Visions and Strategies for Reinforcing Additively Manufactured Constructions 2023

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Advances in Structural Applications of Digital Fabrication With Concrete

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Abstract. The construction industry needs to reduce its large environmental footprint drastically. Building with less material is one of the main levers for reducing this negative impact. This material reduction can be achieved with structurally efficient geometries requiring a higher degree of complexity than typically applied in conventional construction practices. Digital fabrication with concrete has been proposed as one of the solutions to facilitate the fabrication of efficient structures.

Over the last few years, extensive research has been conducted within the National Centre of Competence in Research (NCCR) Digital Fabrication at ETH Zurich to investigate digital fabrication with concrete for structural applications. Various digital technologies were investigated, including 3D concrete printing, digital casting, Mesh Mould, printed polymer formworks and knitted formworks. This contribution highlights the main findings of these investigations with a particular focus on the development of reinforcement strategies, as these strategies are an essential step to ensure compliance with existing design guidelines and ease of mass-market adaptation. Promising future research areas are identified based on the assessment of the technology readiness and sustainability potential of the investigated approaches.

Keywords: Structural Concrete, Digital Fabrication, Reinforcement Strategies, Sustainability

1. Introduction

Concrete is the most used construction material worldwide [1]. This success is mainly due to the universal availability of the required raw materials at low cost, besides the concrete's ability to be cast in any shape, high durability, fire resistance and excellent mechanical properties when combined with reinforcement resisting tensile forces. These properties led to the use of reinforced concrete as the base for modern civilisation, being suitable for applications ranging from housing to infrastructure. The massive amounts consumed make reinforced concrete the primary driver of the construction industry's environmental impact: the worldwide production of cement from calcined clinker currently accounts for approximately 10% of anthropogenic CO_2 emissions [2].

Reducing the environmental impact of construction is not trivial in the context of rapid growth in infrastructure and housing stock needed for a growing and more developed world population. Achieving this goal requires shifting towards holistic decision-making in construction, where environmental and social sustainability are considered similarly to construction efficiency (cost) and structural safety [3]. This shift will pave the way for new building concepts that use fewer and more sustainable materials while being competitive in countries with different levels of technological maturity. The vast amounts of concrete used and its versatile properties make its full substitution impossible. Therefore, concrete will continue to play an essential role in sustainable construction. As material-efficient concrete structures are likely to have a degree of geometric complexity higher than found in most current construction works, it is crucial to find ways of constructing such complex geometries at a reasonable cost and without excessive formwork waste.

Digital fabrication with concrete (DFC) has been proposed as one of the solutions to facilitate the fabrication of efficient concrete structures [3–6], as it allows (i) building complex shapes without high cost and (ii) tailoring the materials and their properties according to requirements. However, most digital technologies face difficulties penetrating the market due to the challenge of integrating reinforcement required to comply with existing building codes [7,8]. Over the past few years, extensive research has been conducted within the National Centre of Competence in Research (NCCR) Digital Fabrication at ETH Zurich to find structural applications of digital fabrication with concrete, where the integration of the reinforcement has been a key driver of technological developments. This paper highlights the main findings of these investigations, which cover a wide range of digital processes to produce concrete and reinforcement.

2. Opportunities of digital fabrication towards sustainable concrete construction

The environmental footprint of construction works is mainly driven by the total material usage, the embodied CO_2 of the used materials, and the achieved service life [9]. Therefore, improving environmental sustainability in construction requires addressing one or several of the following actions:

- Reducing the carbon footprint of the used materials.
- Using structural systems that (i) require fewer materials or (ii) use materials with a lower environmental footprint.
- Increasing the service life by using more durable systems or materials.

The most readily available lever for structural engineers is to reduce material consumption by structural optimisation. Producing material-optimised concrete structures with conventional construction processes is typically costly and wasteful, except for the case of modular construction, where formworks for complex shapes can be reused many times. DFC comprises a wide range of technologies that rethink, improve, and digitise traditional formwork processes to make the production of optimised structural systems competitive and more sustainable, even for one-of-a-kind members. Digital technologies can be split into technologies using no formwork and technologies incorporating "non-conventional formwork" [10].

Most digital fabrication technologies rely on additive processes that allow rethinking the combination of different materials. While in conventional construction, it is frequent to cast structural elements or members using a single concrete defined by the requirements of the highest loaded area, additive processes open the way to tailor the concrete grade to the actual needs. Reducing the concrete strength in those areas where high strength is not required is a straightforward way to use materials with a lower carbon footprint. Integrating non-conventional reinforcement systems such as fibres or textile materials into digital concrete processes also has great sustainability potential as they enable slender sections [11] and increased service life due to the lack of corrosion issues.

The following sections present specific applications and investigations where the sustainability potential of DFC is highlighted. The focus is on how reinforcement approaches compatible with the digital process can be integrated to ensure structural integrity. While Section 3 discusses reinforcement strategies that have been applied to digital concrete and digital formwork processes, Section 4 deals with approaches where the primary digital process is reinforcement fabrication.

