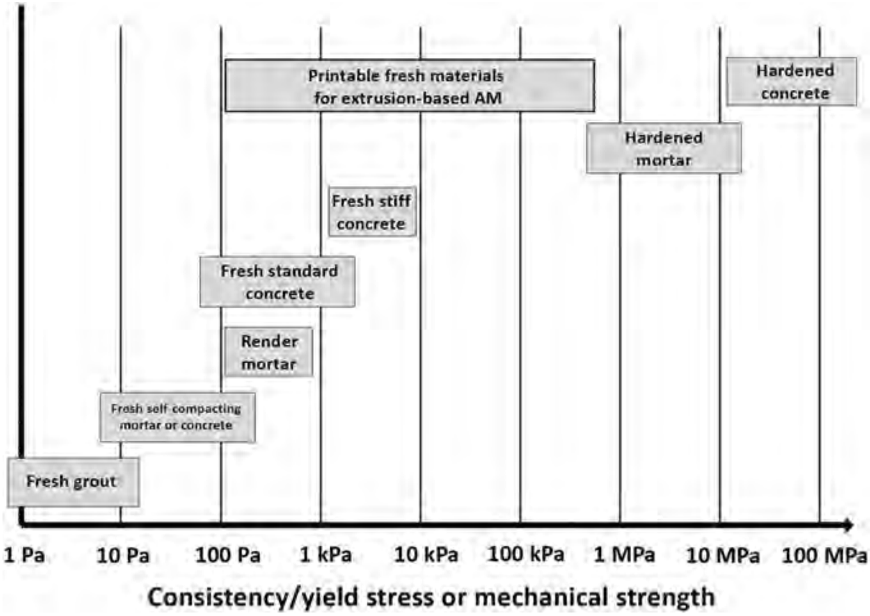

Figure 2.15: Spans of typical values for yield stress or mechanical strength in cement-based materials. Reproduced from [109].

In the case of concrete, fresh and hardened properties also define two research areas with very different methods, equipment, and experts for these contrasting states. The chemical reactions that underlie the hardening process have a profound impact on the material properties, from a visco-elastic fluid to a brittle material with a high disparity in compressive and tensile strength. Also, the forces for changing its state i.e., flow initiation in fresh concrete and cracks in hardened concrete, are several orders of magnitude apart, from 10^1 Pa in fresh concrete to 10^8 Pa in hardened material [109], as illustrated in Figure 2.15.

This section assesses the challenges related to the material composition of materials used for 3DCP. The two upcoming sections provide a closer examination of the properties of printable materials in their fresh and hardened state, in Sections 2.6 and 2.7 respectively.

2.5.1 Mix design for 3D printing

The concurrent and often contradicting requirements for the 3DCP process make mix design an intricate issue. Mixes for concrete 3D printing are often high-cement, self-compacting cement mixtures with tailored rheologies facilitated by various thickening agents. As only fine aggregates are used, the materials available for the system are technically mortars rather than concrete. In response to this problem, a multi-level mix design process Lu et al. proposed for the development of printable materials [110]. The first level is related to the rheological properties, which decide the use of Supplementary Cementitious Materials (SCMs), superplasticisers, and additives such as Viscosity Modifying Agents (VMA). These elements significantly influence the rheological behaviour of the material. The second layer relates to pumpability and buildability among other process-related attributes. At this stage, adjustments can be made to accommodate equipment-specific variables. The third and final level is centred on achieving the desired structural performance of the printed object.

Cementitious materials used for 3DCP typically contain higher amounts of cement compared with normal concretes. This elevated cement content is attributable to various factors required for processability requirements that use a higher cement paste content. Additionally, material delivery systems, which involves pumping the material through hoses and extruders, restrict the size of the aggregates in the mix. The typical upper limit for aggregate size was reported between 2 and 3 mm [4], but several commercial available premix have a maximum aggregate size of $\sim$1 mm [2]. Rahul et al. [111] have reported successful pumping up to 30% of lightweight coarse aggregates with a maximum size of 10 mm.

Mohan et al. reported the binder content of ten different printable mixtures, ranging from 750 to 1050 kg/m^3, with most mixtures surpassing 800 kg/m^3 [112]. A further review by Flatt and Wangler reported the Ordinary Portland Cement (OPC) content for another set of mono-component and bi-component mixes, which was in the range of 300 to 800 kg/m^3 given substitution percentages ranging from 10 to 60%. Typical values for standard concrete mixes are in the range of 250 to 400 kg/m^3 for normal concrete to high-performance concrete mixes, respectively. An explanation for this imbalance is the comparison between typical values found in real-world applications with promising results in recent publications. For example, although binder values for UHPC can easily exceed 1000 kg/m^3, recent publications have shown formulations with less than 300 kg/m^3 OPC by heavily relying on SCMs [113]. Commonly used SCMs include Fly Ash (FA), Ground Granulated Blast-furnace Slag (GGBS), and silica fume (SF), which are used as partial substitutes for OPC or clinker in 3D printable cementitious materials. The primary motivation for incorporating SCMs in the context of printable materials is to enhance the packing density, cohesion, and flow consistency of the mixtures [114]. While the impact of SCMs on the rheological attributes of fresh mixtures is significant, it is imperative to note that different SCMs exert varying influences on these properties. A further discussion on the sustainability aspects of the material composition is discussed in Section 2.8.

A continuous and stable material flow is an essential requirement for any 3DCP process. Therefore, the consistency of the mix proportions is the first step for achieving a predictable mix. While the use of premix material is optimal, the availability of this type of material cannot be guaranteed in all locations [87].

2.5.2 Accelerated mixes

To modulate the temporal development of yield stress, two distinct approaches exist: either by using ‘thickening’ agents that provide an effect after the deposition, or the use of accelerators. Mono-component mixes are the prevalent form of material for 3DCP. Nevertheless, these mixes present operational challenges that pose limitations to the productivity of 3DCP. Since mono-component mixes are produced via single-stage mixing with thickening agents, they present a limited open time for pumpability and buildability. Surpassing this time frame can lead to blockages in the material delivery system or the extruder due to the increased material stiffness, which in turn is a consequence of the high structuration rate of the material. To overcome these limitations, the use of bi-component approaches has been gaining adoption both in material development and in equipment for 3DCP materials [56].

The enhancement of material printability through the use of accelerated mixes has been a rising topic in recent research. These techniques rely on mixing a secondary constituent at the printhead right before the extrusion, allowing faster build rates as they enhance the yield stress development of the fresh material. While accelerators for concrete materials have existed for a long time, the use of precise rheology control has been enhanced with the development of digital fabrication technologies. This process has been also used in digital fabrication with concrete (DFC) other than 3D printing (cf. Section 2.1.1), for example using a computer-controlled slip forming [115] or the use of fast-setting concrete poured on thin 3D printed plastic formwork [116]. The rationale behind this approach is the use of digital control to manipulate the behaviour of the material [63]. A prominent example of the applicability of this technique is the digital fabrication of a slab system that dynamically varies the activator amount, ranging from 1.5% to 10% CAC to OPC weight ratio, enabling a seamless transition from casting to 3D printing material [117].

Accelerators are admixtures that have a direct influence over the hydration kinetics of concrete, either by promoting hydration or counteracting the effect of retarders [62]. These agents can be generally categorised into three groups. (i) The first group predominantly comprises inorganic salts like calcium chloride and calcium nitrate which elevate ion concentrations in the pore solution. (ii) The second group relates to compounds commonly used in shotcrete accelerators, which act mainly on aluminates to expedite etringite formation. While effective for rapid stiffening of the mix, these accelerators can induce flash set through sulphate depletion, which potentially compromises long-term strength development. Moreover, accelerators like sodium aluminate can alter hydration kinetics, leading to a rapid depletion of sulfate ions, and thereby accelerating the hydration of C3A at the expense of C3S hydration. This imbalance may result in diminished compressive strength at later stages [52]. (iii) The third group encompasses seeding agents that offer C-S-H surfaces to accelerate the growth of these phases, exerting a less potent effect than the aforementioned accelerator mechanisms, but more beneficial effects in long-term strength. Approaches based on dispersion may use a chemical accelerator that accelerates the hydration reactions by modifying the silicate/aluminate balance, or a flocculant that bonds the finest particles in the mix. The inclusion of accelerators into the mix also affects bond strength, as the accelerated early-age hydration rate in such mixtures impairs the absorption of free water at the interfaces. These approaches rely on very small quantities, typically in the range of a small percentage of the total volume. Alternatively, an alternative binder can be mixed such as aluminate-based materials, which conversely require amounts above 10% v/v [62].

Since the strength of bi-component mixes is given by the reaction with the accelerator, they have a lower viscosity and lower yield stress. An important consequence of this approach is a reduced energy demand when mixing and pumping, which can have a significant impact on the environmental footprint of the process [46].

2.6 Fresh properties

The early-age behaviour of concrete in 3DCP presents a fundamental contradiction in terms of its rheology: the necessity for high flowability during pumping and rapid transformation to a high-yield stress state post-deposition. The success of a 3DCP process from a material perspective depends on the correct balance of these two material qualities. From a rheological standpoint, the material must remain flowing and have a low viscosity to facilitate pumping, and then immediately after extrusion, it must quickly transit into a solid state with sufficient strength to resist deformation [118].

In the broader spectrum of material extrusion 3D printing technologies, different materials use separate approaches. As discussed in Section 2.1.2, 3D printing with thermoplastics (FDM or FFF) has emerged as the most widespread 3D printing technology. This technique is based on extruding the material into a liquid state that is then solidified through cooling. Therefore, the extension of this technique to concrete, a material that also changes from liquid to solid, seems to be a natural choice [11]. Nevertheless, the operating principle for yield-stress fluids such as concrete differs substantially. In this case, as the pump or extruder mechanism applies stress exceeding its yield stress, it enables the material to flow and be extruded through the nozzle, at which point it subsequently retains its form due to its high yield stress. However, concrete hardening involves several chemical and physical processes that make its properties much less predictable. Additionally, several difficulties arise when attempting to scale up the printing process to building size.

The behaviour of fresh concrete can be modelled as a Bingham material i.e., that the material does not flow unless a critical shear stress is reached. Under a critical yield stress (τ_0), and critical shear strain (γ_0), fresh concrete behaves as elastic solids. However, when the stress and strain in the material exceed the critical values, they exhibit the properties of a viscous fluid, where the shear rate is proportional to the plastic viscosity of the material.

$$\tau = \tau_0 + \mu \left(\frac{d\gamma}{dt} \right) \tag{2.1}$$

This model is based on two key parameters that describe the relationship between the shear stress (τ), shear rate ($\frac{d\gamma}{dt}$), and plastic viscosity (μ). Static yield stress refers to the peak shear stress necessary for initiating concrete flow. As used for formwork pressure, simple models can be applied to estimating feasible building heights. After extrusion, the initial yield stress needs to support itself:

$$\tau_0 = \frac{\rho g h}{\sqrt{3}} \tag{2.2}$$

Where ρ is the density of the material, g is the gravitational acceleration, and h is the height of the material, in this case the printed filament. The required yield stress at any given time $\tau_0(t)$ can be calculated as a function of the height of the structure $H(t)$, by:

$$\tau_{0(t)} = \frac{\rho g H_{(t)}}{\sqrt{3}} \tag{2.3}$$

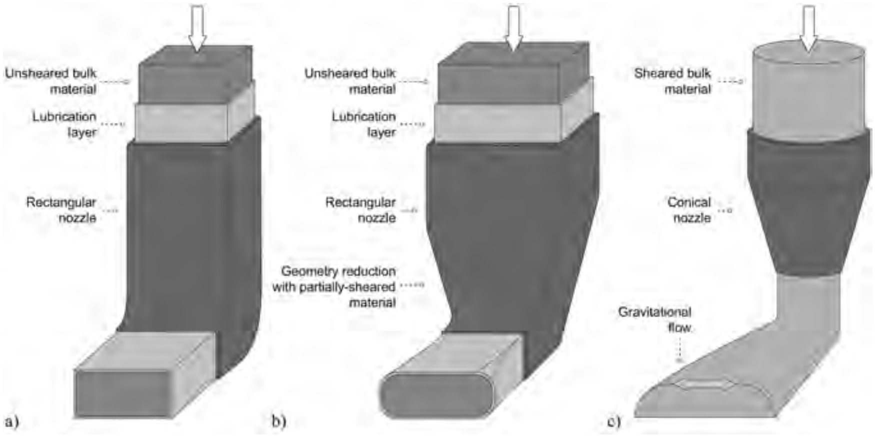

Figure 2.16: Three contrasting regimes for material deposition in 3DCP: (a) the 'infinite brick strategy' for highly stiff material, (b) an intermediate regime that balances stiffness and flowability via nozzle geometry, and (c) involving sheared material in the so-called 'free-flow deposition'. Reproduced from [53].

2.6.1 Processing steps

Pumping When pumping fresh concrete material, the shear stresses induced during the process create a lubrication layer by the movement of particles away from the high-stress zones. This lubrication layer is composed mainly of fine particles and water and is formed due to the high shear forces in the pumping system, in a process called shear-induced particle migration [53]. Consequently, the shear rate is primarily concentrated within this layer, while the bulk material remains largely unsheared, dependent on its yield stress. Therefore, the rheological behaviour of the bulk material is less relevant than the propensity of the material to form a lubrication layer [119]. It may be important to note that the lubrication layer is not an additional lubricant applied to the system as it may be misinterpreted from other publications [66].

Extrusion As defined by Rousell [91], extrusion regimes can be split into two antipodal regimes according to the mechanics of the flow. The first is characterised by a laminar flow of stiff material, where shear is confined to the interface with the nozzle, forming a lubrication layer analogous to the one described in pumping. An unsheared plug of material is deposited without being affected by flow or gravity and the cross-section of the filament is the same as the nozzle (Figure 2.16a). Conversely, if the nozzle applies a reduction in diameter or uses a screw mixer or extruder at the nozzle the material is sheared before the deposition. In this second case, the material flows upon contact with the print surface or the previous layer, until the stresses induced by the extrusion and gravity equal the yield stress of the material (Figure 2.16c). These were then widely referred to as 'infinite brick extrusion' and 'free-flow deposition', respectively [5, 53, 66]. Materials are also classified accordingly as rigid printable material for the infinite brick extrusion and soft printable material for the free-flow regime. The dichotomy between these two regimes serves as a fundamental framework for understanding the dynamics of concrete extrusion in 3DCP. Beyond these ideal scenarios, Mechtcherine et al. [53] introduced a third, more realistic intermediate state defined by the extrusion of sufficiently stiff material that undergoes partial shearing due to a geometry reduction, balancing form retention and flowability, as illustrated in Figure 2.16b. These regimes serve as a conceptual framework for understanding material behaviour during the extrusion process.

Deposition The volumetric flow rate of the extrusion should theoretically be equal to the volumetric flow of printing, by virtue of mass conservation. As explained in Section 2.2.2 the inherent symmetry of round nozzles avoids the need for an extra rotating axis to align the nozzle with the print direction. However, this advantage also reduces the efficiency of the load transfer along the stack of printed filaments. Given the rounded profile created by free-flow deposition, only a portion of the filament width is in contact with the layer below, limiting its load-bearing capacity [120]. Freshly extruded concrete must have the capability to support the shear stress generated by its own self-weight immediately after extrusion, and thereafter the weight of subsequent layers. This capacity is the main idea of the concept of 'printability' or 'buildability', which entails minimum yield stress at the nozzle level to ensure precise control over the extruded layer. As the printing process continues, the gravity-induced stress increases in the first layer, requiring a corresponding rise in yield stress to maintain structural integrity.

Failure In order to achieve a successful concrete print, the primary factor is the strength build-up of the fresh material. Two main types of collapse are defined in this context: trough plastic failure and elastic buckling failure [53]. Plastic failure occurs due to insufficient strength development and takes place when the self-weight of the structure exceeds the yield stress of the first layer, resulting in a collapse. On the other hand, elastic buckling is a stability-related failure that occurs when the stiffness of the structure is incapable of maintaining its stability, ultimately leading to a collapse. An

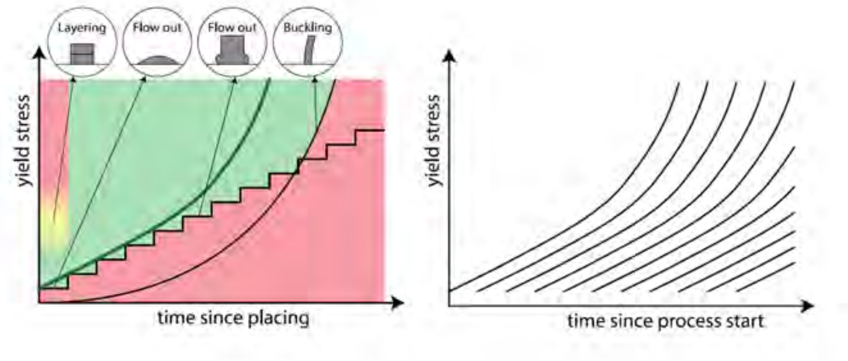

Figure 2.17: The evolution of yield stress as a function of age after placing is crucial for layered extrusion in 3D Concrete Printing (3DCP). Reproduced from [62].

example of each of these two modes is shown in Figure 2.18. After a certain critical height, the stability of the object is no longer dominated by plastic yielding but by elastic-induced buckling [119]. To mitigate this, several printing facilities have adopted the use of sand or gravel as a support to stabilise the fresh material during the print. While this loose material also can be used to print overhangs, it is also relevant for preserving the stability of the part during the early stage of the print. Examples of the application of this method can be found both in academic research environments and in commercial production [102].

2.6.2 Testing fresh concrete

The slug-test offers a quick inline method for quality control of printable materials, allowing to make a quick assessment of the yield stress at the nozzle level [121]. The test analyses the extensional flow of the material that leads to the formation of ‘slugs’ when the material falls freely i.e., when the nozzle is placed vertically and sufficiently apart from any surface. The analysis is based on the reading of a digital scale that records the mass over time. Assuming the extruded material as a perfectly plastic fluid, an analytical solution, based on the Von Mises plasticity criterion, at the nozzle can be used to estimate the yield stress at the nozzle:

$$\tau_0 = \frac{gM_s}{\sqrt{3}S} \tag{2.4}$$

Figure 2.18: Main failure modes in 3D Concrete Printing (3DCP). Left: Plastic yielding due to insufficient yield stress (material failure). Right: Elastic buckling due to insufficient stiffness (stability failure). Reproduced from [53].

The test is particularly effective when the yield stress significantly contributes to the apparent viscosity and the nozzle diameter is small relative to the slug length.

2.7 Hardened properties

The 3DCP process introduces a distinct set of characteristics compared with conventional casting methods. A layered and formwork-free approach to manufacturing, absence of compaction, and specific material compositions in printable cement-based mixes are the main points that influence the hardened properties of printed material. The discrete layer deposition generates a multitude of interfaces between concretes of different ages, each requiring adequate bonding, which is a well-studied topic and is especially crucial in the context of concrete repairs. Numerous variables influence the tensile and shear bond strength of concrete, including concrete properties, surface quality, placement, and curing protocols, along with factors that refer particularly to concrete repairs, such as methods for removing old concrete [122].

2.7.1 Testing

Unlike traditionally cast concrete, 3D printed concrete exhibits a distinctive layered structure. The resultant anisotropy is mostly due to the porous and weakly bonded interfaces between successive layers that constitute the weakest links in the structure. Material deposition further induces flow-oriented alignment of short fibres, which is not a process particular to 3D printing but well documented for cast concrete, such as in the case of fibre-reinforced ultra high-performance concrete (UHPC).

In the context of mechanical behaviour, a widely reported property in the literature is the anisotropic nature of printed concrete. This can be attributed to the heterogeneity resulting from the interfaces between the discrete layering process. Generally, the bulk of the printed filament presents less porosity due to the compaction resulting from the extrusion process [52]. In contrast, the interfaces between layers represent weak links with higher porosity. The flexural stress of printed elements is dependent on the region subjected to maximum bending stress. If this stress is induced at the interfaces, the resulting flexural strength can be significantly compromised. Conversely, if the maximum bending stress is restricted to the bulk concrete, higher flexural strength can be achieved, even surpassing that of cast concrete.

Conventional testing methods typically require the concrete to be filled and vibrated in a mould. Given the absence of formwork and compaction in 3D printed concrete, some of these conventional testing methodologies require special measures while the rest are rendered inapplicable. For hardened materials, tests can be conducted on specimens cut from printed elements. However, the irregular surfaces of these printed specimens often require cutting or polishing, processes that may introduce additional stresses and consequent inaccuracies in the material characterisation.

In the context of 3DCP, Mechtcherine et al. [123] proposed a classification of test specimen preparation into three distinct approaches: (i) casting the printable material into conventional moulds, (ii) print samples utilising simplified laboratory equipment that is different from full-scale applications, and (iii) printed specimens using full-scale equipment. These progressive levels of correspondence with the actual process require increasing levels of technical complexity and specific equipment. Although not mentioned explicitly, a similar assessment can be made on the conformity of the techniques used for mixing and pumping concrete (cf. Section 2.2.1) in three corresponding levels: (i) use a conventional mixer and place the material by hand in the mould or extruder, (ii) mixing the material in batches and using a pump to deliver the material to the extruder, and (iii) use equipment analogous as those used in real-scale applications, such as continuous mixing and pumping systems. These levels of correspondence in material processing are not necessarily linked to those proposed by Mechtcherine. For example, some laboratory equipment may simulate the extrusion using printing equipment, but not use a pump to deliver the material.

Cast specimens (i) provide valuable insights into the properties of printable mixtures and their specific formulations, such as the limited size of the aggregate, high binder content, and the use of admixtures. Yet, these samples do not account for the anisotropic properties induced by the printing process or changes in the material quality due to the material processing system. Printed specimens with laboratory equipment (ii) address the layered effects introduced by 3DCP and the absence of formwork, but the divergences in printing equipment introduce variations in material shear history, printhead compaction, and deposition rates. This variation is most significant for simulated printing systems using ram extruders or mortar guns. Using full-scale 3DCP equipment (iii) encompasses the entirety of the effects of automated material processing and delivery systems. This level offers the most comprehensive approach for assessing material properties and process-related considerations.

An adequate assessment of the material properties is critical for complying with existing building codes. Variations in the structural design and approval process pertain to whether the 3DCP structure is load-bearing or not, as the latter case requires less rigorous approval protocols. Conversely, fabricating load-bearing structures using 3DCP introduces several levels of complexity in terms of structural design, including unknown material properties, minimum reinforcement, adaptability to process constraints, and more importantly, code compliance [3].

2.8 Concrete and sustainability

Concrete is the most used material in the world. This fact is often the opening sentence in several research papers on concrete highlighting the environmental challenges of the material. Within this context, cement production is the main contributor to the environmental impact of concrete construction, primarily for the burning of clinker at high temperatures. Compounding with the massive amounts of concrete used globally and the sustained increase in demand, concrete production accounts for a significant percentage of the global CO_2 emissions [1]. Nevertheless, concrete plays a crucial role in providing essential infrastructure and the built environment on which all levels of society rely on [48]. A set of unique properties like high compressive strength, versatility, and durability in combination with worldwide availability and a relatively low cost have established concrete as the cornerstone for modern civilisation. Even with the multiple environmental and societal consequences associated with the overuse of the material, concrete is still less energy intensive than most construction materials [124]. Considering that moving away from using concrete is not seen as a viable alternative [41]. The current dilemma for sustainability is the pressing need to mitigate the environmental impact of concrete without impairing essential societal needs, such as the provision of housing and basic infrastructure. Nevertheless, there are still several ways forward to increase the efficiency of the material. The imperative reduction of the environmental impact of concrete can be taken from several approaches, predominantly encompassing partial cement replacement with SCMs, the exploration of alternative binders, the expansion in the utilisation of concrete mix designs with reduced cement content, the recycling of demolished concrete, designing structures for longer service life, and refurbishment or reuse of existing concrete.

3DCP has been proposed as an opportunity for improving the efficiency of concrete construction. Reducing the amount of cement in a concrete mix or recycling used concrete are strategies that apply equally to all concrete structures. Conversely, 3DCP offers unique advantages for creating material-efficient structures at no extra cost. Therefore, from a sustainability standpoint, it is the potential for material efficiency that distinguishes 3DCP from conventional concrete. This section provides an overview of 3DCP from the standpoint of its potential impact on the environment. It also expands on the impact of concrete materials and the overall concept of sustainability from a wider perspective. Finally, this section provides some concluding remarks on the role of 3DCP in reducing the carbon footprint of the industry and some possible paths forward to maximise this effect.

