Investigation of novel 3D-printing methods for freeform construction

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Investigation of Novel 3D-Printing Methods for Freeform Construction

Lim Jian Hui

School of Mechanical and Aerospace Engineering

July 18, 2021

**Investigation of Novel 3D-Printing Methods for
Freeform Construction**

Lim Jian Hui

School of Mechanical and Aerospace Engineering

A thesis submitted to the Nanyang Technological University
In partial fulfillment of the requirements for the degree of
Doctor of Philosophy

Statement of Originality

I hereby certify that the work embodied in this thesis is the result of original research, is free of plagiarised materials, and has not been submitted for a higher degree to any other University or Institution.

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Lim Jian Hui

Supervisor Declaration Statement

I have reviewed the content and presentation style of this thesis and declare it is free of plagiarism and of sufficient grammatical clarity to be examined. To the best of my knowledge, the research and writing are those of the candidate except as acknowledged in the Author Attribution Statement. I confirm that the investigations were conducted in accord with the ethics policies and integrity standards of Nanyang Technological University and that the research data are presented honestly and without prejudice.

7/28/2021

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Date

Prof Pham Quang Cuong

Authorship Attribution Statement

This thesis contains material from 3 manuscripts published/submitted where I am the first and/or corresponding author, and 1 manuscript published where I am the co-author.

Chapter 3 has been published as "Improving flexural characteristics of 3D printed geopolymer composites with in-process steel cable reinforcement Construction and Building Materials, Volume 178, 30 July 2018, Pages 32-41

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The contributions of the co-authors are as follows:

- Assoc. Prof Pham is in overall charge of the research topic and provide guidance/supervision throughout the study.
- Assoc. Prof Pham edited the manuscript drafts.
- I proposed the research area and prepared the manuscript drafts.
- The manuscript was revised by Dr Panda Biranchi and Assoc. Prof Pham.
- I designed the study and performed all the laboratory work with Dr Panda Biranchi at the School of Mechanical and Aerospace Engineering and the Singapore Centre for 3D Printing. I also analysed and interpreted the data.
- All experiments were conducted by Dr Panda Biranchi and me in the Building and construction lab and the Protection Engineering lab.

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- Assoc. Prof Pham is in overall charge of the research topic and provide guidance/supervision throughout the study.

- Assoc. Prof Pham edited the manuscript drafts.
- I proposed the research area and prepared the manuscript drafts.
- The manuscript was revised by Mr Weng Yiwei and Assoc. Prof Pham.
- I designed the study and performed all the laboratory work with Mr Weng Yiwei at the School of Mechanical and Aerospace Engineering and the Singapore Centre for 3D Printing.
- I also analysed the data.
- All experiments were conducted by Mr Weng Yiwei and I in the Building and construction lab.

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The contributions of the co-authors are as follows:

- Assoc. Prof Pham is in overall charge of the research topic and provide guidance/supervision throughout the study.
- Assoc. Prof Pham edited the manuscript drafts.
- I proposed the research area and prepared the manuscript drafts.
- The manuscript was revised by Ms Zhang Xu and Assoc. Prof Pham.
- I co-designed the study with PhD student Zhang Xu and performed all the laboratory work with PhD student Andrew ting at the School of Mechanical and Aerospace Engineering and the Singapore Centre for 3D Printing.
- I also analyzed the data.
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- Assoc. Prof Pham edited the manuscript drafts.
- Dr Pham Tien Hung and I proposed the research area, performed all the laboratory work, and prepared the manuscript drafts.
- The manuscript was revised by Assoc. Prof Pham.
- All experiments were conducted by Dr Pham Tien Hung and me in the Building and construction lab.

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Journal Articles:

- Lim, J. H., Panda, B., & Pham, Q. C. (2018). Improving flexural characteristics of 3D printed geopolymer composites with in-process steel cable reinforcement. *Construction and Building Materials*, 178, 32-41
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Abstract

3D Concrete Printing (3DCP) is a technique of sequentially layering of cementitious material to create a three-dimensional structure. Recently, it has gained much attention for its advantages, such as customized production, waste reduction, and increased productivity for construction.

Currently 3DCP is still at an early age of industrial adoption. Most research and development in the field of AM for concrete structures are focused on material development and neglected the freeform aspect of additive manufacturing. This partly contributed to the 3DCP competing against classical concrete techniques in the low-cost field of manufacturing rectilinear walls. The cost competitiveness and attractiveness of 3DCP can be improved, by focusing on the manufacturing of freeform structures.

The objective of this thesis is to develop an ensemble of methods, spanning multiple scales, from the mechanical reinforcement of the materials to the global shape of the architectural elements to the printing mechanism, expanding the development of 3D Concrete Printing technology for additive manufacturing of freeform structures.

Four levels are outlined in the conceptualized research objective. Structural improvement to 3DCP allows for engineers to print freeform design with structural strength. Therefore, there is a need to develop freeform reinforcement which incorporates steel wire into the printed concrete filament as it is printed, through an in-nozzle impregnation process. To improve the printability of concrete of freeform design, we need to support the green concrete which lacks the necessary stiffness and strength to carry its self-weight. Through an adaptable membrane formwork,

we can support the concrete in freeform design and re-used the supporting adaptable membrane for other design, in line with 3DCP goal of waste reduction and freeform fabrication. Printing path design for freeform 3DCP is also considered to develop a printing path that accounts for the anisotropic mechanical properties of 3D printed concrete. The printing path produces a stress-cognizant printing scheme that directs the printing of freeform concrete structure to follow the flow of stresses and allow the structure to support the mechanical load on its strongest axis, making the freeform printed concrete more structurally stable. Finally, to improve the scalability of classical gantry printers and print large freeform 3DCP structure, we developed a mobile, multi-robot, printing platform. This has greatly increased the reachability of the robot printer, extending the effective printing area of the system, so that we may print the entire architectural structure in one go.

Chapter 1

Introduction

1.1 Background

3D printing is a new manufacturing technology which has been fast evolving in recent years. It is referred to as the process of sequentially depositing materials in a layer-by-layer manner to build expected product as per Computer Aided Design (CAD) models [5]. 3D printing has many applications in various industrial fields [6], such as in the aerospace industry [7] and printed electronics industry [8]. In these applications, the adoption of 3D printing lowers the manufacturing costs and time for objects with individualized freeform designs. It is in this note, that 3D Concrete Printing for the construction industry develops.

The construction industry is a key unit of the economy. It drives productivity and has a major role in developing the built infrastructure for other units of the economy to thrive in. In this respect, the construction industry is expected to innovate and remain cost competitive in the global market. In Singapore economy, the construction industry is the sixth largest contributor to the Gross Domestic Product (GDP) [9]. The construction industry operates in both the private and public sectors, engaging in three broad areas of activity: residential building, non-

residential building and engineering construction. Demand for, and supply of, these services are driven by economic factors including population growth, availability of resources, such as labour and building materials, and changes within closely linked sectors e.g. agriculture, mining and manufacturing.

Traditionally, the building and construction industry uses two dimensional (2D) drawings, drafts, and designs to represent and evaluate the architectural design process. Increasingly, the industry is moving into three dimensional (3D) visualizations, such as the use of modeling in the virtual environment such as building information modeling (BIM) [10]. BIM is a digital representation of building model, that includes the blueprint and also information from the building life cycle. One advantage of BIM is that it readily complement 3D concrete printing as the full geometrical information of the building is captured by BIM.

3D Concrete Printing (3DCP) is a method of additive manufacturing (AM) that deposits concrete/mortar layer by layer following a digital Computer Aided Design (CAD) model with help of a gantry or robotic system. This technology has shown the potential to be used in Building and Construction (B&C) sectors due to significant advantages in terms of increased efficiency and productivity by minimizing material wastage and labour when compared to traditional methods. Furthermore, as 3D Concrete Printing does not require the use of construction formwork, up to 40% of the construction can be saved and this will also hasten the construction project [11]. Statistic survey by ASDReports shows that 3DP market with concrete would rise to from USD 24.5 Million in 2015 to USD 56.4 Million by 2021 [12], however, there are still significant challenges present such as the geometric scale, mechanical strength, material and cost of the printed concrete. Fundamental scientific understanding of design process, and structural strength need to be explored in future for large-scale application in practice.

The field of 3D Concrete Printing has had notable research, however as of today the possibility of freeform construction, remains largely theoretical [13, 14, 15, 16,

17]. As genuinely freeform 3D Concrete Printing is still impeded by many practical obstacles. The objective of this thesis is to develop an ensemble of methods, spanning multiple scales, from the mechanical reinforcement of the materials to the global shape of the architectural elements to the printing mechanism, to bring genuinely freeform 3D Concrete Printing to reality.

First, it is noted that conventional reinforcement, such as steel rebars, must be bent to shape before being used, and a special self-consolidating concrete may be required to ensure adequate flow-ability and bonding to the rebars. This difficulty is exacerbated when constructing freeform elements. Here, we develop a novel reinforcement technique for 3D Concrete Printing that is not dependent on manual insertion and bending of steel rebars. This is achieved through the incorporation of steel wire into the printed concrete filaments as it is printed, through an in nozzle impregnation process.

Second, 3D Concrete Printing requires intricate supporting structures when printing freeform designs, as green concrete lacks the necessary tensile strength to support itself. Such supporting structures, if they are single-use, might offset the advantages of 3D Concrete Printing. Here, we develop an Adaptable Membrane Formwork that can support the concrete for freeform 3D Concrete Printing design, while being easily re-targeted and re-used for different designs.

Third, 3D printed concrete has anisotropic mechanical properties. By recognizing this property, we develop a stress-cognizant printing scheme to direct the printing of the freeform concrete structure so that most of the mechanical load is supported by the strongest axis of the structure.

Finally, in an effort to further the advancement of 3D Concrete Printing and improve work efficiency, we develop a mobile, multi-robot, printing platform. This greatly increases the reachability of the robot and hence the effective printing area of the system. As such, this thesis seeks to develop the above ensemble of methods,

to bring about genuinely freeform 3D Concrete Printing.

1.2 Problem statement/motivation

The objective of this thesis is to develop an ensemble of methods, spanning multiple scales, from the mechanical reinforcement of the materials to the global shape of the architectural elements to the printing mechanism, expanding the development of 3D Concrete Printing technology for additive manufacturing of freeform structures.

Fig. 1.1 illustrates the methodology of this thesis, which provides a systematic flowchart for the development of 3D Concrete Printing technology for additive manufacturing of freeform structures. The thesis is organized according to the flowchart.

As such, by addressing the above research gaps, this thesis seeks to develop the above ensemble of methods, to bring freeform 3D Concrete Printing to the next stage and applied in the construction industry.

Figure 1.1: A multi-scale approach to 3D Concrete Printing for freeform construction. Each level interacts with its neighboring smaller-scale and larger scale levels, as discussed in this thesis.

- Hybrid reinforcement method

Classical method of reinforcement such as rebars runs counter to the freeform

fabrication capabilities of 3DCP. The usage of rectilinear rebars restricts the architectural design to the dull rectilinear form of the rebar shell, effectively discount the competitive edge of 3DCP over classical concrete casting techniques. Using a hybrid flexible cable reinforcement allows for reinforcement that takes the shapes of the printed freeform structure without constricting its design.

This freeform reinforcement process would pave the steps for freeform printing, by allowing us to provide tensile reinforcement in curved freeform structure, which previously might risk cracking under its own self-weight.

- Adaptable membrane formwork

3D Concrete Printing requires intricate supporting structures when printing freeform designs, as green concrete lacks the necessary stiffness and strength to support itself. Classical supports from Fused Filament Fabrication uses a secondary material for support that is thrown away after use. Here, we develop an Adaptable Membrane Formwork that can support the concrete for freeform 3D Concrete Printing design, while being easily re-targeted and re-used for different designs.

This adaptable membrane formwork and our in-nozzle reinforcement impregnation module would serves as the hardware for freeform printing and our next chapter will explore the software aspect of freeform printing.

- Printing path framework

There is a research gap in designing of printing path design for freeform 3DCP. The classical printing path design for 3DCP is largely an adoption from fused filament fabrications raster scanning path technique. It is commonly used due to its simple implementation. However, 3D printed concrete has anisotropic mechanical properties. By recognizing this property, we develop a stress-cognizant printing scheme to direct the printing of the freeform concrete structure to follow the flow of stresses and allow the structure to support the

mechanical load on its strongest axis, increasing the structural strength of the freeform printed concrete.

With both hardware and software, we have shown that freeform concrete printing can be achieved. Although the samples we have thus printed were small in dimensions, it can be readily scaled up through our developed mobile robotic 3D concrete printer which we will present next.

- Mobile robotic 3D concrete printer

The classical 3DCP printers is a derivation of fused filament fabrication gantry printers with an optional 4th axis that orientates the rectangular filament used in 3DCP to the printing direction. However, gantry style printers face the scalability limitations and is only able to print freeform structures up to the printing volume imposed by the gantry envelope. Therefore, to improve work efficiency and to address the scalability issue when printing large freeform 3DCP structure, we developed a mobile, multi-robot, printing platform. This has greatly increased the reachability of the robot printer, extending the effective printing area of the system, so that we may print the entire architectural structure in one go.

In total, we have presented a multi-scale approach to freeform 3D Concrete Printing that seeks to address the research gaps in freeform reinforcement, freeform printing path, freeform support, and freeform large-scale printing. Through ensemble of methods, we aim to bring freeform 3D Concrete Printing to the next stage and applied in the construction industry.

1.3 Contributions

Based on the limitation and restriction of conventional concrete to the fabrication of 3D printing concrete, the objective of this research is as follows:

1. Investigation of freeform reinforcement for 3D Concrete Printing.
2. Investigation of a printing system to allow for the 3D printing of non-developable doubly curved concrete panels.
3. Investigation of a Stress Line Cognizant (SLC) printing path for 3D Concrete Printing, in order to maximize the inherent advantages of AM that is not being fully utilized to date.
4. Investigation of a scalable robotic 3D Concrete Printer.

1.4 Organization of thesis

This thesis has been organized as follows:

In Chapter 2, the literature of existing 3D printing systems for Building and Construction, reinforcement methods for Building and Construction, construction methods for design of curved structures, and stress analysis in Building and Construction is reviewed.

In Chapter 3, the development of a novel reinforcement system for 3D Concrete Printing application, and the results of the reinforcement system are presented.

In Chapter 4, the development of a printing system and methodology for the printing of non-developable doubly curved concrete panels, and the geometry fidelity of the printing method are shown.

In Chapter 5, Stress-cognizant 3D printing of free-form concrete structures, and the results of the printing method are reported.

In Chapter 6, the development of a scalable mobile robotic printer is presented in details and the results of the robot printing experiment are reported.

Finally, in Chapter 7, the thesis is concluded and some directions for future work are sketched.

Chapter 2

Literature review

The construction industry has been recognized as one industry that consumes considerable amount of resources, notably physical labor, particularly with an aging work forces as in many developed countries. This is even more pronounced with in situ concrete casting with bespoke geometries, when both the erection of molds and the placement of reinforcement require strenuous expertise and labor.

Additive manufacturing or 3D Concrete Printing seeks to resolve this problem by printing concrete structures without formwork. This is a major advantage in terms of production rate, architectural freedom and cost reduction; as noted in [18], formwork represents 35% to 60% of the overall costs of concrete structures. In addition, by removing the need to install construction formworks, 3D Concrete Printing can reduce the need of human labor on the construction scene, and replace them with digitally controlled robots [15].

Another main advantage of 3D Concrete Printing that is often discounted is the ability to print freeform architectural elements without the need for costly (in terms of time, labour or materials) molds. However freeform construction is still restricted by many practical obstacles such as mechanical reinforcement of the materials to the global shape of the architectural elements to the printing

mechanism. By solving the above problems, this thesis seeks to bring genuinely freeform 3D Concrete Printing to reality.

The environmental impact of the construction industry is huge. the construction industry alone accounts for 40% of the global energy consumption, 28% of the global greenhouse gas emissions, 12% of the global water usage, and 40% of solid waste generation [19]. Concrete and cementitious material are the main feedstock of the construction industry, having increased 34 times in the last 65 years [20]. Concrete production has a large carbon footprint, accounting for 5% of worldwide emission of CO_2 [21]. In addition, a significant amount of waste is generated in the construction process, primarily from formwork wastage used to create temporary molds for pouring and forming concrete [22]. Apart from the environmental concerns, the concrete construction sector is a labor and capital intensive industry, requiring high costs for material usage, equipment, and labor [23].

3D Concrete Printing promises to increase production efficiency through automation of concrete construction. 3D Concrete Printing aims to decreased costs, time and labor, while increasing the productivity and quality of construction. In addition, 3D Concrete Printing allows freeform construction, eliminating geometrical constraints of structures imposed by conventional concrete building techniques. In our in-house study, Nanyang Technological University printed a prefabricated bathroom unit using 3D Concrete Printing and demonstrated an overall 25.4% reduction in cost, a 85.9% decrease in CO_2 emission, and an 87.1% decrease in energy consumption as compared to a similar bathroom unit built using the precast method [23]

2.1 Current reinforcement systems

2.1.1 History of concrete

Concrete is the most used building material worldwide. The raw materials used to the production of concrete are economical and readily available. It is high compressive strength, is durable and fire resistant, and due to its fluidity before curing, it can cast to fit any shape the mold is in. However, concrete is brittle and have low tensile strength, therefore there is an inherent need for reinforcement in structural applications.

Modern concrete is reinforced with additional materials to compensate for its tensile deficiencies. The first method for reinforcing concrete was the introduction of rebar into the concrete structure. Generally, the structural reinforced concrete is cast in a constructed formwork in which steel reinforcement is installed before casting. This method can be applied on the construction site or factory shop floor. Off-site casting in a factory would allow for higher concrete qualities and quality control. However, both method requires considerable labor for both the formwork and the positioning of the reinforcement. The formwork may often be reused but it is not always done so.