2.8.1 Environmental impact of concrete

Concrete has become the bedrock of modern civilisation as it provides critical infrastructure, from roads to power plants, but also most of the built environment that enables our daily lives. The global use of concrete is uncontended even by the combined usage of all other industrial building materials, including wood, steel, plastic, and aluminium [43]. Moreover, the raw materials of concrete i.e., limestone, sand, and gravel, are virtually unlimited resources locally available at a global scale [46]. The demand for concrete is not expected to decline in the near future, especially as developing countries expand their infrastructure while industrialised nations need to maintain their own. Increased demand poses significant environmental challenges and highlights the urgent need to address the impact of concrete construction. Nevertheless, no alternative material seems to be viable to replace concrete to meet the societal need for infrastructure, housing, and protection in the foreseeable future [1, 41, 43, 125]. Neither the transition to renewable energy nor the demands posed by the current climate crisis seem to move societies away from concrete use. For example, the installation of renewable energy installations like wind farms relies on massive volumes of concrete for their foundations.

The largest part of the environmental impact of concrete comes from the production of Ordinary Portland Cement (OPC) which is an energy-intensive process that generates large amounts of greenhouse gases. The main raw material is calcium carbonate ($CaCO_3$) from limestone that is ground and calcinated into an intermediate material known as clinker, which in turn is ground into a fine powder and mixed with 3–5% gypsum and other additives to form OPC. This process emits an average of 842 kg of CO_2 per tonne of clinker [1]. Less than 40% of this figure is derived from fossil fuel combustion, whereas the remainder is a consequence of the calcination reaction of limestone ($CaCO_3 \rightarrow CaO + CO_2$). Since CO_2 is a by-product of the chemistry of cement production, improvements in energy efficiency are insufficient for substantial emission reductions. Some of this released carbon will be reabsorbed during the lifetime of a concrete structure, as part of the carbonation process. This is however a slow process that has a limited effect. Despite its positive climate impact, carbonation is a matter of concern as this process is detrimental to the reinforcement. For this reason, the implementation of carbon capture and storage (CCS) technologies are compulsory for any decarbonisation plan of concrete production. Given the higher concentrations of CO_2 from a cement kiln (14%–33% v/v), it is easier to capture CO_2 from cement production than from gas ($\sim$3%) or coal ($\sim$14%)power plants [126].

Unlike conventional concrete, 3DCP creates concrete structures in an automated process without the use of formwork, which is one of the most recurring argument for the advancement of the technology. When compared with conventional concrete construction, 3DCP is expected to lower the cost construction costs due to the elimination of formwork and reduction of the required labour, resulting also in a shorter building duration. While it is estimated that up to 50% of the cost of concrete is related to formwork, most of this cost is related to labour [45]. While these costs may be considerable, this difference is most significant in unique structures, and it is not the case modular prefabricated structures where the formwork can be used multiple times. Remarkably, the use of prefabricated modular concrete is still the fastest construction method [127]. Moreover, these savings are mostly economical rather than environmental, as formwork only represents a small percentage of the environmental impact of concrete construction [46]. In terms of environmental impact, 3DCP is expected to contribute to lowering the environmental impact of concrete construction by eliminating formwork and minimising material waste, but this effect depends largely on the type of formwork and the level of industrialisation [128].

Within the construction industry, nearly every building component is custom-sized. From an architectural perspective, this means that often fluctuating space requirements are squared into standardised modules in order to avoid bespoke moulds or trimming standardised materials. Thus, repetition is introduced for implementing economies of scale in the production of identical elements for a project. It is worth noting that these economies of scale are not only derived from the physical reuse of formwork for identical components but mostly from the reuse of design and calculation of different elements subject to the same structural requirements. By leveraging standardised designs and calculations, construction projects can benefit from increased efficiency, reduced design time, and optimized material usage. Reusing design and calculations enables the replication of successful structural solutions across multiple elements, leading to cost savings and improved overall project performance. This also depends on the robustness of the printing system and the whole design-to-manufacturing workflow. While 3D printing techniques expand design freedom by offering complexity at no extra cost, the development of unique printed parts requires prototyping and testing, which still poses a constraint to formal freedom.

The environmental footprint of a concrete structure primarily depends on four factors: The total material usage, the embodied CO_2 of the material, the embodied CO_2 of the fabrication process, and the expected service life of the structure [45]. The potential for material efficiency is a key aspect that separates 3DCP and other DFC technologies from conventional construction in terms of sustainability. This relative advantage of 3DCP primarily depends on the point of comparison. When printing standard simplified forms that were developed for the limitations of formwork-based techniques For example, filling a concrete element with the linear deposition of a small printing nozzle results in a very long and energy-intensive process. Still, it is difficult to make a universal claim that 3DCP is inherently more environmentally friendly than conventional casting methods since several factors need to be considered when comparing these methods [47]. Whereas cost considerations may be one of the main driving factors for implementing digital concrete processes, it is mandatory not to overlook the increase in cement content of the materials used. The reduction in labour costs should not come at the expense of a higher environmental impact due to excessive cement usage [45].

2.8.2 Sustainable materials

Conventional concrete development often relies on the use of SCMs to reduce the environmental greenhouse emissions from cement production. Common SCMs such as fly ash (FA), ground granulated blast furnace slag (GGBS), and silica fume (SF) have been used as substitutes for clinker in cementitious mixes for 3DCP. The use of SCMs can have a marked influence on the rheological behaviour of fresh material, enhancing density, cohesion, and consistency [114] On the other hand, materials developed for 3DCP require fast setting and high performance, which is usually achieved with ordinary Portland cement (OPC).

Most of the cementitious materials developed for 3DCP are in the form of mortar with only fine aggregates (most commonly <2 mm). As explained in Section 2.2.1, the use of larger aggregates is mostly limited by the requirements of the printing equipment. These mixtures are made of four main constituents: binder, fine aggregates, water, and additives. Unlike conventional concrete mixes developed for casting, printable cementitious materials typically require a higher paste content to ensure pumpability and buildability [56]. The content of OPC in a 3DCP mix typically exceeds 20% w/w, while the aggregate-to-binder ratio (A/B) is less than two [114]. Developing low-OPC for 3DCP can rely on two different approaches. The first is the use of supplementary cementitious materials (SCMs) or low-carbon cement to replace OPC. The second is to reduce the binder content through an increase in the amount of aggregates.

From an environmental standpoint, the long-term applicability of SCMs to partially replace OPC is only viable if the accounting for the emissions is taken by the processes generating these by-products [125]. Also, the availability of these by-products needs to meet the current and future demand required for cement production. For example, the use of FA is only viable as long as the material is a waste product available in sufficient quantities to meet the demand in the concrete industry. In this case, it is mandatory to find alternatives as coal power plants are not compatible with any sustainable scenario.

Despite not being normally considered manufactured materials, the sheer volume of sand and aggregates also needs to be addressed. When stating the massive amounts of concrete poured each year, readers must keep in mind that most of this volume is, in fact, aggregate. The logistical aspects of aggregate sourcing and transportation add another layer of complexity. Also, the extraction process itself leads to environmental issues other than carbon emissions, such as depletion of natural resources. Utilising recycled and locally generated raw materials, especially in the form of waste or industrial by-products, is the leading strategy to reduce the embedded emissions of the material. Nevertheless, the use of these materials has only been showcased in particular demonstrator projects. For the potential applicability of 3DCP in remote areas, the use of locally sourced raw materials is a key aspect in terms of sustainability [1].

2.8.3 A wider approach to sustainability

Although discourses on sustainability usually revolve around CO_2 emissions, it is important to remark that the concept of sustainability is much wider than reducing carbon emissions. Sustainability, in its wider scope, extends beyond the simple reduction of raw materials and energy consumption. To achieve a comprehensive assessment of sustainability, a common framework is the distinct consideration of environmental, economic, and societal repercussions of actions and decisions. Different methods exist to quantify the impact on each category, where the economic consequences are the easiest to quantify while the societal implications are the most intricate aspect to assess [128]. Beyond the environmental impact addressed in the previous subsection (2.8.2), the advancement of 3DCP is expected to provide several economic benefits through the avoidance of formwork, reduction in labour costs, and accelerated project timelines. These savings are currently counterbalanced by elevated costs for printable mortars with a higher cement content and specific additives. From a societal perspective, 3DCP is also expected to have a substantial positive influence, through the reduction of manual labour and development of higher-skilled jobs for printing operations [49]. Experts in robotics, programming, and advanced concrete technology will become central for the expansion of the industry [50]. Additionally, the reduction of errors and accidents derived from automation can also be accounted as an important societal impact [54].

The Sustainable Development Goals (SDGs) is a framework for sustainable development developed by the United Nations which consists of 17 interlinked goals and was backed by all UN member states in 2015 [129]. These goals span a wide range of areas, from eradicating hunger and poverty to promoting sustainable cities and consumption, and serve as a shared blueprint for dignity, peace, and prosperity for people and the planet by 2030. While the SDGs encompass a wide range of sectors, the concrete industry stands in a unique and paradoxical position. On one hand, concrete serves as the basis of modern infrastructure and occupies a primary role in the built environment, making an important contribution to the fulfilment of several SDGs. For instance, SDG 9 (Industry, Innovation, and Infrastructure) and SDG 11 (Sustainable Cities and Communities) are directly dependent on the ability of concrete to provide robust and durable structures. However, the industry is also at odds with several sustainability demands that clash with various SDGs. The large environmental footprint associated with cement production conflicts with SDG 13 (Climate Action). Furthermore, the extraction of raw materials for producing concrete can contribute to source depletion, land degradation, and biodiversity loss, which is in direct conflict with SDG 15 (Life on Land). The emergence of 3DCP brings new possibilities to mitigate these challenges. Automation, efficiency, and waste reduction are beneficial to SDG 12 (Responsible Consumption and Production). Yet, at the current stage of the development of the technology, its real impact across the full lifecycle is still uncertain. A summary of alignments and conflicts between the current state of development of 3DCP and pertinent SDGs is presented in Table 2.1.

Table 2.1: Possible alignments and conflicts of 3DCP with UN's SDGs

SDG	Alignment	Conflicts
9: Industry, Innovation, and Infrastructure	3DCP promotes technological innovation in the construction industry, aligning with the goal of industry development.	Potential for job displacement in traditional construction sectors.
11: Sustainable Cities and Communities	3DCP contributes to building sustainable infrastructure, thus aiding in the creation of sustainable cities.	Energy-intensive processes could offset sustainability benefits.
12: Responsible Consumption and Production	3DCP allows for precise material usage, potentially reducing waste.	Full lifecycle impacts, including waste management, are not yet fully understood.
13: Climate Action	3DCP has the potential to reduce greenhouse gas emissions through optimized designs and localized supply chains.	Energy consumption could contribute to carbon emissions if not managed responsibly.
17: Partnerships for the Goals	The collaborative nature of 3DCP technology development involves various stakeholders, aligning well with this goal.	Equitable distribution of benefits and costs remains an ethical concern.

The environmental benefits of the technology need to be balanced with their corresponding costs. Adopting eco-friendly technologies is profoundly influenced by economic considerations. Adopting 3DCP within existing construction ecosystems is a complex question since decision-making often involves trade-offs between economic costs and environmental benefits. While 3DCP may offer potential environmental advantages, these are often at conflict with current tendering processes and regulations. The adoption of 3DCP requires addressing critical decisions around material selection, design choices, supply chain logistics, waste management, and regulatory compliance, each of which can significantly influence its sustainability [130]. In this scenario, it is often governments that have a major influence as the major stakeholder in large infrastructure projects. Following the inherent uncertainty surrounding this nascent technology, it is difficult to adopt a clear strategy. 3DCP may also produce significant societal benefits, by reducing manual labour or replacing it for skilled operators [51]. Automation can lead to higher safety in the building place and fewer errors, translating into less material waste and personal injuries (cf. Section 2.1.3).

2.8.4 Process impact

Compared to other 3D printing processes, the process-related emissions of 3DCP are relatively low, accounting for 1–12 % of the total emissions [131]. This is not surprising given the high cement paste ratio of the mixtures used for 3DCP. Nevertheless, given the low-tech nature of conventional concrete technology, the process impact of concrete construction is even lower [46]. Therefore, the primary challenge to the sustainable use of 3DCP is related to the production of 3D printable cement-based mixes.

This raises the question about the balance of a production-efficient structure with excess material against a material-efficient structure with an increased processing energy. According to Kuzmenko et al. [46], for high-resolution structures, the process impact can reach orders of magnitude as high as the material impact of mixtures developed for 3DCP.

These process-related impacts have been shown to strongly depend on printing parameters such as resolution and printhead velocity [46]. For instance, a higher resolution might require more energy, thus increasing the environmental footprint. Similarly, the speed of the printhead can also influence the energy consumption of the process. Faster speeds might lead to higher energy usage, but could also reduce the overall printing time, potentially offsetting some increased energy consumption. Moreover, the type of concrete used in the printing process can also significantly impact the environmental footprint. Digitally produced concrete typically has a much higher environmental footprint per unit volume than ordinary concrete [45]. This is due to the specific requirements for the concrete mix to be suitable for 3D printing, such as the need for a quick setting time and high early strength, which often require the use of additional materials or additives.

The choice of mix in 3DCP, whether mono- or bi-component, significantly influences the process impact. Mono-component systems use a single mixture of all the components, including cement, aggregates, water, and any additives. This mixture is prepared before the printing process and is then extruded through the printer. The main challenge with mono-component systems is the need to balance the workability of the mix for extrusion and the rapid hardening required for layer stability. This often leads to a higher cement content, which can increase the environmental impact and cost [46]. Bi-component systems, on the other hand, involve the separate mixing and extrusion of a printing mortar(containing cement and aggregates) and a liquid component (containing an accelerated cement paste) [56]. The two components are combined at the nozzle of the printer, allowing for more control over the hardening process. This reduces the viscosity of the fresh material and therefore lowers the process impact of mixing and pumping [46]. However, Bi-component systems are more complex and may require a secondary mixing unit operation, which can increase the complexity and cost of the printing process [56].

2.8.5 Potential solutions

The environmental footprint of a concrete element is dependent on several of factors, encompassing not only the embedded emissions within the material itself, but also those derived from the fabrication process, inclusive of equipment and energy consumption. As discussed by Flatt and Wangler [45], the environmental impact of a concrete structure is directly proportional to the environmental footprint per unit volume and to the total volume of the structure while inversely proportional to the expected lifespan of the structure. Nevertheless, this equation does not include the impact of the printing process, which has been demonstrated to be mainly dependent on the printing time, which increases significantly for smaller cross-sections of the filament i.e., high printing resolution [46]. The relationships between these factors are shown in Equation 2.5. Therefore, four main lines of action can be pursued to improve the environmental performance of 3D printed concrete: (i) reducing the embedded CO_2 per unit volume of the material (material CO_2), i.e., using better concrete, (ii) minimising the total volume of concrete being used, by using concrete materials more effectively, (iii) prolonging the service life of concrete structures, and (iv) limiting the environmental impact of concrete processing (process CO_2).

$$\begin{matrix}\text{Environmental}\\ \text{impact}\end{matrix} \propto \frac{Material\ CO_2 \times \text{Total volume} + Process\ CO_2}{\text{Service life}} \tag{2.5}$$

The production of complex concrete elements by 3DCP often relies on high cement contents per unit volume [45]. High-performance concrete is preferred as it provides early strength and enhanced buildability without the need for coarse aggregates, but this fact can lead to overdesign [45]. To offset this impact, the reduction of the total volume of the structure needs to be significant. The potential benefit of digital fabrication to reduce the environmental impact of the industry remains somewhat ambiguous. While several studies have emphasised different aspects of the environmental contribution of 3DCP, the scope of these studies is limited [130].

The concept of designing for longer lifespans is yet another vital aspect that aligns with the precision and customization capabilities of 3DCP, which could potentially contribute to building structures with enhanced durability and longevity. One important approach in this area is the design for disassembly (DfD) which incorporates features that facilitate the dismounting and reuse of structural elements in multiple cycles. Structures designed to last longer inherently reduce the frequency of rebuilding, thereby conserving resources and reducing waste. This strategy can be augmented by incorporating adaptive and modular designs, which can be easily disassembled and reused. As such, future research could delve into the development of design methodologies specifically for 3DCP that prioritize longevity and adaptability.

One promising approach to reduce the demand for new raw materials is the reuse of existing concrete. Unlike the potential impact of a new element designed to be disassembled at the end of the lifespan of the building i.e., in 40–50 years, with reuse the environmental savings can be effective immediately. This minimises the extraction of new raw materials, but more importantly, it preserves the structural capacity of existing concrete elements. More prominently, it saves the energy-intensive process of producing new cement. Waste reduction is often highlighted as a potential environmental benefit, although its impact is less significant than the aforementioned points. Recent advancements in the digitalisation of the AEC industry, including technologies like BIM, digital twins, tracking technologies, and IoT, can be key for the reuse of concrete components [84, 132]. These technologies can facilitate the efficient dismantling and adaptive reuse of concrete buildings. Moreover, the integration of digital design-to-manufacture workflows, made possible with the development of 3DCP, holds the potential to significantly impact the reusability of concrete structures, offering a way of drastically reducing the material use of concrete construction.

Reuse is a promising approach that has the potential to drastically reduce the environmental impact of concrete construction. As discussed by Huuhka et al. it is unlikely that architects and their clients would also consider reusing the original flat plans [133]. In particular, the use of 3DCP can be a key technology to provide the flexibility needed for the reuse of diverse concrete elements. Accordingly, integrating reuse into 3DCP construction projects can alleviate the environmental burden of printable materials, which in most cases have a higher carbon footprint due to high cement content. The flexibility provided by 3DCP provides useful synergies for the feasibility of reuse projects. Similarly, the reuse of concrete elements can significantly reduce the material use and the printing time for a 3DCP project. However, the practice is not without its challenges. Quality assurance, regulatory hurdles, logistical complexities, and market acceptance are significant obstacles that need to be addressed [134]. Despite these challenges, the potential advantages make a compelling case for the broader adoption of concrete component reuse as a sustainable construction practice.

Chapter 3

Design for 3D concrete printing

Freedom-of-form and customisation have been widely promoted as the main advantages of 3DCP technology [5]. However, when looking at some projects made with 3DCP it seems that this freedom is not as widely available or free as proposed. In fact, several manufacturing constraints must be addressed when designing for 3DCP. Moreover, limitations within the design approach itself may also impose restrictions on what can be printed. The actualisation of the technology's potential is contingent upon the development of adequate design tools that can take advantage of the possibilities of the process. The present chapter provides an overview of the design tools and workflows used for 3DCP, aiming to extend the design scope. The first section in this chapter presents a review of the 3DCP workflow developed in this research, from the design of the parts to the generation of printing instructions. The next section focuses on the design possibilities derived from the use of print paths as design elements. Finally, the chapter concludes by examining the concept of Functionally Graded Materials (FGMs) and its application in 3DCP, considering the potential of this approach.

3.1 Design-to-manufacture workflow

As discussed in Section 2.1.1, 3DCP belongs to the category of additive manufacturing techniques based on material extrusion. While this type of 3D printing comprises a wide range of materials, methods based on thermoplastics extruded through a heated nozzle i.e., FDM or FFF, have emerged as the most ubiquitous. During the last two decades, plastic 3D printers have become the most popular type of 3D printer in industrial applications, but also as household items, which represented the main vector for the massification of the technology, as discussed in Section 2.1.2. Even if

3DCP, in general, does not employ heated extrusion, it has inherited several principles from this type of 3D printing.

As in other AM processes based on material extrusion, 3DCP is defined by the sequential extrusion of strands of fresh concrete, most often termed filament, which are deposited conforming to a 3D model. This process entails the formation of a 3D volume out of 1D strings of material organised, most commonly, into 2D slices that serve as a simplified procedure to decompose the 3D model into sequential layers for the manufacturing process. This approach enforces a simplified procedure where the design is defined, and restricted, to the 3D volume, whereas the arrangement and filling of the layers are defined separately by process parameters. Conversely, using the spatial disposition of the printed filaments as design elements in themselves allows for a more comprehensive approach to create complex structures at the scale of the printing nozzle [135, 136].

The 3D printing process consists of a sequence of computer-controlled steps to move from the CAD 3D model to the physical manufactured part. This series of steps typically takes place across different software environments and potentially by different experts. Focusing on the steps prior to the manufacturing, a design-to-manufacture workflow for 3D printing involves several steps, that can be globally grouped in (i) design, (ii) material distribution, and (iii) toolpath planning [77]. While the design part (i) is unambiguous, steps (ii) and (iii) require additional attention, as they may include some specific processes. The engineering of material distribution involves the definition of the position and orientation of the printed parts in the build volume of the printer. A key process for the generation of machine instructions is the slicing process. Therefore, as discussed in Paper III, toolpath planning is explicitly divided into slicing and toolpath planning.

The geometry is most commonly imported as an STL file, which is the de facto industry standard file format for 3D printing [48]. This file format was originally developed for the early STereoLithography 3D printers, most commonly referred to as SLA. The name STL originated from that process, although alternative backronyms have also been suggested [9]. STL files are limited to triangle representation and lack the capability to store information related to scale, colour, material, or any other metadata. An alternative development to overcome these limitations is the AMF (Additive Manufacturing Format), developed by ASTM and defined by the ISO/ASTM 52915:2020 Standard [137]. Several software companies and manufacturers of 3D printing equipment formed a consortium that released an alternative format called 3MF [138], which has some improvements and is more supported for different software. Although the AMF standard has been presented and improved for more than 10 years, support has been slow. Conversely, the 3MF was initially released in 2015 and has wider support from manufacturers, but the adoption by end-users has been slow. While the main goal of ASTM was to develop a non-proprietary format, the industry stance behind an open, but potentially proprietary file format, makes it unclear whether either file format will eventually supersede .stl as the industry standard.

In 3DCP, the layer-by-layer deposition of fresh material requires that each layer is supported by the one below it, which is in turn determined by the printing orientation. This orientation can differ from the part's intended usage and may be adjusted to minimise the need for additional support structures. The first layer is fully supported by the base surface, known as the build plate, ensuring a flat interface. The chosen printing orientation not only impacts support needs but also influences the resulting anisotropic properties of the part, which is crucial for subsequent structural analysis, as discussed in Section 2.7.

3.1.1 Print path planning

Toolpath planning is the process of determining the optimal trajectory of the printing nozzle during the printing process. The idea of toolpath planning dates back to the preparation processes for subtractive digital manufacturing technologies, such as CNC milling machines. A toolpath refers to all the movements of the tool during the manufacturing process, both in subtractive and additive. Conversely, print paths refer specifically to movements where the nozzle is depositing material, and is therefore preferred in the context of additive manufacturing. The toolpath planning process involves the sequencing of nozzle movements and optimisation of the process most commonly aiming to minimise the printing time.

Spiralised print paths, also called 'vase mode', constitute a method commonly applied in small-scale 3D printing to seamlessly connect printing layers into a continuously ascending print path. The deceleration produced by the change in direction creates a material overflow, commonly referred to as 'seams', which can be observed in multiple projects. Other measures for mitigating this effect in 3DCP are discussed in Bos et al. [14], for example progressively lifting the nozzle, creating a ramp to transition between layers. The use of spiralised print paths is also applicable to self-intersecting print paths as long as the topology is consistent and the print paths are continuous i.e., that the print path forms a closed loop.

3.1.2 Generation of machine instructions

A print file primarily comprises an array of positional data along with velocity and acceleration parameters that collectively define the trajectories of the nozzle throughout the fabrication process. Once the trajectories are defined, these are encoded into machine instructions, which are generally specified in machine-specific programming languages. In Europe, the two main vendors of robotic systems are Kuka and ABB, which use Kuka Robot Language (KRL) and RAPID, respectively.

The movement of articulated robotic arms is based on a sequence of poses, each one defining a specific position, expressed in Cartesian coordinates (X, Y, and Z), and the orientation, expressed in angles (often roll, pitch, and yaw), of the robot's end effector. The trajectory, on the other hand, is a sequence of poses that the robot must follow to complete a specific task. In robotic systems, manufacturing instructions are most often written in proprietary programming languages from the manufacturer. In KRL, the orientation of a robotic tool or end-effector is represented using the XYZ-ABC convention. This convention specifies three rotational angles A, B, and C about the Z, Y, and X axes, respectively, as illustrated in Figure 3.1. The sequence of rotations follows the order: first, a rotation of angle A about the Z-axis, followed by a rotation of angle B about the Y-axis, and finally a rotation of angle C about the X-axis. The XYZ-ABC convention is based on a special type of Euler angles, known as Tait-Bryan angles, which also consist of three rotations about different axes. In the context of Tait-Bryan angles, these rotations are often referred to as yaw (rotation about the Z-axis), pitch (rotation about the Y-axis), and roll (rotation about the X-axis). These represent rotation about three distinct axes using $z - y' - x''$ as a rotation convention. Contrarily, in RAPID orientation is most commonly defined as a quaternion that represents the orientation of the TCP as a four-element array, although the definition of angles is also available.