Another method of reinforcing concrete with rebar is by prestressing the concrete. The steel reinforcement can be cast into the concrete matrix, as in pre-tension concrete or inserted after the concrete is cured, as in post-tension concrete. The steel reinforced can be placed either within the concrete volume (internal prestressed concrete) or adjacent to the concrete volume (external prestressed concrete). The steel reinforcement is tensioned, and the resulting prestressed concrete is placed under compression prior to and when supporting any loads, inclusive of its dead weight. Other materials that are now used to improve the tensile strength of concrete are polymers or mixtures of composite materials with or without addi-

tional support from rebars. These polymer and composite material reinforcement can be in the form of fibers (fiber reinforced concrete), sheets (fiber reinforced polymer sheets) or tendons.

2.1.2 Theory in concrete reinforcement

To illustrate the theory behind reinforced concrete, a tensile reinforced simple support beam shown in Fig. 2.1 is tested. The reinforced concrete beam is sufficiently long such that shear effect is not significant on its behavior. The reinforced concrete beam is then loaded in its transverse direction by gradually increasing amount until beam failure. The beam failure can be described in three distinct stages. The first stage is (1) the uncracked concrete stage, the second stage is (2) is the concrete cracked elastic stress stage, and the third stage is (3) the ultimate strength stage. Fig. 2.1 shows stress-strain variation in the cross-sectional area of the reinforced concrete beam when subjected to these small loads in the concrete uncracked stage. From the figure, it can be seen both the concrete and the steel reinforcement carries the tensional stresses, and it can be subsequently inferred that the tension stresses carried by the steel cable is proportional to the distance the steel cable is located away from the central axis. Therefore, it would be more efficient to position the steel cable as far away from the central axis as reasonable possible, while ensuring that the steel cable is adequately encased in concrete so as to protect the steel cable from corrosion.

Upon testing, the reinforced concrete beam is loaded until failure, which the modulus of rupture is said to have exceeded. Cracks is observed at the lower surface of the beam where the moment force due to tension is the greatest. The cracking moment, M_{cr} , is when the cracks first appear, and is when the tensile stresses reached the modulus of rupture. As the load is further increased, the cracks propagates rapidly along the direction of the neutral axis, and the neutral axis is shifted upwards. Fig. 2.2(a) shows the crack region when the cracking

Figure 2.1: Uncracked concrete stage

moment has been exceeded.

Figure 2.2: Cracked concrete in elastic stress stage

As the bottom of the reinforced concrete beam has cracked, it is now in the cracked elastic stresses stage. The concrete in the cracked zone is no longer able to resist the tensile stresses and only the reinforced concrete beam's steel rebars is resisting the tensile forces. The concrete will be in the cracked elastic stresses stage until the compression region of the concrete beam exceeds one half of the concrete's compression strength, f_c , and the stresses in the steel rebar does not exceed the steel's yield stress.

Fig. 2.3 shows the stress-strain of the reinforced concrete beam in the cracked elastic stresses stage. At this stage, the magnitude of the compressive stress is linearly proportional to the distance from the neutral axis. This straight line stress-

strain can occur normally in the reinforced concrete beam under normal service condition, and at these load, the stress is less than $0.50f_c$.

Figure 2.3: Concrete cracked in ultimate strength stage

When the load is further increased, the magnitude of the compressive stresses gradually increases to $0.50f_c$. The reinforced concrete beam is now in the beam failure ultimate strength stage as shown in Fig. 2.4. Tensile cracks propagate towards the neutral axis, and the neutral axis shifts upwards as well. The concrete compression stress line changes from a straight line to a curved line as shown in Fig. 2.5. The steel rebars would have also yielded in an under reinforced beam setup, as required by reinforced concrete design guidelines [24].

Figure 2.4: Stage 3: Compression crushing failure in ultimate strength stage

In Fig. 2.6, the first stage of the moment curvature graph shows small moments with magnitude less than the cracking moment, M_{cr} . At this initial stage, the entire beam is used to resist bending, the magnitude of strain is small and the

Figure 2.5: Concrete cracked in ultimate strength stresses stage

graph is almost vertical. At the second stage, the magnitude of the moment has increased beyond the cracking moment, and the gradient of the graph decrease as the beam is no longer as stiff as the initial stage. The graph shows a near straight line from M_{cr} to the point where the reinforcing is stressed to its yield point. The reinforced concrete beam is able to resist a fairly large additional load and deflect significantly before the yield stress of the steel rebar has been exceeded. When the steel rebars yields, the reinforced concrete beam has very little moment capacity before failure. A small amount of load will substantially increase the beam curvature and deflection, and the gradient of the graph is near constant.

Reinforced concrete (RC) is a composite material in which concrete's low tensile strength and ductility is reinforced by the addition of reinforcement that has high tensile strength and ductility. Common methods for reinforcing concrete requires the application of rebars and various types of fibres. Reinforcing bars (rebars) are typically made using plain steel for economic reasons, although other types of rebars can include stainless steel, aluminum bronze, and fibre-polymer composites. The other types of materials while having a higher upfront cost, can sometimes be cheaper to maintain, repair or replace, increasing their viability as reinforcing

Figure 2.6: Moment curvature diagram for reinforced concrete beam with tensile reinforcement

materials. Rebars are typically made from twisted strands of plain steel with nobbles and ridges on them that can be used to firmly anchor the rebars inside the concrete without slippage. Plain steel has a similar coefficient of thermal expansion and would not crack the concrete that surrounds it as another material might if it expanded at a different rate.

2.1.3 Prestressed concrete beam

Prestressing of reinforced concrete beam is done by imposing internal stresses into a concrete structure that is of opposing character to those that will be caused by the service load. Generally, in prestressed concrete beams, the prestressing is used to resist the tension stresses caused by the weight of the concrete and the working load. When the resulting load causes a positive moment in the beam, prestressing introduces a negative moment to resist part or all the positive moment. This eliminates the bending moment and maintains the concrete in the compressive region and therefore does not undergo tensile cracking.

In Fig. 2.7, prestressing is done by reinforcing the concrete beam by the addition

Figure 2.7: Prestressing Process

of steel cables as shown by the dashed lines. The steel cables are cast in place, in the lower half of the concrete beam to resist the tensile forces. The steel cables are pulled in tension to the required tensile stress to resist bending. The concrete is cast in place and allowed to cure before cutting the steel cables. The steel cables retain the tension forces and compress the reinforced concrete beam and produce a negative bending moment. This negative bending moment resists the positive bending moment caused by the weight of the concrete beam and any working load that the concrete is required to carry under service conditions.

Prestressed concrete beams are crack free under normal working conditions, and as a result, would look better aesthetically. As the prestressed concrete beam is crack free, the concrete is able to properly encase the steel cables, providing a waterproof casing around the steel cables and preventing corrosion. In addition, prestressed concrete beams require less maintenance and have a longer service life as compared to the reinforced concrete beam.

Fig. 2.8 shows the stress of the cross-sectional area of a prestressed concrete beam. The steel cables are placed at the lower half of the concrete beam, below the neutral axis of the beam. The prestressed concrete beam is subjected to a combination of direct compression and bending moment due to the prestressed

steel cables. This compression and bending moment works to directly resist the tension forces and bending moment due to the weight of the prestressed concrete beam and the service load. The resulting stress at any point in the beam caused by these three factors can be written as follows, where P is the prestressing force:

$$f = -\frac{P}{A} \pm \frac{Pec}{I} \pm \frac{Mc}{I}$$

Where P is the prestress force, e is the eccentricity or distance of the prestress force with respect to the centroid of the cross section, c is the distance from the central axis to the extreme fibers, M is the applied moment from external load, A is the uncracked concrete cross-sectional area, and I is the moment of inertia of the concrete cross section.

Fig. 2.8 shows the stress diagram of the different element in the prestressed concrete beam. The resultant of the stresses due to the prestressed steel cable, the weight of the concrete beam, and the service load gives the final stress diagram that the prestress concrete beam is subjected to. It is noted that the prestressed steel cables produces a compression force on the concrete beam and keeps the concrete beam in the compressive region under normal working conditions.

Figure 2.8: Concrete stress distribution due to eccentric prestress forces

For post tensioned concrete beams, the steel cables are pulled in tension and stressed after the concrete has already cured. The steel cables are placed in plastic or metal tubes, in the lower half of the concrete beam. After the concrete has cured, the steel cables are pulled and stressed in tension. The stressed steel cables are loaded in anchorage devices to maintain the tension stresses. As a result, the post tensioned steel cables are able to transfer the tensile forces to the concrete beam and keep the concrete beam in a compression stage, through the end anchorage.

It is also possible to bond the post tensioned steel cable to the concrete beam. The tubes of the steel cables can have concrete cast in, to bond the post tensioned steel cables to the tubes. This additional concrete is able transfer tensile stress to the concrete beam and protect the steel cables from corrosion. If the post tensioned steel cables are not protected by concrete, they are chemically protected by grease or coating to prevent corrosion.

2.1.4 Reinforcement in 3D Concrete Printing

3D Concrete Printing is required to be reinforced before it can be used in structural application. Therefore the development of suitable reinforcement method is one of the impedances of commercial adoption of 3D Concrete Printing. Numerous reinforcement strategies for 3D Concrete Printing are discussed to demonstrate the methodology by which reinforcement can be added, ranging from the conventional methods to new and under development reinforcement strategies. The reinforcement strategies can generally be classified into reinforcement before printing, during printing and after printing.

Reinforcement before printing

In literature, the most widespread approach for reinforcing 3D printed concrete is the cast in-place formwork method, first seen in Contour Crafting [17] and later,

adopted by WinSun and Heijmans [25]. The cast in place formwork method combines both printing and casting methodology. It requires the printing of concrete filaments to build a permanent, integrated formwork that is subsequently installed with horizontal and vertical reinforcement bars and filled with flowable concrete to form a reinforced structure. A subsequently development from the cast in-place formwork, is the selective printing of a lattice structure, which prestressed steel tendons can be added, as mentioned in [26]. This cast in-place formwork method may restrict the freeform capabilities of concrete additive manufacturing, as they all require printing linear segment prior to conventional steel reinforcement and create a cold joint between the cast concrete and the printed permanent formwork.

This reinforcement method was also adapted by Chinese construction company HuaShang TengDa Ltd [27]. In their printing system, a rebar cage was manually installed prior to printing and concrete was printed on either side of the rebar using their customized dual nozzle system. The dual nozzle system has shown to successfully print vertically ascending reinforced elements, through continuous manually installation of rebars after each section, it is limited to the construction of rectilinear elements. Currently, literature has not published the mechanical performance of the dual nozzle reinforcement system.

An alternative reinforcement method is developed by ETH Zurich as Mesh Molding that additively prints the steel reinforcement [28]. In Mesh molding, the concrete is manually plastered onto the steel reinforcement cage, as the holes between the mesh are too wide for the application of shotcrete. Peng Feng et al. [29] used moldable fiber reinforced polymer sheets as an external reinforcement for additive manufacturing of concrete. The fiber reinforced polymer sheets are flexible before curing, and allowing it to be pasted over a nonlinear printed structure. Use of fiber reinforced polymer sheets may also be prestressed to provide additional strength enhancement by reducing the effective stresses in the concrete structure [30]. Although, these two methods allow free-form additive manufacturing, they are quite labour intensive because of the hand layup technique used to attach all

required reinforcements.

In a recent paper by Freek P. Bos, an automated cable entraining reinforcement has been introduced for 3D Concrete Printing has been introduced for reinforcing printed concrete [31][32]. The authors used single continuous steel cable as reinforcement in the longitudinal direction of the printer sample using active feed mechanism and performed four-point bending (flexural) test on 28 days experiment by varying cable diameter, but this is done without a control group. It was found from the experimental results that the flexural strength of the samples increases with cable diameter, however the two experiment sets suffered from cable slippage before reaching their failure strength.

Reinforcement during printing

In literature, reinforcement during 3D Concrete Printing is the most prevalent method for reinforcement. This category of reinforcement includes the addition of fibers in the concrete mix design, or entraining the fibers at the nozzle.

Various strategies are designed for reinforcing during printing, parallel to either the mixing, extruding or building tasks. Of the eight strategies, fibers are typically added during mixing or entrained at the nozzle, whereas cables or mesh are entrained at the nozzle by a specialized entrainment mechanism attached to the end-effector. Furthermore, reinforcement is incorporated during object building by the remaining strategies presented in this section.

Entrained fibers In literature, fiber entrainment is the most common reinforcement. Its widespread adoption is also partly supported by advances in classical concrete, such as fiber reinforced concrete, this is also coupled with the ease and minimal disruption to the existing printer setup for Fiber Reinforced 3D Printed Concrete (FR3DCP).

Studies in FR3DCP are focused on the use of various fiber materials such as polyvinyl alcohol (PVA) fibers, micro glass fiber, steel fiber, etc. Apart from the fiber materials, researchers have also based their studies on the characterization of fiber length, fiber stiffness and volume of fiber added to the concrete mix. Depending on the different types of fibers, they can be advantageously added at the concrete mixing stage or are required to be separately added at the nozzle extrusion stage. Short flexible fibers are typically added in the concrete mixing stage as they are able to be pumped through the hose pipe and nozzle without significant difficulty when the fiber proportions are within range [33]. On the other hand, stiff and long fibers must be entrained at the nozzle section as they can block and damage the pump and hose pipe. Short flexible fibers are more commonly used to reinforced 3D Printed Concrete as the addition of such fibers does not requires any adaption of the printing system. However, stiff and long fibers require modifications of the extruder to provide for an additional inlet for fiber addition and fiber mixing at the extruder [34].

Fiber Reinforced 3D Printed Concrete has reported improvement in mechanical performance in increasing the tensile strength and strain hardening and softening behavior in concrete [35, 36]. However, research in Fiber Reinforced 3D Printed Concrete is still ongoing and it is still unable to match the performance of concrete reinforced with conventional rebars. The extrusion process of Fiber Reinforced 3D Printed Concrete results in the fibers being primarily aligned with the printing path direction and thus limits the reinforcement effort to only the longitudinal direction [37, 38, 39]. The lack of fusion between filaments and layers are therefore not addressed and remains a potential failure point.

Entrained continuous reinforcement Entrained cables reinforced 3D Printed Concrete is another reinforcement strategy. This method entails a continuous steel cable rope during the printing process. The steel cable rope is typically entrained using a stepper motor extruder setup that is mounted and adapted onto the existing

concrete extruder nozzle. During printing, the steel cable rope is unwound by the stepper motor and pushed into the concrete extruder and entrained in the concrete [40].

The steel cable ropes are specifically chosen for a low bending stiffness, to ease extrusion at the nozzle and allow the steel cable ropes to conform to the freeform characteristic of 3D Concrete Printing. The reinforcement using steel cable provides strength and ductility to the 3D Printed Concrete [31, 41, 40, 42]. The steel cable is reported to be aligned in the printing path direction, and therefore does not address the lack of fusion in the interlayer and between filaments. However, when the printing path is suitably designed, cable reinforcement can provide a confinement effect on printed structure and improves the mechanical performance in all directions [43]. The strategy of entrained continuous reinforcement can also be extended to included continuous fibers such as Mineral-impregnated Carbon-Fiber [44, 45]

Mesh reinforcement Mesh reinforcement is a reinforcement strategy that entrains a steel mesh using a customized split nozzle design [46]. The mesh reinforcement is a proof of concept to provide longitudinal and orthogonal reinforcement. In the proof of concrete study, a mesh is manually added to the nozzle during extrusion so that overlapping mesh bridges the interlayer interfaces. The mesh strips overlap every consecutive layer and as a whole, the structures are tied together by the overlapping mesh strips.

Layer Penetrations reinforcement In the layer penetration reinforcing method, the reinforcement method involves the printing of a predefined number of layers, and the subsequent penetration of pre-cut reinforcement bars vertically through the fresh layers, then the process is repeated [47, 48, 49]. The insertion of the reinforcement bars is conceptualized to be undertaken by a secondary independent robot or as an accessory robot to the printer. As the reinforcement bar is hy-

pothesized to create void during the insertion, cementitious coated bar can be used filled the void formed, thus providing a consistent bond to the surrounding concrete while maintaining the efficiency of the layer penetration reinforcing method. The layer penetration reinforcing method reported improved mechanical performance in flexural and compressive strength, but also greater variation in the mechanical results which may be due to the current manual insertion method and void formed during insertion.

A variation of the layer penetration reinforcement method is the screw reinforcement method. In the screw reinforcement method, a linear reinforcement element, a screw, is introduced into the fresh concrete after printing, by directly screwing of the reinforcement screw into the fresh concrete. The screwing motion is necessary to minimize disruption to the fresh concrete in terms of void forming as opposed to direct insertion. The helical surface accentuation also provided increase pulled out resistances through mechanical interlocking. As the current work was structured as a proof of concept, no comparison was made against an unreinforced concrete element.

The layer penetration reinforcement method can also be applied to the Shotcrete 3D Printing [50]. The paper proposed a similar idea of integration short reinforcement bars into the printed filament while printing. The reinforcement bar proposed could be directly inserted, inserted with a grouting mortar coat or screwed into the filament. The paper visualized the automation of the insertion mechanism while manually performing the insertion, as a proof of concept. The paper did not perform any comparison against a control unreinforced concrete element, and focused on the demonstration of the proof of concept.

Steel Staples reinforcement is a method of adding orthogonal reinforcement using steel staples [51] The steel staples are inserted perpendicularly to the interlayer interface, thus bridging the interlayer interface. The study reported post-crack softening behavior when imposed under a flexural load parallel to the interlayer

direction. A similar study uses steel nail [52]

Reinforcement after printing

Reinforcement after printing is the method of introducing reinforcement after the 3D Concrete has been printed.

External reinforcement In external reinforcement, Asprone et al partitioned a 3D printed concrete beam into printable segments and subsequently assembled using an external reinforcement system [53]. The segments were designed to be printed with infill ducts to accommodate subsequent addition of threaded rods. The threaded rods were mounted in place by pouring high strength low viscosity mortar. The segments were then assembled by joining the threaded rods to the external reinforcement system. The segment could be seen as modular designs of a strut and tie system. Each segment can be individually printed and joined, allowing for the design freedom expected of the 3D Concrete Printing framework. However, this system may be difficult and expensive to assemble, in addition to the weakness of exposing steel reinforcement to the weathers.

Permanent formwork The most used method of reinforcement is the permanent formwork method, which uses the printed concrete as a permanent formwork onto which mortar and reinforcement are cast in [54, 55, 56, 57, 58, 59, 2]. In this strategy, both orthogonal and longitudinal reinforcement is provided, but the design freeform embodied by 3D Concrete Printing has to be limited to accommodate ease of adding reinforcement. The strategy also has to account for the high hydrostatic pressure imposed by casting and therefore the 3D Printed Concrete structure might be required to be overly thick. However, despite the practicality and ease of reinforcement, this reinforcement strategy is not well received due to the laborious installation of reinforcement and casting, which erodes the advantages of 3D

Concrete Printing.

Post-tensioning The method of post tensioning of reinforcement is similar to the strategy of permanent formwork. The 3D concrete is printed and cured before reinforcement is added by post tensing high strength steel cables. As the 3D Printed Concrete is required to withstand the high compressive strength imposed by the post tensioned steel cables, the 3D Printed Concrete is typically left to cured for the entire 28 days, thereby extending the construction timeline. Nonetheless, this strategy has demonstrated practical use by the full-scale 3D Printed bridge at TU Eindhoven [60].

Additively manufactured reinforcement

The strategy of additively manufactured reinforcement is unique from the above-mentioned reinforcement, in that the reinforced element is also additively manufactured. This is envisioned to couple the synergy between before additive manufacturing process such that the reinforcement element is printed at the same time to reinforce the 3D Printed Concrete. One strategy is the 3D printing of reinforcement through gas metal arc welding [61, 62] and wire arc additive manufacturing [63, 64, 65] Their works are targeted as proof of concept at automating the both the reinforcement process and the manufacturing of the reinforcement element. However as both gas metal arc welding and wire arc additive manufacturing are time consuming and expensive welding processes, these strategies are yet to be successfully synchronized with the concrete printing process and are expected to bottleneck the reinforced 3D Printed Concrete process [66].

2.2 3D printing of curved surfaces

Architects and engineers have become increasingly skilled in designing freeform structures that are aesthetically interesting and structurally sound, through the inclusion of Computer Aided Design software and numerical analysis programs when designing and building. This naturally complements the adaptation of additive manufacturing methods such as 3D Concrete Printing which uses the same tool and promises freedom in manufacturing. However, at this early stage of 3D Concrete Printing, researchers are focused more in producing and reproducing regular rectilinear panels or walls. This discount the advantages of 3D Concrete Printing and forces 3D Concrete Printing to compete in the low-cost field of mass manufacturing of walls. The matured prefabricated panel industry is involved in the mass manufacturing of rectilinear walls, and unless 3D Concrete Printing is able to bring about significant cost saving, the building and construction industry would be reluctant in adopting this new technology given the stringency of checks that the industry faces and infancy of 3D Concrete Printing.

However, 3D Concrete Printing is capable of more than printing rectilinear walls. 3D Concrete Printing can focus on its unique characteristic of printing concrete without formwork, and therefore is able to print freeform shapes in concrete. A well-designed 3D printed curved concrete panels can be aesthetically pleasing and structurally efficient. Nevertheless, printing curved concrete panel is not without challenges. Green concrete has low yield strength at an early age, and this low yield strength prevents overhanging concrete from being printed, and hence to date free standing curved concrete structures have not been printed.

2.2.1 Methods for 3D printing of curved surfaces

Concrete is fluid in its green state, and therefore it can be molded to fit any form. The conventional methods of manufacturing curved concrete panels is to

produce the relevant negative molds and cast the concrete in the molds, and thus producing a cast curved concrete panels. The types of formworks used are mainly milled formwork and permanent formworks made of wood or metal. The cost of formwork can be substantial, as the formwork is often difficult to produce and requires significant amount of manual labor and expertise.

In the milled formwork method, a solid material such as polystyrene foam is milled to produce the required mold to be used as the concrete formwork. A computer numerical controlled (CNC) mill is used to subtractively remove material from a simple shape into the required 3D mold design. The CNC mill translates a rotary cutter according to the process code and removes material progressively from a rough cut to increasingly finer details. The CNC milling technique is plagued by certain limitations such as the maximum polystyrene foam size, rotary cutter axis movement, and the inability to create straight edges. Polystyrene foam is typically utilized as it is comparatively economically and easy handling in the milling process. The milled polystyrene foam formwork can be covered by a thin plastic film on which concrete can be cast. When the concrete has cured, the polystyrene foam can be cut, in order to release the cast concrete.

In the permanent formwork method, a negative mold design is sliced into X and Y planes, creating a waffle-structure. These X and Y planes designs form the ribs of the negative mold which can be subsequently joined together to create a sub-structure grid on which a layer of plywood or steel plates may be placed to form the casting surface. This top surface often requires expert craftsmen to shape and rest upon the sub-structure grid. The X and Y planes are typically made of wood for its ease of manufacturing and low cost. However wooden ribs can deform over multiple use from concrete casting. Fig. 2.9(a), shows a traditional wooden formwork. The complexity of the mold design and required accuracy can quickly increase the labor cost and time of production. This kind of formwork cannot always be used and can be very expensive.

These production methods require high material investments and are only economical when the mold can be reused several times. This goes against the ideology of additive manufacturing which promises design freedom, and designs that can be customized and unique. This is especially critical when designing for iconic structure in cities, where each building has its own signature and beauty. However, a disadvantage of this method is that the formwork can not be used over and over again. A building facade would require a series of curved concrete panels, with the geometry of each panel differing slightly from each other. An example of a static formwork is PERI, Fig. 2.9(b). PERI first introduces a wall formwork system that uses pre-assembled panels for curved walls [67]. However, PERI's system is only suited for the construction of single curved elements, with a minimum radius of 1m. To increase the efficiency and re-usability of the formwork, a flexible mold system can be adopted. The flexible mold would allow engineers to change its shape for every individual concrete panel by making temporary adjustments to the mold and printing concrete over it. An example is ADAPAs flexible formwork that prefabricates non-structural double-curved concrete facade panels [68], Fig. 2.9(b). The formwork consisted of a membrane that is supported and adjusted by CNC controlled actuators. This membrane is required to have both flexibility and rigidity, to form doubly curved surfaces and high stiffness to avoid sagging due to the concrete load. ADAPAs system requires the concrete to be first poured on to the planar shaped formwork prior to the actuators deforming the concrete into the predefined geometry, after the concrete has gained sufficient strength through curing. However ADAPAs system would thus risk dislocations in the curing concrete and as it bend the concrete after the concrete has set. In a similar work by Schipper et al. [69], their group adopted the same technique as ADAPA and manufactured doubly curved concrete through deliberate deformation of the flexible mold after casting. In their work, they studied mainly the rheological properties of concrete, as they recognize that deliberate deformation of concrete in an open mold, can cause the concrete to either spilled out of the mold if the concrete has not cured sufficiently or cracked if the concrete is too stiff. In addition, the maximum radius

of curvature achieved by their system is 1.5m.

In 3D printing application, Costanzi et al. discussed the possibility of adopting a flexible mold developed at TU Delft [70] for 3D printing applications. In the paper, they highlighted a possible work flow of using a flexible mold alongside 3D concrete printing. However Costanzi et al. did not print the concrete over a flexible mold, instead they printed the perimeter of the structure over a CNC-milled static mold and cast concrete to fill the structure. Also, the authors did not provide a quantitative assessment of the print quality or of the geometric fidelity.

2.2.2 Optimization of printing paths for 3D printing of curved surfaces

In 3D Concrete Printing, the application of the fused filament fabrication method using specially designed concrete offers unique advantages and also challenges. This is because the 3D Concrete Printing method prints concrete filament sequentially, resulting in difference in material properties between filaments and layers. This unique material property has been well studied in literature and experimentally[29, 74, 75, 76].

This orthotropic property therefore introduces new challenges to the traditional concrete which in literature has been considered to be an isotropic and homogeneous construction material. Researchers have to take into account the material orientation when printing 3D concrete for construction application. And in doing so, researchers can take advantage of this mechanically superior orientation by printing concrete in a predefined and load specific direction, making full use of the strength of 3D Concrete Printing's orthotropic property.

Structural design optimization for 3D Concrete Printing is the process of computationally obtaining the most efficient or optimal structure while satisfying a set

(a) Wooden formwork[71]

(b) Static curved formwork[72]

(c) CNC controlled curved formwork[73]

Figure 2.9: Types of concrete formwork

of design criteria. In this process, the structural problem is solved using mathematical optimization techniques to optimize the shape and material distribution of the printed design. Particular to 3D Concrete Printing, structural design optimization is the design of a viable printing path that prints concrete in a load specific direction designed to maximize material strength due to 3D Concrete Printing's orthotropic property. Unfortunately, there is a gap in literature for computational approaches for determining preferred filament direction that gives the stiffest or strongest part [77, 78].

In this thesis, we use Finite Element Modeling as a computational tool for computing the optimum material distribution of a structure for optimum properties. While conventional Finite Element Modeling methods have been applied in industry and numerous research fields, they have not taken into account 3D Concrete Printing specific limitations. We theorized that Finite Element Modeling can be a viable tool for designing the structure of the 3D concrete printed part, through designing for a stress cognizant printing path for structural 3D Concrete Printing.

2.3 Current concrete printing systems

Various techniques have been developed in recent years, just as smart dynamic casting which is the combination of slip forming and digital fabrication technique [18, 79]. Another family of concrete digital manufacturing has been inspired by the 3D printing technique [80]. This technique is commonly called additive manufacturing and consists of joining materials to produce objects, layer upon layer, from 3D model data, and is the topic of discussion in this report. Additive manufacturing of concrete or 3D Concrete Printing was first known to be published in literature, by Pegna in 1997 [80]. Development of his idea began shortly after by Khoshnevis who called the technique Contour Crafting [1, 81]. Contour crafting Fig. 2.10(CC) is a gantry based robotic system that extrudes material in a layer

by layer manner to construct on-site structures. The key feature of CC is the use of trowels, which act as a solid surface, to create smooth and accurate surfaces as shown in Fig. 2.10. This trowel can be controlled at different angles to create various gradients in the concrete surfaces. This would also allow for the deposition of higher layer thickness and use of larger concrete aggregates without compromising on the surface texture and quality [1].

Figure 2.10: Contour crafting process[1]

Fig. shows some of the specimen printed with the CC technique using ceramic and concrete materials. The detailed material composition and printing procedure are described in [82, 83]. It is also reported that, printed walls with embedded conduits for electricity and plumbing and reinforcement can be achievable automatically through CC [84], and hence more research is needed to be done in this direction for better service as well as structural requirements of the buildings.

Another leading research group at Loughborough University [85, 86, 87, 88, 59], uses the same concrete extrusion process to fabricate geometrically complex parts by depositing concrete selectively without the use of any labour intensive formwork. Fig. 2.12 shows concrete printed bench done at Loughborough University, UK using a high-performance fibre-reinforced concrete material [2].

Pioneering industrial leaders in 3D Concrete Printing were Shanghai based contractor Winsun[89], and the company Total Kustom [90], Minnesota, USA who

(a) Ceramic printed specimens[1]

(b) Cement printed specimens[1]

Figure 2.11: Contour Crafting printed specimens

Figure 2.12: Concrete printing at Loughborough University [2]

printed Fig. 2.13(a) and (b). Both companies advanced the 3D Concrete Printing community by drawing attention to this innovative new construction technique. An alternative to working with single large robot/gantry was introduced by the Institute of Advanced Architecture of Catalonia (IAAC) in 2014 where a group of small robots were printing together using swarm base group technology as shown in Fig. 2.13[91].

Figure 2.13: Industrial concrete printers

Figure 2.14: D-Shape concrete printer [3]

Most printers discussed above were largely similar and built upon an Additive Manufacturing technique called Fused Deposition Modeling method. However En-

rico Dini introduced a new approach named D-shape, based on Stereo-Lithography. The D-shape process uses layers of powder and adhesive (binder) rather than the cement-like paste used in other methods. Binder is ejected in droplet form onto a thin layer of powder material spread on top of the build tray which essentially glues 2D cross section of the intended component, simultaneously gluing it to the previous layer or the substrate [3]. Subsequently, another layer of material powder is coated over the previous layer and the cycle is repeated, until the full 3D model has been printed as shown in Fig. 2.14. Any raw material that is not glued by the binder remains inside the constrained build container and is used to support subsequent layers. This allows designs to have voids and overhanging features which enables the printing of complex geometries. The unbound material can be removed from the print bed using a vacuum cleaner after the printing, which can be recycled and deployed for another printing task [59]. The disadvantage of these types of process is that an additional deposition device is requiring more maintenance, cleaning and control [92].

All the printers discussed thus far, were stationary printers with a finite build dimension which is ultimately limited by the gantry size. Such printer imposed a fixed limitation on the size of the concrete structure fabricated, necessitating joints and other constraints, damping the effectiveness of 3D Concrete Printing has on the construction industry. Therefore the next logical step in the development of 3D Concrete Printing beyond unnecessarily scaling up the printer, would be to make the printer itself mobile as shown by MIT and Cybe, giving the printer extended printing range [93, 94]

2.4 Conclusion

From literature, it was noted that a scalable solution for 3D concrete printers need to advance away from needlessly expanding the scale of the printer and towards a

mobile robotic printer that is capable of continuously printing a concrete structure with an extended print dimension. A continuous printing method will also greatly reduce the need for connector joints and weakness points found in those joints.

In order to print structural concrete, and not just concrete showpieces, there is a need to incorporate reinforcement into the printed concrete. Addition of reinforced should be fully automatic and not discount the workforce saving afforded by 3D Concrete Printing. Additionally without the need for formwork in 3D Concrete Printing, reinforced concrete structure should maximize its freeform capabilities. Hence there is a need to develop new novel reinforcement technique for 3D Concrete Printing and not depend on manual insertion and bending of steel rebars found in traditional concrete.

Chapter 3

Reinforcement methods for 3D Concrete Printing in Building and Construction

This section describes the experimental program carried out on a hybrid reinforcement method on fibre reinforced geopolymer with an in-process embedded steel reinforcement. A continuous steel cable impregnation nozzle system is introduced in which reinforcement is directly entrain inside a printable geopolymer mortar, thus creating a hybrid reinforcement. This improves the concrete composite's flexural strength and ductility with respect to a control specimen. Different cable reinforcements were explored and compared for structural performance, based on 4-point bending test.

3.1 Materials and Methods

3.1.1 Materials

Geopolymer Fly ash based geopolymer was chosen as feedstock in this chapter and to formulate the binder, 80% class F fly ash, 10% ground granulated blast-furnace slag (GGBS) and 10% micro silica was mixed uniformly in a high shear planetary mixer. Potassium silicate ($SiO_2 = 24.94\%$, $K_2O = 19.09\%$) was consumed (liquid/solid = 0.135) as alkaline reagent in the mixing process with fine river sand (sand/binder = 1.7) of maximum particle size 1.18 mm. Thixotropic additives were separately added into the mortar mixture for 3D printing of geopolymer using a 4 axis gantry and grouting pump set up. 8 mm PVA fibers (spec) were also used (0.5 wt.%) in this research to investigate and compare the reinforcement (steel cable) performance in both fiber reinforced and regular (without fiber) geopolymer.

Table 3.1: Mixture proportions of Geopolymer Concrete

Materials	Silica Fume	Slag (GGBS)	Fly ash	Thixotropic Additives	Sand	Potassium Silicate	Water
Weight by Percentage	3.36	1.68	27.85	0.875	49.55	12.5	4.16

3.1.2 PVA fiber properties

Table 3.2: Properties of PVA fiber

Specific Gravity (g/cm^3)	Diameter (mm)	Thickness (dtex)	Cut length (mm)	Tensile Strength (MPa)	Young's Modulus (GPa)	Elongation (%)
1.29	0.0014	1.8-2.3	12	1500	41.7	7

Stainless steel cable All stainless steel cable of varying diameter were purchased from the same Japanese supplier, Otokomae MonotaRO, and was of the same material, SUS304, whose properties were listed in the table below. The diameter used were 1mm, 1.5mm and 2mm. The diameter of the cable refers to the diameter of a circumscribed circle that will enclose all the strands of wire, it is also the larger

of cross-sectional measurement of the wire. As the cables were twisted together from a combination of smaller wire strands bundles, the perimeter of the cable's cross section is larger than πd , as seen from the Fig.3.1. This increase in surface area provides better interface adhesion between the cables and geopolymer matrix, leading to a better load transfer mechanism, and hence higher strength.

Figure 3.1: Cross section of stainless steel cable

Table 3.3: Properties of Stainless Steel cable

Grade	Tensile Strength (MPa) min	Yield Strength 0.2 Proof (MPa) min	Elongation (in 50mm) min	Density (kg/m ³)	Elastic Modulus (GPa)	No of Strands
SUS304	515	205	40	7900	193	7x7

3.1.3 Methods

3D printing of hybrid geopolymer composite

A four-axis gantry printer (Fig.3.2) was used to print 8 straight walls of dimension $1000 \times 30 \times 39 \text{ mm}^3$, with varying cable reinforcement (C10, C15 and C20)¹ and a control group (C0). The printed filaments were ambient cured prior to flexural testing. Each filament was cut into 3 piece on the seventh day, resulting 6 test samples for each variable and control. The flexural strength results are shown in the following section. Since geopolymer binder has higher stiffening rate than normal concrete (OPC), its open window for printing is also much shorter [95]. The time gap between mixing and printing has been reported to contribute towards the

¹C10,C15,C20 indicates matrix reinforced with 1mm, 1.5mm and 2mm stainless steel cable

Figure 3.2: Gantry printer

tensile strength of 3D printed element, especially when pulled in the layer build up direction, owing to an improved bond strength in the 3D printed interface layer when print time was kept to a minimum in both geopolymers [96] and high strength cementitious material [97]. From the results of tensile bond test conducted at Nanyang Technological University, Singapore [96], we found the open time for ideal bond strength of geopolymer is under 20 minutes and therefore all printing activity in this chapter has been completed within this open time period. Rest parameters such as speed, feed rate etc are reported in Table 3.4.