On the other hand, most other systems use G-code as a programming language. G-code is traditionally used to control CNC machines for tasks like milling, turning, and folding, by providing a set of instructions for machine control, including movement along axes, spindle speed, and tool changes. While modern extensions of G-code may include loops and conditionals, the standard version is closest to an imperative programming paradigm, where each line corresponds to a specific command that tells the machine what to do. G-code employs a set of commands, where each command starts with a letter followed by a number. The letter denotes the type of action the machine should take, while the number provides additional information such as the rate of movement or the axis of rotation. A clear advantage of G-code is its universality, from desktop plastic 3D printers to large-scale 3DCP systems run on the same code. This study uses parallel export to G-code and KRL, for scale testing and full-scale production, respectively, as further explained in Section 4.2.

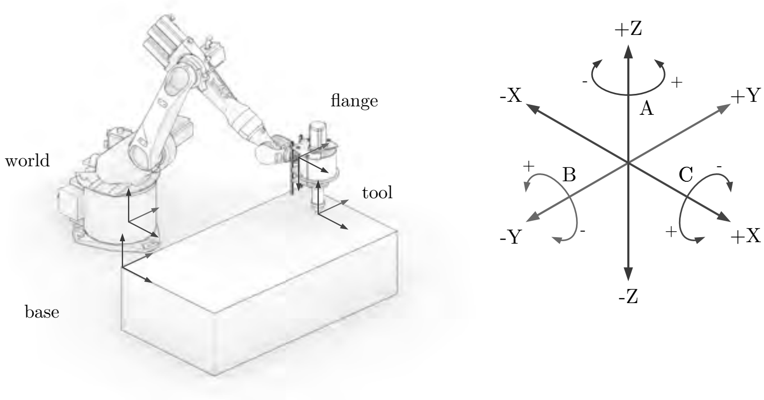

Figure 3.1: Degrees of freedom of an object are divided into three translations along the X, Y, and Z axes; and three rotations around the X axis (roll), Y axis (pitch), and Z axis (Yaw). The rotational movements are conventionally written using A, B, and C angles, corresponding to yaw, pitch, and roll, respectively.

3.2 Design tools

The new capabilities offered by 3D printing technologies open up new opportunities for customisation, enhanced performance, multifunctionality, and reduced manufacturing costs. While traditional workflows segregate design and manufacturing into distinct stages in separated computer programs, there are integrated approaches that consolidate these processes within a unified software environment. Such integrated workflows facilitate a seamless transition and iterative review across the entire design-to-manufacture spectrum. Software solutions like Autodesk Fusion 360 offer modules with CAD, CAE, generative, design, and CAM, functionalities. In the architectural domain, Rhinoceros is favoured for its robust geometric engine, and visual scripting capabilities via Grasshopper (GH), first introduced as a plugin but now an integral part of the software. Furthermore, the Rhinoceros offers a versatile application programming interface (API), which allows to perform geometric operations from external scripts of software and integration with third-party software libraries. Similarly, specialised software libraries such as COMPAS [139], further extend this integration by incorporating functionalities for robotics, digital fabrication, and finite element analysis (FEA), among other tools. Throughout the integration of software pipelines, libraries, and APIs, the design scope can extend into the engineering and manufacturing stages. This study uses the same software environment for CAD, CAE, and CAM processes, using the scripting capabilities provided by the Rhinoceros API, several Python scripts are used to process the design input and automatically process the different stages of the design-to-manufacture workflow. Disadvantages of this type of integrated CAD-CAM environment relates to the reduction of the flexibility and modularity of solutions. Additionally, the integration of workflows in a single software environment is prone to creating case-specific routines that are also software-dependent, compromising the flexibility of the system. A solution to this is relying on open-source and low-level implementations that are software-agnostic.

These extended capabilities for part complexity encompass several aspects of the design. One important aspect is shape complexity, based on the extended formal freedom offered by 3D printers. Similarly, digital design allows the creation of multiscale structures, which provide enhanced flexibility to the design. As presented by Westerlind [140], a 3D printed concrete structure can be looked upon in three different scales. The overall form and features correspond to the *macroscale* and are the focus of interest of structural engineering. Related to material composition, the *microscale* of concrete is the focus of interest of material science that is the foundation of the macroscopic properties of the material. In conventional concrete structures, a material grade with specific properties is defined, in most cases uniformly, to fulfil the material properties required for the forces defined at the macroscale. Nevertheless, the introduction of 3DCP technologies requires the consideration of an intermediate scale defined by the nozzle and the printed filament, referred to as the *mesoscale*. As 3DCP necessarily operates at this scale, it can be understood as a tool to grade the macroscopic properties of the printed structure. Similarly, the same macroscale can be filled with different material features at the mesoscale, extending the possibilities of the designer to include fabrication-driven features and bespoke material properties into the realm of 3DCP. This capacity for mesoscale manipulation allows for the integration of fabrication-driven features and bespoke material properties, thus broadening the design possibilities in 3DCP. Material complexity is also enhanced when the 3D printing process allows the customisation of material properties throughout the print part. Overall, these capabilities allow the extension of the concept of design in multiple aspects of the process.

The first layer is critical to provide stable support for the rest of the printed part. Often, a few first layers are purposely printed with overflow, to ensure proper adhesion to the build plate and provide extra strength against failure due to plastic collapse, as discussed in Section 2.6. This strategy is commonly found in other types of extrusion-based 3D printing.

3.3 Stress-based design

The introduction of digital fabrication enables the technical and economical feasibility of realising topologically optimised structural elements designed according to the principle of 'form follows force' [53]. This approach allows for the creation of material-efficient and resource-saving structures [141]. Furthermore, the increased availability of computing power allows the substantial increment of numerical models to predict and enhance the structural capabilities of concrete structures.

Topology optimisation (TO) aims to identify the optimal structural layout under given design constraints through an iterative process that progressively eliminates structurally inefficient areas. Since its introduction in the 1980s, TO has progressed into several methodologies, including but not limited to the homogenisation method, solid isotropic material with penalization (SIMP), level set method, and evolutionary structural optimisation (ESO), and bi-directional ESO (BESO). These methods are reviewed comprehensively in existing literature [142]. Additive Manufacturing (AM), with its capacity for complex geometries, aligns well with TO, thereby overcoming the limitations posed by traditional manufacturing methods. Numerous studies have explored the synergies between AM and TO. In the context of large-scale construction, integrating 3D Concrete Printing (3DCP) with TO offers promising avenues for crafting structures that are both aesthetically compelling and structurally efficient.

However, the applicability of these advanced designs is still restricted to the manufacturing methods available. Beyond material optimisation, these geometrically complex structural elements also enable the integration of additional functionalities into the design. Although this was already possible with subtractive digital manufacturing methods, the introduction of 3D printing allows this process to be efficient while reducing its environmental footprint.

Optimising 3DCP components is a two-step process: (i) Finding the optimal material distribution for a specific component and load case, and (ii) the optimal print path for 3DCP i.e., the trajectory followed by the printhead when depositing concrete. The aim of the study consists of finding an optimal print path design (ii) for a given material distribution (i) considering the manufacturing constraints of the 3DCP process. This optimisation problem consists of finding the most effective print path for a given material distribution i.e., a structure where the material savings are greater than the loss in strength. This can be quantified as the highest strength by material weight. These principles also need to be taken into consideration when integrating advanced material configurations with the reality of the manufacturing technology.

While structural optimisation has received the most attention, other goals also need to be taken into account. For example, architectural elements have to provide thermal and acoustic insulation, factors that often control the use of materials over the structural requirements. Similarly, the creation of intricate structures with high porosity presents practical limitations for indoor use, while the ribbed surfaces left by the 3DCP process have several question marks in terms of durability for outdoor applications.

3.4 Functionally graded concrete

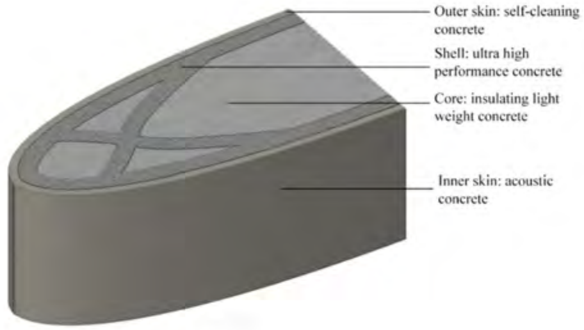

Figure 3.2: Conceptual proposal of a ‘colour printer’ presented by Bos et al. in 2016 [14]. This concept suggests the idea of a multi-material printer capable of depositing various ’colours’ i.e., materials with distinct properties in specific locations within a single printed element.

In a seminal paper, Bos et al. [14] conceptualised the development of a ‘colour printer’, akin to a multi-material 3D printer. However, the picture displays an ideal 3D model forming a solid volume featuring different material properties, which is typically outside of the current capabilities of extrusion-based 3DCP. Furthermore, the possible development of a 3D printing technology capable of rendering multiple material qualities would be also capable of interpolating in between these different properties, eliminating possible defects at the interfaces. A material with these properties is known as a Functionally Graded Material (FGM), and it has been an expanding field of study from its origins in the 1980s, especially in high-tech industries. FGMs, defined by their spatially varying material properties in one or more dimensions, can be achieved through computational modulation of the material composition or the creation of microstructures.

In the case of concrete, this definition may create confusion as the idea of microscale refers to the scale where the basic constituents of concrete interact and give rise to its characteristic properties. Microscale phenomena include the formation of cement hydration products, features of the aggregate-matrix interfaces, micro-cracks, and micro-pores, among others. Conversely, in 3D printing parlance, the idea of microstructure refers to details at the scale of the printed filament, which is normally a couple of orders of magnitude smaller than the printed part. The digital precision afforded by 3DCP ostensibly allows for the seamless integration of material grading into the printing process, ostensibly at minimal incremental cost. This potential has given rise to proposals for creating graded concrete elements, echoing advancements in multi-material 3D printing technologies. This is already a reality for multi-material 3D printers where the 3D model can be infused with multiple material properties, delivering an extra degree of freedom in the design.

Grading material properties has been an interesting field of research in smaller-scale 3D printing, where several techniques have been claiming the creation of FGMs just by influencing the material properties while printing with a single material. However, the pragmatic application of graded materials within a robust 3DCP process has proven elusive. This not only poses technical challenges but also requires a reconsideration of established design-to-manufacture workflows. Traditional design protocols may not accommodate the complexity associated with spatially graded materials, necessitating a paradigm shift in design methodologies to exploit the full potential of FGMs within 3DCP. This concept is discussed in detail in Paper I, which reviews the current attempts to apply the principles of FGMs to 3DCP, as featured in some key studies. Moreover, this paper offers a classification of the possible approaches to achieve functional grading by means of 3D printing with cementitious materials.

Nevertheless, the complexities of developing a robust processing system for fresh concrete, coupled with the logistical challenges of the automation required by the 3D printing process, are the main obstacles against the implementation of functionally graded concrete with 3D printing. This field of research remains a compelling alternative in the pursuit of optimising material efficiency and structural performance, which are key to enhancing automation and reducing the environmental impact of the concrete industry.

Chapter 4

3DCP System Operation and Prototyping

This chapter provides a detailed description of the laboratory-scale 3DCP system and the experimental methods used for the additive manufacturing of concrete parts. It first describes the custom-built open concrete extruder developed as part of this research and the operation of the kinetic system based on an industrial robotic arm. Subsequently, the chapter focuses on the prototyping approach, material mixing, and the step-by-step printing procedure. Finally, the chapter focuses on the use of variable printing speed to modulate the width of the printed filament, a feature that is proposed as an extended DOF in the design of 3DCP parts.

4.1 3DCP system

The experimental work in this study uses a small-scale 3DCP system based on a custom-built open concrete extruder mounted on an industrial robotic arm. The extruder is based on a screw, sometimes called an auger, that presses down fresh material through a nozzle. The extruder is built in a transparent material for visual monitoring of material flow. Additional agitator arms were added above the screw to ensure the shear stress within the material remains above its yield stress, thereby maintaining its workability. These arms actively scrape the inner surfaces of the hopper, preventing the material from sticking to the walls or settling, which in turn, helps in maintaining a consistent material flow and workability. The concrete mixture is prepared using a 20-litre mixer and fed into the extruder's hopper manually. The build surface is made of film plywood, with a printing area of 800 $\times$ 1500 mm^2. The 3DCP system and its main parts are illustrated in Figure 4.1.

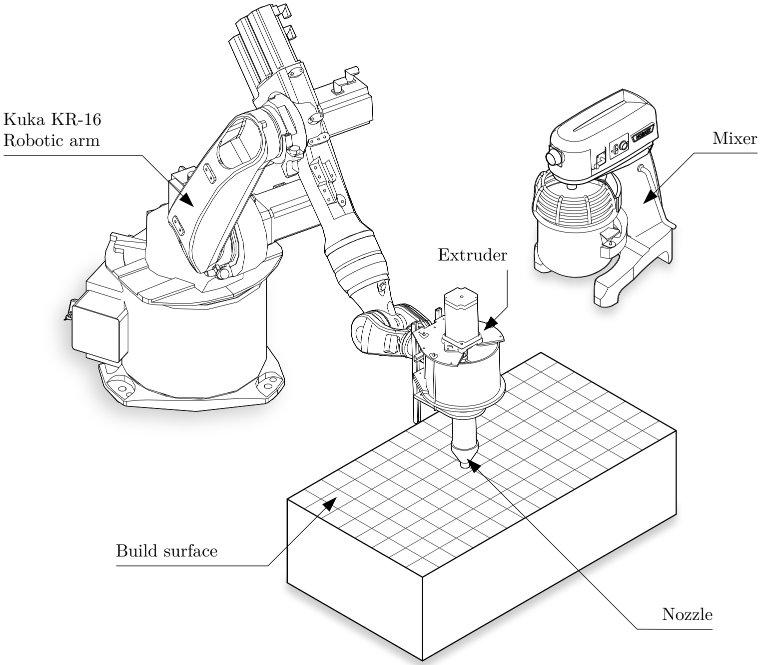

Figure 4.1: 3DCP system at the KTH School of Architecture

The robotic system is a Kuka KR-16 industrial robot arm with a KR C4 robot controller. An important limitation of this robotic arm is its comparatively low payload of 16 kg. Reported robotic arms used in 3DCP are usually larger, with payloads ranging from 60 to 550 kg [23, 46]. The total weight of the extruder, including the motor, is 8.3 kg, leaving a slender margin for the material inside the extruder. Therefore, a spring balancer with a pulley system was installed from the ceiling of the laboratory to reduce the effective weight of the extruder during the operation.

The material utilised in all the conducted experiments is Sikacrete 751–3D [26], a commercially available mono-component dry-mix specifically formulated for 3DCP. According to the product data sheet [2], the compressive strength is rated at ∼30 MPa after 1 day and ∼50 MPa after 28 days. Its flexural strength is rated at ∼3.5MPa and ∼10 MPa after 1 and 28 days, respectively. Labelled as micro-concrete, the mix has a maximum

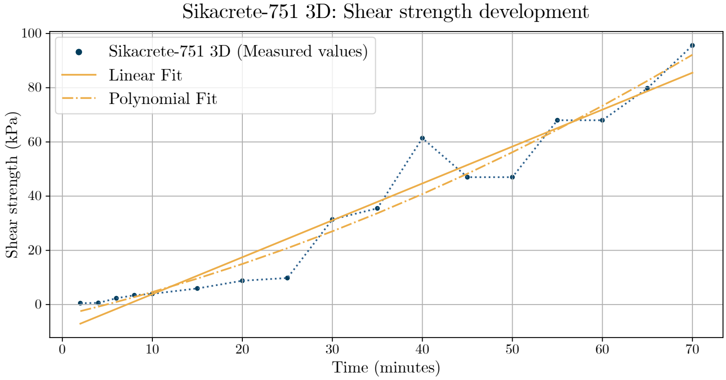

Figure 4.2: Shear strength development from penetration tests

grain size of approximately 1 mm and a fresh mortar density of ∼2.140 kg/l. This material is mixed with 14.5% w/w water, conforming to the specifications of the manufacturer, and then fed into the extruder in small batches. Continuous material feeding in small amounts yielded a sustained continuous flow of material. The material that remained in the mixer was also mixed continuously during the printing operation to ensure that it remained in a fluid state. This method allowed an open printing time ranging from 10 to 90 minutes. The evolution of the shear strength of the material over time is presented in Figure 4.2. This time-dependent yield stress development is critical fur successful prints, as discussed in Section 2.6.

The extrusion system relies on a separate controller where the rotational speed of the screw is specified manually. Rotational speeds are available between 0 and 60 RPM at 3 RPM increments. Typical printing speeds are set in the range of 18 to 30 RPM. The extruder can accommodate nozzles between 20 and 40 mm, although a 20 mm nozzle was used for all experiments. As in other 3DCP systems based on industrial robotic arms, the speed is limited when printing in manual reduced velocity mode (known as T1). Further modes (T2, AUT, EXT) enable full-speed operation but require an enclosed production cell that prevents human access during the operation, and therefore not compatible with the manual feeding of the extruder.

4.2 Prototyping

The experimental work of this thesis centres on 3DCP laboratory tests. However, to explore the feasibility of experimental designs, prototypes are

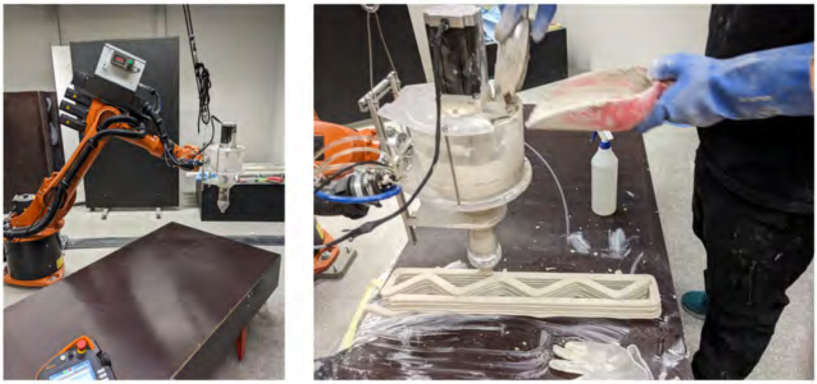

Figure 4.3: 3DCP system at the KTH School of Architecture

created at various scales and using different materials. Scale models were printed in polylactic acid (PLA) polymer at a scale of 1:10 using an Ultimaker 2+ extended 3D printer with a modified 2 mm nozzle. Full-scale parts were then printed in concrete using the aforementioned robotic 3DCP system. Despite the differences between the material behaviour of thermoplastics and printable cementitious materials, scale models provide valuable feedback for adjusting printing parameters and testing early-stage design iterations while minimising material waste. This multiscale prototyping workflow also allows the generation of printing instructions simultaneously for different printing platforms.

4.3 Printing procedure

Preparatory work starts with a preliminary examination of the print file through a dry run i.e., executing the printing file without material extrusion. This step enables the verification of positions and speeds, aiming to identify possible bugs in the code. According to estimations obtained from the print file, the dry mix and water are pre-measured and stored. In the case of larger prints, they are divided into multiple batches. The mixing process starts by adding water into the rotating mixer along with the pre-dosed dry mix, which also serves as the starting point for measuring the printing time. The extruder is primed with sprayed water and then started at a reduced speed (12 RPM) for the first filling. After the mixing period is completed, fresh material is scooped into the rotating extruder in small amounts. Fresh

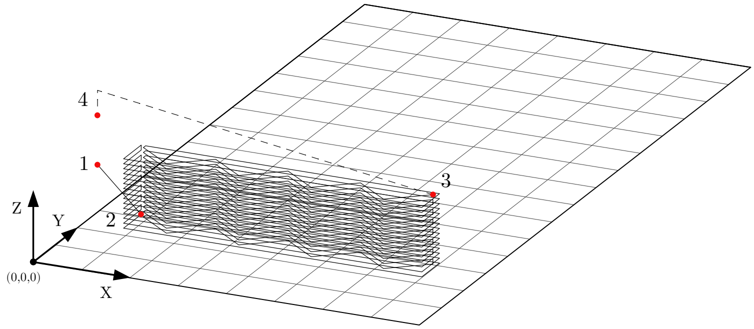

Figure 4.4: Schematic showing the start and end point of a print

material is extruded until it reaches a correct rheological behaviour, which is assessed visually. Once a consistent flow of material is achieved, the extruder is set to printing speed (24 RPM) and then moved to the start position until the flow of material stabilises. This start position for the nozzle is set up outside the build surface at a 50 mm height, as illustrated in Figure 4.4. On early printing attempts, an external digital output was used to send a start/stop signal for pausing the flow of material between the start point and the first point of the print. While this allowed a precise start for the material deposition, this pause disrupted the stability of the flow in the first printed layer. This leaves a trail of filament on the build surface to the first point of the print. This function was still used for stopping the material flow at the end of the print.

The manual feeding of the extruder has been identified as a critical factor contributing to problems encountered during the printing process. Inconsistencies in the material feeding caused variations in the amount of material in the extruder which was found to be the primary variable causing these issues. Insufficient material supply leads to filament tearing, whereas excessive material input increases the load on the motor, in some cases exceeding its torque and leading to a reduced rotational speed. When such problems arose, printed material was removed from the build surface and put back into the mixer to restart the process. However, the extrusion process largely increased the exposed surface area of the material, which induced a loss in water content that affected the rheology of the material. To address this issue, additional water was sprayed into the mixer with the already extruded fresh material during remixing to compensate for the water loss. Although no strict protocol was followed to gauge the right amount of compensation for water loss, the records show that the amount of water

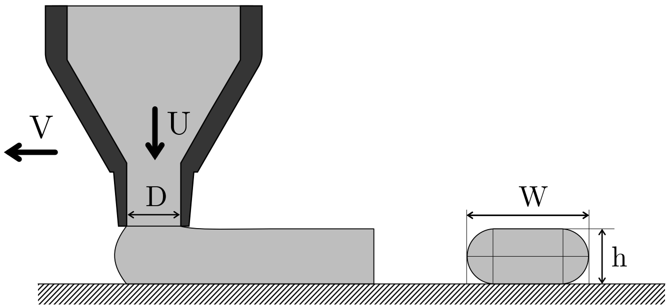

Figure 4.5: Diagram showing the main parameters influencing the deposition and therefore filament measurements. The area of the nozzle must match the cross-section area of the printed filament. Adapted from [143].

used was proportional to the elapsed times and the number of 'resets'. After each print, the parts were covered with plastic and left to harden for 24 hours, and then moved into a curing chamber with water saturation. Further details on the printed results are presented in Section 5.2.

4.4 Variable filament width

The modulation of the ratio between extrusion (U) and travelling (V) speeds enables control over the dimensions of the filament throughout the 3DCP process, as illustrated in Figure 4.5. Both of these parameters can be calibrated to ensure that the speed of the material being extruded matches the movement of the nozzle (cf. Section 2.6). Printing with rigid material is predominantly conducted at this nominal speed, as deviating from it may cause problems such as tearing or buckling of the filament [80]. Conversely, when using soft printing material, the modulation of the printing speed enables the control of the dimensions of the printed filament [66]. Higher extrusion to travelling speed ratios yields narrower printed filaments. Inversely, lower travelling speed or higher extrusion speed generate wider filaments. An important advantage of this approach is that it allows dynamic control over the geometry of the filament without requiring specialised equipment. This facilitates the implementation of variable filament as an extended design parameter that expands the design scope of 3DCP.

3DCP systems based on industrial robot arms typically have greater acceleration capabilities, which allows for easier modulation of the travelling speed of the extrusion nozzle. Additionally, these robotic systems often have separate speed controls for the material pump, setting constant extrusion speeds that need to be regulated manually [23, 77]. In contrast, large-scale gantry systems are characterized by their high inertia due to their considerable mass, limiting their ability to dynamically adjust travelling speeds. Moreover, these gantry systems frequently employ synchronised screw extruders, making it easier to modulate the extrusion speed independently. These fundamental differences underscore the importance of carefully considering the unique capabilities and limitations of the selected 3DCP system when determining optimal printing parameters.