Table 3.4: Gantry printing parameters

Parameters	Value
Print length	500mm
Layer height	13mm
Layer width	30mm
Nozzle dimension	13mm x 30mm
Feed rate	60mm/s
Pump mass flow rate	110g/s

Insertion Method and Mechanism

The concept of embedding continuous reinforcement is similar to the conventional fused deposition method printer that is available on the market. Embedding continuous reinforcement in additive manufacturing was first described in FDM printers,

printing carbon fiber in a thermoplastic matrix. We borrowed on the idea, and embedded a continuous steel cable into a geopolymer concrete matrix. In our extruder setup, we used a direct extruder feeder system, that was powered by a stepper motor and controlled by a microcontroller. The choice of a direct cable extruder over the Bowden extruder was that it requires less torque to push the cable into the geopolymer concrete matrix, hence saving on a lighter motor, and conforming to the specifications of our gantry printer. A lighter nozzle would also allow for a more precise and controllable motion, with less jerk due to inertia. The extruder unit was a stand alone unit, which can be fitted onto the gantry's existing nozzle, through a slip ring connection. The slip ring is essential in allowing the nozzle to retain its rotating capabilities without being entangled by the electrical wiring, necessary for data communication and handshaking between the microcontroller and the onboard main computer. The extruder is configured to take up to a 2mm diameter cable. Traction of the cable was maintained by the spring pushing the idler wheel and keeping the cable in constant contact with the drive gear of the extruder. As the extruder pushed the cable into the concrete nozzle, the pressure inside the nozzle encased the cable in the concrete matrix and extruded a reinforced concrete composite, with the cable at a predefined section. The microcontroller was set to control the stepper motor to keep pace with the traverse speed of the concrete print nozzle. It prevented the cable from slipping in the fresh concrete matrix due to the different speed. Steel cable was chosen over conventional steel rods due to its bending stiffness afforded by flexible cable. Steel cable will be increasingly easier to bend as the number of strands within the cable is increased. In this experiment, 7x7 strands of varying diameter cable was used. From the Fig.3.1, it can be seen that the diameter of a singular strand is $\frac{1}{9}$ of the cable diameter, namely 0.11mm for a 1mm diameter cable, 0.16mm for a 1.5mm diameter cable, and 0.22 for a 2mm diameter cable. The minimum bending radius of the 7x7 steel cable was about 8 times its diameter, as such the print nozzle should not turn a radius smaller than the minimum bending radius of 16mm for a 2mm diameter cable, which is sufficient as the nozzle width alone is 30mm wide.

Figure 3.3: CAD drawing of the nozzle equipped with the cable extruder add-on.

Figure 3.4: Top view of the prototype of the cable extruder.

Figure 3.5: CAD design and prototype of the cable extruder.

3.2 Experimental Procedure

The four-point bending was conducted on an Instron universal testing machine according to the loading configuration and dimension as shown in Fig.3.6. Specimens were printed and left to ambient cured for 7 days, before being cut using a radial arm saw to 280x30x39mm pieces for testing. The load was applied at a rate of 1mm/min without shock to the specimen. A one-way ANOVA test at $p = 0.05$ sig-

Figure 3.6: 4 point bending test with dimensions

nificance were used to evaluate statistical significance in the four groups regarding the improvement due to hybrid reinforcement in max load, deflection and fracture energy.

The micro structure of the reinforced specimen was examined using a JEOL JED-2300 scanning electron microscope (SEM) equipped with a concentric back scatter detector, under high vacuum at 10KV with a working distance of 100 μm . Large back scatter electron (BSE) mapping areas were collected using its microanalysis software. The imaged specimens were taken from an unbroken portion of the printed concrete, and cut with a diamond cutter exposing the cross section of the reinforced concrete, and subsequently cut to expose the longitudinal side of the steel cable.

3.3 Results

3.3.1 Bending strength of hybrid geopolymer composite

The hybrid reinforced printed geopolymer specimen is shown below in Fig.3.7. On four-point loading, it shows a series of flexural cracks, which develops upwards through the printed layers. The cracked layers were restrained by the steel cable, and held in tension. As the load was increased, the steel cable elongates and the crack mouth extends upwards. The experiment was stop when the top most layer of the printed specimen was observed to fail in compression crushing.

The hybrid reinforced printed geopolymer sample is shown in Fig.3.7. On four-point loading, it shows a series of flexural cracks, which developed upwards through the printed layers. The cracked layers were restrained by the steel cable, and held in tension. As the load was increased, the steel cable elongates and the crack mouth extends upwards. The experiment was stop when the top most layer of the printed geopolymer sample was observed to fail in compression crushing.

In Fig.3.8, the load deflection graphs of the 3 sets of specimen and control group were shown above in a common axes plot for ease of comparison. The load deflec-

(a) Front View

(b) Cross-sectional View

Figure 3.7: Cable reinforced printed geopolymer beam

Figure 3.8: Load Displacement graph

tion graph represents the strength and service characteristics of the specimen as it undergoes loading, helps to describes the flexural properties of the geopolymer composite. Properties such as ultimate flexural strength, loading at first crack, deflection at failure and flexural stiffness (gradient) were taken from the load deflection graph.

All specimens reinforced with hybrid reinforcement of stainless steel cable and PVA fiber shows a similar trend in their load deflection graphs, with their first crack occurring before the max load. However for the control group, C0, it began to undergo flexural softening upon first crack. Flexural softening behavior of this fiber reinforced geopolymer system is expected due to the strain softening properties of the PVA fibers used in this experiment, coupled with the opening of the crack mouth as load increase. As the crack mouth expands, a lesser amount of short fibers were able to successfully bridge the spacing across the crack and provide tensile strength to the reinforced system. Together they results in a decrease in flexural strength and thus unable to bear incremental loads.

For specimens reinforced with hybrid reinforcement, the steel cable continues to carry increasing load after the concrete has cracked. The steel cable provides the majority of the tensile strength after crack, with a small amount provided by the short PVA fibers at the crack tip. However there is a secondary effect of the short PVA fibers in this hybrid reinforcement system. As the steel cable elongates, it is pulled out of the geopolymer matrix, causing secondary cracks in the pull out region. This small cracks were restrained by the short PVA fibers and contributes to the system's flexural strength. On failure, most hybrid reinforced specimens failed by compression crushing at the top layer of the printed geopolymer as shown in Fig.3.9a, with noticeable yielding of the stainless steel cable. A small portion of the specimens experienced shear slipping between the interlayer bonds of the printed geopolymer filaments, which causes a sudden and steep drop in loading before being restrained by the steel cable, as seen in Fig.3.9b.

(a) Compression crushing at top layer of printed geopolymer

(b) Shear slip between printed geopolymer filaments

Figure 3.9: Shear slip and compression crushing during 4 point bending test

(a) Max load

(b) Deflection at max load

(c) Energy absorption to max load

Figure 3.10: Consolidated values of specimens against control

From Fig.3.10, it was seen that hybrid reinforced geopolymer was able to bear higher loads, have higher fracture toughness and higher energy absorption, seen from the much larger area under the load deflection curve[98]. Fig.3.10 also shows that with increasing diameter of stainless steel cable, increases the flexural properties of the hybrid reinforced geopolymer. The increase in flexural toughness for all hybrid reinforced test specimens was much more significant than the increase in its flexural strength. This finding that enhancement in energy absorption being much higher than flexural capacity have also been observed by researchers investigating normal fiber reinforced concrete [99] [98].

For 2mm stainless steel cable reinforcement, although its flexural properties were higher than geopolymer concrete with 1.5mm stainless steel cable reinforcement, the increase in ductility is not increasing as great as compared to 1mm and 1.5mm. This suggest that increasing diameter of stainless steel cable will reach an optimal point where any additional increment in cable diameter can no longer significantly improves fracture toughness and ductility.

The energy absorption mechanism of the hybrid reinforcement specimens utilizes both the short PVA fiber and long stainless steel cables. During the four-point bending test, microcracks first appears on the tensile side of the geopolymer composite. These microcracks were bridged by the short PVA fibers. As the crack grows and develops into macrocracks, the stainless steel cables becomes active in joining the two cracked regions together and continue to resist tensile stresses. With increasing load, the cable start to transfer tensile loads to the subsequent 2nd and 3rd topmost layer of the printed composite through shear stresses in the geopolymer matrix. The cable will continue to carry the increase loads and finally yield. This is seen from Fig.3.10, that specimens with cable reinforcement have much higher ductility than plain PVA fiber reinforced geopolymer.

3.3.2 Statistical analysis

Statistical analyses were undertaken using one way ANOVA test and Tukey HSD post hoc test. Tables 3.5,3.6 and 3.7 presents the results of the one way ANOVA test which was carried out to compare the effect of steel cable reinforcement on geopolymer's flexural strength in C10, C15 and C20 conditions. The analysis has been performed at $p = 0.05$ level of significance.

Through the analysis, the p-values for max load, elongation and fracture were calculated to be ($P = 0.00001$, 0.00034 and 0.00001) respectively, and less than the p level of significance 0.05 , we can reject the null hypothesis that that steel cable reinforcement is not meaningful and accept the alternative hypothesis that it was meaningful to use steel cable as a reinforcement to improve on the flexural strength of the geopolymer mortar samples for the three conditions, C10, C15 and C20

Table 3.5: One way ANOVA (Geopolymer sample max load)

Treatments	1	2	3	4	Total
N	6	6	6	6	24
$\sum X$	4.3×10^3	9.1×10^3	1.2×10^4	1.2×10^4	3.7×10^4
Mean	7.2×10^2	1.5×10^3	1.9×10^3	2.1×10^3	1.6×10^3
$\sum X^2$	3.2×10^6	1.4×10^7	2.2×10^7	2.6×10^7	6.5×10^7
Std.Dev.	1.3×10^2	9.4×10^1	2.1×10^2	3.0×10^2	5.7×10^2

(a) Summary of Data

Source	SS	df	MS	
Between-treatments	6.6×10^6	3	2.2×10^6	$F = 56$
Within-treatments	7.9×10^5	20	4.0×10^4	$P = 1.0 \times 10^{-5}$
Total	7.4×10^6	23		

(b) Result Details

Table 3.6: One way ANOVA (Geopolymer sample deflection)

Treatments	1	2	3	4	Total
N	6	6	6	6	24
$\sum X$	6.9	15	22	29	64
Mean	1.2	2.6	3.7	3.3	2.7
$\sum X^2$	8.3	40	91	71	210
Std.Dev.	0.27	0.31	1.4	1.0	1.3

(a) Summary of Data

Source	SS	df	MS	
Between-treatments	22	3	7.5	$F = 9.8$
Within-treatments	15	20	0.76	$P = 3.4 \times 10^{-4}$
Total	37	23		

(b) Result Details

Because we have found a statistically significant result in the one way ANOVA test, we conducted a Tukey HSD post hoc test. This test is designed to compare each of our conditions to every other conditions, and determine the degree of impact of adding steel cable reinforcement to geopolymer mortar.

Table 3.7: One way ANOVA (Geopolymer sample fracture energy)

Treatments					
	1	2	3	4	Total
N	6	6	6	6	24
$\sum X$	4.3×10^3	9.1×10^3	2.2×10^4	1.2×10^4	4.8×10^4
Mean	7.2×10^2	1.5×10^3	3.7×10^3	2.1×10^3	2.0×10^3
$\sum X^2$	3.2×10^6	1.4×10^7	8.7×10^7	2.6×10^7	1.3×10^8
Std.Dev.	130	94	830	300	1.2×10^3

(a) Summary of Data

Source	SS	df	MS	
Between-treatments	2.9×10^7	3	9.8×10^6	F = 49
Within-treatments	4.0×10^6	20	2.0×10^5	P = 1.0×10^{-5}
Total	3.3×10^7	23		

(b) Result Details

The critical value in the studentized range distribution used in Tukey HSD test for $\alpha = 0.05$, κ number of samples = 4 and degrees of freedom for the error term $\nu = 20$ is $Q_{critical}^{\alpha=0.05, \kappa=4, \nu=20} = 3.96$. The Tukey HSD score is given by $HSD = \frac{M_i - M_j}{\sqrt{\frac{MS_w}{n}}}$, where M_i and M_j are the means of the sample to be compared, MS_w is the mean square within sample (error) and n is the number of samples in each condition (C0, C10, C15 and C20).

Tables 3.8, 3.9 and 3.10 show the Tukey's score for all possible pairs of different mean for max load, deflection and fracture energy. When the Tukey's score is higher than the critical value of 3.96, it shows that the varying the diameter of the steel cable reinforcement is meaningful for improving max load, deflection or fracture energy.

From tables 3.8, 3.9 and 3.10, it is worth noting that the adding steel cables of all three diameters are meaningful in improving the flexural strength of the geopolymer mortar. However the effect of a small increase in steel cable diameters (C10 to C15, C15 to C20) does not have meaningful impact in improving the geopolymer's deflection and fracture energy, and only helps to increase the max load that the geopolymer mortar is able to sustain without cracking.

Table 3.8: Tukey HSD score for all pair's max load

	C20	C15	C10
C0	17	15	9.8
C10	6.9	5.0	
C15	1.9		

Table 3.9: Tukey HSD score for all pair's deflection

	C20	C15	C10
C0	6.1	7.1	4.0
C10	2.2	3.1	
C15	0.9		

Table 3.10: Tukey HSD score for all pair's fracture energy

	C20	C15	C10
C0	10	8.2	5.2
C10	5.1	3.0	
C15	2.1		

3.3.3 Microstructure image of steel cable reinforced concrete

(a) Reinforced concrete's cross-sectional view (b) Reinforced concrete's exposed longitudinal view

Figure 3.11: SEM images of the hybrid reinforced concrete

The micro structure of the reinforced specimen (Fig3.11) showed penetration of the geopolymer mortar into the steel cable core, suggesting good mechanical bonding between the steel cable and the geopolymer mortar, and that method of insertion of steel cable into the printed geopolymer mortar did not introduces noticeable air voids into the concrete. In the longitudinal view, by nature of the

twisted strands of steel threads into a cable, provides grooves for mechanical lock to the concrete, similar to the ribs in the traditional rebars.

3.4 Discussion

The objective of this chapter was improve the structural capabilities of 3D printed concrete, which was achieved by the addition of a hybrid reinforcement system with continuous steel cable and short PVA fibers, and demonstrated through flexural bending. The flexural performance of the hybrid reinforced system was shown in Fig.3.10 to significantly improve in contrast to fiber reinforced geopolymer.

In this experiment, stainless steel SUS 304 wire were chosen can woven into 7 bundles of 7 strands each, as known as the 7x7 cable configuration. The cable configuration was used for the 3 specimen group. In order to further increase the tensile load capacity of the reinforced geopolymer, one simple solution is to use thicker diameter cable. However the thicker the cable, the stiff it gets, and it would require a higher minimum bending radius, limiting the freeform design of 3D printable concrete. One solution is to use a higher wire strand configuration such as 6x37 or 8x19, which has a smaller minimum bending radius at the same cable diameter.

Another solution is the adopting a different cable design such as the Filler wire or Warrington design, instead of the single size cable design. Both the Filler wire and Warrington wire design, used a variation of small and large diameter wires to provide greater flexibility and strength. As shown in Fig3.12, the Filler wire design uses small wire to fill the voids between the larger wires. This provides the Filler wire design with a high load resistance, as there is more steel in the cross-sectional area of a steel cable. However as the voids between large wires are reduced, the bending flexibility is likewise reduced. This would limit the Filler wire design to be used in situation where rectilinear walls are designed, which does not

require high bending flexibility. The Warrington design fills the outer layer with alternate large and small wires. This design provides good bending flexibility and higher strength as compared to the regular single sized steel cable design. However as the Warrington design has alternate large and small strands, it has low crush resistance, as the small strands may be misaligned when subjected to high bending load.

Figure 3.12: Steel cable design

As in this experiment, a majority of the specimen failed through compression crushing, which was a sign of overly reinforced concrete. Therefore there was a need to use higher strength geopolymers matrix, to improve the overall performance of the reinforced system or use smaller diameter cables, such that the system would be an under reinforced concrete structure, and fail through ductile yielding of the reinforcement cables.

In some of the specimens, as in Fig.3.96.6b, where shear slips occur due to poor bonding between the printed filaments. Such a failure is undesirable, as they are sudden and can be catastrophic. This poor bonding between layers can be extensively studied in multiple 3D printing concrete papers[100][96], and this orthotropic nature is characteristic of 3D printed concrete. It is possible to avoid shear failures, through improvement to the bonding between layers by improving the 3D printing process, the inclusion of additional reinforcement stirrups (perpendicular to the longitudinal axis of beam) or the application of fiber reinforced polymer (FRP) sheets as a near surface mounted reinforcement on the 3D printed concrete

structure [101].

3.5 Conclusion

The performance of hybrid reinforced printable geopolymer concrete with different cable diameter was investigated in this research, with the following conclusion drawn:

First, this method of hybrid reinforcement is a new technique with statistical significance in enhancing the performance of geopolymer concrete in flexural, with a 300% increase in flexural strength over the control plain fiber reinforced geopolymer can be achieved.

Second, usage of hybrid reinforcement in printable geopolymer with short PVA fiber and continuous stainless steel cable helps to address the issue of cable slip-page reported by Freek P. Bos's group [31] and our initial experiments with single cable reinforcement in plain geopolymer. This improvement is attributed to the interaction between short PVA fibers and microcracks formed due to the pull out of the long steel cables. In normal fiber reinforced concrete, upon the growth of crack mouth, the role played by short fiber is reduced drastically. In the case of singly reinforcement by long cable, the cable has the tendency to slip on pull out, reducing its effect on flexural improvement. And in the case of singly reinforcement by short fibers, the fibers were unable to bridge the macrocracks after crack initiation. With hybrid reinforcement, the short PVA fibers arrest the microcracks caused by the pull out of the long cable, allowing it to continue reinforcing the concrete specimen, and improve flexural strength and ductility.

Third, all specimens reinforced with cable shows an increase in their first crack load, with positive association in increasing diameter of the stainless steel cable used.

Fourth, the fracture toughness of the hybrid reinforced geopolymer composite improved significantly when compared to the control group, with an increase in cable diameter, increasing its toughness.

Future work on the development of this new hybrid reinforcement method can focus on cyclic loading on the behavior of hybrid reinforcement printable concrete. Also, the effectiveness of this reinforcement method should be tested and compared to large scale reinforced concrete beams.