The experimental work consisted of various printing tests conducted at variable speeds, with subsequent measurements of the resulting filament dimensions. It was noted that the modulation of the travelling speed offers a much more straightforward control mechanism than changing the speed of the extruder, as the travelling speed can be modulated directly from the robotic controller. Initial trials demonstrated that altering the extrusion speed presented additional challenges for the precise control of the filament dimensions. Due to the characteristics of the control system of the extrusion, changes in the speed are delivered as sudden changes instead of continuous increments.

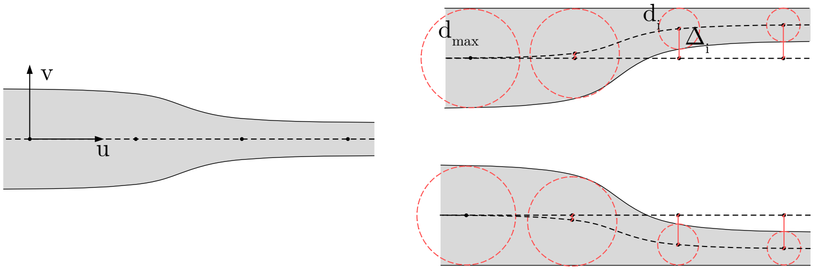

Figure 4.6: Compensation method for aligning the effect of print paths with variable width to one side of the print.

Moreover, a specialised compensation method was applied to the print paths featuring variable printing speed to limit this effect to only one side of the printed part. This is done by shifting the control paths proportionally to the expected variation in width.

$$\Delta_i = \frac{d_{max} - d_i}{2} \tag{4.1}$$

Where Δ_i is the compensation offset, d_i is the expected width of the filament at each control point, and d_{max} is the maximum with along the part, as illustrated in Figure 4.6. Positive values will align the filament to one side of the print path ($+v$) while negative values will align the print to the other side ($-v$). However, these measurements depend on the rheology of the material and need to be determined experimentally. Figure 4.7 shows the printing results before and after calibration. It is worth noticing that even with the calibration, the pattern applied with variable printing speed is still visible from the outside, probably due to the effect of the accelerations involved.

Figure 4.7: Examples of the mismatch of the alignment compensation settings before the calibration (left) and after correcting the algorithm with experimental values (right).

Chapter 5

Results

This chapter summarises the results from Papers II and III, grouped into three sections: The first presents the results of the design methods, focusing on the extended design possibilities for 3DCP; the next section presents the results of the physical printing of the prototypes; Finally, the last section presents the results of flexural testing for paper III.

5.1 Extended design scope for 3DCP

This investigation introduced an extended approach for the definition of material properties throughout the print part by using colour information as an extended DOF of the 3D model. Variable properties could therefore be applied to a 3D model considering different methods. One alternative, as presented in Paper II, is based on the modelling of the element as 2D surfaces, to which a given thickness is defined and modulated procedurally during the slicing process. Another alternative is presented in Paper III, in which an external boundary was defined, and customised material distributions were applied internally. Whereas these methods were used for grading material properties throughout the print, they could also be extended to the application of other procedural variations in the print patterns, such as the use of sine waves that have been featured in several projects as a way of customising the surface texture. Similarly, more complex patterns can be defined and applied to different parts of the printed element, as the application of customised 'stitches' featured in previous research [135].

As discussed in Section 3.1, conventional workflows create a disconnection between design and manufacturing tools. This study proposed an integrated design-to-manufacture workflow wherein all these steps are accomplished within a single software environment. This is done through several modules that are written as Python scripts inside GH. Although this could have also been done using the Python API in Rhinoceros, the use of GH provides a user-friendly interface which allows the extensibility of this approach to non-programming users. Therefore, instead of focusing on particular software developments, the focus of this research centred on the global design-to-manufacture workflow, which is based on different modules or subprocesses. In Paper II, an integrated design-to-manufacture method is introduced to include colour information to modulate the width of the printed filament following a design specified by a projected texture map, as presented in Figure 5.1. Unlike a conventional workflow, where the information between CAD and slicer programs is limited to the triangulated geometry supported by STL files, this approach enables the design and manufacture of elements with graded properties, here represented as colour gradients.

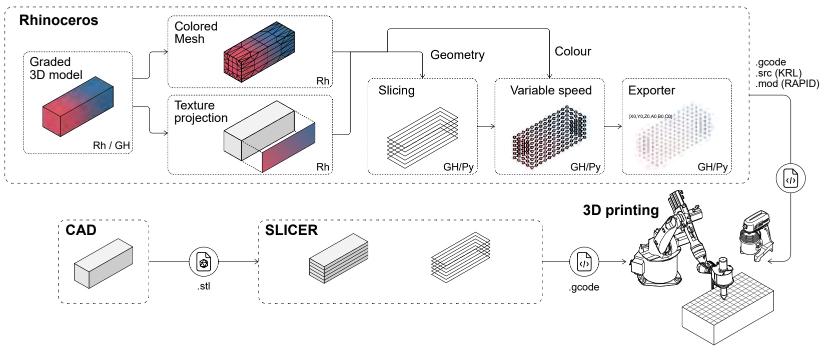

Figure 5.1: Integrated design-to-manufacture workflow in a single software environment, as presented in Paper II.

Whereas these steps remain mostly unnoticed by the end user, it is critical for the designer to understand the operations that make up these processes in order to expand the design possibilities. This extended design scope is particularly important for the application of structural optimisation methods. Unlike other 3D printing processes, in the case of concrete printing, these methods are bounded by limitations in terms of resolution and processing parameters. Regarding structural optimisation methods, 2D optimisation approaches are preferable over 3D methods due to their superior design control and manufacturability. Additionally, numerical methods in 2D domains are simpler and require fewer computational resources. Planar results can therefore be interpreted to create 3D structures that comply with the principles of a simplified 2D optimisation while using a printing typology within the restrictions of 3DCP.

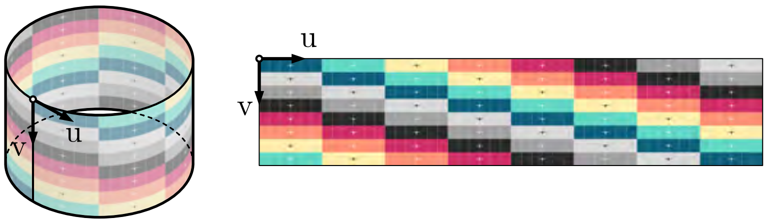

Figure 5.2: Mapping of a texture map on the 3D cylinder.

The use of texture maps in 3D models can be traced back to the early origins of computer graphics, employing various methods to transfer colour information from a 2D raster image to a 3D model. An example of such an approach is presented in Paper II where a prototype is developed by projecting an image into a cylinder, as illustrated in Figure 5.2. Through the definition of a UV parameter on the reference surface, the corresponding coordinate can be located on the image, and then use its colour information to modify the printing process. Multiple methods exist for creating and storing multi-colour 3D models, based on standard data types such as texture mapping and coloured meshes, which are also discussed in Paper II.

A similar approach was used in Paper III, where a 2D material distribution obtained from TO was projected to determine the internal structure of concrete beams. Here the concept of pre-slicing and post-slicing was introduced to separate the different approaches for defining the material distribution of the printed part, depending on the application of material distributions before or after the slicing operation. Pre-slicing implies the manipulation of solid geometry previous to the slicing process. Conversely, post-slicing optimisation involves the manipulation of the spatial curves derived from the slicing operation, incorporating aspects of toolpath planning and therefore granting precise control over the printing process parameters. The method for modulating the material distribution in the optimised beam is based on the following design considerations:

- Printing orientation is constrained to up-right vertical printing.

- Application elements are restricted to thin-plate elements, like walls or beams.
- A minimum amount of material is enforced to preserve the external boundary of the element and to provide support for further layers.

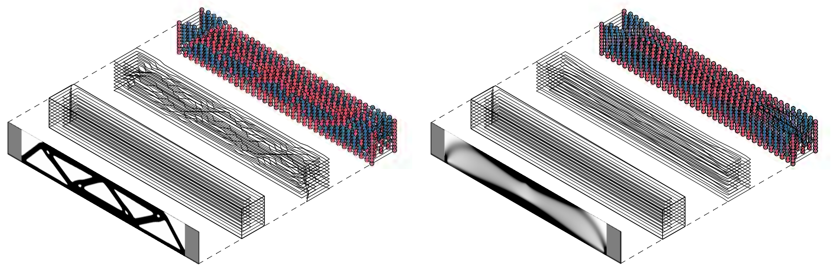

Figure 5.3: Print paths are modified according to the projected TO results, defining a variable-speed printing process. Left: OPT-A. Right OPT-B

This procedure is executed for two different optimisation targets: the first beam (OPT-A) is generated using a fully converged TO result, while the second one (OPT-B) uses a partial TO result featuring smooth gradients. Previous studies have used cast elements or solid printed beams as control subjects, where the use of optimised 3DCP specimens demonstrated an advantage in load-bearing capacity per unit mass over cast concrete [144, 145]. However, it is worth noting that demonstrating an advantage over solid-printed beams is less relevant as they are rarely used in real-world applications. Therefore, the paper proposes a 3D printed beam with a triangular infill as a comparison to represent a common printed pattern used in 3DCP (cf. Section 2.4.1), hereinafter referred to as TRUSS. This prevalent printing pattern maximises the moment of inertia yielding higher stability during the printing process [91], and it has been used from the early stages of 3DCP technology, most commonly referred to as contour crafting at the time [35].

5.2 Printed results

In Paper II, a prototype planter, with dimensions 600 mm in diameter and 270 mm in height, was used to test the applicability of the method, as

Figure 5.4: Printed results from the test specimens

portrayed in Figure 5.4. The body of the planter showcases a customised surface pattern, devised from a projected image texture.

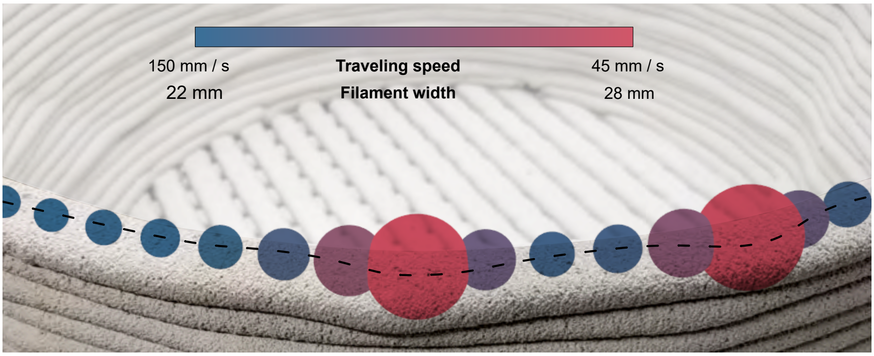

Figure 5.5: Colour and size illustrate the variable printing speed for each control point along the print path, as a way to modulate the printed filament width according to the texture mapping.

The design of the planter is divided into two distinct segments: a permeable base and a single-wall envelope with adjustable filament width. The base is filled with a 'zigzag' infill pattern, which forms a square grid with 5 mm voids for water drainage that was printed at a constant travelling speed of 100 mm/s. The extrusion rate was calibrated to attain a printed filament width of 25 mm, a parameter that was subsequently kept constant throughout the remainder of the printing procedure. The rest of the body was printed using variable speeds between 45 and 150 mm/s modulated by the image projection, which generated filament widths between 28 and 22 mm, respectively, as illustrated in Figure 5.5. The variation of the printing speed also controlled a proportional shifting of the control points, aiming to apply the projected pattern only on the external face of the prototype, as explained in Section 4.4. The printing process was divided into three equal batches of material. Despite the technical feasibility of printing at higher speeds, the speed was limited to ensure the stability of the print.

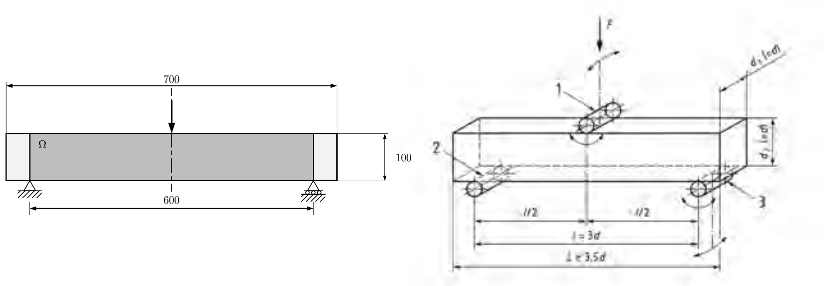

Figure 5.6: Discrepancy in the span-to-height ratio between the topology optimisation problem and the standard for testing flexural strength in concrete. Left: Topology optimisation problem. Right: Specification of loading by centre-point load according to the SS-EN 12390-5 [146]

In Paper III, a set of topology optimised 3D printed concrete beams was fabricated to evaluate their flexural strength. The minimum compliance TO problem is typically formulated using a support span to height with a ratio of 6 to 1, while the standard for testing the flexural strength in concrete prescribes the span as three times the height of the specimen [146]. Furthermore, given the feasible resolution when printing with a 20 mm nozzle, using a shorter beam will drastically reduce the amount of detail in the optimisation pattern. Hence, test specimens were designed to align as closely as possible with the concrete standard while deviating in length, using a 6:1 span-to-height ratio from the optimisation problem, as illustrated in Figure 5.6.

All the beams utilised in this study have the same overall dimensions, measuring 700 × 100 × 100 mm^3. They were subjected to a uniform loading scenario where a centre-point load was applied over a 600 mm span. Optimised designs are applied over a double-wall print that forms a singular continuous print path, as shown in Figure 5.3. This path is then modified with a variable filament width following the material distribution obtained from TO. Control points for variable printing speed were sampled at intervals of 20 mm, mirroring the dimensions of the printing nozzle as a measurement for printing resolution. For the filled segments the printing filament is dimensioned to 25 mm, covering the full breadth of the printed beam in four lines. Although the TO material distribution indicates zones with no material, it is required for the support of subsequent layers. Enforcing this minimum of material is also essential to preserve the external boundary of the printed element, which was one of the premises of this proposal on internal optimisation. Void sections were therefore filled with a thinner filament, at 16 mm or 64% compared to the filled sections of the material distribution. To keep the external faces flat, the print paths were shifted inwards using the compensation algorithm, as described in Section 4.4. Conversely, TRUSS beams were printed with a constant filament width of 20 mm.

Figure 5.7: Covering the printing specimens to avoid excessive shrinkage due to water loss

The beams were printed subsequently using individual material batches and covered with plastic film as they were completed. Once the printing session was complete, all beams were covered and left to cure for 24 hours, as shown in Figure 5.7. After this period, the beams were marked and moved into a controlled humidity chamber partially filled with water (Figure 5.8). The beams were cured in this chamber at 20° and 99% relative humidity for 13 days before testing.

5.3 Laboratory testing

The printed beams in Paper III were tested at the Department of Civil and Architectural Engineering at KTH. These tests were conducted following the SS-EN 12390-5 standard for flexural strength [146], using a centre-point loading method to align with the TO problem under study (Figure 5.6). The bottom surface of the beam, being flat from contact with the print

Figure 5.8: Controlled humidity curing chamber.

Table 5.1: Results of the test specimens

Beam design	**TRUSS**			**OPT-A**			**OPT-B**		
Sample	1	2	3	1	2	3	1	2	3
Weight (kg)	9.7	9.85	9.5	13.95	14.95	15.5	13.5	13.05	13.85
Mean (kg)		**9.68**			**14.82**			**13.43**	
Max load (kN)	2.14	1.53	1.71	4.12	3.96	4.5	2.83	4.41	5.48
Mean (kN)		**1.79**			**4.19**			**4.24**	
Max load-to-weight (kN/kg)	0.22	0.16	0.18	0.3	0.26	0.29	0.21	0.34	0.4
Mean (kN/kg)		**0.19**			**0.28**			**0.31**	
Flexural Stregnth (MPa)	1.93	1.38	1.54	3.71	3.56	4.05	2.55	3.97	4.93
Mean (MPa)		**1.61**			**3.77**			**3.81**	
Strength-to-weight (MPa/kg)	0.20	0.14	0.16	0.27	0.24	0.26	0.19	0.30	0.36
Mean (MPa/kg)		**0.17**			**0.26**			**0.36**	

base, was placed directly onto the support rollers. To ensure optimal contact between the load-applying steel plate and the beam, low-density fibre boards were used to distribute the load. The results of the tests are summarised in Table 5.1

The type of failure presented in all samples is characteristic of what is expected for unreinforced concrete, in the form of a single vertical crack. Nevertheless, some cracks appeared slightly deviated from the centre, shifting between the printed layers, as shown in Figure 5.9. All concrete samples cracked open into two parts except for sample OPT-B.2, which cracked much earlier than other samples. For the calculation of flexural strength, the standard calculates the cross-section based on the bulk dimensions of the beam [146], given by the formula:

$$f_{ct,fl} = \frac{3 \times F \times l}{2 \times d_1 \times {d_2}^2} \tag{5.1}$$

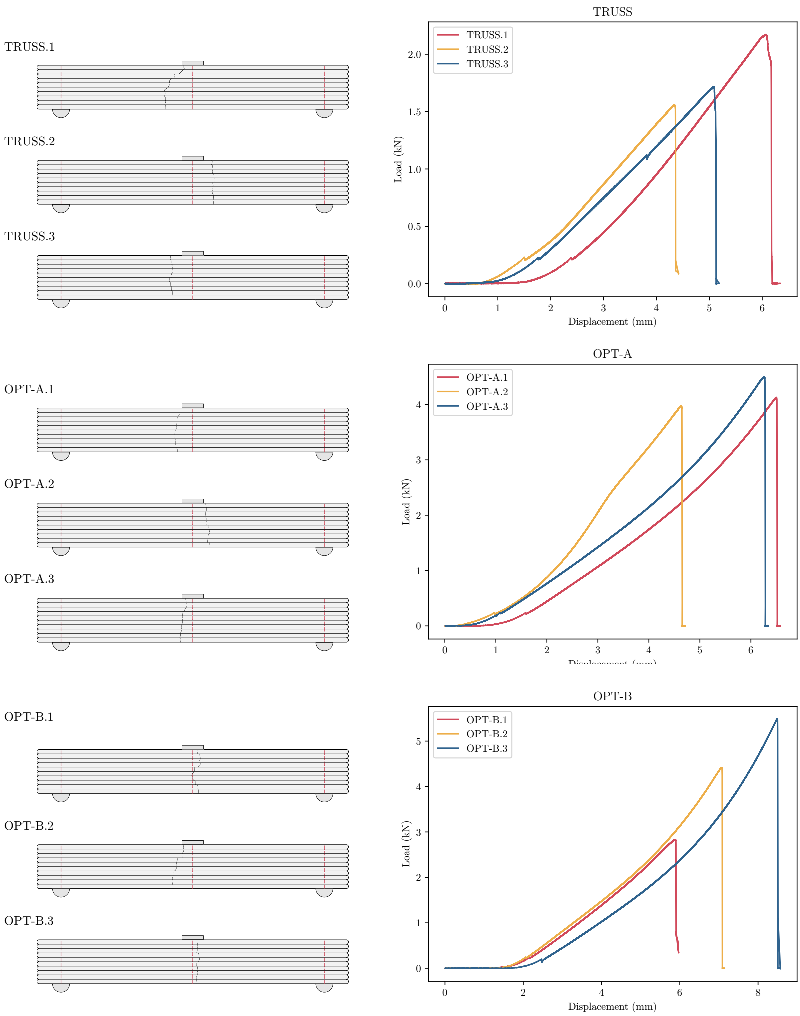

Figure 5.9: Test results from all samples

Where $f_{ct,fl}$ is the flexural strength, in MPa; F is the maximum load, in N; l is the distance between the support rollers, in mm; and d_1 and d_2 are the lateral dimensions of the cross-section of the specimen, in mm. Nevertheless, in the case of 3DCP structures, these do not represent the area of the cross-section of the beam, which is different for each beam design.

Chapter 6

Discussion and conclusions

The development of 3D Concrete Printing (3DCP) has been marked by significant advancements at an increasingly rapid pace. Over the past decade, the technology has transitioned from early explorations within research institutions to a great variety of completed projects and several new developments. This rapid progression increases the momentum for expanding the field and further expansion will certainly follow. This advancement is built on the confluence of multiple disciplinary expertise, encompassing aspects of design and print control, printing equipment, and material composition and behaviour. As presented in Chapter 1, the main objective of this dissertation is the advancement of the design methods for 3DCP. This is unfolded into four research questions:

RQ 1: *What are the design possibilities afforded by 3DCP?*

RQ 2: *Which design parameters are relevant for 3DCP?*

RQ 3: *How can the freedom of shape offered by 3DCP allow for manufacturing concrete elements with enhanced structural design?*

RQ 4: *How can the structural performance of 3D printed concrete parts be optimised within the bounds of manufacturing constraints?*

This thesis encompasses a literature review of several topics related to 3D printing, especially the extended design possibilities of 3DCP as presented in Paper I. Research on design methods presented in Paper II and Paper III introduced and evaluated specialised design-to-manufacture workflows that allow the definition of customised material distributions for 3DCP. Experimental work involved the development of a custom-made

3DCP system, the programming of customised printing instructions, the fabrication of several prototypes, and laboratory testing. This chapter presents the discussion on the results encompassing revised design workflows for the 3D printing process, robotic manufacturing of concrete parts, and a structural assessment of different types of 3DCP beams. The following sections present conclusions and suggest future research directions for the further advancement of the technology.

6.1 Discussion

3DCP, akin to other material extrusion-based AM processes, is defined by the sequential extrusion of printed filament, which is placed in accordance with a 3D model. This procedure implicates the creation of a 3D volume from 1D strings of material, typically organised into 2D slices, simplifying the decomposition of the 3D model into sequential layers for manufacturing. This approach imposes a simplified logic where the scope of design is confined to the 3D model, while the layer arrangement and its decomposition into lines of extruded filament are determined by separate process parameters, usually outside the scope of the designer. It is by focusing on the discrete arrangement of printed filaments as objects of design that the current study proposes an integrated approach that enlarges the scope of design for 3DCP to be able to model and include printing parameters.

Paper I presents a literature review on the concept of Functionally Graded Materials (FGMs) and specifically focusing on the application of 3DCP to generate Functionally Graded Concrete (FGC). The paper proposes a process classification for the approaches to develop FGC by means of 3DCP: (i) variable mixing ratios, (ii) variable addition of particles, and (iii) varied densification. The recent proliferation of bi-component systems is based on the development specialised materials and equipment, enabling adjustable in-line addition of admixtures to actively control the rheology of fresh material. This approach provides a framework to develop FGC by controlling mixing ratios (i) along the print. Similarly, the idea of creating FGC by varied densification (iii) questions the distinction between structure and material, as mesostructures introduced by the 3DCP process can be considered gradation on the macrostructure of the material. The theoretical possibility of a full-scale robust 3DCP system applying material gradations would be a significant advancement for the applicability of complex engineered structures which are currently limited by the manufacturing methods available. This requires a comparable development of design tools to take advantage of these extended capabilities.

Paper II presents the design of an object with a customised surface pattern controlled by an image. The printed results show that modulation of the filament width by texture mapping is feasible, allowing the creation of parts with variable wall thickness. However, the effect of this method is limited by the printing speed. While the travelling speed was reduced to 30% of the maximum speed, the increase of the filament width was only 20%. The explanation for this effect is two-fold: (i) when printing at low speeds, the accumulation of material at the nozzle restricts the material flow, diminishing the extrusion rate even if the rotational speed of the screw was kept constant, and (ii) the reduction of the travelling speed reached the maximum for a single control point, where the effect of the acceleration of the nozzle restricted the section where the printing speed was effectively reduced to one point where the lowest speed was reached instantaneously. This is due to the reduced printed speeds used in the experiment, where the fastest printing speed, and therefore the thinnest filament, is still wider than the printing nozzle. These speeds were enforced to maintain the stability of the print. Printing at a higher speed yields more linear relationships, as those reported in the literature. Moreover, despite the use of a compensation algorithm to limit the effect of this variation to the external face of the printed part, the applied pattern is still discernible from the inside. Previous methods for printing with variable filament width required a 3D model with a special algorithm or the definition of variable printing properties through scripting. Contrarily, this study uses common data types in computer graphics, like texture mapping or coloured meshes, to grade material properties for 3DCP. This method applies to most 3DCP systems where the material is sheared at the nozzle upon extrusion, which is the case in most screw-based extruders and rounds nozzles with reduction.