In 3DCP, printable cementitious material was developed to print without formwork and with the goal of freeform printing, enabling it to print curved buildings. Research was emphasized on producing cementitious material with low dynamic yield stress (pumpable) and high static yield stress (printable). The extruded layers are also required to possess good bonding between layers, and thus able to print progressively larger structures. This low dynamic yield stress during pumping also facilitated the bonding of cementitious material to the reinforcing wire that we had developed in this chapter. The cementitious material is flowable enough to penetrate the grooves of the reinforcing wire, thus providing good mechanical interlocking, additionally the cementitious material encases the steel wire and provides good bonding to the steel wire, therefore allowing us to successfully develop the in-nozzle impregnation process of freeform wire reinforcement for 3DCP.

In this chapter, we developed an in-nozzle impregnation process to incorporate steel wire into the printed concrete filament while printing. As the system prints both steel wire and concrete simultaneously together, the flexible steel wire will take the form of the printed design when the concrete harden. As such, this system allows for freeform printing while improving on the mechanical strength of the printed concrete.

This freeform reinforcement process would pave the steps for freeform printing. 3DCP generally prints 2.5D design, as the printed structure would be loaded

with internal compressive forces and concrete is stronger in compression. Complex curved design would impose internal tensile forces and would therefore be required to be reinforced. For 3DCP, fresh concrete is particularly weak in tension and would require support, and therefore in the next chapter, we have developed an adaptable membrane formwork to support the fresh concrete self-weight during printing and facilitate the expansion of possible freeform design that can be printed.

Chapter 4

Development of a printing system to 3D print non-developable doubly curved concrete panels.

4.1 Introduction

Curvature adds possibilities to architecture that would not exist if only straight lines and linear layer surfaces make up the architect's toolbox. The use of curvature results in richer and more expressive designs. Although the use of curvature is not new, until now it has mainly been restricted to high profile projects or iconic architecture. This is caused by the higher costs of curved buildings as result of the extra effort needed for correct measurements in drawings and on the building site, the need for unconventional construction methods on the building site, or, in case of manufacturing, the extra costs of manufacturing complex shapes in the factory.

3D Concrete Printing has demonstrated its potential to disrupt the construction industry by printing concrete walls without conventional formworks [102]. 3D Concrete Printing achieves this by modifying the cementitious mix design to allow for

higher fresh yield strength, fast setting and easy extrudability. This mix design is extruded from a nozzle that is accurately positioned with a robotic / gantry printing system. The extruded cementitious mix is printed in a layer wise manner and the concrete structure is build up without formwork. This system is first described as Contour Crafting [17] and has been the basis for other 3D Concrete Printing setup [103]. In this generic printing setup, 3D Concrete printing has a limitation of not being able to fabricate overhung parts because of the cementitious materials low green strength properties after extrusion. Unless the cementitious material is reinforced or the use of corbeling (cantilevering) is used, significantly overhung parts cannot be printed [14]. As such, to print non-developable surfaces, it is necessary to provide temporary supports to print gradient and curved structures. A non-developable surface is described as a surface with a non-zero Gaussian curvature, they can be doubly curved like a hyperbolic paraboloid or a sphere, which can be more difficult to manufacture.

Other pioneers of 3D Concrete Printing have explored Shotcrete 3D Printing so as to print freeform 3D structure with large overhangs [104][105]. Lindemann et al [104] describes Shotcrete 3D Printing as a highly controlled process using a robotic arm to spray the concrete onto a surface so as to built up the 3D structure. However Lindemann et al also mentioned that due to the complexity involved in Shotcrete 3D printing, the resolution and accuracy of the printed 3D structure is difficult to achieve.

In this chapter, we investigate a method to support the printing of doubly-curved concrete surfaces, which are non-developable, on an Adaptable Membrane Formwork. The system is a temporary formwork consisting of a grid of adjustable threaded rods, covered by a flexible membrane. We used an specifically-designed algorithm to slice and generate the curved print path for 3D Concrete Printing. This experimental method is evaluated with regards to surface quality and geometric fidelity.

The remainder of this chapter is organized as follows. In Section 2, we review existing manufacturing techniques for curved concrete. In section 3, we present in detail the proposed curved concrete printing set up. In section 4, we report the results of the modeling and accuracy and precision assessment. In section 5, we conclude by discussing the limitation of our current system and the direction for future work.

4.2 Related work

While 3D printing in the general sense promises the possibility of freeform fabrication, 3D Concrete Printing has largely been limited to the printing of planar structures. This is due to the low yield strength of early age concrete that has just been freshly extruded. This low yield strength prevents overhanging concrete from being printed, hence to date free standing freeform curved concrete structures have not been printed.

The common strategy to manufacture curved concrete is to cast concrete using static formwork. To increase the efficiency and reusability of the system, reusable mold systems have been developed. Renzo Piano first introduced the idea of a flexible formwork for the production of freely formed panels in the 1960's, however it has proved difficult to manufacture double-curved concrete panels in practices. PERI introduced a wall formwork system that uses pre-assembled panels for curved walls [67]. However, PERI's system is only suited for the construction of single curved elements, with a minimum radius of 1m. ADAPA developed a flexible formwork that prefabricate non-structural double-curved concrete facade panels [68]. The formwork consisted of a membrane that is supported and adjusted by CNC controlled actuators. This membrane is required to be have both flexibility and rigidity, to form doubly curved surfaces and high stiffness to avoid sagging due to the concrete load. ADAPA's system requires the concrete to be first poured

on to the planar shaped formwork prior to the actuators deforming the concrete into the defined double-curved geometry, after the concrete has gained sufficient strength through curing. However ADAPA's system would thus risk discontinuities in the curing concrete and as it bend the concrete after the concrete has set. In a similar work by Schipper et al [69], their group adopted the same technique as ADAPA and manufactured doubly curved concrete through deliberate deformation of the flexible mold after casting. In their work, they studied mainly the rheological properties of concrete, as they recognizes that deliberate deformation of concrete in an open mold, can cause the concrete to either spilled out of the mold if the concrete has not cured sufficiently or cracked if the concrete is too stiff. In addition, the maximum radius of curvature achieved by their system is 1.5m.

In 3D printing application, Costanzi et al [70] discussed the possibility of adopting a flexible mold developed at TU Delft for 3D printing applications. In the paper, they highlighted a possible work flow of using a flexible mold alongside 3D concrete printing. However Costanzi et al did not print the concrete over a flexible mold, instead they printed the perimeter of the structure over a CNC-milled static mold and cast concrete to fill the structure. Also, they did not provide a quantitative assessment of the print quality or of the geometric fidelity.

In this chapter, we outlined the design, selection and simulation study for the Adaptable Membrane Formwork, open sourced algorithms to generate the printing path of curved structure and validation process for 3D printing of freeform curved structures. We will demonstrate 3D concrete printing of the full curved structure directly onto an Adaptable Membrane Formwork, in contrast to the work by Costanzi et al. This presents new challenges as unlike printing on a fully supported CNC-milled static mold, an adaptable mold would deform if the mold surface's force equilibrium is not accounted for. The force analysis is conducted in Abaqus to ensure that the Membrane formwork is not overly deformed that it loses geometrical consistency to the designed shape.

As the full curved structure is being printed using 3D printable concrete, as opposed to the work by Costanzi et al, there is the challenge of designing a printing path that produces smooth curved surfaces. In normal 3D Concrete Printing of curved structures, the curvature is digitalized. When combined with the stiff, shape retenting properties of 3D printable concrete, the printer produces a staircase effect (Fig.4.1). This problem is not seen when casting concrete, as a self compacting concrete of good flowability can be used to allow the concrete to flow along the curve. However using self compacting concrete on a curved structure cannot guarantee that the produced curved surface is of uniform thickness. We adopted a method from curved layer fused deposition modeling in polymer 3D printing [106] to produce a smooth curved surface. Therefore, we expect our system to be able to produce surface with higher radius of curvature when compared to convention printing of non rectilinear structure as described by Lim et al [2].

Figure 4.1: Staircase effect in existing schemes for curved concrete printing.

4.3 Materials and methods

4.3.1 Adaptable Membrane Formwork

The Adaptable Membrane Formwork consists of a grid of threaded rods, whose heights are adjustable, covered by a membrane sheet. The rod grid and the membrane are further described below.

Rod grid

The rod grid is pictured in Fig. 4.2: it consists of 4×4 stainless steel threaded rods of 10 mm diameter and 300 mm length. The distance between the centers of two neighboring rods is 70 mm, yielding a base surface of 210 mm $\times$ 210 mm. The heights of the rods above the surface can be manually adjusted according to the structure design, defining thereby a temporary surface on which the membrane formwork is laid. In the experiment, the individual rod heights are taken from the surface profile of the design structure and the rods rotated until the required height is reached. Alternatively, the rods could be fitted to servo motors, which would enable their heights to be automatically adjusted.

Figure 4.2: Rod grid with height-adjustable rods.

Printing structures

The doubly curved structures we set out to model and print are a Dome and a Saddle with base area of 210 mm $\times$ 210 mm, mathematically defined by the following equations (see Fig. 4.5)

$$z_{\text{Dome}} = f_{\text{Dome}}(x, y) := (-\sqrt{(190^2 - x^2 - y^2)} + 190) \quad (4.1)$$

$$z_{\text{Saddle}} = f_{\text{Saddle}}(x, y) := \frac{\frac{x^2}{5} - \frac{y^2}{5}}{40} \quad (4.2)$$

Membrane selection

The membrane must be able to follow the curves and contours of the desired shape, without too much sagging. Fig. 4.3 shows two ways how a wrong membrane can affect the concrete panels: an overly rigid material prevents the membrane surface from being adjusted to the desired shapes, while an overly flexible material leads to uneven sagging on the surface. This sagging can be due to the weight of the cementitious material deforming the flexible membrane and causing it to lose its geometric fidelity, visually this can be observed as bumps on the printed panel.

Figure 4.3: Effect of the flexibility of the membrane material. Left: high Young's modulus (stiff). Right: low Young's modulus (flexible).

As we are printing a non-developable surface, we require that the flexible form-work material to be sufficiently elastic, such that it may be stretched to the required dimension, and still sufficiently rigid to resist excessive deformation caused by the weight of the printed concrete, we estimated that Spandex (Young's modulus of 200 MPa and Poisson's ratio of 0.3) is a good option. To verify this hypothesis, we conducted a Finite Element Modeling (FEM) analysis in Abaqus, reproducing the actual loading conditions, rod spacing, etc. A linear elastic model was used in the FEM analysis for a light bidirectional woven flexible membrane of 2mm thickness, undergoing uniform loading due to the weight of the printed concrete. As the flexible member is expected to be reusable, it should not experience any plastic strain and is assumed that the deformation of the flexible membrane remains in the elastic region. The flexible membrane is meshed with a total of 44100 elements, with a mesh density of 1mm.

We then compared the results of the FEM simulation to the desired shape. For completeness, we also conducted the FEM simulation for two other materials: Wood (Young's modulus of 15000MPa and Poisson's ratio of 0.35) and Rubber (Young's modulus of 1MPa and Poisson's ratio 0.5) and compared to the desired shape.

The membrane experiences increased loading with increasing number of concrete layer being printed on it. As such, to minimize loading, only one layer of concrete is printed on the membrane formwork. The thickness of the concrete layer can be increased by increasing the nozzle stand off distance from the membrane formwork and increasing the diameter of the extruder nozzle. If multiple layers of the concrete panel is required to be printed, the concrete is allowed to cured and gain enough yield strength before subsequently layers are printed on it. This would allow the concrete panel to bear the additional load, and avoid causing additional strain on the membrane formwork. However the subsequent layers should be printed while the prior layer is still fresh, as the bond strength at the interface degrades if the time gap between printing exceeds the printability time.

The results from the FEM simulation of the three materials are intersected with 6 test planes normal to $x = -60 \text{ mm}, 0 \text{ mm}, 60 \text{ mm}$ and $y = -60 \text{ mm}, 0 \text{ mm}, 60 \text{ mm}$. These planes were chosen so as to lay in-between the support nodes and thus likely to contain the greatest Z-errors ϵ , due to sagging or bulging of the membrane.

Next, we evaluate the print quality as follows. For each point $(x_{\text{FEM}}, y_{\text{FEM}}, z_{\text{FEM}})$ of the FEM simulation, the Z-errors ϵ between the model defined by equations (4.2) and (4.1) and the results of the FEM are given by (eq) and similarly for ϵ_{Dome} .

For each test plane $\mathcal{P}$, we select all the points $(x_{\text{FEM}}, y_{\text{FEM}}, z_{\text{FEM}})$ located within a distance of 0.5 mm from $\mathcal{P}$, and compute the mean and standard deviation of the Z-errors ϵ across those points.

4.3.2 Printing system

Fig. 5.5 shows the physical printing setup, which comprises a 6-axis robotic arm, a concrete mixing and delivery system (mixer, pump, hose, nozzle), and the Adaptable Membrane Formwork. The robot is mounted on a mobile platform, which could allow the printing system to print larger structures [107, 108].

Figure 4.4: Experimental setup comprising robotic printing system and Adaptable Membrane Formwork.

The robotic arm has a horizontal reach of 87 cm with an accuracy and repeatability of 0.02 mm. The accuracy and repeatability of the robotic arm is a measure of the performance of the robotic arm. The robotic arm can repeatedly achieve precise positioning of the end effector when executing the same task, this makes it highly suitable for positioning the extruder nozzle of a 3D Concrete Printing system. A extruder nozzle is mounted to the end effector of the arm, and a hose pipe attached around the length of the arm. The pump system delivers cementitious material to the extruder nozzle for selective deposition of concrete. The printing path can be generated from a given design or CAD file and sliced into a series of tool path coordinates for the robotic extruder nozzle to follow, and build up the printed structure. Our path planning system will solve for feasible and reasonable pose for each tool coordinate [107, 108]. A feasible solution is defined if the robotic

arm can position the extruder nozzle accurately onto the printing path without self collision or exceeding its joint limit. A reasonable solution is defined if the robotic arm is able to avoid failure points if there is a better solution.

4.3.3 Printing materials and process

Formulations used in this study consist of Ordinary Portland Cement (OPC, ASTM type I, Grade 42.5) [109], silica fume (SF, Undensified, Grade 940, Elkem company) [110], river sand, fly ash (FA, Class F) [111], natural river sand, water and superplasticizer (SP). The mix design of the concrete is important to maintain good extrudability and shape stability of the concrete filament. Mixing process is fixed to maintain rheological consistence [112]. After printing, the concrete shell structure is covered by a plastic sheet and demolded after one day. [113].

Table 4.1: Mixture proportions of 3D Printed Concrete

Materials	OPC	Sand	Water	Fly ash	Silica fume	Superplasticizer/(g/l)	PVA fibre
Proportion	1	0.5	0.3	1	0.1	1.3	0.05

Note: All ingredients contents are expressed as weight proportion of cement content

4.3.4 Generation of printing path

Using the equations of the Dome and Saddle in (4.2) and (4.1), one can generate PLY files, which are then processed as point clouds. The point clouds are digitally orientated onto the membrane formwork. The points and normals were taken from the bottom surface of the point cloud using a normal estimation algorithm.

The points and their normals of the point clouds were arranged in according to a print path strategy that starts from the lowest point to the highest point without overlaying of the path as shown in Fig. 4.5. The print path starts from blue to red. This print path strategy allows for fresh concrete to be printed on the prevailing

concrete filament and hence a more stable built up of filaments. The print path is also designed to be continuous to avoid disruption and throttling of the concrete extruder pump. This ensures that the concrete undergoes a constant flow rate and will not disturb the rheological properties of the concrete caused by changes in the shear rate of the extruder pump.

Figure 4.5: Printing path

4.3.5 Print validation method

As the technique of printing doubly curved concrete structure is targeted at printing architectural designed structures, the concrete panel is measured for geometrical fidelity and aesthetics. Given that the concrete panel is doubly curved, and to be able to capture all the measurement in its entirety, we chose imaging techniques as our validation method. In a previous paper, researchers have used a Kinect V2 3D camera to help map out the surface shape of a fresh concrete cylinder as it undergoes deformation[114].

The printed structure is placed against a clear background, at a distance of 0.5m normal to a Kinect V2 3D camera. The printed structure is ensured to be free from occlusion, and the bottom surface can be captured. The captured point cloud is then registered to the model point cloud using an iterative closest point (ICP) algorithm [115], and compared for Z-errors ϵ .

The ICP algorithm is able to handle the 6 degrees of freedom and perform rigid transformation of the captured point cloud, until the mean-square distance metric of the points in the captured point cloud is minimized against the points in the model point cloud. As the ICP algorithm described in [115] is known to converge monotonically to the nearest local minimum of the mean-square distance metric, a good initial alignment and pre-processing is required.

The captured point cloud is first pre-processed by passing through a pass-through filter that removes points in the background and NaN points. This step would effectively segment the points of the printed structure from the captured point cloud. Subsequently, a statistical outlier removal filter is also used to remove all noises from the capture point cloud. The initial alignment of the captured point cloud of the printed structure is transformed manually by objectively positioning the printed structure in the same normal direction as the model point cloud. The ICP algorithm is then applied to refine the pose of the point cloud.

The refined point cloud is then intersected with 6 test planes normal to $x = -60 \text{ mm}, 0 \text{ mm}, 60 \text{ mm}$ and $y = -60 \text{ mm}, 0 \text{ mm}, 60 \text{ mm}$. These planes were chosen so as to lay in-between the support nodes and thus likely to contain the greatest Z-errors ϵ .

Next, we evaluate the print quality as follows. For each point $(x_{\text{printed}}, y_{\text{printed}}, z_{\text{printed}})$ of the point cloud, the Z-errors ϵ between the model defined by equations (4.2) and (4.1) and the printed specimen are is given by eq

and similarly for ϵ_{Dome} .

For each test plane $\mathcal{P}$, we select all the points $(x_{\text{printed}}, y_{\text{printed}}, z_{\text{printed}})$ located within a distance of 0.5 mm from $\mathcal{P}$, and compute the mean and standard deviation of the Z-errors ϵ across those points.

4.4 Results

Results of both simulation on selection of membrane and printing of concrete shell structures are presented in this section.

4.4.1 Membrane modeling

Fig. 4.6 shows the FEM model of the 3 different materials for the Dome and Saddle structure. In Fig. 4.6(a),(d), for model built using the rubber, there is noticeable sagging of the surface when under loading due to the weight of the concrete deposited when printing. While in Fig. 4.6(c),(f), the center of the surface retains a distinct planar face as it resists the bending forces from the weight of the concrete. It is only in Fig. 4.6(b),(e), that the surface is still curved after concrete printing.

As such, it can be seen that it is necessary to carefully select the right material that is sufficiently flexible to be bend into shape and stiff enough to resist sagging when concrete is printed over it.

Fig. 4.7 and Fig. 4.8 shows the comparison of the different materials against the desired model at 6 test planes normal to $x = -60\text{ mm}, 0\text{ mm}, 60\text{ mm}$ and $y = -60\text{ mm}, 0\text{ mm}, 60\text{ mm}$. Fig. 4.7a and Fig. 4.8a shows the surface profile of the different materials against the desired model. Fig. 4.7b and Fig. 4.8b shows the mean absolute Z-errors ϵ of the different materials and the standard deviation of the Z-errors ϵ over the 6 test planes.

It is observed that the profiles of the spandex material follows the closest to the model profile, with a mean absolute error of 2.5mm, standard deviation of 0.45mm and mean absolute error of 4mm and standard deviation of 0.8mm for the dome and saddle shape respectively. This is in comparison to the rubber with mean absolute error of 2.7mm and 5.8mm and the lumber with mean absolute error of

3.4mm and 5.9mm for the dome and saddle shape.

Additionally, the rubber model shows significant sagging in the saddle model, with the weight of the concrete depressing the rubber membrane. The lumber model shows significant resistance to bending in both the dome and saddle model, as its young modulus is too high and it does not deform to fit the model. This results in higher mean absolute error for both rubber model and lumber model.

Figure 4.6: Comparison of the Dome model and the Saddle model using different materials in FEM

The flexible mold assumes the geometry of the designed shape and must have sufficient strength required to resist bending and the loading from the concrete printing while maintain geometrical fidelity.

The finite element model shows good agreement with the CAD model with mean absolute error less than 4mm for both the Dome and Saddle structure. This demonstrate that the selected material (spandex) is capable of bearing the pressure exerted by the fresh concrete and the bending required to adhere to the curvature of the CAD model, at a rod spacing of 70mm, in a 4x4 grid setup.

(a) Surface profile of the 3 materials at $[x = -60 \text{ mm}, 0 \text{ mm}, 60 \text{ mm}]$ and $y = -60 \text{ mm}, 0 \text{ mm}, 60 \text{ mm}]$

(b) Mean absolute Z-errors ϵ of the 3 material at $[x = -60 \text{ mm}, 0 \text{ mm}, 60 \text{ mm}]$ and $y = -60 \text{ mm}, 0 \text{ mm}, 60 \text{ mm}]$

(c) Mean absolute Z-errors ϵ over the full surface

Figure 4.7: Comparison of the Dome model and the different surface at 3 planes simulated by Finite Elements

(a) Surface profile of the 3 materials at $[x = -60 \text{ mm}, 0 \text{ mm}, 60 \text{ mm}]$ and $y = -60 \text{ mm}, 0 \text{ mm}, 60 \text{ mm}]$.

(b) Mean absolute Z-errors ϵ of the 3 material at $[x = -60 \text{ mm}, 0 \text{ mm}, 60 \text{ mm}]$ and $y = -60 \text{ mm}, 0 \text{ mm}, 60 \text{ mm}]$.

(c) Mean absolute Z-errors ϵ over the full surface

Figure 4.8: Comparison of the Saddle model and the different surface simulated by Finite Elements

The finite element model shows localized stress, particularly in the area where the rods are. Those areas have a higher stress state than other regions and may be areas where higher strain is likely to occur at this localized area.

4.4.2 Printed structures

The printed shell structures are shown in Fig. 4.9. The structures are visually smooth, with no observable surface roughness, as it was printed with mortar grade cementitious mixture using fine aggregates. There is even color variation as the printing was done continuously using a single batch of cementitious mixture. There is no staircase effect between layers as the printing path is printed normal to the curved surface, rather than normal to the substrate print bed as in the generic 3D Concrete Printing setup. Using a vernier caliper and measuring along the edges, the shell thickness is roughly 10mm.

Figure 4.9: Printed structures, viewed from the top and from the bottom. Left: Saddle. Right: Dome.

4.4.3 Quantitative assessment of print quality

An overlay of the printed part's point cloud and desired model's point cloud is shown in the top right of Fig. 4.10 and Fig. 4.11.

Fig. 4.10(b),(c) and Fig. 4.11(b),(c) shows the distribution of Z-errors ϵ of the Dome shaped part and the Saddle shaped part against an imaginary plane that intersects the printed part normal to $x = -60\text{mm}, 0\text{mm}, 60\text{mm}$ and $y = -60\text{mm}, 0\text{mm}, 60\text{mm}$. Individual plots of the profile of the printed parts against designed model can be found in Fig. 4.10d to i and Fig. 4.11d to i. It is observed that the profiles of the printed part are generally close to the target surface, with mean absolute error across the 6 planes is less than 2mm for the dome, mean absolute error of 4mm for the saddle. The biggest standard deviation is 0.5mm from the mean absolute error. The maximum absolute error for the 5mm for the dome model and 9mm for the saddle model.

The high standard deviation error might be attributed to the use of the Kinect V2 camera used to capture the point cloud. Yang et al found that at a distance of 0.5m, the average depth accuracy of the Kinect V2 camera is around 2mm [116].

The robotic printer shows no bias in printing along the longitudinal direction or transverse direction. It is observed that the robotic printer shows a higher average absolute error of 4mm when printing the Saddle part as compared to 2mm when printing the Dome part. The maximum error observed is 5mm on the dome and 9mm on the saddle structure. As when printing the Saddle part, it is a hyperbolic paraboloid shape which would require more support nodes to accurately reflect its shape as compared to the Dome part.

When printing the Saddle part, which has a hyperbolic paraboloid shape, the printing path translates down along the x-axis and up along the y-axis. This changing of gradient of the print path when simultaneously depositing concrete may have caused the printer to deposit an excess of concrete at those points, hence there are

Figure 4.10: Comparison of the Dome model and the actual printed surface measured by Kinect

Figure 4.11: Comparison of the Saddle model and the actual printed surface measured by Kinect

Z-errors ϵ of both positive and negative nature.

As all prints were performed on a thin spandex membrane, the actuators tips were seen to impart an indentation mark on the final product. We used a vernier caliper and measured along the edges of the printed part. The average shell thickness is found to be 10mm.

4.5 Conclusion

This chapter presents a novel method for the 3D-printing of curved concrete structures. Our setup consists of a 6-axis robotic printer and an Adaptable Membrane Formwork. This affords an increase in the level of flexibility and geometry complexity for the manufacturing process of concrete architectural elements. As a case study, we printed two non-developable, doubly-curved, surfaces: a Saddle and a hemisphere Dome. We showed that our setup could 3D-print these thin (10mm) concrete shell elements with good accuracy and surface finishing. This opens the way to flexible yet economically-sustainable schemes for manufacturing curved concrete surfaces.

Relative to simple rectilinear structures, curved structures contain internal tensile forces, which must be resisted by reinforcement. One example of reinforcement can be the embedded reinforcement discussed in Chapter 3. However, when printing freeform concrete, we must also account for the fresh concrete stage. At the fresh concrete stage, the fresh concrete must also be supported as the static yield stress has not developed sufficiently to hold its self-weight, as such we developed an adaptable membrane formwork to support the concrete self-weight during printing and facilitate the expansion of possible freeform design that can be printed.

In this chapter, we presented a novel method to improve on the printability of concrete of freeform design. Green concrete has low stiffness and mechanical

strength, and therefore it is unable to carry its self-weight, placing a limitation on the design that can be printed. The adaptable membrane formwork can support freeform concrete designs and is easily re-used for different design, which is also in line with 3DCP goal of waste reduction and freeform fabrication.

With a hardware system for freeform reinforcement and adaptable membrane formwork to support the freeform printing, we will also need to develop the software or printing path that can capture the advantages of freeform concrete printing. In the next chapter, we will present a printing path that directs the printing of concrete along the flow of stresses, which serves to orientate the printed structure to support mechanical loads on its strongest axis.

Chapter 5

Stress-cognizant 3D printing of free-form concrete structures

5.1 Introduction

In recent years, 3D concrete printing has been developed based on the layer-based 3D printing principle. Recent advances in material, process and machine development have enabled 3D concrete printing process to progress from experimental prototypes to full scale buildings. By building the physical model layer by layer, the 3D printing process can build complex geometry at relatively low manufacturing cost. This presents opportunities for engineers to design and manufacture complex engineering structures and the printed structure to be more material efficient, than possible using traditional construction techniques

Topology optimization is a field that naturally complements 3D printing. Topology optimization [117, 118, 119, 120, 121] is used at early stages of design to automatically reduce weight and material usage while satisfying constraints on performance. The complex design achieved through topology optimization can be easily manufactured through additive manufacturing technologies. Additionally

additive manufacturing can reduce its material consumption through printing a smaller optimized design [122, 123].

Existing research in topology optimization for 3D concrete printing has however left out a crucial aspect: 3D printing produces structures by selectively depositing material in a filament- and layer-wise fashion. This results in material anisotropy and weakness along the build direction. This material anisotropy can become critical when the printed part is designed for functional use and has to satisfy strength requirements.

However in the construction industry, the manufacturing and designing phase are often separate parts of a project. The architect may react strongly to changes to his design. As such adopting topology optimization to the 3D printed construction industry should minimize changes to the architectural design and use only the principles of topology optimization to design for 3D printable concrete structures.

In literature, the mechanical properties of 3D printed concrete exhibit significant anisotropy as compared to cast concrete using the same concrete mix design. This is due to the layer-by-layer and filament-by-filament manufacturing technique as shown in Fig. 5.1.

Figure 5.1: Anisotropic properties of 3D Concrete Printing.

The filament-wise printing causes an observable interface between the layers. This interfacial concrete matrix demonstrates significantly mechanical weakness compared to a homogeneous cast sample. This is due to partial drying of preceding layers while printing, which results in a poor concrete bond and the absence of aggregates at the layer interface.

Furthermore, reinforcement for 3D concrete printing is also directional. Reinforcement for 3D concrete printing can be done by the incorporation of fibers into the concrete mix, giving fiber reinforced concrete [124] or the use of an entailing steel cable in the concrete filament [31, 40]. In conventional fiber reinforced concrete, the fiber matrix is known to be randomly distributed. However, in 3D printed fiber reinforced concrete, the fibers are aligned along the filament direction as shown in Fig. 5.2 [125, 39]. In the case of the cable reinforced 3D printed concrete, the cable runs through the core of the printed filament and as such displays significant anisotropic properties as well.

Figure 5.2: Anisotropic properties of 3D printed fiber reinforced concrete.

This anisotropic property of 3D printed concrete can cause the printed samples to have significant variance in their strength when tested along different directions. As such, it is important to account for this anisotropy when designing a 3D printed concrete structure. A naive method in accounting for this anisotropy would be to over engineer the entire concrete structure, by taking the strength of the 3D printed concrete in its weakest direction as its core strength. However, this approach is not feasible as the 3D printed concrete has variance as much as 10 times when tested

along the Z axis as compared to the X axis [126, 88, 38].

Here, following [127], we proposed to design a printing path that is tailored for 3D concrete printing through numerical analysis of the finished structure, subjected to the designed loading conditions in its concrete application and subsequently print the concrete along its direction of principal stresses. This would mimic the stress flow inside the concrete sample produced by 3D Concrete printing and improves its ultimate fracture strength. This idea was inspired by previous work in 3D printing for fused filament fabrication [127, 128, 129], but here, we consider the specificity of concrete as further discussed in section 5.2.3.

Several concrete samples were 3D printed and mechanically tested. The mechanical test results were analyzed by comparing with classical Rectilinear printing path (REC) and the proposed Stress Line Cognizant printing path (SLC). An independent T-test with $p = 0.05$ significance were used to evaluate the statistical significance of using the SLC printing path in improving the printed concrete specimen mechanical performance and the SLC printing path influencing the weight of the printed sample.

The remainder of this chapter is organized as follows. In section 2, we review related work and use of principal stress lines in 3D printing. In section 3, we present in detail our proposed method in generation of the SLC printing path method. In section 4, we report the results of the mechanical test conducted on the printed concrete specimens using both the SLC printing path method and the REC printing path method. Additionally, we report the statistical analysis on the results of two printing path methods. In section 5, we conclude by discussing the direction for future work.

5.2 Related work

5.2.1 Anisotropy of 3D printed concrete

3D printed concrete has been characterized with material anisotropy [75, 130, 38]. This anisotropy can be process-induced anisotropy or planned anisotropy. The process-induced anisotropy is inherent of the 3D printing manufacturing technique, which extrudes concrete filament layer by layer. This results in an interlayer region between filaments and layers which has weaker micro structures and hence its anisotropic material properties. In contrast, planned anisotropy such as functionally graded concrete based on a multi-layer sandwich concrete panel or lattice concrete walls can be designed and printed. Overall, researchers seek to minimize or eliminate process-induced anisotropy while seeking to make full use and design for planned anisotropy.

In process-induced anisotropy, it is observed that the printing direction is critical in influencing material properties, as such optimization of the printing direction can significantly enhance the structural performance of the printed concrete structure [131]. To achieve this, printing path can be designed to extrude concrete along the direction of the principal stress direction, and is a stress-based method. This approach can be effective for shear weak materials such as plain concrete, and especially so in anisotropic 3D printed concrete. Another approach can be based on strain energy, by minimizing the strain energy of the structure under loading.

5.2.2 Principal stress lines

Principal stress lines are flow lines along the resolved principal stress direction of the infinitesimal small elements in a structural continuum. For a structural continuum under loading, finite element analysis solves for the stress tensors of

the elements in the structure. Each element has its individual stress tensor, as shown in Fig. 5.3, that shows axial forces and shear forces when decomposed into its directional components that acts on each face of the element. The stress tensor can be rotated such that the new rotated element has a stress tensor that resolves its shear components, and the normal axial forces are maximized. The rotation does not change the state of stress, but only describe the stress in that new orientation. Stress transformation allows the orientation of planes with special stress properties to be obtained. Specifically, the normal stress components corresponding to the planar orientation with zero shear stress and maximum normal stresses is known as the principal stress directions [132]. By tracing the principal stress vectors, a stress flow line can be observed. Structural designers are interested in principal stress lines because they provide a visualization of the natural flow of forces, and this flow can indicate the critical areas of material continuity due to the subjected load, as shown in Fig. 5.4.

Figure 5.3: Stress tensor of a 3x3 matrix.[4]

5.2.3 Principal stress line cognizant 3D printing

In the literature, there are some researches based on the use of principal stress lines in topology optimization for 3D printing. Topology optimization [117, 118, 119, 120, 121] is used at early stages of design to automatically reduce weight and material usage while satisfying constraints on performance. The complex design

Figure 5.4: Stress line of a cantilever beam.

achieved through topology optimization can be easily manufactured through 3D printing technologies. Additionally 3D printing can reduce its material consumption through printing a smaller optimized design [122, 123].

Tam and Mueller first explored the use of principal stress lines in 3D printing [128]. They used principal stress lines as a basis for topology optimization. In their paper, Tam and Mueller use nodal stresses and a criterion of maximum and minimum spacing in their generation of stress lines. However, the limitations of their strategy is the presence of gaps between non linear lines with nonuniform spacing as seen in Fig. 12 of "Additive manufacturing along principal stress lines" by Tam and Mueller. [128]. A topology optimization process based on principal stress lines was also proposed by Kwok, Li and Chen [129]. Their work demonstrated a good correlation with other topology optimization methods, as presented by Andreassen et al. [133]. However, topology optimization method removes materials from the structure, which would deviates from architectural design in 3DCP. This can be a source of limitation in 3DCP as concrete panels are required to be printed fully in design and the presences of holes or gaps can be source of stress concentration and structural weakness for the printed concrete panels.

Additionally, these works are based on the fused filament fabrication of Poly-Lactic Acid (PLA) material. Principal stress line ordered 3D printing is based on the assumption that the material's Shear modulus is less than its Young's modulus. It also assumes that the compressive strength is similar to the material's tensile strength when designing the printing path. As such, these frameworks is based on both tensile and compressive principal stress. However, concrete is known to have a much smaller tensile strength as compared to its compressive strength. As such, any printing path based on principal stress lines for 3D concrete printing should primarily focus on the compressive principle stress.

Alternatively, topology optimized ribs and stress transfer truss structures can be designed and cast, before a 3D printed shell structure be printed over the load carrying truss structures as done by ETH block research group [134, 135]. However, ETH block research group mainly focused on compression based structures. These structures are designed such that the structures when in service are stressed only in compression. This is because concrete has high compressive strength, and maintaining the concrete stresses in compression would allow it to remain serviceable under high loads. However, this would restricts the geometric shapes that can be utilized and printed, as true freeform structures would inevitable be placed under tensile stresses.

The goal of our work is to apply principal stress lines techniques in the printing path design of structural concrete when subjected to 3D concrete printing constraints of continuous printing and interlayer and interfacial anisotropy. Additionally, we develop new techniques that guarantee that the printing path will not change the overall design look of the structure, nor generate gaps in the printed specimens (100% material infill).

5.3 Materials and methods

5.3.1 Printing system

Fig. 5.5 shows the physical printing setup, which comprises a 6-axis robotic arm, a concrete mixing and delivery system (mixer, pump, hose, nozzle), and the Adaptable Fabric Formwork. The robot is mounted on a mobile platform, which could allow the printing system to print larger structures [107, 108]. The robotic arm has a horizontal reach of 0.9m with a repeatability of 0.02 mm. The extruder nozzle is mounted to the end effector of the arm, and a hose pipe attached around the length of the arm. The pump system delivers cementitious material to the extruder nozzle for selective deposition of concrete. More details on the system can be found in our previous work [107, 108].

Figure 5.5: Experimental setup comprising robotic printing system and curved formwork.