Paper III develops a workflow for the design and manufacturing of optimised 3DCP beams which entailed the projection of a 2D material distribution derived from TO onto the internal structure of concrete beams. The approach is grounded in three design considerations: an upright vertical printing orientation, restricting the target applications to thin-plate elements such as walls or beams, and the enforcement of a minimal material threshold to preserve the external boundary of the element and ensure the required support for subsequent layers. Results from laboratory testing marked a notorious increment in maximum load for the optimised designs, particularly when compared in terms of maximum load per weight. Both optimised beam designs outperformed the reference TRUSS beam, providing a 47% and 63% higher maximum load-to-weight ratio for OPT-A and OPT-B respectively. However, a pronounced spread in the results was observed, especially in OPT-B. This variation is mostly due to the considerable underperformance of one of the samples (OPT-B.1) compared to the other two specimens, which may be indicative of a singular defect. While OPT-A represented a fully converged TO result, the rationale behind using an intermediate step in OPT-B was to avoid large contrasting sections in the internal structure in favour of smooth gradients. Despite the use of identical printing files and process parameters, there is a broader spread in the results attributable to unnoticed variations in the material processing arising from the manual nature of the feeding system. This inconsistency is mirrored in the spread of the weight of the printed beams.

Initial work relied on the use of components and plugins for Grasshopper i.e., the visual programming interface of the CAD software. All these components were replaced by customised scripts written in Python, which allow for a higher level of flexibility and modularity. Moreover, text-based programming allows for higher levels of abstraction and is easier to maintain. Solutions aimed to be software-agnostic, since even though some functions are built specifically with platform-specific methods, the methods are built on essential types such as points and vectors, which can be ported to other software environments. The use of robotic control in these printed attempts remained limited to offline programming. While this limits the accuracy when compared with systems with real-time feedback, this approach represents the majority of 3DCP systems. Similarly, although the screw-based extruder developed for this research makes it technically possible to start/stop the flow on demand, experiments enforced the requirement of continuous printing flow.

6.2 Concluding remarks

The literature review presented in Chapter 2, provide an extensive overview of the complexity of the field, encapsulating its complexity accross various disciplines. Moreover, Paper I presents a framework for developing FGC by conceptualising different approaches for material grading through 3DCP. It emphasises the necessity for a concurrent evolution of design tools to fully exploit the extended capabilities offered by 3DCP, especially by integrating manufacturing limitations into the scope of structural design and engineering.

RQ 1 This investigation introduces an extended approach for the gradation of material properties throughout the printed part by using colour information as an additional Degree of Freedom (DOF) of the 3D model. This framework enables the application of tailored properties to a 3D model through two different methods. One is presented in Paper II, where the part is modelled as a zero-thickness surface model, where a thickness is applied and modulated procedurally in the slicing process. An alternative approach is presented in Paper III, where an external boundary is defined by a volumetric model while an internal material distribution is controlled by a projected image. These integrated workflows allow the generation of an extended range of variations without specialised modelling expertise. While these examples are still in an early stage to be claimed FGC, they can enable future developments towards functional grading.

RQ 2 Experimental results from Paper II and III demonstrate methods for controlling the filament width by modulating the relationship between travelling and extrusion speed, and subsequentially using this parameter as an additional DOF of the model. These results underscore the potential of 3DCP for the creation of complex structures with customised distributions. The modulation of printing parameters presented a viable method for grading properties within a printed element, and provide insights for further research on customising additional properties throughout the printed element.

RQs 3 and 4 The production of optimised beams discussed in Paper III presented a new workflow for applying optimised material distribution by means of 3DCP while conforming with the process requirements of the 3DCP process. Preserving the external boundary of the printed part ensures full support during the printing process for the application of optimised material distributions. This is achieved while adhering to the constraints of upright vertical printing and an uninterrupted flow of material. The feasibility of this method was verified by the manufacture of several prototypes while laboratory results addressed the potential of this method to enhance structural performance. The comparison between standard and structurally informed print patterns revealed a marked increase in the load-bearing capacity of the latter. This method opens up a pathway towards material-efficient and structurally optimised concrete elements.

6.3 Further research

The applicability of the methods presented in this study was tested in a limited set of applications. In particular, the method for the internal optimisation of 3DCP beams was not designed specifically for these elements but holds the potential to be applied to other shapes and load scenarios and would be suitable also for other vertical elements such as walls. Further research will broaden the spectrum of applications while including other design factors.

The integrated design-to-manufacture workflows delineated in Paper II and Paper III provide an important advantage over traditional discrete workflows by combining engineering and manufacturing aspects into the design process. Although this allows a more dynamic and flexible design procedure, it also poses the question of the limits on the customisation of these solutions. As each application will require case-specific adaptations, these workflows will necessarily have a limited scope. While the integration of manufacturing into design procedures will certainly open up new opportunities for innovation in design for 3DCP, the scalability of these tools will require further development through new standards and modular solutions.

As stated in Section 2.8, addressing the environmental impact of concrete construction is one of the main drivers of research in the field. In the case of digital fabrication, and 3DCP in particular, environmental benefits relate to the possibility of reducing material use derived from stress-aware designs. However, given the high cement content of printable materials, these volume reductions need to be significant. As the global climate crisis becomes more evident, there is a growing interest in the research community into the development and implementation of circular economies. Prolonging the lifespan of concrete elements is one of the main strategies to reduce the use of cement, although the durability of 3DCP structures is one of the weak points of the technology. This can be further enhanced through adaptive and modular designs, facilitating easier disassembly and reuse. The current research is leaning towards crafting design methodologies that promote longevity and adaptability.

The potential of 3DCP to contribute to extended lifespan structures is anchored in its precision and customisation capabilities, notably aligning with the Design for Disassembly (DfD) principle which emphasises the ease of dismounting and reusing structural elements across multiple cycles. An even more promising approach is the reuse of existing concrete structures with their existing structural capabilities. Unlike the future savings anticipated from new elements designed for disassembly, reusing existing concrete offers immediate environmental savings by averting the extraction of new raw materials, preserving the structural integrity of existing concrete elements, and circumventing the energy-intensive production of new cement. The ongoing digitalisation in the Architecture, Engineering, and Construction (AEC) sector, embodied by advancements like BIM, digital twins, tracking technologies, and the Internet of Things (IoT), presents a conducive ecosystem for the efficient dismantling and adaptive reuse of concrete structures. The synergy of digital design-to-manufacture workflows and 3DCP could markedly enhance the reusability of concrete structures, proffering a pragmatic pathway towards substantial reduction in material usage in concrete construction. In this context, 3DCP can become a key enabling technology to provide the flexibility needed to integrate diverse reused elements in a single project. Concurrently, the integration of reused elements into projects can drastically reduce the printing volume and, in turn, the environmental impact associated with the cement content of printable materials.

The advancement of 3DCP towards the development of FGC presents an appealing route for increasing material efficiency and structural performance, which are critical for mitigating the environmental impact of the concrete industry. The integrated gradation of material properties can also enhance automation and reduce further processing steps. However, the difficulties entailed in developing robust processing equipment for fresh concrete, in conjunction with the automation requirements for the 3D printing process, constitute the primary obstacles preventing the accomplishment of FGC within the realm of 3DCP.

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Grading Material Properties in 3D Printed Concrete Structures

José Hernández Vargas
PhD. Candidate, KTH Royal Institute of Technology
Dept. of Civil & Architectural Engineering
Div. of Concrete Structures
Brinellvägen 23
SE 100 44 Stockholm, Sweden
joseh@kth.se

Helena Westerlind
Senior researcher, KTH Royal Institute of Technology
School of Architecture
Osquarsbacke 5
SE 100 44 Stockholm, Sweden
helwe@kth.se

Johan Silfwerbrand
Professor, KTH Royal Institute of Technology
Dept. of Civil & Architectural Engineering
Div. of Concrete Structures
Brinellvägen 23
SE 100 44 Stockholm, Sweden
jsilfwer@kth.se

ABSTRACT
Functionally graded materials (FGMs) describe composite materials with a gradual change in properties along one or several axes. A major advantage with this approach is the avoidance of discontinuities between different layers of material. 3D Printing offers the possibility to control

the material composition and spatial placement along the printing process to create structures with graded properties. However, there are very few examples of the application of this approach to 3D concrete printing (3DCP). This paper presents a review of the current approaches of and methods to grade the material properties of a 3DCP structure, as well as a review of similar methods used in other 3D printing processes. Finally, the potential applicability of these principles into concrete are presented and discussed.

Key words: 3D concrete printing, additive manufacturing, functionally graded materials, digital fabrication

1. INTRODUCTION

Concrete is typically graded in different qualities according to the requirements for each application. This gradation, however, is mostly restricted to discrete batches, making it increasingly difficult to include different values of the multiple properties in different parts of the same structure. In most cases, the low cost of the material makes the savings marginal when compared to the extra cost of multiple mixes and pours and the overall increased cost of logistics. This may no longer be the case when accounting for the environmental impact of concrete, as the assessment of the need to reduce the emissions associated with the material can make us reconsider the benefits of actively grading concrete structures [1]. Furthermore, automated construction techniques and digital building modelling technology have progressively enabled the implementation of advanced manufacturing technologies in concrete construction [2].

Nevertheless, the gradation of concrete has been studied in specific applications such as layered concrete where different grades of concrete are cast in discrete stages to optimise cement use and reduce the overall weight of the structure. The continuous gradation of material properties across the volume is known as functionally graded materials (FGM) and has been a specialised focus of research in aerospace and medical applications, where they serve specific requirements [3]. Current advancements in the field of digital fabrication with concrete allow the manufacture of non-standard forms with enhanced functionality at a lower cost when compared with conventional construction [2]. The introduction of Additive Manufacturing (AM), also known as 3D printing (3DP), in the concrete industry leads to the possibility to completely rethink the conceptualisation of the material [4] and represents an important opportunity for increasing the efficiency of the industry.

In recent years, several studies have suggested the possibility to introduce advanced fabrication methods into concrete technology. This paper seeks to situate and compare the state-of-the-art of the development of FGMs using AM and their applicability to concrete construction. The scope of this study is limited to extrusion-based additive manufacturing of cement-based materials, commonly referred as 3D concrete printing (3DCP), which is based on deposition of cement-based mortars that builds an object layer by layer using computer-controlled motion. The same precise movement can be used to actively control the composition and placement of concrete throughout the printing process. The application of 3DCP provides a framework to the development of functionally graded concrete, which can optimise the use of materials while providing extended functionality and therefore, can potentially reduce the environmental impact of concrete construction [5]. The research question for this study is therefore: How the concept of FGM can be applied into concrete construction using 3DCP? This review is organized in three overlapping topics, and for each one, Scopus and Web of Science were searched for relevant papers. i) A general overview of the field of FGMs and associated methods using AM. Search terms for this section were “functionally graded materials, graded materials, material gradients, multi-material, microstructures, additive manufacturing, and 3D printing.” ii) A specific review of the articles claiming the application of FGM to concrete. These articles included both “graded materials, multi-material, functional grading” AND “concrete printing, additive manufacturing concrete, 3D concrete printing, concrete technology”. iii) The last section is a review addressing the challenges of modelling and simulating structures with variable properties . For this section, search terms were “3D printing, additive manufacturing, 3D printed concrete” AND “modelling, finite element, optimization”. Section 2, below, provides an overview of FGMs and the use of AM to create them. Section 3 describes closely the concepts of microstructure and its applicability to different materials and processes. Section 4 depicts the state-of-the-art of the applications of FGMs in 3DCP. Finally, Section 5 identifies relevant methods and limitations for the design of FGMs.

2. FUNCTIONALLY GRADED MATERIALS

2.1 Definition of FGM

Functionally graded materials (FGMs) are advanced manufactured materials characterised by a continuous gradation of material properties through progressive changes in material composition or structure to achieve an intended function [6]. By embedding different qualities in a single material, further layering or assembly can be avoided, resulting in a superior performance and prevention of defects at the interfaces between different materials. First conceptualised as gradient composites in 1972, FGMs were defined as a continuous gradation of a certain characteristic of the composite material [7]. This concept was then extended to materials of varying composition across the volume of the object where a material grading is designed to perform a certain function. Grading refers to the gradual change of structural, mechanical, electrical, chemical, biochemical, and physical properties as opposed to layering of different materials on top of each other. Depending on the nature of the manufacturing process, this gradient can be continuous or discrete, where the latter has been considered a special case of FGM [7] also known as layered FGMs [6]. FGMs have long been observed in nature, where many natural structures exhibit spatial gradation of properties that respond to internal and external factors. For example, bone exhibits mesostructures that grow denser and change orientation in response to stress [8]. This is also the case of bamboo structures, where fibres grow progressively denser in response to stress [9].

The extensive field of FGMs emerges from early applications in the aerospace industry, but their use has extended rapidly into other research areas. Since the early development of FGMs has been related to high-performance requirements with very specific constraints, the high cost associated with these techniques has limited the scope to high-added-value industries. Across the multiplicity of definitions there are many nuances that change the scope of what is considered an FGM in different fields [10]. Accordingly, different classification schemes have been proposed depending on the manufacturing process [11], the materials involved [12], or according to particular features achievable with each technique [13]. Three main types of FGMs are described according to the type of gradient used: (i) composition gradients, (ii) porosity gradients and (iii) microstructure gradients.

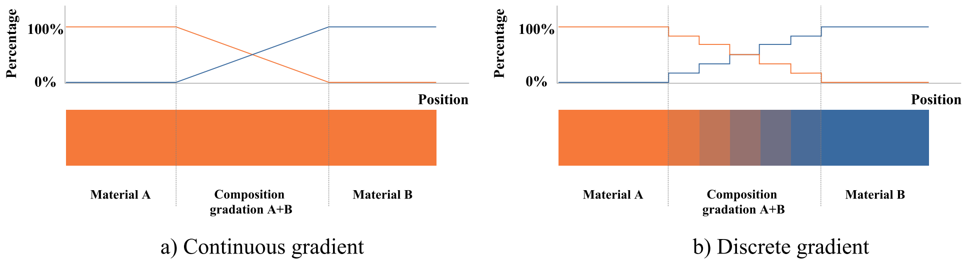

Figure 1 – Continuous and discrete gradients between two materials.

The first type of FGM is achieved by gradually changing the composition of the material along the spatial position. In this category it is possible to include all the processes that create progressive changes in material composition by changing mix ratios, adding particles or fibres. Figure 1a shows an example of a continuous material gradient between two materials while Figure 1b displays discrete stages. Porosity control is another common type of FGM where the size and distribution of pores can be designed to change the density or thermal properties of the material. In medical applications, for example in implants, porosity serves important physiological functions [14]. The use of microstructures has received a lot of attention in the last decades, as improved performance can be achieved by creating materials with lattices and small-scale features. This approach has been used to create structures with high strength and reduced weight. By successively changing the dimensions or shape of the microstructures the material properties can be seamlessly graded as a continuous object. A detailed discussion of this approach as well as its applicability to new fields will be further discussed in Section 3.

2.2 The use of 3DP to generate FGMs

Additive manufacturing (AM), commonly referred as 3D printing (3DP), is a manufacturing technology based on the precise deposition of material according to a digital model that enables the direct fabrication of complex geometries in an automated process. AM and 3DP can be used interchangeably in most contexts, but according to the ISO/ASTM 52900:2015 [15] AM refers to the layered placement of material according to a 3D model, while 3DP refers more broadly to any deposition-based fabrication process. AM is often preferred to refer to advanced systems used in the manufacturing industry while 3DP commonly refers to low-end systems, such as consumer grade Fused Filament Fabrication (FFF) desktop 3D printers. Accordingly, this paper uses the term AM when referring to the manufacturing industry whereas 3DP is used to refer to construction, as used in 3DCP.

From the early development of AM, the capabilities offered by the technology have been applied to the development of FGMs [16]. The use of digital control and the layering process enables the gradation of the material properties to be seamlessly incorporated into the manufacturing process, since the gradient arrangement is no longer directly constrained to a specific technique. This means that the desired material properties can be added to the digital model as an extra degree of freedom. AM-based methods for creating FGMs can be classified in (i) single-material FGMs that create density gradients by adjusting the porosity or spatial microstructures, and (ii) multi-material FGMs using different compositions in discrete phases or continuous gradients [17]. The application of digitally controlled materials has been extensively researched in the field of multi-material AM [18, 19, 20]. In deposition-based 3D printing, the material is extruded through a nozzle that has to transverse the entire volume of the printed object, which can adapt the material properties for each location without interfering with the process. Some materials can be graded by controlling the parameters in the printing process, whereas the exact control method depends on the 3D printed method in use.

3. DEFINITION OF MACRO, MESO, AND MICROSTRUCTURE

The definitions of micro, meso, and macroscale depend on the field and material in use. These terms are relative and can overlap for different scopes within the same structure. In the development of FGMs, the use of microstructures refers, as in materials science, to the use of manufacturing processes to grade the internal structure of the material, such as the metallographic properties in different alloys [21]. Microstructures can strongly influence the properties of the material at the overall scale, and in this sense, the definition has been extended to larger scales than the microscopic structure usually meant in materials science. The creation of FGMs using AM establishes new processes that redefine the boundaries of these concepts. Some AM techniques can generate microstructural gradients at the scale of the grain of the material, such as in selective laser melting (SLM), where controlling the laser power and other parameters can produce different crystallographic structures with anisotropic properties [22]. For example, materials with a negative Poisson's ratio can be manufactured by 3D printing lattice structures that are called microstructures [23, 24, 25]. Extensions of this approach are also called engineered or architected materials which refer to the spatial placement of material and empty space designed to achieve performances not obtainable with existing materials [26] or specifically to the design of microstructures to improve the properties of the material [27].

Other applications extend the use of microstructures to the creation of infill lattices customised and distributed in the print volume to generate varying properties as shown in Figure 2. When contrasted with the types of FGMs described earlier (cf. Section 2), these techniques can be classified both as microstructure generation [28, 29] as well as porosity control [24]. In the scope of this paper, the distinction between porosity and microstructures is made in terms of geometry control. The use of porosity is reserved by the creation of density gradients resulting from material processes while the use of microstructures refers to spatial distributions achieved by the active control of the 3DP process.

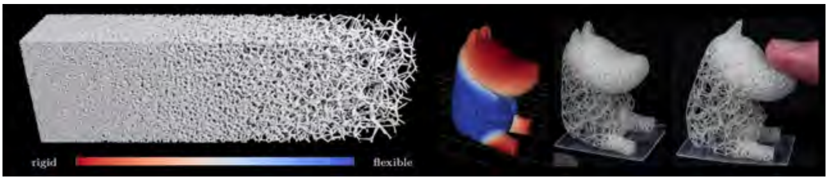

Figure 2 – An example of a 3D printed FGM by generation of variable microstructures to control flexibility. Reproduced from [28].

3.1 Applicability to concrete construction

Whereas concrete can be considered a homogeneous mass at the metre scale (10^0 m), its composite nature becomes evident at the millimetre scale (10^{-3} m) where its structure is determined by the aggregate distribution in the cement paste matrix. In concrete material science, microscale commonly refers to the internal structure of the cement paste, normally at the micrometre scale (10^{-6} m) for which X-ray micro-computed tomography (μCT) and Scanning Electron Microscopy (SEM) are used [30, 31]. The introduction of 3DCP allows the definition of a mesoscale that refers to the scale of the printed filament, i.e., the extruded concrete strand, and their internal arrangement in the overall geometry [32, 33, 34], analogous to the use of the term in small scale 3DP processes [35, 36]. In 3DCP, the use of the macroscale can be defined to the overall shape of the object being printed, typically in the range of (10^{0} m); while mesoscale can be defined in the range of (10^{-1} m) to (10^{-2} m) and microscale in the range of (10^{-3} m) and below.

Mesoscale structures can be used to control a wide range of material properties along the overall geometry of the object. These properties include stiffness, strength, heat dissipation, heat transmission and others [37]. The introduction of mesostructures to the construction industry is aimed to fill the gap between the developments in materials science at the microscale and the work of structural engineers [38]. While developments in this scale have been reserved to specific applications such as metal trusses, new degrees of freedom offered by digital manufacturing can be used to create optimised substructures at different scales. The same approach can be applied to 3DCP with the use of mesostructures to control the mechanical properties of the printed component [33, 39]. The homogeneous infill structure can be graded to match the expected structural performance. Many authors have studied the adaptation of these internal infill structures to the different stresses along the print, although these studies are yet to be applied into full-scale construction [29, 32, 40].

Figure 3 – An example of controlled segregation by rotating the fresh mix on a lathe. Reproduced from [45]

4. FUNCTIONALLY GRADED 3D PRINTED CONCRETE

4.1 Current methods for functionally graded concrete

The initial development of FGMs is closely linked to the development of advanced manufacturing methods, and therefore their classification responds to the manufacturing industry and their applications into different fields. The use of concrete as a casting material limits the implementation of FGMs to different batches, by successive horizontal layering or specially designed moulds with vertical separators for different mixes. A detailed overview of the methods for functionally graded concrete is presented in Torelli et al. [5]. However, this study does not include other AM methods based on the controlled addition of particles or fibres. Several studies have demonstrated the advantages of using functionally graded concrete to selectively improve the material properties of concrete to meet specific design requirements without over or under specifying the entire batch. This also allows solving conflicting requirements without making a compromise on either end. Applications for functionally graded layered concrete include fibre reinforcement for pavements [41], low-permeability layers for reinforcement protection [42], beams with layers of fibre-reinforced lightweight concrete [43], and beams with a layer of high-volume fly-ash concrete [44]. Additional methods include controlled segregation, in which fresh concrete separates in non-homogeneous properties by the application of external forces, as shown in Figure 3. Graded spraying offers another possibility to create gradients by using two nozzles simultaneously with different mixes and varying the mixing ratios [45]. This approach was further developed in [46] where functionally graded concrete beams were manufactured using a stepwise gradation of increasing porosity. This method can be classified today as 3D printing using material jetting (shotcrete) [47], which is beyond the scope of this paper.

4.2 Functionally graded 3D printed concrete

The introduction of 3DCP allows the creation of structural members with higher complexity without the associated costs of customised formwork. This increased complexity can be applied to the development of materially efficient shapes. Another fundamental advantage of the digitalised process is the possibility of automation. As the manufacturing instructions are fully contained on a digital description, the process can be driven seamlessly from the digital model, closing the gap between Computer-aided design (CAD) and manufacturing (CAM). 3DCP allows the generation of continuous gradation by digitally controlling the composition or disposition of fresh concrete during the printing process. Since concrete is a composite material, the mixing proportions for each of its components can be graded as the material is deposited in different parts of the print [48]. However, different mixes may result in very different rheological properties that can present a challenge to the 3DP process. Another constraint is that the methods for grading concrete should be compatible with the continuous extrusion required for 3DCP since additional steps can counteract the benefits of the automated process. In this section, a new classification is proposed to group different applications to functionally grade 3D printed concrete, divided in the following subsections: 4.3 “Variable mixing ratios”, 4.4 “Variable addition of particles”, and 4.5 “Varied densification”.

4.3 Variable mixing ratios

The properties of concrete can be specified by adjusting the mix proportions to meet particular requirements. Under this principle FGMs can be created by digitally controlling the material proportions to achieve a variable material mixture. This can be done by creating different mixtures with specific material properties that are combined during the extrusion process. By digitally controlling the mixing ratios the material properties can seamlessly transition between the individual properties of the starting mixes [49]. While some studies have mentioned the possibility of controlling the concrete mix in 3DCP [48, 50], only a few actual examples teams have been developed into actual applications. The use of multiple concrete mixes greatly increases the complexity of the system as specialised equipment is required to convey and control two different mixes simultaneously. This has been mostly developed by Craveiro et al. as a proof-of-concept using other materials [51, 52], and then applied to 3DCP by combining two different mortars with different aggregates and controlling the mixing ratios along the print [53]. Although this is similar to the method presented in Section 4.4, here the lightweight aggregate is previously added to the mix and the gradation is made by controlling the mixing ratios of different materials.

Another example of this approach is the active rheology control developed by Reiter et al. [54] that changes the amount of accelerator in real time to control the setting time of concrete. This has been applied in different applications using digital fabrication with concrete by Anton et al. [55, 56, 57]. This approach enables the adaptation of properties of fresh concrete from casting to 3D printing material, which can be considered functionally grading. The challenge with this approach is maintaining a compatible rheology for different mixes to match the printing settings. Variations in the pumping ratios of the two mixes and their time dependency also create a challenge to ensure the consistency of the rheological properties of the two mixes.

Figure 4 – Functionally graded 3D printed concrete by variable addition of lightweight fillers within higher ratios of insulating material away from the centre. Reproduced from [62]

4.4 Variable addition of particles

The functional gradation of concrete can also be achieved by controlling the addition of particles during the printing process. This approach can be divided between two main types of particles: (i) the use of reinforcement fibres and (ii) the addition of lightweight fillers. In the case of reinforcement fibres, the base mix represents the lower bound of the material gradation, while a higher concentration of particles corresponds to improved tensile strength.

Selective addition of fibres has received the most attention, but the same principle can be potentially extended to the addition of steel fibre links or other discrete reinforcement units. Ahmed et al. [58] presented a comprehensive study where the effect of variable addition of reinforcement fibres and lightweight aggregates mixed with the printing material, and fibres added in between layers of freshly printed concrete. The results show a significant improvement in ductility, especially when adding glass fibres at the print head [58]. Gebhard et al. also studied the impact of interlayer fibres as secondary reinforcement for 3DCP beams [59]. Larger aggregates can also be added in varying quantities to improve the mechanical resistance of concrete. The effect of large aggregates in 3DCP has been investigated in [60], however this study did not consider any variable gradation. The implementation of an on-demand mixing system is particularly challenging due to the differences in the pumpability of concrete mixes with different maximum particle sizes.

The second approach is the incorporation of lightweight fillers into the mix, a procedure that reduces the density of the print material. Duballet et al. [61] investigated this approach where the addition of lightweight aggregates reduces the density and improves the thermal insulating capabilities of concrete. The resulting sample shown in Figure 4 uses a core with pure mortar and uses increasing ratios of insulating material for each layer closer to the walls. Ahmed et al. presented an airborne system to transport particles to the mixing nozzle, which successfully graded the density of concrete samples, although a higher volume of particles is necessary to achieve significant reductions in density. The density reduction reduces the dead load of the structure and the mass needed to be transported and lifted in the case of prefabricated structures, which needs to be balanced with the negative impact in the compressive strength of concrete.

4.5 Varied densification

FGMs can be also achieved from a single source of material by controlling the deposition process to create structures with varying degrees of porosity or average density. As discussed in Section 3, 3D printing technologies offer the possibility to create structures at different scales: from random entrapment of air at the microscale to manufactured structures at different scales. 3D printed elements are most often manufactured as shells with internal infill structures, which can reduce the overall weight and optimise the use of material. The internal structure can be optimised to follow the expected loads in the print [23, 24]. By manipulating the print paths, a gradation of the material density can be achieved by creating mesostructures throughout the print. This enables the production of functionally graded 3D-printed concrete structures without the use of specialised equipment. In this approach it is possible to classify methods from the controlled generation of voids at the millimetre scale, to the introduction of variable infill patterns or mesostructures in the range of decimetres and potentially metres. The progressive introduction of air can be used to reduce the overall weight and material use in regions with lower stress requirements, as the air content reduces the strength of concrete.

Although there are examples of this approach in other materials [63], the implementation of single-material FGMs with varied densification has received little attention in the field of 3DCP. In Tay et al. [64, 65] an experiment is presented as functionally graded concrete by 3D printing using different extrusion parameters. Using topology optimisation, the model is divided in solid and void regions, which are then translated into solid and support parameters for 3D printing. Support regions correspond to the same print paths printed at a higher speed resulting in a thinner extruded filament. However, there is a limited range of variation in the filament dimensions that are limited by the extrusion speed [66].

4.6 Material limitations

The application of FGM methods to concrete construction increases the complexity of the 3DCP system that can extend the printing time or introduce points of failure in the system. Overall, the introduction of functionally grading concrete presents two main challenges for 3DCP: (i) The development of methods for efficiently varying the composition of concrete during the printing process, and (ii) ensure the compatibility of those methods with the time dependency of the mix. The rheological properties of fresh concrete can be affected by varying mix compositions or the inclusion of fibres or particles which should be controlled to ensure the printing quality. Conversely, differential drying shrinkage maybe alleviated by the smooth gradation of material properties in functionally graded concrete, as sudden changes at the interfaces may be avoided. While many of the current methods show promising results, further development and standardisation is needed before they can become reliable methods for production. Currently, there are no standard procedures specifically developed for 3D printed concrete, and specialised equipment needs to be further developed for achieving functionally graded 3DCP. Although in a very early research stage, methods based on the varying densification by manipulating the print path and process parameters present the advantage of not requiring additional equipment.

5. DESIGN AND MODELLING OF FUNCTIONALLY GRADED CONCRETE

The existing methods for designing concrete structures have been largely shaped by the historical development of concrete as a casting material. Although optimisation methods allow the design of complex geometries for specific load cases [67, 68] the increased complexity is often constrained to what can be done with traditional building techniques, as the extra cost of customised fabrication can make the proposed optimisation impractical. Although some systems feature discrete deposition of multiple materials, they are not suitable for the production of spatially variable physical elements with gradual spatial change [69]. When referring to design, as in most 3DP structures, it is generally restricted to the overall geometry of the element. Furthermore, existing 3DP technologies are most commonly used to manufacture elements with uniform material properties. While structural optimisation is the most common design objective, the same tools can be set up to multiple goals, like considering structural and thermal performance at the same time [62, 32].

Hence, the introduction of advanced manufacturing technologies in the construction industry requires the broadening of the scope of the design to take advantage of the full potential of their application. As the design of FGMs respond to functional requirements, the integration of effective workflows between Computer-aided design (CAD) and Computer-aided engineering (CAE) software is critical to analyse and optimise the design objectives prescribed. The development of innovative manufacturing technologies requires higher control of the printing parameters that in most cases are specified in close relation with the design. Although analytical models have been developed for common structures and gradients [3] the application of FGM to concrete requires the adaptation of these methods. Additionally, the introduction of 3DCP allows for higher geometrical complexity that would limit the applicability of analytical models in favour of numerical simulations. Therefore, numerical simulations play a major role in the design of FGMs as the arrangement of gradients respond to specific functional requirements.

5.1 Numerical simulations

In order to prevent collapse, a proper assessment of material behaviour plays a critical role as it directly influences buildability. The rheological requirements for 3DCP involve low to zero slump and therefore special tests are required to characterise the printability. Several models have been developed to analyse the mechanical behaviour of fresh concrete during the printing process. An analytical model proposed by Rousell [70] is based on material rheology. A mechanistic model is developed by Suiker [71].

Numerical models have received the most attention, mostly based on the finite element method (FEM) that have become widely used for simulating the incremental printing process and the strength development of the material. In this approach, the mechanical behaviour of fresh concrete is most often modelled using the Mohr-Coulomb yield criterion with a time-dependent development of the material properties [72]. This requires an experimental characterisation of the mechanical properties, especially the early age properties of fresh material. Improvements of this method include a damping mechanism to increase the robustness of the simulation [73]. Furthermore, the modelling of 3DCP structures contains several challenges to translate the print paths into a model that allows the correct settings in the FEM software. Sharp edges and self-intersecting print paths create topological problems that impede the simulation. Voxel-based methods offer a simplified approach that create less accurate simulations but are robust against these issues [74]. The multiple forces and parameters involved in the deposition have also been studied with computer fluid simulation (CFD) methods that offer higher accuracy, but their higher computational requirements make them not suitable for full-scale simulations [75, 76]. Still, complex features such as material bridging or self-intersecting print paths have not been incorporated in the numerical models. By applying the results of finite element analysis and adapting the material properties according to the expected stresses it is possible to formulate optimised structures with increased complexity.

5.2 Software limitations

With the introduction of 3DP the material gradation can be specified independently of the geometry of the object. This implies a challenge to the use of boundary representation modelling to describe solids with non-homogeneous properties. These constraints have been addressed in multi-material printing, where the use of voxels allows the 3D representation of the different material properties using discrete spatial units [77]. Still, these tools are specialised and have not been developed beyond the experimental setups. Further development of digital tools is necessary to increase the availability of this technique.

6. CONCLUDING REMARKS

The introduction of 3D printing into concrete construction industry can facilitate the manufacturing of elements with extended complexity without the increasing the costs of custom-made formwork. This increased complexity can be used to create optimised structures with reduced material use or to deliver extended functionality. However, the complexity of the structure is generally limited to the geometry of the outer shell, to which a regular infill lattice is uniformly applied. The further inclusion of mesostructures and tool path generation to the design domain make the material properties another design variable to be considered. This is relevant for both optimisation goals and as an extension of the design possibilities of 3DCP elements.

This paper presents a review of the current methods for implementing functionally graded concrete through 3D printing. Although these studies are still in a very early stage, several development routes have been suggested to create 3DCP structures with functional grading, that could potentially take advantage of the digital process to create structures with optimised structural and thermal properties. In this study, several advancements in FGMs using 3DP are discussed as potential routes for further developments applicable to concrete construction. By controlling the composition or spatial disposition of the material throughout the printing process the design can be further extended to the gradation of material properties in different parts of the print. The use of 3DCP to produce functionally graded concrete structures represents an opportunity to optimise material efficiency and enhance the digital modelling to prescribe material properties into the design. This study proposes a definition of what can be referred as micro, meso, and macroscales as well as a classification framework for different types of functional graded concrete. Although these studies are still in an early stage, several development routes have been traced to create 3DCP structures with functional grading that take advantage of the digital processing to create structures with special properties. Several advancements in 3DP to create FGMs are suggested as potential approaches applicable to concrete technology.

Moreover, the development of advanced concrete materials needs to be accompanied by corresponding development of appropriate methods for structural analysis to ensure their implementation in the industry. Prior studies have noticed the potential to apply FGM methods into concrete construction. However, further development of the technology should be achieved before the benefits can offset the additional costs of processing and equipment. Further research is also needed to evaluate the scalability of these technologies into full-size construction, as well as the development of standardised processes, before widespread use can take place.

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Paper II

Spatially Graded Modeling: An Integrated Workflow For 3D Concrete Printing

José Hernández Vargas[1]

[1]KTH Royal Institute of Technology, Stockholm, Sweden
joseh@kth.se

Abstract. While 3D concrete printing (3DCP) has surged in popularity, methods to harness its design potential remain largely underdeveloped. Existing design-to-manufacture workflows most commonly restrict the design to the overall geometry and a set of print parameters that may fall outside of the scope of the designer. This study presents a novel approach to integrate design and manufacturing by an integrated design-to-manufacture workflow that allows the gradation of the wall thickness along the printed part, which can be independently manipulated using established computer graphic techniques like texture projection and mesh coloring. The effectiveness of this workflow is demonstrated through the fabrication of a test body featuring a customized surface pattern. This approach aims to extend the design scope for 3DCP, enabling the addition and editing of surface patterns without geometry or code manipulation.

Keywords: Robotic fabrication, 3D concrete printing, Variable filament width, Design for manufacturing, Print path design.

1 Introduction

Extrusion-based 3D Concrete Printing (3DCP) has become the leading technology for digital fabrication with concrete. As with other 3D printing techniques, 3DCP is an additive manufacturing process that builds an object through the layer-by-layer deposition of materials according to a 3D model. Although there are other methods for 3D printing with concrete, 3DCP most commonly refers to the dominant approach of extruding fresh cementitious materials (Bos et al., 2022). The key advantage of 3D printing lies in its ability to build complex geometries and intricate structures that might be not economically or technically feasible with traditional methods. When applied to construction, 3D printing can increase productivity by building parts with extra functionality or by allowing the creation of material-efficient structures where the material distribution follows the distribution of forces (Menna et al., 2020).

Although several academic institutions and companies are rapidly expanding the possibilities of this technology, methods for exploiting the design potential are still largely underdeveloped (Ma et al., 2022). In particular, design methods mostly remain unchanged from the workflows of the early development of 3D printing. A typical design-to-manufacture workflow has at least three distinct steps: i) the design of the overall part, ii) the design of the material distribution, and iii) the generation of manufacturing instructions. While step i) can be easily associated with CAD software, steps ii) and iii) correspond loosely to what is referred to as 'slicing' and are usually performed using a different software tool. Between steps ii) and iii) the file is exported, establishing a sharp line between design and manufacturing, where design is restricted to the overall geometry of the part and a limited set of printing parameters, such as number of walls, infill patterns, and density. This gap between design and manufacturing is typically restricted to the information conveyed through STL files, a simple triangulated format that can only describe the surface geometry without any information related to scale, color, texture, or any other metadata.

One innovative approach to enhance this workflow is by incorporating color information into a model that can be used as an extra degree of freedom. Beyond its literal application in 3D printing methods that allow color printing, it can be used to represent variable properties in different parts of the printed part. This idea of a 'color' 3D printer has been formulated as a reference for advanced 3D printing methods (Bos et al., 2016), but it remains a challenge, both in terms of technical capabilities as well as the corresponding design methods for this extended design space.

This paper presents a design-to-manufacture workflow that enables the application of color information to control customized printing properties. This allows the independent manipulation of the color grading using established computer graphic methods, such as texture projection and mesh coloring. Color information is stored in a separate data source representing material gradations as extended degrees of freedom. This is done through a modularized slicing process that can spatially adapt printing parameters in specific regions of the concrete element. Specifically, the color information informs the variable filament width, which in turn leads to variable wall thickness. The upcoming sections present a background on current methods, the proposed design for manufacturing workflow, and the printing process for experimental validation of the proposed method.

2 Existing Workflows

The prevalent workflow for 3DCP relies on conventional methods for 3D printing that do not allow the specification of material properties. The reliance on separate design and slicer software, and the use of STL files to transfer the information between the two, create a technical limitation to the scope of design.

While STL is still the industry standard, there have been substantial efforts to solve the limitations of this file format. AMF (Additive Manufacturing Format) was proposed as an open-source alternative defined by the ISO/ASTM 52915:2020 standard (ISO, 2020). Similarly, the 3MF file format is backed up by several manufacturers and software companies (3MF Consortium, 2022), which is also an open-source alternative that is better supported. Nevertheless, the adoption of dedicated 3D printing file formats has been slow.

Unlike small-scale 3D printing, 3DCP imposes several manufacturing constraints that favor simple and continuous print paths. An interesting alternative to extend the design scope of 3DCP is based on the direct manipulation of print paths i.e., the trajectory followed by the printer when depositing concrete, as the base for the design. Given the comparatively low resolution yielded by 3D printing with the 20-50 mm nozzles typically used at the construction scale, customized design features can be achieved by manually editing the print paths obtained after the slicing process. These techniques expanded rapidly, especially with the popularization of clay 3D printers (AlOthman et al., 2019; Aguilar, 2020). Parametric methods, which use algorithms to drive the design process, have contributed to further extend the design spectrum by procedurally creating or altering the shape of print paths to generate different material effects and surface qualities (Breseghello, 2021; Breseghello & Naboni, 2022; Westerlind & Hernández, 2020). Nevertheless, most of these methods are confined to the generation of specific geometries and depend on the expertise of a proficient designer or programmer in ad-hoc solutions. Similarly, procedural print path generation, i.e., generating print files without a 3D model, offers great flexibility in grading material properties (Moetazedian et al., 2021), but its applicability is limited as the method is based on direct code manipulation.

Printing with soft printable materials allows the modulation of the filament width by simply adjusting the ratio between the traveling speed of the nozzle and the extrusion speed (Yuan et al., 2022). Increasing the extrusion speed results in wider printed filaments, while conversely, increasing the traveling speed reduces the filament size. An advantage of this method is that it provides the ability to dynamically control the printing dimensions without requiring specialized printing equipment. This adaptability in the dimensions of the printed filament serves a dual purpose: it can be used to optimize material use and process efficiency while concurrently expanding the design possibilities of 3DCP.

Grading material properties has also been an interesting field of research in smaller-scale 3D printing (Zhang et al., 2019). While some attempts have been already tried using concrete (Ahmed et al., 2020; Craveiro et al., 2020), integrating functionally graded concrete by 3DCP remains a challenge (Hernández Vargas et al., 2022). From a design standpoint, this also presupposes the tools to develop designs featuring spatial gradations, a capability that is not available in traditional workflows. Currently, there is a shortage of design workflows that can accommodate these extended capabilities. This paper aims to address this gap by integrating design and slicing into a flexible design-to-manufacture workflow that extends the scope of design for 3DCP beyond the 3D model.

3 Methods

The present method aims to enhance flexibility in the definition of material properties during the slicing process in a flexible manner. This is done through a two-part slicing process, which integrates volumetric data with spatial gradations that can be applied on top of the 3D model: First, the object is sliced into equally spaced contour lines, which are in turn divided into control points for manufacturing. Secondly, the color information is sampled for each control point to determine variable printing parameters. Consequently, a spatial gradation from color information can be manipulated and stored as colored meshes while the other is based on projected raster images, akin to texture mapping in computer graphics. Thus, a single object geometry can be infused with properties specified by different images, creating design variations that can be achieved just by editing these input textures, as displayed in Figure 1.

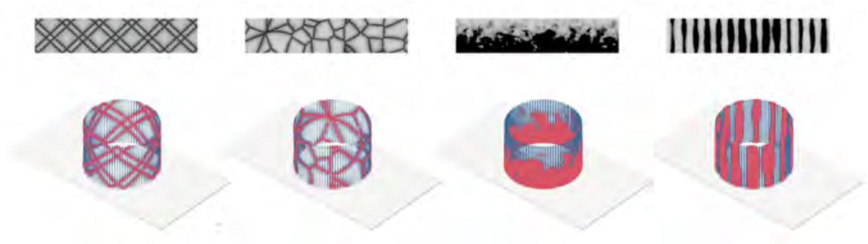

Figure 1. Design variations by applying different textures over the same geometry. Printing properties can be modulated by sampling the information from the texture, in this example as variable printing speed represented by the size and color of the control points.

Color information can be mapped to contain an extensive amount of data. In this study, only the value parameter is extracted from the HSV (hue, saturation, value) color model. This means that, when using 8-bit precision, a printing parameter can be specified with 256 distinct levels, that are used to specify the width of the printed filament. However, using all three channels allows the user to represent three-dimensional data with the same precision. Alternatively, the combination of all three color channels into a single parameter with the full 24-bit range allows more than 16 million distinct values, which expands the potential for further innovations in future applications. Furthermore, the support for RGBA colors in AMF and 3MF file formats can provide even more room for data storage.

In this example, the image controlled the wall thickness that is remapped into corresponding values for each control point. This forms a four-dimensional array of control points with a speed parameter that can be used to inform the manufacturing process. In the printed prototype, color values between 0 and 1 were sampled into printing speeds between 45 and 150 mm/s respectively i.e., thicker printing width in darker areas and thinner ones in lighter parts. These are represented as colored spheres, as displayed in Figure 2, where the radius and the color indicate the required printing speed and accordingly the estimated filament width.

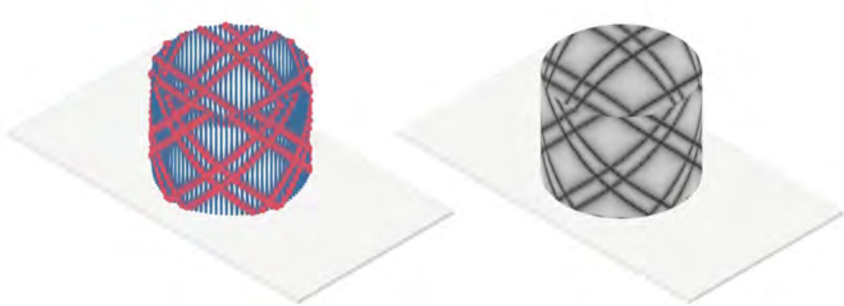

Figure 2. Thickness mapping and control points with variable speeds.

The colored geometry can be stored and edited using different methods: texture mapping or colored polygon meshes. The application of a texture is based on a surface that defines the mapping. After slicing, every control point from the 3D model is projected to its closest point on the surface, which is then used for sampling the color information by relating the UV parameters of the surface to the XY coordinates of the raster image. This model can be saved as a geometry with texture mapping. This method allows the further modification of the part geometry without generating or affecting the mapped information.

Colored meshes use the vertex color property that saves an RGB value for every mesh vertex. Since color information is saved for each vertex and interpolated in between, the mesh size directly influences the resulting resolution from the gradation process. This allows for saving the 3D model with the color information on a single file. However, the resolution is dependent on the size of the mesh, which means that modifying the mesh geometry also affects the existing color information. Also, this method can import colored meshes from structural engineering software that can plot forces to be adjusted during the print.

A third hybrid approach is the use of UV unwrapping, which generates texture coordinates for every vertex in polygon meshes, usually also creating and editing a custom texture. While this is one of the most widely used methods in the computer graphics industry, its vast specialized potential remained outside of the scope of this paper.

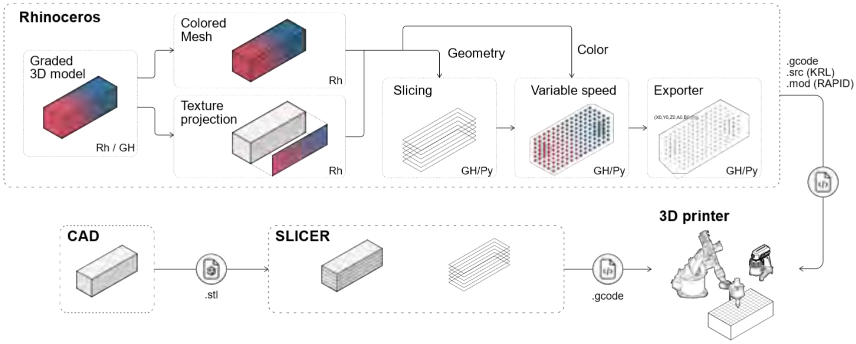

Figure 3. Proposed workflow for the design of graded structures for 3D printing. All the design-to-manufacture workflow is carried out in an integrated software environment as GH/Python scripts in Rhinoceros and then exported as KRL (.src) for printing.

3.1 Code Generation

All stages of the workflow take place in Grasshopper for Rhinoceros, a powerful CAD platform with visual programming capabilities. Different modules were written in Python and handled tasks such as slicing, sampling the spatial gradation, and exporting the printing instructions as robot code. The overall workflow used in this study is presented in Figure 3. Instructions for robotic fabrication are typically specified as a list of control planes, each indicating 3-axis position and 3-axis orientation. Since circular nozzles are symmetrical in all directions, they do not need to be orientated to the printing direction when using planar layers. Therefore, all control points are assigned to the same printing orientation. After slicing, a script assigned variable printing speeds according to the color information read from the model. Printing files were generated by another Python module that transforms planes and speeds into KRL code.

By default, the effect of variable filament width will be applied to both sides of the print path. This can be compensated to preserve a flush surface on either side by strategically shifting the print path proportionally to the change in filament width, as illustrated in Figure 4.

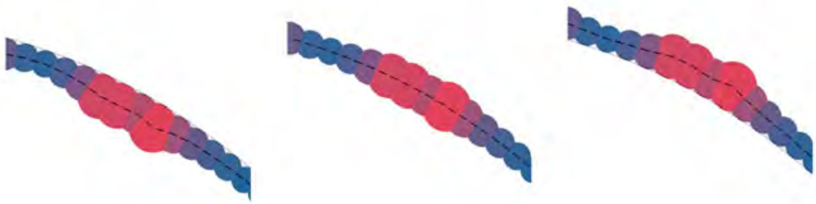

Figure 4. Alignment possibilities of the variable filament width. Shifting the trajectory of the nozzle proportionally to the change in filament speed allows the creation of flush sides in the printed structure. Center: Unmodified print path with the variation affecting both sides of the print. Left: Compensated print path where the variation is contained on the inside while the external face is kept flush. Right: Reversed compensated print path with internal flat surface and external variation.

3.2 Printing Setup

The printing tests were conducted at the School of Architecture at the KTH Royal Institute of Technology. The 3DCP system is based on a six-axis Kuka industrial robotic arm coupled with a specially developed concrete extruder based on a screw using a circular printing nozzle of 20 mm in diameter. Extrusion speeds are controlled separately from the robot controller and need to be set up manually. However, the extruder's controller includes a start/stop function that is regulated directly from the robot code.

The material used for the test was Sikacrete-751 3D, a commercially available mono-component dry mix specifically developed for 3DCP. This material was mixed with water and manually fed into the extruder in small batches to maintain a continuous flow. During the printing process, the material was mixed continuously to ensure it remained in a fluid state. This method allowed for an open printing time ranging from 10 to 90 minutes.

4 Results

The proposed method was tested through the fabrication of a test planter, measuring 600 mm in diameter and 270 mm in height, printed at 10 mm layer height with a 20 mm nozzle. The text body features a customized surface pattern based on a projected image texture. The design of the planter encompasses two distinct parts: a permeable base and a single-wall envelope with variable filament width. The base consists of a zig-zag infill pattern with 5 mm gaps for water drainage. It was printed at a constant traveling speed of 100 mm/s for which the extrusion speed was calibrated to obtain a printed filament width of 25 mm and then was kept steady for the rest of the printing.