5.3.2 Printing materials and process

Formulations used in this study is shown in Table: 5.1, it consists of Ordinary Portland Cement (OPC, ASTM type I, Grade 42.5), Silica Fume (SF, Undensified, Grade 940, Elkem company), River Sand, Fly Ash (FA, Class F), water and Superplasticizer (SP) . The mix design of the concrete is known to be important in maintaining good extrudability and shape stability of the concrete filament [112]. Mixing process is fixed to maintain rheological consistence[113].

Table 5.1: Mixture proportions of Fiber Reinforced 3D Printed Concrete

Materials	OPC	Sand	Water	Fly ash	Silica fume	Superplasticizer (g/l)	PVA fibre
Proportion	1	0.5	0.3	1	0.1	1.3	0.05

Note: All ingredients contents are expressed as weight proportion of cement content.

The formulation of the cement used in this chapter was designed for 3D concrete printing, as such, it has a lower water to binder ratio than normal OPC cement. The lower water to binder ratio was used to help make the concrete stiffer and reduce shrinkage cracking. 3D printed concrete is more susceptible to shrinkage cracking, due to the absence of formwork and when printing panels, the large surface area to volume would result in higher moisture loss. As such, the low water to binder ratio is critical for a successful print. The low water to binder ratio also makes the concrete sticky, and therefore it has better adhesion to the fabric and does not slip during printing of the curved concrete panel.

After printing, the concrete shell structure is left to cure under a plastic sheet to prevent moisture loss for 24 hours before demolding. The printed concrete shells were very easy to demold and does not require any oil or demolding agent.

5.3.3 Design of the Stress Line Cognizant printing path

The generation of stress lines follows the methodology outlined below.

The initial printed structure is designed by an architect and submitted for manufacturing. We start by loading the CAD model of the structure to be printed into Abaqus for finite element analysis in a stipulated design space, with applied loads and boundary conditions. The analysis outputs the internal stress tensor of the designed printed structure.

The stress tensor is then used to plot the stress vector and the printing path is designed to follow along the stress vector with consideration of 3D Concrete Printing limitations. Starting from an initial printing point as the seed point, the printing path is developed along the direction of the stress flow through a weighted-averaged search in each seed point's neighborhood:

1. The weight of each point p in the neighborhood is calculated by

$$\text{weight} = w * |\text{angle}| + (1 - w) * \text{dist}_{pv},$$

where $w \in [0, 1]$ is the weighting factor. angle is the dot product of the stress vector of point p and that of the seed point, indicating the angle between these two vectors. dist_{pv} is the shortest distance from point p to the straight line through the seed point's stress vector.

2. The point in the neighborhood with the smallest weight is connected to the end of the path and removed from all further neighborhood checks. It then acts as the new seed point for the next round of path generation, until there is no more candidate in the neighborhood of the last active seed point.
3. Randomly select a seed point for each region that contains unvisited printing points and repeat step 1) and 2), until all the printing points are included in the preliminary printing paths.
4. Post-processing is performed to handle the 3D Concrete Printing limitations, in that the final printing path must be continuous and in a single path. This is

to avoid disrupting the flow of the concrete, which could lead to discontinuous and uneven extrusion, and will affect the interlayer and interfacial bonding of the printing concrete filament, thereby reducing its mechanical strength [136, 137].

In the experiment, we consider the architectural slab as shown in Fig. 5.6. The slab can be freeform and asymmetric, and will result in a stress vector that is distinctively different and unintuitive as compared to a conventional concrete slab. This is to demonstrate that the proposed printing path can account for seemingly complex designs. The designed printed structure would follow the similar loading conditions as conventional one way slabs. The flat sides of the design structure are subjected to encastre boundary conditions and a point load is placed directly on the center of the printed structure. The printed structure is meshed with C3D8 elements with suitable mesh size to ensure local stress values is accurate. The finite element model is solved to generate the stress tensor of each element. The principal stresses for each element can be calculated from the stress tensor by solving the eigenvalue problem. After calculating the principal stresses of each element, the stress vector, $\vec{X}_i$ with magnitude σ_1 can be integrated as lines across the designed structure. These lines are identified as the principal stress lines, and only the compressive component of the principal stress is used in the generation of the printing path.

$$\begin{pmatrix} \sigma_{xx} & \tau_{xy} & \tau_{xz} \\ \tau_{xy} & \sigma_{yy} & \tau_{yz} \\ \tau_{xz} & \tau_{yz} & \sigma_{zz} \end{pmatrix} - \begin{pmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \end{pmatrix} * \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} = 0$$

with σ_{ij} denoting normal stresses, τ_{ij} denoting shear stresses, and σ_1, σ_2 and σ_3 is the eigenvalue representing the principal stresses and $\vec{X}_i$ is the eigenvector representing the principal stress axes. Visually, it can be observed that the stress flows from the loading point towards the boundary. The printing paths used in this

chapter are shown in Fig. 5.7. The printing path starts from the red point and terminates at the blue point.

$$\left[\begin{pmatrix} \sigma_{xx} & \tau_{xy} & \tau_{xz} \\ \tau_{xy} & \sigma_{yy} & \tau_{yz} \\ \tau_{xz} & \tau_{yz} & \sigma_{zz} \end{pmatrix} - \begin{pmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \end{pmatrix} * \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \right] * \vec{X}_i = 0 \wedge \vec{X}_i \neq 0$$

5.3.4 Experimental section

Compression testing: A compressive test was conducted to verify the mechanical strength improvement when concrete structures were printed with the Stress Line Cognizant printing path (SLC). A control test set was printed using the classical RECTilinear printing path (REC). All test samples are printed using the same cementitious mix design. The filaments have a diameter of 10mm and a layer height of 10mm. The test samples were weighed to confirm that they have the same amount of cementitious material. The fabricated test specimens are those in Fig. 5.9. The samples were tested using a INSTRON 5960 dual column compression test machine as shown in Fig. 5.8. The test specimens were loading and tested until failure. The load displacement graph will be presented in the result section.

Statistical analysis: Independent T-test at $p = 0.05$ significance were used to evaluate the statistical significance of the SLC printing path affecting the weight and mean fracture load over the REC printing path samples.

Figure 5.6: FEM model of the design panel.

REC printing path

(a) Isometric View

REC printing path

(b) Top View

SLC printing path

(c) Isometric View

SLC printing path

(d) Top View

Figure 5.7: Printing path used in experiment.

Figure 5.8: Compression testing setup.

5.4 Results

5.4.1 Compression test

The printing of the asymmetric architectural structure is shown in Fig. 5.9. The printing is done in a continuous fashion and at the same flow rate. As concrete is a thixotropic material, the material flow rate of the concrete has a non-linear relationship to the shear rate of the concrete pump. By ensuring that the concrete pump operates at a consistent motor rpm, we can avoid affecting the shear rate of the concrete and therefore ensure a constant concrete flow rate. This would ensure that the printed concrete specimens are consistent throughout the experiment and across the sample groups.

Fig. 5.10 shows the load vs displacement graph of the SLC printing path samples and REC printing path samples. The load displacement graph represents the strength and service characteristics of the sample as it undergoes loading, which helps to describe mechanical properties of the printed concrete and allows engineers

(a) Printed samples using REC printing path method

(b) Printed samples using SLC printing path method

Figure 5.9: Printed samples of the designed panel.

Figure 5.10: Mechanical test results, comparison between the REC (control) and the SLC print path.

to compare the different printing paths used. From the load displacement graph, we can observe that the load drops sharply after reaching its maximum fracture load. This is also consistent with the observations during the compression test, with the concrete specimen cracking abruptly and the crack propagating rapidly through the specimen, stopping the compression test. This is theoretically expected as the concrete used in the experiment is a standard mix design without any reinforcement materials such as fibers. The concrete is a quasi-brittle material, and after reaching its maximum strength, an unstable crack propagation will occur.

The results are computed into Table 5.2 showing the average mechanical fracture load, average displacement, and weight of concrete samples in each group. From Fig. 5.11(a), we can check that the printed samples are of similar weight and the test results from the compression test is independent of their weight. From Fig. 5.11(b), it was noticed that the SLC printing path samples have a higher fracture load than the REC printing path samples. This shows that by printing with a SLC printing path, engineers can increase the maximum strength of the concrete by 24.5% as compared to the classical REC printing path.

Type	Maximum applied force to Fracture (N)	Displacement (mm)	Weight (Kg)
REC #1	688.0	1.8	3.78
REC #2	745.4	2.2	3.79
REC #3	724.5	1.2	3.64
REC #4	806.9	1.5	3.71
REC #5	705.8	2.4	3.70
REC average	734.1 ± 41	1.9 ± 0.5	3.72 ± 0.06
SLC #1	886.6	1.5	3.71
SLC #2	1032.9	1.7	3.79
SLC #3	1017.6	3.8	3.70
SLC #4	863.9	3.2	3.71
SLC #5	769.5	1.4	3.65
SLC average	914.1 ± 99	2.4 ± 1.0	3.71 ± 0.05

Table 5.2: Test results of the REC samples against the SLC samples.

(a) Specimen weight before compression test

(b) Specimen max load at failure.

Figure 5.11: Specimen test data

5.4.2 Statistical analysis

Statistical analyses using independent T-test was conducted to determine the statistical significance of the SLC printing path affecting the weight of the printed sample and improving the structural strength of the printed sample against the REC printing path.

The set of 5 samples printed using the SLC printing path method ($M = 914.1\text{N}$, $SD = 99.0$) compared to the 5 sample printed using the REC printing path method ($M = 734.1\text{N}$, $SD = 41.1$) demonstrated significantly higher maximum applied force to fracture, $t(8) = 3.36$, $p = 0.00498$. These results suggest that the SLC printing path improves the fracture strength of the printed concrete samples and the SLC printing path is a viable method for structural 3D Concrete Printing.

Next, we wanted to investigate whether the increased in load resistance could have been caused by an increase in weight, as this effect has been reported in literature [138]. The set of 5 samples printed using the SLC printing path method ($M = 3.71.1\text{kg}$, $SD = 0.0449$) compared to the set of 5 sample printed using the REC printing path method ($M = 3.724\text{kg}$, $SD = 0.0554$) demonstrated non significant changes in printed weight, $t(8) = 0.336$, $p = 0.745$. The SLC printed samples were largely similar in weight relative to the REC printed sample, and only differ in their orientation of their filaments and therefore the layout of their filament interfaces.

5.4.3 Crack pattern

The quantitative results have shown that the test samples printed with the Stress Line Cognizant printing path (SLC) have a higher mean fracture strength of 24.5% as compared to the control RECtilinear printing path (REC) test samples.

Here, we further investigate the crack patterns, see Fig. 5.12. For the test samples printed with the control REC printing path, the fracture crack is observed

Figure 5.12: Test samples after destructive compressive test.

to propagate along the filament interface region, from the initial crack at the loading point to the termination at the boundary. This is expected as the mechanical strength along the filament interfacial region was the weakest and the crack tip will easily propagate along the path of least resistance or mechanical strength [139, 140].

Comparatively, the test samples printed with the SLC printing path show a crack pattern that propagates from the loading point and terminates at the boundary. However, due to the printing path design, the propagating crack tip advances along the weak interface region and also shears through the solid concrete filament. As the crack path propagates along the interface, it reaches the solid concrete filament, which increases the effective surface area of the crack and therefore requiring a higher load, before shearing the solid concrete filament [141]. Visually, it is observed in the cracked SLC concrete piece, that the crack follows a path from the center along the filament interface and also shearing some solid concrete filaments.

This also results in higher mean strain as seen in Fig. 5.10, as the crack requires a higher load to initiate, resulting in the printed specimen having a higher fracture

toughness. The cracking mechanism observed here has been previously reported by Moini et al [142], who hypothesizes that the cracking mechanism which shows crack deflection at filament interface could be considered a Bouligand architecture damage mechanism. A Bouligand architecture like fiber reinforced polymer sheets can increase its mechanical strength and ductility by varying its fiber orientation along its layers. This improves the stress transfer along the layers as the propagating crack is partially deflected when advancing to another rotated layer and it makes the propagating crack less favorable, and strengthens the material.

5.5 Conclusion

This work applies a new printing path planning methodology that considers both design and 3D printing constraints previously used for fused filament fabrication on plastic to 3D Concrete Printing. It uses the principal stress lines techniques to order the printing path for 3D Concrete Printing. The mechanical test results demonstrated an improvement of 24.5% in mechanical strength by printing the Stress Line Cognizant printing path over the classical RECtilinear printing path control group. This shows that in 3D Concrete Printing research, the design of the printing path is equally important as material and process control research.

Additionally, research in printing path as such the Stress Line Cognizant printing path is general, as it is not dependent on geometric models, loading conditions or material properties. Therefore, it can be easily adopted and used in structural application by improving the mechanical strength without affecting other research areas. Through this method, we can make use of the anisotropy nature of 3D printed concrete to design and print stronger parts that is application and load specific.

The work presented used a simple compression loading condition so as to facilitate validation with the instron universal testing machine. In a real world condition,

concrete structures are designed for multiple loading conditions, which better simulate the different loads that the structure can be expected to experience throughout its service life. We expect the proposed method to perform similarly on a multiple load condition. Under multiple loading conditions, the Abaqus simulation will produce a slightly different set of stress tensor for the designed printed structure, but the same printing path design methodology will be applicable, to track the stress vector and generate the proposed stress cognizant printing path.

Through the preceding chapters, we have showcased our hardware of freeform reinforcement and adaptable membrane formwork that supports freeform printing. In this chapter, we have presented our software printing path for freeform concrete printing.

In this chapter, we presented a printing path that is designed for freeform 3DCP. We observed that 3DCP concrete has anisotropic properties and developed a stress-cognizant printing scheme to direct the printing path to follow the flow of stresses. This orientates the printed structure to support mechanical loads on its strongest axis and allow the freeform printed concrete to have increase structural stability. In the case study, we used an arbitrarily shape to demonstrate that the stress-cognizant printing scheme can be adapted for freeform shapes and arbitrary loading conditions.

With the preceding chapters of freeform reinforcement, adaptable membrane formwork and stress line cognizant printing path, we have shown that freeform concrete printing can be achieved. Although the samples we have thus printed were small in dimensions, it can be readily scaled up through our developed mobile robotic 3D concrete printer which we will present next.

Chapter 6

Mobile robotic 3D concrete printer

In a standard gantry concrete printer, the size of the print object is by necessity constrained by the dimensions of the build chamber of the printer. This limits the scalability of concrete printing in application to the construction industry, particularly when the nature of the industry requires large structures (i.e. houses) to be printed, and would be unimaginative to have ever larger printers just to accommodate bigger structures.

A provisional solution for building large structure while retaining a suitably sized printer, could be to use joints in the assembly of the printed parts. Small printed pieces can be mechanically joined together to form the final big structure. However joints may poses an additional challenge of complicating construction design and introduces weakness points along the joints. As such, the ideal situation is to print a large structure in a continuous fashion while keeping the size of the printer at a manageable size.

This section describes a framework for mobile robot 3D Concrete Printing, which addresses the above scalability problem, by attaching a standard concrete

extruder nozzle system on to a mobile robotic system. On the mobile robot setup, the concrete extruder nozzle will be able to build object of virtually unlimited footprint without compromising construction design and speed and can be further scaled up by including multiple mobile robots.

6.1 Robot Setup

The mobile robotic system is divided into hardware and software portions.

6.1.1 Hardware of the Mobile Robotic Printer

In this section, the basic hardware components to the mobile robotic printer is described. These are shown in Fig. 6.1, which includes a robot system made up of the robotic arm and mobile platform, a vision system made up of a stereo camera and fiducial markers, and a material delivery system which is made up of a nozzle extruder and concrete pump. The nozzle extruder can fitted with a custom printed nozzle attachment to adjust the nozzle diameter according to printing resolutions, Fig. 6.2

The robot system uses a Denso VS-087 6-axis position controlled robotic arm. The robotic arm has a payload of 7kg at the end effector, which allows mounting of the concrete extruder nozzle. It has a reach of 900mm from its base, with a repeatability of 0.02mm. The robotic arm is mounted onto a mobile platform (Clearpath Ridgeback). The Clearpath Ridgeback is a holonomic platform, with Mecanum wheel mechanism. This gives the mobile platform 3 controllable degrees of freedom, allowing it to move sideways and rotate stationary without executing complex maneuver and in a congested environment [143]. The mobile platform comes with a host of on board sensor which provides a rough low-cost localization capability, which is estimated from its odometry, inertial measurement unit (IMU)

Figure 6.1: Mobile Robotic Printer

(a) Pictor nozzle

(b) Nozzle attachment

Figure 6.2: Custom printed nozzle to adjust print resolution

and a 2D laser scanner. The localization ability of the mobile platform is considered rough as the error is estimated within a range of 1cm, and relatively low-cost with an update frequency of 30Hz.

The vision system is made of an Ensenso N35 stereo camera and ArUco fiducial markers [144]. The vision system helps to fine tune the pose estimation provided by the localization module using the onboard sensors of the Clearpath Ridgeback. Prior to printing, the print environment was seeded with a number of ArUco fiducial marker boards shown in Fig. 6.3b and Fig. 6.1. Each marker board is made up of six ArUco markers (Fig. 6.3a) that have a wide black border for easy detection in the camera image and an inner binary identifier matrix. Upon seeing the markers, its pose can be estimated from the four corners of the marker and in turn estimate the location of the mobile robot. To increase the robustness of the marker system, we used marker boards. The marker boards has a pattern of 6 markers whose corner locations are known in a common reference system. With multiple markers, it is harder to lose all the markers at the same time, and therefore more robust against partial occlusion, and the corners of all six markers are also available for pose estimation and thus the pose obtained is less influenced by noise.

Figure 6.3: ArUco marker board

Building on the localization sensors onboard the Clearpath Ridgeback, the Ensenso N35 stereo camera helps to achieve more accurate localization on a fine-scale. It tracks fiducial markers that are placed throughout the printing space. The fiducial markers have a wide black border and inner binary identifier matrix. These seeded square markers provides for fast detection of landmarks with extremely

strong feature signature, allowing for good localization and pose estimation capability by the mobile platform and camera system.

The material delivery system is mounted on the end effector of the robotic arm. It comprises of a custom nozzle of varying dimensions and a Mai Pictor grouting pump. The pump uses a screw conveyor mechanism to push concrete through the pipes into the nozzle where it is extruded out. Flow speed is controlled at the pump end.