Subsequently, the rest of the body was printed with a variable filament width controlled by the image projection. This resulted in printed filament widths between 28 and 22 mm, as illustrated in Figure 5. The variation in printing speed is also connected to a proportional shifting of the control points so the projected pattern would only be visible on the exterior face of the object. The printing process took place in three batches, primarily due to the capacity of the concrete mixer. Although higher printing speeds were technically possible, the robot speed was reduced to preserve the stability of the print.

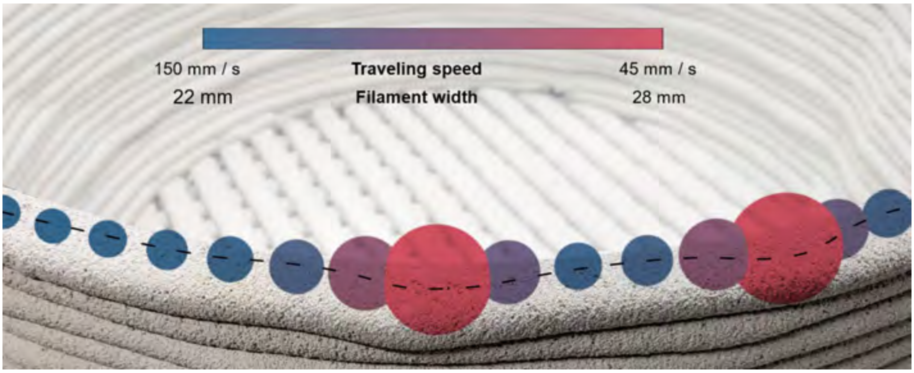

Figure 5. The filament width is modulated by adjusting the printing speed, a parameter that is represented by the color and size for each control point along the print path. These values are controlled by texture mapping, allowing for nuanced control over the material deposition process.

Figure 6. Printed prototype showing the projected image as variable wall thickness. Variations in printing speed are combined with a compensation algorithm to restrict the effect of the variation to the outer face of the printed part.

5 Discussion

The proposed method allows the integration of design and manufacturing into a single workflow that takes advantage of the flexibility offered by 3D printing to enlarge the design space, in this case specifically for printing at large scales with cement-based materials. Such integration induces a more dynamic and adaptable design process that can incorporate manufacturing considerations directly into the design phase. While this integration enables design possibilities far beyond conventional workflows, it is challenging to generalize these customized methods as the steps must be adapted for every application.

Both color grading formats, texture mapping, and mesh coloring, were found feasible alternatives for this workflow, generating almost identical results. Whereas colored meshes offer the advantage of containing all the information on a single entity, allowing the color grading and the mapping to be unambiguously defined on a single editable file. However, the editing of colored meshes is less accessible for end users than editing raster images that can be manipulated using common photo editing software. These principles are compatible with the proposed AMF/3MF file format, which allows the inclusion of color specification and texture maps.

Although this workflow is developed using the Rhinoceros API, the use of scripting allows the method to be adapted to other platforms. A condition for the potential standardization of file formats and workflows specifically designed for 3D printing, the ability to process data at a low level is fundamental for research to be software agnostic.

The printing results show that varying the filament width from a texture mapping is possible, although the effect was limited. Despite the use of an alignment algorithm to restrict the effect of the variable filament width to one side of the print, the applied pattern is still faintly visible from the inside, as shown in Figure 6. This raises the question about the precision of the shifting compensation to the alignment method, which may need further adjustment. Higher variations in traveling speed can provide a clearer variation of the filament width, but higher printing speeds compromise the stability of the print. Likewise, printing at lower speeds favors the strength development of the fresh material, avoiding material failure when the strength of the fresh material is exceeded, most often resulting in the yielding of the first layer. Also, the image texture used in this example represented an extreme case, where sections with thicker filaments were confined to small areas with high contrast. Consequently, the robot lowered the traveling speed for a single control point, limiting the change in filament width achievable. Considering these observations, smoother transitions would be probably preferable to improve the definition of the projected pattern and the overall printing quality.

6 Concluding remarks

This paper presented a novel design-to-manufacturing workflow for 3DCP that integrates color information into the model. The method was validated by printing a test object with variable filament width, demonstrating its ability to design parts with extended complexity. The modular nature of this workflow enables the specification of printing parameters independently from the geometry. This allows a vast number of variations to be produced from the same file, which is an improvement from previous methods that required crafting 3D models for every design iteration. These variations can be achieved by manipulating either the geometry or the color information, extending the scope of design for 3DCP.

Integrating all steps within a CAD environment allows for accelerated design iterations, but maintaining the modularity of the process is key to offering versatile tools that are not limited to a particular application. Slicing, color sampling, and code generation modules were easier to develop and maintain as separate scripts.

A prominent feature of this workflow is the capability to apply density maps on existing geometry that can respond to specific structural conditions that use concrete only where required, limiting material use, and consequently reducing their environmental impact. This study opens new ways for creativity and optimization in 3D printing, where the ability to determine material properties as part of the design process enhances the potential for producing customized and complex structures. Further work will investigate process-specific methods for optimizing the material distribution on 3DCP elements according to structural requirements.

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Paper III

Internal topology optimisation of 3D printed concrete structures: A method for enhanced performance and material efficency

José Hernández Vargas[a,b], Andreas Sjölander[a], Helena Westerlind[b], Johan Silfwerbrand[a]

[a] *Department of Civil and Architectural Engineering, Brinellvgen 23, Stockholm, 100 44, Stockholm, Sweden*
[b] *School of Architecture, Osquars backe 5, Stockholm, 100 44, Stockholm, Sweden*

Abstract

Extrusion-based 3D concrete printing (3DCP) is a promising technique for fabricating complex concrete elements without formwork, offering advantages like cost reduction and enhanced design flexibility by decoupling manufacturing costs from part complexity. By placing material only where structurally needed, 3DCP can lead to significant material savings, potentially reducing the environmental footprint of the construction industry. However, this extended formal freedom is still constrained by the fabrication process and material properties. This paper presents a novel method for applying topology optimisation internally i.e., preserving the external boundaries of the concrete element while reducing material use and weight. This method adapts the extrusion thickness along the part according to the expected stresses, reducing the material use while enhancing structural performance. To validate this method, the mechanical behaviour of three different unreinforced 3DCP beams is tested in three-point bending. Results show that beams with optimised material distributions presented a higher strength-to-weight ratio than the conventional 3D printed beam. An important advantage of the proposed method is that it can be easily implemented in existing 3DCP systems without specialised equipment. This paper demonstrates the potential of internal topology optimisation for improving the efficiency and sustainability of 3DCP.

Keywords: 3D concrete printing, additive manufacturing, optimised concrete, topology optimisation, robotic fabrication

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1. Introduction

The extensive use of concrete stands as one of the most pressing environmental challenges of our era. A combination of unique properties and worldwide availability at a relatively low cost, has made concrete the backbone of societal development [1]. However, this ubiquity comes at a significant environmental cost. Given the massive amounts of concrete being poured globally, the manufacturing of Portland cement, the primary binding agent in concrete, accounts for 5–8% of all human-generated CO_2 [2]. While part of this footprint is related to the use of fossil fuels in the high-temperature processing of clinker, the decarbonation process of limestone is essential for the chemical composition of cement and can only be removed by integrating carbon capture into the process [3]. Additionally, when compared to almost any other industry, the efficiency of construction has stagnated or even declined over the last decades [4]. This trend underscores the urgent need for innovative solutions, particularly in harnessing the potential of digital technologies to advance the efficiency of the construction industry. In light of the pressing need for achieving a carbon-neutral construction industry, material efficiency is gaining renewed interest. Given the predominant significance of concrete in the construction sector, the ability to optimise its usage can have a profound impact in reducing the carbon footprint of the industry.

The rapid emergence of computer-aided design has empowered architects and engineers to envision advanced structures with increasing geometric complexity and a high level of digitalisation [5]. In recent years, the catalyst for digital fabrication in construction has largely arisen from a desire to expand architect's design spaces. Concurrently, advancements in digital manufacturing technologies allow for overcoming existing manufacturing constraints and improve overall efficiency by seamlessly translating digital designs into physical products. This makes it economically feasible to construct increasingly complex structures. Digital fabrication has therefore been increasingly advocated as a means to reduce the environmental footprint of the construction sector while enhancing its productivity [4, 6, 7].

Among the various types of additive fabrication with concrete, extrusion-based 3D concrete printing (3DCP) has emerged as the leading technology for digital fabrication of concrete structures [4, 8]. The inherent automation of 3DCP allows the placement of fresh material without the need for formwork, leading to a significant reduction in manual labour. By integrating concrete into a digital process, 3DCP provides precise control over its placement, which in turn mitigates human errors and enhances construction quality [1]. Furthermore, the introduction of digital workflows facilitates a seamless transition from digital models into physical structures, streamlining the communication among stakeholders. A key premise for this advancement in complexity is that digitally manufactured structures have the potential to only use material where is structurally required, thereby enabling significant material savings [9, 10, 5]. The most prominent advantage of 3DCP in terms of reducing the environmental impact of concrete relates to the optimisation of structures and therefore reducing the amount of material used [5]. Despite the concerns about the large amount of cement in mixtures for 3DCP [11], these combined benefits position 3D printing as a potentially sustainable alternative compared to conventional concrete construction methods [12].

Research on optimisation methods for 3D printing has shown important improvements in structural strength by using the extended capabilities of digital fabrication to materialise stress-aware fabrication methods [5]. Topology optimisation (TO) encompasses several methods for creating intricate structures that can deliver optimal use of material for specific use cases. The unconstrained complexity produced by TO methods has been a limitation its applicability in construction. While complex geometries can still lead to increased fabrication costs, recent advancements in digital manufacturing technologies have significantly reduced the associated overhead. Although 3DCP represents a major leap in the feasibility of complex concrete structures, these optimised shapes still need to be designed considering process-related restrictions. However, the application of stress-aware design principles to larger scales, and in particular to 3DCP, remains limited in current research. Moreover, these complex shapes may generate other challenges as they are primarily optimised in terms of structural performance while neglecting other architectural requirements, such as those related to the habitability of spaces. For instance, walls not only serve as load-bearing elements but also provide acoustic insulation, thermal regulation, and spatial division within a building.

This study introduces a new approach for optimising the material use of 3D printed concrete elements internally, that is, preserving the exterior boundary of the element, aiming to keep other non-structural functionality of the element. The optimisation is driven by modulating the thickness of the extruded filament according to the results of TO while ensuring uninterrupted extrusion. An important restriction of this study is to print the beam in its upright position i.e., on its intended use orientation, thereby making the method applicable to on-site 3DCP. This approach enables the manufacturing of complex TO layouts while providing continuous support during the printing process. Therefore, these elements should maximise their strength-to-mass ratio while conforming with the outside boundary of the printed element. The effectiveness of this approach is demonstrated through the design, 3D printing, and testing of unreinforced concrete beams.

2. Optimisation in 3DCP structures

2.1. Topology optimisation (TO)

The design freedom enabled by 3D printing provides a significant advantage for the applicability of TO, as the geometric complexity of the TO results often restricts its application with conventional manufacturing [13]. Examples of the integration of TO using 3D printing can be found in the literature, especially considering the manufacturing restrictions as part of the optimisation problem [14]. Given the inherent anisotropic characteristics of 3D printed parts, it is essential to introduce a stress direction variable into the TO process. This is especially important in the case of material extrusion 3D printing, which is based on the deposition of material in the form of filament. Advancements in topology-optimised internal infill patterns have been demonstrated in other forms of 3D printing in studies featuring porous infill optimisation and lattice [15]. Still, methods developed for other high-resolution forms of 3D printing are unlikely to be implemented in 3DCP. However, the applicability of these methods in 3DCP is limited by the printing capabilities of the 3DCP system. Applying efficient workflows for the development of topological optimised 3DCP structures incorporates requires specialised frameworks for the correct modelling of the behaviour of concrete. While several studies have demonstrated the applicability of TO in 3DCP, most of the problem focuses on the application of the optimisation result to the requirements of the 3DCP process i.e., incorporating manufacturing constraints of the material and the printing process into the optimisation problem [13].

For example, Vantyghem et al. developed a 3D printed post-tensioned girder using TO (Figure 1a)[16]. The design of the girder is based on the results of a simultaneous shape and topology optimisation for the geometry and the reinforcement tendon [21]. Since in this case the TO problem is defined in 2D, the results need to be interpreted and adjusted to a 3D volume considering material and process restrictions. A second iteration of this work

Figure 1: 3DCP projects incorporating structural optimisation: a: Topology-optimised girder from Ghent University [16]. b: Topology-optimised bridge from Ghent University [17]. c: Functionally graded beam with TO from NTU Singapore [18]. d: Topology-optimised 3DCP arch structure from Hebei University of Technology [19]. e: Stress-based optimised beam from SDU [20]. f: Topology optimised 3DCP structures from RMIT [13].

is presented by Ooms et al. [17] in the form of a topology-optimised bridge featuring a wider top surface and a longer span (Figure 1b), also based on the same 2D optimisation result [21]. Tay et al. presented a fabrication method based on TO for unreinforced concrete beams (Figure 1c) featuring different volume fractions [18]. The results are nevertheless only supplied in solid and support regions, which are defined by the variation of material properties by controlling the printing parameters. Although based on different methods, Breseghello and Naboni [20] presented an experimental comparison of three 3DCP beams with different levels of optimisation (Figure 1e). While a first reference beam is printed on the base, subsequent beams are printed on its section. The optimised beam implements a toolpath-based design that follows the principal stress lines derived from finite element analysis. Further development of this design method is presented using shape and design optimisation [22]. Also printing on the longitudinal section of the beam, Yang et al. proposed a topology-optimised arch printed in three separated sections (Figure 1d) [19]. Bi et al. proposed a TO framework for 3DCP considering several manufacturing constraints, such as self-support, continuous extrusion, domain segmentation, and the anisotropic behaviour of 3D printed concrete [13] (Figure 1f).

A particular field of interest is the application of Functionally Graded Material (FGM) to concrete [23], especially taking advantage of the computer-controlled process offered by 3DCP [24]. This would imply the spatial gradation of material properties in one or more dimensions through the variation of the composition or microstructure of the material. Since the introduction of 3DCP would in principle imply that material grading can be introduced as part of the printing process at virtually no cost, the idea of creating graded concrete parts has been proposed akin to multi-material 3D printing technologies [25]. Nevertheless, while this idea has been successfully demonstrated in small-scale prototypes, its application into a robust 3DCP process seems elusive [18, 26, 27]. From a design perspective, this also implies the capability to create designs with embedded spatial gradations, something that falls outside the current capabilities of customary design-to-manufacture workflows.

2.2. Design for 3D printing

The technical possibilities offered by 3DCP are still limited by the design possibilities, as several formal restrictions derive from simplified slicing workflows rather than the technical limitations of printing systems. The development of digital design tools is one of the most underdeveloped areas of the field [28]. Overcoming this requires specific design tools that can integrate manufacturing constraints into the early stages of design.

The extended design space offered by 3D printing has inspired architects and engineers to create intricate structures that were previously unfeasible with conventional manufacturing methods. However, in the specific case of 3DCP, the design complexity is limited by the resolution of the printing process, which is ultimately determined by the nozzle size and the properties of the material. Other manufacturing constraints also need to be taken into account when designing for 3DCP, such as the continuity of the print paths, may be required depending on the capabilities of the extrusion system. When printing on-site, parts are necessarily printed on their intended orientation. Similarly, maximum overhang angles are limited by the properties of fresh concrete and the stability of the overall part [29].

To overcome these limitations, several academic studies and industrial applications rely on off-site manufacturing and printing segmentations [30, 31]. This allows printing parts larger than the printing system. Even if the part can be fitted in the build volume of the printer, dividing the element into smaller parts minimises the risk of collapse during the print, allowing for a more robust production process. Segmentation also allows taking advantage of printing orientation, this topic is further discussed in Section 3.2.

3. An integrated design-to-manufacture workflow

3D printing typically follows a discrete progression, from a virtual 3D model to a physical object. Within this framework, a design-to-manufacture workflow encompasses all the steps involved in preparation for the printing process, including design for manufacturing constraints and the fabrication setup. The process can be broadly subdivided into logical steps, including (i) part design, (ii) material distribution, (iii) model slicing, and finally, (iv) toolpath planning. These stages may take place in distinct modules, as parts of an integrated pipeline, or within a unified software environment.

(i) **Design:** First, the part is conceptualised and designed as a 3D model. This is typically carried out using CAD software, which allows for precise modelling and adjustments.

(ii) **Material distribution:** The second phase focuses on the location and distribution of objects within the build volume, including possible changes in part orientation inherited from the previous step. During this stage, other properties and features are specified for the 3D printing system in use, according to structural and process constraints. This is a crucial step that determines how the material will be allocated throughout the structure to meet specific functional or aesthetic requirements. While these properties are most commonly set up uniformly for the entire part, some studies have incorporated Computer-Aided Engineering (CAE) software to create force-aware material distributions [32].

(iii) **Slicing:** The manufacturing setup involves the division of the 3D model into discrete layers that can be sequentially printed, most commonly as planar, equally spaced slices, and maintaining a single orientation. These 2D sliced are then contoured and filled by printing paths, which in turn define a series of control points (or planes) defining the trajectory of the printing nozzle.

(iv) **Toolpath planning:** Tool path planning is the process of preparation and optimisation of the trajectories followed by the nozzle during the 3D printing process. Here, factors like printing speed, system acceleration capabilities, and extrusion rate should be calibrated to maintain consistent print quality. This phase ensures that the design is accurately translated into a physical object, adhering to the specifications set during the earlier phases, in a process analogous to the preparation step for subtractive manufacturing. While the toolpath describes all trajectories of the printing nozzle, the print path refers only to the segments where material is extruded and is therefore preferred in the context of 3D printing. This critical phase defines the precise path for the nozzle during the printing process, which is sequenced and in most cases optimised. Additionally, this final phase commonly also implies the generation of manufacturing instructions for the 3D printing system, converting the sliced model into a set of machine-readable commands.

While printing and post-processing steps mostly vary depending on the process category of 3D printing in use, the design-to-manufacture workflow is mostly shared between all types of 3D printing. Several authors emphasize an intermediate step between (i) and (ii) [33, 34, 35], where the 3D model is most commonly exported as an STL file from a CAD to a 'slicer' software, which performs all the further steps (ii-iv) in the process. This separation also implies that what is referred to as design, is normally restricted to the overall geometry of the printed part. However, despite the STL is defined in the Standard for additive manufacturing [36], this step describes the typical workflow rather than a necessary step in the process. A 3D printing workflow most commonly takes place in different software environments and conceivably by different specialists. Nevertheless, some workflows allow the integration of these steps in a software pipeline or a single software environment with CAD-CAM capabilities. Integrated workflows allow the back-and-forth review of the entire design-to-manufacture workflow. Software environments may also offer integrated solutions including diverse modules with CAD, generative design, CAE, and CAM capabilities. In particular, CAD environments offer scripting capabilities that can integrate slicing, toolpath planning, and generation of machine instructions within the same software. One notable example is Grasshopper®, a visual programming tool for parametric modelling in Rhinoceros® [37]. This study uses custom Python scripts for the implementation of a design-to-manufacturing workflow, that allows the generation of print files within the same software environment, as discussed in detail in Section 4.

3.1. Pre-slicing vs. post-slicing

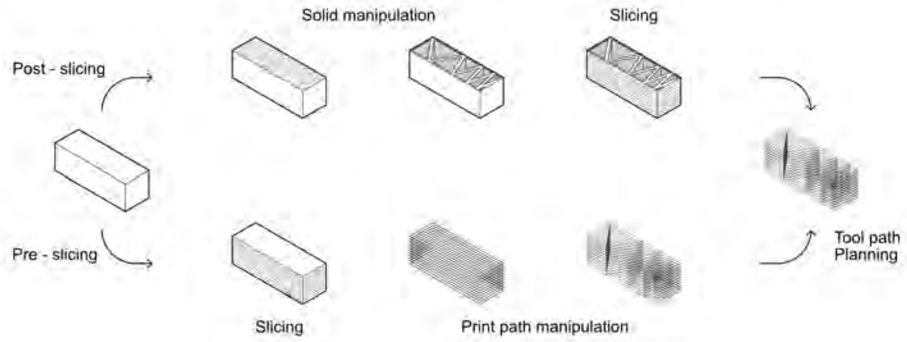

Figure 2: Alternative workflows for the material distribution and slicing of the geometry for 3D printing.

While slicing typically takes place after the material distribution, it is worth noting that the engineering of the material distribution can be either performed before or after this operation. The former case involves the manipulation of the solid geometry to define the material distribution, this will be referred to as pre-slicing optimisation. The latter case involves the direct manipulation of the spatial curves resulting from the slicing process to define the required features of the printing process, which would be a post-slicing optimisation approach. These two alternative workflows are illustrated in Figure 2. Both processes may yield identical results, however, the approach has a strong influence on the results and the probability of errors. An advantage of pre-slicing is that the toolpath planning step is completely independent, which allows for higher modularity. Contrarily, in smaller-scale 3D printing, solid transformations are often preferable due to the high resolution available. Given the linear deposition used in material extrusion 3D printing, defining the material distribution with volumetric operations and then using a conventional slicer may create uncertainty in the feasibility of the resulting print paths. Moreover, in large-scale processes such as 3DCP, fine control of print paths is critical for quality control. Additionally, post-slicing methods involve direct manipulation of print paths, which removes uncertainty on the further effect of the slicing on the printability of the object.

3.2. Printing orientation

As in other extrusion-based 3D printing processes, 3DCP is based on the layer-by-layer deposition of 2D cross-sections that are stacked together to form a 3D object. This requires ensuring proper support for each layer, either by limiting the overhang angles or through the addition of supplementary material dedicated to this purpose. These manufacturing constraints are dependent on the printing orientation, which may be different from the intended use orientation of the part. For example, columns with large overhangs can be printed upside-down to avoid excessive support [9]. However, while the use of support material in 3DCP has been demonstrated [38], it has rarely been applied in practice, probably due to the high cost of the material and the post-process required to remove the material.

The first layer will have a flat surface due to the full support from the build platform. Besides impacting support, part orientation plays an important role in defining the properties of the 3D printed part [33]. Build orientation will define the direction of the layering that has an important effect on the subsequent anisotropic properties of the printed part, due to the time differences between the layers. This aspect is particularly relevant for structural analysis purposes.

Taking a 3DCP beam as an example, the printing orientation will define advantages and disadvantages in terms of material properties and process-related constraints, that presented in this section, illustrated in Figure 3, and summarised in Table 1.

When printing on the horizontal plane (XY), formal freedom is only constrained by the continuity of the print paths. Vertical printing features are therefore limited by support requirements. Similarly, the flexural strength of the beam is also determined by the layering direction. Different print orientations allow for calibration of the advantages and disadvantages of each orientation. These examples are illustrated in Fig. 3. Printing a beam on its base (XY plane) has the advantage of preserving the planarity of the first layer while maximising the flexural strength derived from the layering orientation. Since the part is printed on its target orientation, this is the most

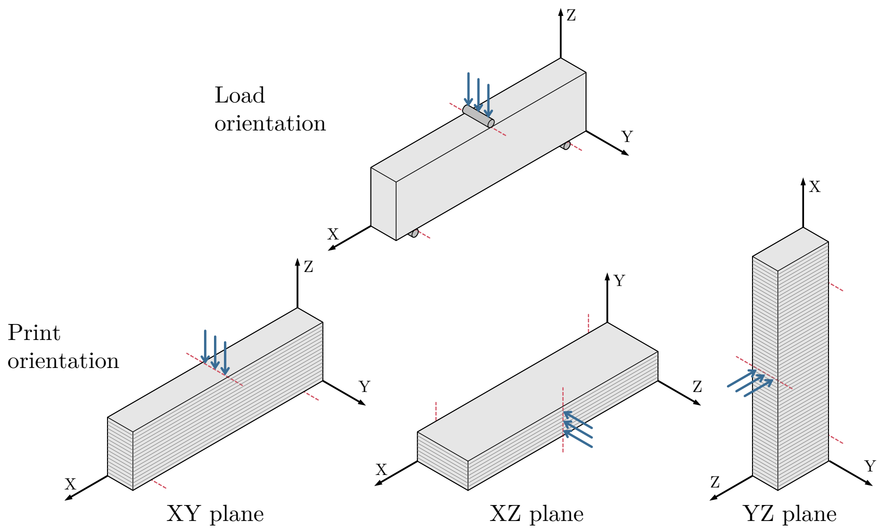

Figure 3: Different possible print orientations for a 3DCP beam. Load is always applied in the -Z direction.

used orientation, especially for in-situ printing [31].