6.1.2 Software of the Mobile Robotic Printer

The printing pipeline of the mobile robotic printer is shown in Fig. 6.4.

Figure 6.4: Software pipeline for mobile robotic printers

A given 3D Computer Aided Design (CAD) model is converted into Standard Tessellation Language (STL) format and sliced with an open source slicer program (Slic3r), which converts the STL file layer by layer into G-code. Which is a series of printing sequence, made up of the 3D points of every vertex in the original CAD model and extruder information. These 3D points are then extracted and processed

as way points in a trajectory for the mobile robotic printer. The trajectory is a time parameterized path, which coupled to the extruder nozzle system to match nozzle print speed and concrete extrusion pump speed.

Motion Planning

In robotic 3D printing, the robot(s) must coordinate to print concrete precisely according to the trajectory while avoiding collision with the printed structure and other obstacles. Motion planners can be coupled or decoupled [145]. A coupled planner computes a path in a combined configuration space, which treats the robots as a single combined and integrated robot. A decoupled planner would compute a path for each robot independently, and then plan a collision free trajectories for each robot along its path. Additionally, it can also plan the robot trajectory by order of priority and avoid the position of other robots which are considered as moving obstacles.

A decoupled planner was chosen as it is faster, with fewer degrees of freedom to be considered at any one time. First, the trajectory of each robot is planned but might not be collision free. Subsequently, the trajectory is re-timed to ensure that the robots are collision free while executing the trajectory. All the motion planning is done in our robot motion server using ROS OpenRAVE, which is able to visualize the tool path for verification. The code is then converted to b-CAP instruction for the DENSO robot to execute.

Localization process

Our motion planner assumes a prefect system model, which the mobile robotic printer is always localized and free of error. However, uncertainty and localization error may be introduced to the system, when the system model fails to account for errors such as wheel slippage, uneven floors or sensor drift. These errors can

accumulate and result in significant position error between the system model and the actual platform position. Therefore, to prevent collision and produce an accurate concrete print, the mobile robotic platform updates their locations at a stated frequency using the vision system and the mobile platform localization system.

Our localization strategy is divided into 3 parts, a system model, Clearpath Ridgeback localization system and the camera vision system. The system model is a generated model based on dead reckoning and tracks robot based on the control velocity given to the mobile platform. It is at best a system estimation and assume system fidelity, hence it is most susceptible to drifting error among the 3 systems. It depends on the constant updates by the robot to track its position and correct any error.

The Clearpath Ridgeback localization system is subdivided into two parts, a dead reckoning system and adaptive Monte Carlo localization system (AMCL). The dead reckoning system calculates the robot current position by using a previously determined position and advances the position based upon odometry and IMU data. While the IMU data is filtered through an extended Kalman filter based on sensor characteristics, error is still inherited from sensor drift. The odometry may also be a source of error due to wheel slippage or uneven floor.

The AMCL is a particle filter that estimates the position and orientation of a robot based on the odometry, IMU and 2D laser sensor readings. A map is initially built using Gmapping. The Gmapping package provides a laser based Simultaneous Localization And Mapping (SLAM). It creates a 2D occupancy grid map from the 2D laser data and pose data (Odometry and IMU) of the mobile platform. This constructed map allows the mobile robotic platform to know where the possible obstacles are and helps to prevent collision. This constructed map is then loaded into the AMCL package as an initial localization estimate. As the robot moves around, the AMCL package updates its particle and predict its new position. Whenever the 2D laser locates a feature in the map, the particles are resampled

based on recursive Bayesian estimate, and the position estimate is updated again.

The last system is the camera vision system which is employed for fine tuning the robots position. It searches for ArUco fiducial markers which are spread throughout the print environment. These ArUco markers have a unique inner matrix design that distinguishes each ArUco marker from each other, hence preventing feature mislabel, which is a source of error when using natural features. As each ArUco marker is unique and its position known, finding an ArUco marker allows the mobile robotic platform to obtain its pose from the relative pose information between camera and marker.

6.2 Results and Discussion

The end product of any concrete printer was the printed concrete structure (Fig. 6.5) and as such, the mobile robotic printers performance is judged on its accuracy, robustness and speed of printing concrete structures. Hence a series of small concrete prints were carried out and is concurrent, part of our groups submission to NASAs 3D printed Habitat competition. Finally, one large concrete print was done to access the full capabilities of the mobile robotic printer when required to print in an extended work environment, that is beyond the robotic arms workspace.

As shown in Fig. 6.6 cone and cylinder model were printed out with a 10mm circular nozzle as per the competitions requirement, and check for dimension accuracy. The cone was measured at 294mm high with a base diameter of 205mm and top diameter of 105mm. The cylinder was measured at 300mm high with a base diameter of 145mm. Both printed models were within the competitions dimension tolerance and accepted. Based on its acceptance in the competition, it can be concluded that our mobile robotic printer is able to comply and maintain strict dimensional accuracy in printing concrete structures.

(a) Hexagon concrete columns

(b) Small concrete basin

Figure 6.5: Printed concrete structures

(a) NASA compeition cylinder

(b) NASA compeition cone

Figure 6.6: NASAs 3D printed Habitat competition submission

In Fig. 6.7, a large scale curved wall was printed and spiral concrete extrudates was observed. This is caused by the discrepancy in nozzle deposition height, a consequence of an uneven floor. Excessive height deviation from the optimal 10mm (for a 10mm diameter nozzle) will increase the spiral patterns. This force inducing the spiral motion as it is extruded out from the nozzle at height is inherit from the pumps screw conveyor mechanism. The screw conveyor impacts a rotational torque to the concrete as it is rotated out of the auger screw. Solutions to eliminate the spiral patterns can be to switch the pump to a piston actuated pump where no rotational motion is imparted to the concrete or ensure that the print nozzle fiducially maintain its deposition height through active control using a laser feedback system.

Figure 6.7: Large scale curved wall with multi robots

A second measure of the printer performance is robustness. During the printing of the cone and cylinder models, no human intervention was required, and the printing proceeded automatically. However in the follow up printing of the large scale concrete curved wall, when the robotic arm is required to maximize its reach. It was noted that the joint 5 link of the robotic arm had drawn excessive current, when the hose pipe was twisted from printing a far out point in the planned trajec-

tory, Fig. 6.8. The joint 5 motor drew the extra current in order to counteract the rotational force caused by the torque in the hose pipe. Excessive current outside the working range is known to shorten the service life of the brushless motor and impact the robustness of the mobile robotic printer.

Figure 6.8: Excessive current drawn by DENSO robotic arm

Through the prints, printing speed of the mobile robotic printer was set relatively conservatively with the robotic at operating at 120mm/s and platform speed cap at 50mm/s, because of the initial focus on accuracy. Speed can be doubled up to 2000mm/s without making hardware changes, however care should be taken at maintaining acceleration limits without stressing the robot and inducing jerky motion that compromises on accuracy.

6.3 Conclusion

We have presented a scalable mobile robotic system for 3D concrete printing in the application of building and construction. The limitations of the classical gantry printer in 3D concrete printing were discussed and the advantages of using a robotic

arm for 3D concrete printing were elaborated. Using a 6 axis robotic arm in 3D concrete printing is necessary for researchers to print curved structures, as the standard 3 axis in a gantry printer does not have the articulate dexterity to orientate the print nozzle to follow a curved path. This is a first step towards fulfilling architectural designs in 3D concrete printing and deliver on its freeform manufacturing capabilities. The robotic printer is also coupled with a holonomic movable base to allow the robotic printer to expand its printing space and print indefinitely in the x-y plane. This would allow the robotic printer to print large scale architectural structures that are no longer confined to the dimensions of the gantry printer. Furthermore, the robotic printer extends the possibility of swarm printing, with multiple robotic printers sharing the same workspace, collaboratively printing a large structure. This would not have been possible in the classical gantry set up.

In conclusion, 3D Concrete Printing increasingly showcase itself as a promising tool of the construction industry. It has the primary advantage of reducing the dependence of construction industry on labour and is able to significantly increase the efficiency by removing the need to erect construction formwork. By solving various design and operational constraints, 3D Concrete Printing can present itself as an innovative technique that will disrupt the construction industry.

In the above chapters, the samples that were printed were small in dimension, as they were designed as a proof of concept of their respective technology, in terms of freeform reinforcement, freeform support, and freeform printing path. In this chapter, we will demonstrate that scaling up of freeform 3D Concrete Printing can be readily achieved through our development of the mobile robotic 3D concrete printer.

In this chapter, we developed a mobile robotic 3D concrete printer to allow for increased scalability of printing area. In the classical gantry style printers, engineers faced the limitations of a finite printing volume imposed by the gantry perimeter,

therefore there is a limit on the size and scale of the freeform that can be printed in a single print. By using a mobile, multi robot, printer, we can greatly increase the reachability of each robot printer and extend the effective printing area of the system. This would allow us to print the entire architectural structure in a single attempt, avoid the need for redesign or joints.

In total, we have presented a multi-scale approach to freeform 3D Concrete Printing that seeks to address the research gaps in freeform reinforcement, freeform printing path, freeform support, and freeform large-scale printing. Through ensemble of methods, we aim to bring freeform 3D Concrete Printing to the next stage and applied in the construction industry.

Chapter 7

Conclusion and Future Work

7.1 Conclusion

Overall, this thesis presents a robotic 3D concrete printing system that opens up the possibility for achieving complex, architectural designs in the field of 3D concrete printing. In literature, the bulk research in 3D concrete printing is currently focused on material development and printer process controls. They seek an early proof of concept of 3D concrete printing, and discourage intricate structurally optimized geometries, but rather prefers geometric simple rectilinear walls. This thesis demonstrates the proof of concept for printing reinforced non developable curved concrete through the use of a scalable mobile robotic printer coupled with a custom built reinforcement nozzle and adaptable fabric formwork. A stress line cognizant printing path planning methodology is also developed to help ensure the printed concrete is structurally sound without additional reinforcement materials.

In the first chapter of the thesis, we have developed a novel reinforcement method for inline reinforcement of 3D concrete printing and demonstrated its mechanical strength improvement. The novel reinforcement method address the shortcoming of the 3D concrete printing technology. As 3D concrete printing inherently

promises freeform designs, the classical methods of rebar reinforcement has to be further developed. The inline reinforcement method uses a flexible steel cable as reinforcement, and its flexibility allows the steel cable to be printed along with the extruded concrete. Therefore, the reinforcement maintains the same print path as the concrete and is freeform, and able to take any architectural shapes as required. A statistical analysis was also completed to demonstrate its the effectiveness of the novel reinforcement method.

As the aforementioned reinforcement method is inline reinforcement, there is an absence of reinforcement across filaments and layers. Confinements effects of the inline reinforcement methods can also be studied, and if different printing path can have advantageous effects when coupled with inline reinforcement.

In the second part of the thesis, we have developed a printing system and methodology for the printing of non-developable doubly curved concrete panels, and verified its geometry fidelity of the printing method. 3D concrete printing allows for the printing of complex, non-developable doubly curved structures. However, as the green strength of concrete does not have sufficient tensile strength, it is unable to print self supporting cantilever structures. Therefore an adaptable formwork was developed to support the 3D printed concrete. The adaptable formwork is able to form any shapes and therefore lend itself to the 3D concrete printing technology. The geometry fidelity of this printing system was also explored by taking 3D point cloud of the printed structures and comparing it to the designed point cloud. Overall, the adaptable formwork is found to be within geometric tolerances.

The adaptable fabric formwork method provides a temporary support for the structurally weak green concrete that is freshly printed. This allows the 3D concrete printing to print a number of complex curved structures that is previously not possible. However this method of temporary support only supports the immediate layer that is closest to the fabric. This does not allow for the printing of hollow structures.

In the third part of the thesis, we have developed of a printing methodology that uses finite element methods to generate a stress line cognizant printing path for 3D concrete printing, and reported the results of the printing method and its mechanical strength improvement. As the printed concrete is orthotropic in nature, the orientation of the printing path is critical in its ultimate mechanical strength when subjected to mechanical loading. The stress cognizant printing path method follows the principal stress lines while printing, and this allows the printed concrete to have a preferred orientation more suited for withstanding mechanical loads. Therefore a changing in printing path design would allow 3D concrete printing to print stronger structures without the inclusion of additional reinforcement materials like fibers. Additionally, the stress line cognizant printing path method is a line based tool-path planning methodology, and is therefore able to be implemented across all 3D concrete printing setups.

Finally, we have presented a scalable mobile robotic system for 3D concrete printing in the application of building and construction. The limitations of the classical gantry printer in 3D concrete printing were discussed and the advantages of using a robotic arm for 3D concrete printing were elaborated. Using a 6 axis robotic arm in 3D concrete printing is necessary for researchers to print curved structures, as the standard 3 axis in a gantry printer does not have the articulate dexterity to orientate the print nozzle to follow a curved path. This is a first step towards fulfilling architectural designs in 3D concrete printing and deliver on its freeform manufacturing capabilities. The robotic printer is also coupled with a holonomic movable base to allow the robotic printer to expand its printing space and print indefinitely in the x-y plane. This would allow the robotic printer to print large scale architectural structures that are no longer confined to the dimensions of the gantry printer. Furthermore, the robotic printer extends the possibility of swarm printing, with multiple robotic printers sharing the same workspace, collaboratively printing a large structure. This would not have been possible in the classical gantry set up.

7.2 Future work

3D printing to the general public implies the concept that any Computer Aided Design (CAD) can be produced independent of process planning, material knowledge and other research particularities. However unlike the matured Fused Filament Fabrication (FFF) technology which in some sense is able to manufacturing printed parts as any other standard 2D paper printers, 3D Concrete Printing still requires the attention of a production and product specialist. Every 3D Concrete printers has a set of research particularities that is unique to the printer that the research is using. The printed concrete properties can vary in both green and hardened state with changes in process parameters which can be non linear. As such the goal of 3D Concrete printing to being accepted by the Construction industry might be the full automation of a 3D concrete printer that can print without the interference of a 3D Concrete Printing specialist.

In the first chapter, the thesis uses a custom reinforcement nozzle for dual extrusion of concrete and reinforcement steel cable. The steel cable is automatically encased by the concrete and provides tensile reinforcement to concrete. However this method of reinforcement limits the dimension of steel cable allowable for tensile reinforcement. The steel cable has to be smaller than the concrete filament and of a diameter that does not bends out of shape when the printer is extruding curved paths. This restricts the possibility of placing significantly more reinforcement steel in a flexural concrete member and requires more steel cable to placed at areas what is non optimal. Future research work could explore the possibility of strategic placement of steel cable in the bottom most layer of a flexural concrete member by varying the dimension of the concrete filament, to printing large diameter concrete at the bottom layers so to accommodate varying amount of steel cable in the filament. Future work could also focus on the introduction of shear reinforcement by having steel cable in the Z-axis direction of a flexural concrete member. This can be achieved by redesigning the printing path of the concrete printer by printing

vertically in some area of the printing job rather than all planar XY-axis approach that is currently used.

In the second chapter, the thesis uses an adaptable membrane formwork to facilitate the printing of non developable curved concrete panels. The formwork system is currently uncoupled with the robotic printer and a re-searcher is required to synchronize the two system before printing. Future work can integrate the two systems. The geometric accuracy of the adapt-able membrane formwork is largely dependent on the material properties of the membrane and the load it is subjected to. The membrane is required to stretch itself so as to create the non developable curved system. Future work can be focus on the selection of membrane material and the automatic calculation of deflection imposed on the membrane under loading by the printed concrete. This can increase the geometric accuracy of the printed concrete.

In the third chapter, the thesis uses a stress cognizant printing path to print a non developable curved concrete panel that is experimentally shown to be mechanically stronger than a panel that is printed conventionally. The work demonstrate that load specified printing can increase the mechanically strength of the concrete part without the use of additional reinforcement material. The stress cognizant printing path is manually corrected from a script that plot the stress lines to address concrete printer particularities,like the enforcement of a continuous printing path. While the stress lines are independent lines from load bearing points to support points, the printing path requires a continuous path, and therefore sections of the stress lines are manually stitched together. Future work can explore the automatic generational of the stress cognizant printing path while following the guidelines of any concrete printer particularities, like the enforcement of a continuous printing path.

In the current implementation of the Stress Line Cognizant printing path,the framework was used to print a concrete panel, this can be considered as simplifi-

cation of a 3D model, sliced into multiple 2D layers and only a single individual 2D layer was plotted with the Stress Line Cognizant printing path. By plotting multiple 2D layers and printing them sequentially, we can form a 2.5D structure. In future work, the Stress Line Cognizant printing path should consider printing a 3D model as a whole model, where stress lines are 3D. This would better mimic the stress flows in a real 3D structure. However such printing may require self supporting concrete filaments which would be a future challenge.

The Stress Line Cognizant printing path is seeded from the load point to support points. As the load point was simulated with a single point load, the seed was naturally guaranteed to initialize in the high stress region. This ensures that the printing path is plotted to account for high stress region first before ending at the support points. In future work, we can consider different loading conditions such as a balanced distributed load, and how the Stress Line Cognizant printing path will be affected. We can also add weights to the high stress regions to ensure that the seed distribution starts in the high stress region and the printing path starts at those places.

In the last chapter, the thesis demonstrate the use of mobile robotic printer to greatly extend the scale of the printing footprint of 3D Concrete Printing. The mobile robotic printer uses a mounts a robotic arm onto a holonomic platform which drives the printer around, and uses a camera and inertial measurement unit for localization purposes. The mobile robotic printer can also be upscaled by introducing multiple robotic units for robotic swarm printing which greatly reduces the printing time [107]. However the localization system is built on the use markers which is artificially introduced into the environment. Future work can improve the system by using the environment as a natural marker and even a real time update of the printed part as a marker for localization. This would remove the need for seeding the environment and extends the possibility of employing the robotic printer in the construction environment as an on site printer.

The robotic printer might be planned for use in an unstructured outdoor environment. As the robotic printer currently assumes ideal conditions for printing, improvements could be made to the printer to include a robust tracking control to cope with the disturbances from the environment and the printing process. The existing camera can also be used to track the printing process and comparing it to the simulated print model, so as to identify deviation in printing, which can be corrected online or to alert the human operator.

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