Printing a beam on its longitudinal section (XZ plane) takes advantage of the freedom of movement on the printer's horizontal plane while fulfilling the support requirement given that most structures have a constant section on this plane. Despite this freedom of movement, a continuous flow is a requirement for many 3DCP systems [9, 39]. Even in systems where the material flow can be controlled on demand, interruptions of the flow need to be minimised to ensure flow consistency and efficient printing times. These process-related limitations can be included as part of the optimisation problem [40]. Therefore, printing on this orientation becomes fundamentally a toolpath planning problem, as it can be seen in the work of Yang et al (Figure 1d) [19].

Finally, printing the beam on its cross-section (YZ plane) allows only the profile to be adjusted. Since vertical reinforcement is one of the major restrictions of 3DCP, this has to be supplied as a separate process. Examples of this orientation use post-tensioned reinforcement on the lower chords to supply the required tensile strength [41]. Another restriction is the height of

Table 1: Advantages and disadvantages of different 3D printing orientations

Printing Orientation	Advantages	Disadvantages
XY Plane	• High flexural strength due to layering orientation. • Preserves planarity of the first layer. • Most commonly used for in-situ printing.	• Limited by the continuity of print paths. • No vertical reinforcement; requires separate process.
XZ Plane	• Freedom of movement on the printer's horizontal plane. • Constant section favours support requirements.	• Limited vertical reinforcement; requires separate process. • May compromise flexural strength.
YZ Plane	• Allows only the profile to be adjusted. • Enables post-tensioned reinforcement on lower chords.	• Limited formal freedom. • Limited by support requirements. • Requires separate process for vertical reinforcement.

the print. When printing on its smaller section, the height is only achieved by the subsequent stacking of layers requiring a substantial strength development to avoid collapse. Vertical build rates are limited by the properties of the fresh material and are mostly feasible for bi-component mixes where an accelerator is added at the nozzle [42].

3.3. Variable filament width

Modulating the relationship between the extrusion and travelling speed allows for controlling the width of the filament desired across the 3DCP process. Either of these two parameters can be calibrated so that the volume of material extruded matches the volume of the filament deposited, this is called 'nominal speed'. Printing with stiff cementitious materials is most commonly carried out at this nominal speed, as deviating from this balance may lead to problems such as filament tearing or buckling, as highlighted by Wolfs et al. [43]. When printing with soft printable materials, the modulation of the printing speeds allows the gradation of the printing filament [44]. This flexibility in adjusting the filament dimensions not only allows for optimising material use but also provides a powerful tool for extending the design domain of 3DCP.

The relationship between travelling and extrusion speed and the resulting filament has been studied by several researchers. The rheological principles of concrete extrusion have been well-reviewed in multiple studies [45, 10]. Comminal et al. provided a detailed insight into the physics of concrete deposition using Computer Fluid Dynamics (CFD) [46]. Similarly, Wolfs et al. studied methods for filament control and their consequences [43]. Furthermore, the modulation of these printing paramters have been used to actively control the filament dimensions. Tay et al. presented a study with several printing parameters and their corresponding resulting filament dimensions and printing qualities [47]. In this work, the authors printed sections at a higher speed to deliberately induce tearing and therefore create weak parts that act as support and can be manually removed after the print. This higher printing speed induced tearing and is used as support material. In later work, the authors use this method to create a topology-optimised beam by modulating the speed to create areas with full material extrusion and support material, which is presented as a functionally graded material [18]. Yuan et al. presented a method for closed-loop feedback to control the filament width [44]. Unlike the previous examples, the use of soft printing material allows the modulation of the filament width. In their study, a special segmentation script is used to extract the middle line for the printing path and the corresponding extrusion speed to match the expected print width. Conversely, this study uses a pre-slicing approach, that modulates the printing speeds to achieve variable filament widths throughout the print. In order to limit this variation to one side of the print, a compensation algorithm shifts the print paths proportionally to the expected filament width, thus creating a flush surface. By reversing the side to which the control points are shifted, the variations can be constrained to either side, as illustrated in Figure 4.

Systems based on industrial robots offer greater acceleration capabilities, making preferable the modulation of the travelling speed [39]. It is common also for robotic controls to have a separate speed control for the pump, making it easier to alter the travelling speed while keeping a constant extrusion speed. By contrast, large-scale gantry systems often have a large mass that limits the possibilities for adjusting the travelling speeds due to their high inertia. These systems often have synchronised screw extruders that, conversely, make it easier to modulate the extrusion speed. This distinction

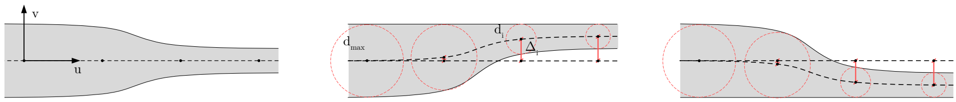

Figure 4: Alignment options for variable filament width. By shifting the control points the effect of the variable width can be restricted to either side of the print.

underlines the importance of considering the specific capabilities and constraints of the chosen 3DCP system when determining the optimal printing parameters.

4. Methods

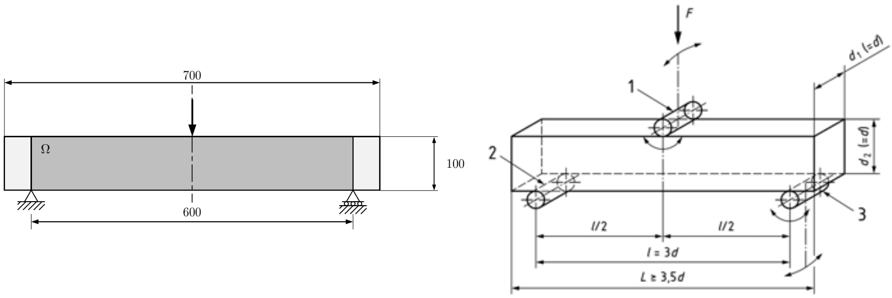

Figure 5: Left: Diagram showing the overall dimensions of the proposed beam specimens and the design space (Ω) for the topology optimisation problem. Right: Definition of the testing for flexural strength of hardened concrete using a centre-point loading method, in accordance EN 12390-5:2019 [48].

The proposed method for internal optimisation of concrete elements is implemented in the design and fabrication of topology-optimised beams. This optimisation problem is typically formulated with an aspect ratio of 6 to 1, span distance to height respectively [49]. The standard for testing flexural strength in concrete defines the span as three times the height of the specimen [48]. Moreover, given the available resolution when printing with a 20 mm nozzle, the achievable amount of detail would be limited for a shorter beam. Therefore, the optimisation problem was kept consistent, and the test specimens were designed to comply as much with the standard while deviating to accommodate the longer aspect ratio of the optimisation problem, as displayed in Figure 5. Optimised beams were designed by projecting an optimisation target into the print paths obtained from slicing the overall geometry of the part. These print paths are then modified to follow this material distribution using 3DCP with variable filament width (Figure 7). This procedure is performed twice using two different optimisation targets. The first beam (OPT-A) is based on a fully completed TO result. The second beam (OPT-B) uses instead a non-converged TO featuring smooth gradients.

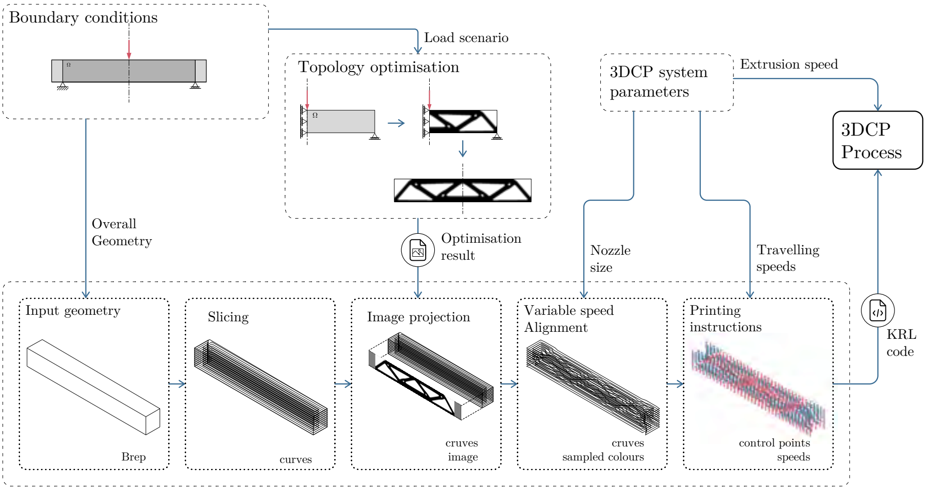

Figure 6: Design-to-fabrication workflow for the generation of print files.

Previous studies have used cast and 3D printed solid beams for comparison, for which the advantages of 3DCP over cast concrete have already been reported [18, 22]. Furthermore, solid beams are seldom used in real-case scenarios. Therefore, this study uses a control beam with a zigzag infill structure (designated TRUSS) that represents the typical printing pattern used for 3DCP [50]. This ubiquitous printing pattern has been used from the inception of 3DCP [45], and allows for a higher moment of inertia and therefore print stabilitywhile minimising the amount of material and printer movements [51]. All the beams used in this study share the same dimensions, measuring $700 \times 100 \times 100$ mm^3. They were subjected to the same loading scenario, with a centred point load applied over a 600 mm span.

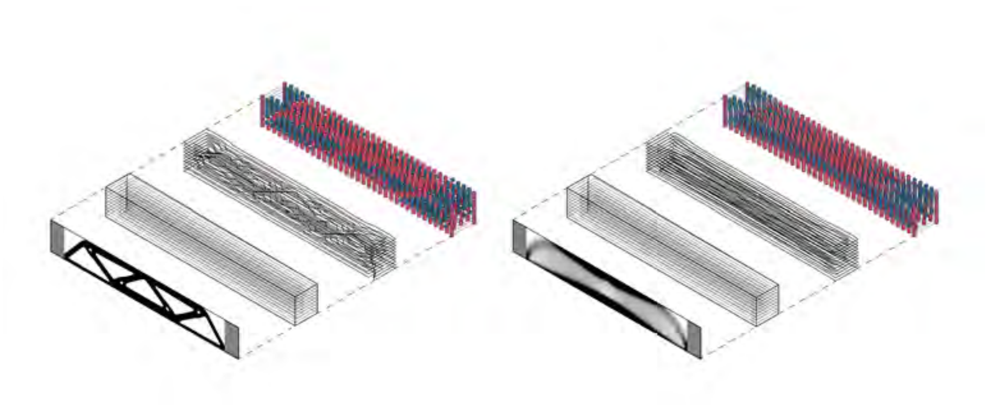

Figure 7: Diagram showing the projected optimisation result to the print paths from the slicing process. These print paths are then modified according to the projected image producing a variable-speed printing process. Left: OPT-A. Right: OPT-B

Table 2: Overall characteristics of the beam test bodies

Beam design	TRUSS	OPT-A	OPT-B
Dimensions (mm)	700 × 100 × 100	700 × 100 × 100	700 × 100 × 100
Layer heigt (mm)	10	10	10
Printing speed	Fixed	Variable	Variable

4.1. Design of the prototypes

In order to grade the amount of material in different parts of the printed element, the width of the printed filament is modulated according to the specified density from the TO results. The variable filament width is achieved by varying the printing speed, which results in a larger cross-section of the extruded filament. The proposed design is based on a double-wall print path that forms a single continuous path, which is then modified with a variable width according to the TO results, as illustrated in Figure 8. For filled parts in the optimisation, the width of the filament is dimensioned to 25 mm i.e., to cover the full width of the printed beam with four lines. The proposed printing strategy relies on the possibility of joining both sides of the part to provide stability during the print. While the results from the TO indicate zones with no material, the translation to manufacturing enforces a minimum of material that serves to preserve the functional boundary of the element as well as support material for the upcoming layers. Void sections were dimensioned at 16 mm i.e., reducing the material to 64% when compared to the solid parts of the print. This material is important to comply with the boundary of the printed element and to serve as support for upper layers. In order to keep the external faces flat, the print paths were shifted inwards according to the filament width, as explained in Section 3.3.

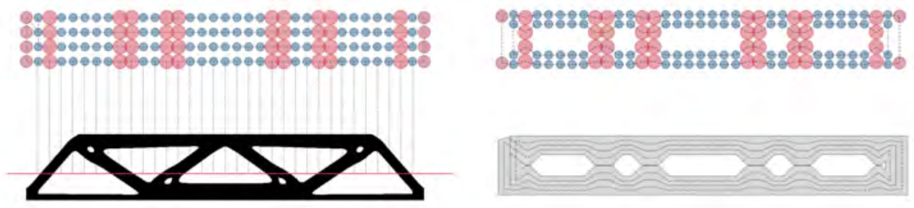

Figure 8: Print path design with modulated filament thickness according to TO results. Left: The section of the TO is projected to the double-wall print path. Right: The values sampled from the image determine the priting speed and deform the print path to align the external surface of the printed element.

In terms of printing speed, the short sides of the beam are printed at a constant rate, while the long sides are printed at variable speeds following the TO results. These results were sampled at intervals of 20 mm, the same dimensions as the printing nozzle. The resulting internal structure reflects the optimisation pattern while the external surfaces comply with the boundary of the volume of the element, as depicted in Figure 9.

4.2. Equipment and setup

The beams were printed at the Digital fabrication laboratory at the KTH School of Architecture. The robotic system utilised for the 3DCP process is based on a KUKA KR-16 robot coupled with a specially developed screw-based concrete extruder (Figure 11). The transparent container allows to have visual feedback from the movement of the material inside the extruder. The build surface is made of film plywood, with dimensions 800 $\times$ 1500 mm. To control the extrusion rate, speeds need to be set up manually, but the extruder controlling system includes a start/stop function that can be sent directly from the robot code. While the extruder system can precisely start/stop the flow, extensive start and stop is avoided as it affects the consistency of the material extrusion. The printing process relies on an open-loop system following a preprogrammed path and with a constant extrusion

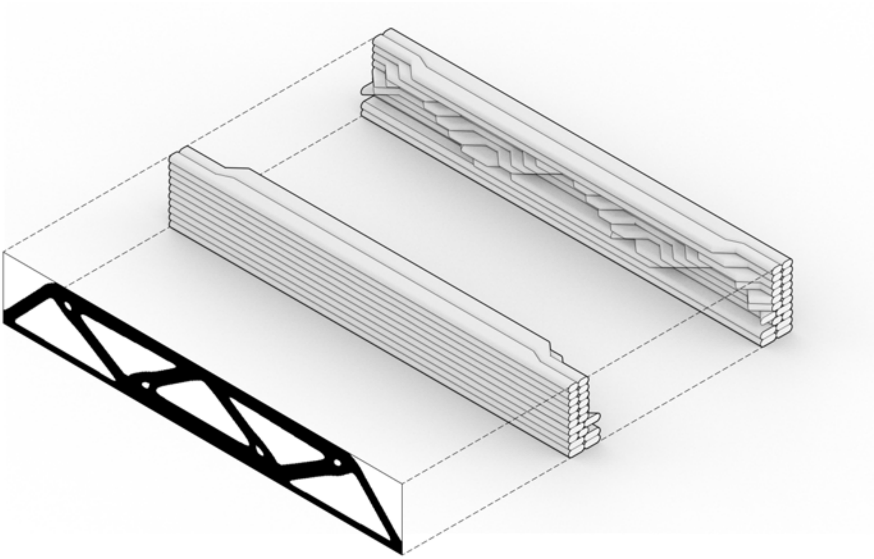

Figure 9: The resulting internal structure reflects the optimisation pattern delineated by the TO, whilst the external surfaces remain congruent with the predefined volumetric boundary of the element

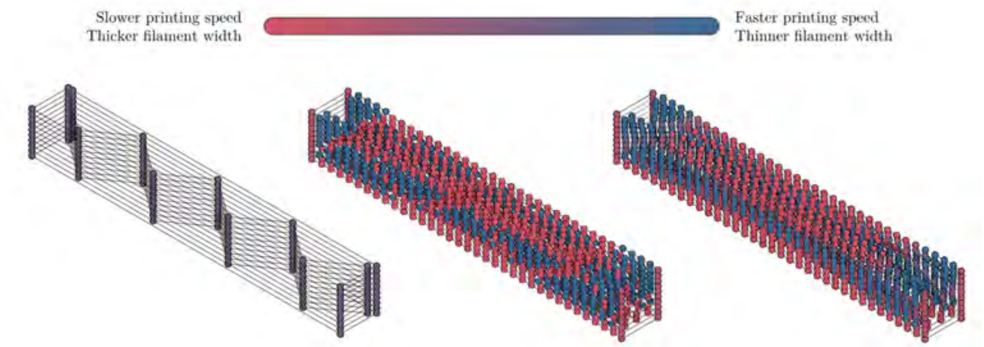

Figure 10: Print paths with printing speed for all the samples. Left: TRUSS (constant) . Centre: OPT-A (variable). Right: OPT-B (variable)

speed. For each beam type, three identical specimens were manufactured. The resulting printed beams are displayed in Figure 12.

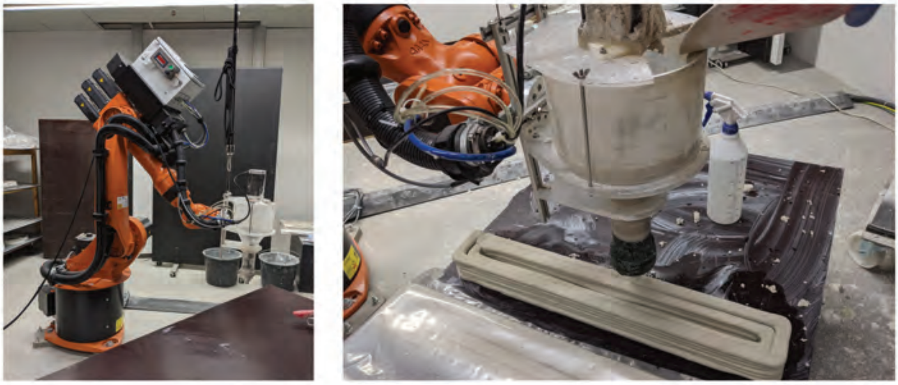

Figure 11: 3DCP robotic fabrication setup at the KTH School of Architecture

All beams were printed using Sikacrete-751 3D [52], a mono-component dry-mix that has been specifically formulated for 3DCP applications and is commercially available. This material is mixed with water according to the manufacturer's specifications and fed into the extruder in small batches to ensure a continuous flow. To ensure the material remains in a fluid state, it is mixed continuously during the printing process. Each beam was printed using a batch of material, and a new batch was prepared at the end of the previous one in a continuous process. After printing the beams were covered with plastic and left to set for 24 hours. Following this period, they were stored in a climate-controlled curing chamber at 20°C and 99% relative humidity.

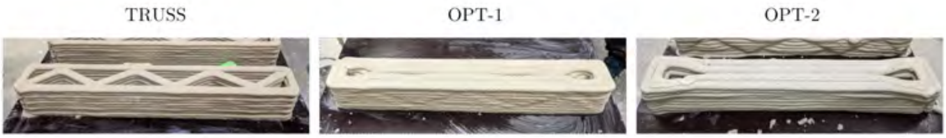

Figure 12: 3D printed concrete beams

4.3. Testing and validation

Tests took place after 13 days at the Department of Civil and Architectural Engineering at KTH. The printed samples were tested in three-point bending, based on the SS-EN 12390–5 Standard for flexural strength [48]. Loading by a centre-point load was preferred due to the correspondence to the TO problem. To ensure good contact between the beam and the load-applying steel plate, low-density fibre boards were placed between the beam and the load plate. The bottom surface is flat due to the contact with the printing base and therefore was placed directly on top of the support rollers. The tests were controlled by the position of the loading piston, at a rate of 0.55 mm/minute.

5. Results

Figure 13: Testing of the 3DCP samples

All samples presented failure in the middle section, under the load point. This failure pattern is consistent with what is typically observed in unreinforced concrete structures, where a single vertical crack often appears directly under the load point, which is the area of maximum stress and therefore the most likely location for the concrete to fail. The results show a significant increase in maximum load for the optimised designs, especially when compared in terms of maximum load per weight. Both optimised beam designs performed better than the reference TRUSS beam, resulting in a 47% and 63% higher maximum load-to-weight ratio for OPT-A and OPT-B, respectively. Results from the testing are summarised in Table 3.

Usually, flexural strength is calculated based on the cross-section of the beam. However, using rectangular cross-sections for the calculation would not provide meaningful results in this case, given the irregular cross-section of the 3D printed geometry. Additionally, using the bulk 100 × 100 mm^2 will only replicate the ratios given by the maximum load, since all the samples share the same overall dimensions.

Table 3: Results of the test specimens

Beam design	TRUSS			OPT-A			OPT-B		
Sample	1	2	3	1	2	3	1	2	3
Weight (kg)	9.7	9.85	9.5	13.95	14.95	15.5	13.5	13.05	13.85
Mean (kg)		**9.68**			**14.82**			**13.43**	
Max load (kN)	2.14	1.53	1.71	4.12	3.96	4.5	2.83	4.41	5.48
Mean (kN)		**1.79**			**4.19**			**4.24**	
Max load-to-weight (kN/kg)	0.22	0.16	0.18	0.3	0.26	0.29	0.21	0.34	0.4
Mean (kN/kg)		**0.19**			**0.28**			**0.31**	

6. Discussion

The integrated design-to-manufacture workflow presented in this study offers a significant advantage over conventional fragmented workflows by integrating manufacturing aspects as part of the design phase, enabling a more dynamic and adaptable design process. However, one of the challenges of this method is its customization aspect; each application may require unique adaptations, making it difficult to establish a one-size-fits-all solution. Therefore, while the integration of this workflow opens up new routes for innovation in design and manufacturing, its scalability and generalisability across different projects remain areas for further investigation.

While both OPT-A and OPT-B presented higher maximum load mean values, OPT-B performed better than OPT-A. Nevertheless, the first sample of OPT-B performed significantly worse than the other two samples, and it may be a product of a singular defect and less representative of the performance of the design. As is commonly the case with 3D printed concrete samples [29], the spread in results is higher than for cast concrete. On top of this, variations in the weight of different samples may further distort the reliability of these values. Although the printing parameters were constant, there was some variation in the flow. The manual nature of the feeding system creates variations in the material flow. This inconsistency is evident in the spread of the weights of the printed beams and is most likely attributable to the manual feeding of the material into the extruder.

While the maximum loads were directly obtained from the testing, the calculation of flexural strength is less applicable given the irregular cross-section of the test bodies.

The use of a compensation parameter allowed to confine the variation in the filament's thickness to the inside of the print. While the applied pattern is still subtly discernible from the exterior, the external faces of the printed part maintained the overall boundary of the element.

7. Conclusions

3DCP allows an extended range of possibilities for concrete construction that allows extended geometric complexity with almost no additional effort. Yet, despite the enhanced possibilities offered by 3DCP to produce intricate structures, this freedom of shape is still bounded by process constraints. This paper presented a novel method for applying TO patterns to 3D printed concrete components while preserving their external geometry. It leverages the capability of extruding concrete in a flowing state to vary the filament width by modulating the printing speed to embed structurally informed shapes in a continuous printing process, The results show a significant increase in the load-bearing capabilities in terms of maximum load. This approach is mostly relevant for slender elements such as beams or walls, where the optimisation can be applied along the shortest dimension of the element. Given that these structural members constitute a substantial portion of the applications of 3DCP within the construction industry, this strategy holds the potential for optimising the material use and structural performance of 3DCP. The potential to optimise the material use and structural performance of these components opens a promising route for future research and development for improving efficiency and reducing the environmental impact of the industry. Consequently, it represents a promising path for reducing the environmental impact of the construction sector. While the samples tested in this study were restricted to a single unreinforced beam, the method is not constrained to these specific boundary conditions. Future research will focus on the application of this method to other structural elements and investigate additional functionalities conferred by the preservation of the external boundary of the element, such as acoustic and thermal properties.

CRediT authorship contribution statement

José Hernández Vargas: Conceptualisation, Methodology, Software, Investigation, Data Curation, Writing — Original Draft, Writing — Review & Editing, and Visualisation
Andreas Sjölander: Investigation, Data Curation, Writing — Review & Editing.
Helena Westerlind: Writing — Review & Editing, Supervision.
Johan Silfwerbrand: Writing — Review & Editing, Supervision.

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