3. Integration of reinforcement in digital concrete processes

3.1 Digitally fabricated formworks

The fabrication of formwork is a straightforward area of application in DFC. Printed polymer formworks combine the geometric flexibility of polymer printing with conventional casting processes. One of the critical aspects to overcome is the hydrostatic pressure of the concrete during casting. The Eggshell technology [12] solves this challenge by casting set-on-demand concrete [13], limiting the casting height or introducing lateral stiffeners, stabilising the ultra-thin formwork (see Figure 1a). This approach was applied for designing, fabricating and structural testing an optimised ribbed slab with significant material savings and load-bearing increase [14,15]. After casting, the polymer formwork is removed, leaving only the cast concrete. Instead of removable formwork, stay-in-place formwork can be produced with 3DCP. This approach was implemented in the Nubian Slab (see Figure 1b), where the lost formwork elements were preduced as 12 cm high vaults to reduce the concrete volume.


(a) (b)

Figure 1: Conventional reinforcement inside digitally fabricated formworks: (a) ribbed slab with polymer formwork (Ribb3d) [14]; (b) 3D concrete printed vaulted formwork (Nubian Slab) (Photo credit: Andrei Jipa).

The advantage of digitally fabricated formworks constitutes of combining conventional reinforcement and casting processes, enabling structural design following typical design standards. This ease of designing allows a fast implementation of these approaches in conventional construction. Concerning the sustainability of such structures, it should be noted that the environmental impact of the formwork might be significant, especially for stay-in-place solutions. However, the geometric flexibility is limited by the fabrication tolerances and the ability to insert the reinforcement. For geometrically complex reinforcement, digitally fabricated reinforcement might offer a viable solution (see Section 4.2). Alternatively, the geometric complexity can be increased by using fibre-reinforced concrete to replace part of the conventional reinforcement [15].

3.2 Digitally fabricated RC components

The fabrication and reinforcing processes are typically decoupled when using digitally fabricated non-functional formworks. When digitally fabricating entire reinforced concrete elements, it is still possible to split the digital concrete process from the installation in some instances. For example, the reinforcement can be post-installed in voids or the specimen surface, while fixed to the digitally fabricated element by grouting or spraying. The fixation allows activating the printed concrete structurally. This post-installation approach was used to manufacture shell elements (see Figure 2a) [16]. Alternatively, the digital fabrication process can also be done around pre-installed reinforcement (see Figure 2b) [17], or the reinforcement can be added during fabrication, e.g. between the layers of printed concrete (see Figure 2c) [18,19].


(a) (b) (c)

Figure 2: Reinforcement strategies for printed concrete elements: (a) post-installed reinforcement mesh with subsequent spraying [16]; (b) printing around pre-installed mesh [17]; (c) aligned interlayer fibre reinforcement [18].

Within this study, all fabrication processes were combined with conventional reinforcement to resist the main tensile forces. However, unlike the approaches relying on digitally fabricated formworks (see Section 3.1), the structural performance depends on the digitally fabricated concrete and its interaction with the reinforcement, i.e. bond: Tensile tests on the post-installed reinforcement shells showed no significant influence of the fabrication method [16], and the bond of conventional reinforcing bars between printed layers was higher than for conventional concrete [19]. The layering, typical for DFC processes, can have an effect on the cracking behaviour of concrete members that allows to reduce the reinforcement required for crack control [5].

Similar to formwork applications, geometric flexibility depends on the tolerances of the reinforcement. This geometric flexibility can be increased by adding different reinforcement types, such as fibres or cables between layers (see Figure 2c) [20]. The structural performance of these approaches differs significantly from conventional reinforced concrete.

3.3 Digitally fabricated connections

The size of digitally fabricated elements is limited by the operational space of the fabrication device, e.g. the reach of the robotic arm. Therefore, connections between elements are an essential part of DFC. A study on different connection typologies (see Figure 3) [17,21] highlighted the potential of using digitally fabricated connections structurally.

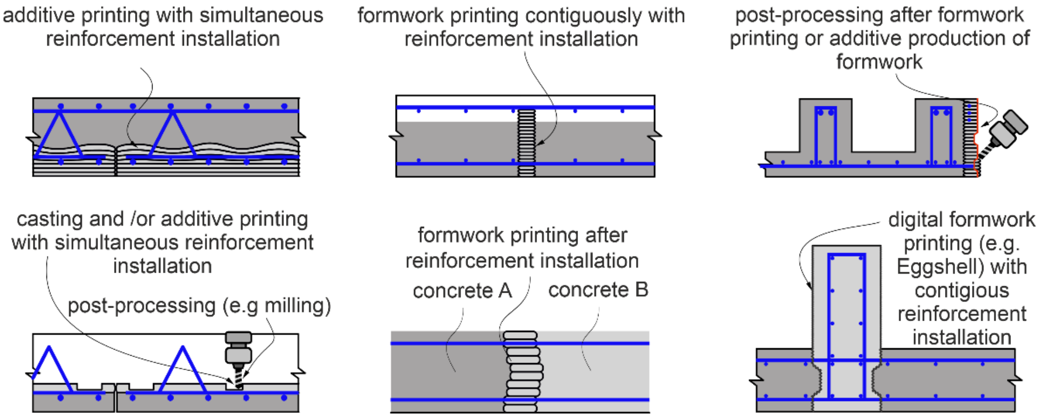

Figure 3: Different digitally fabricated concrete connections with crossing conventional reinforcement (adapted from Bischof 2023 [22]).

The connections can be used similarly to conventional construction joints or prefabricated elements, but the integration of reinforcement penetrating a joint is easier due to additive processing. Additionally, they can enable the casting of different concrete in different regions depending on the required performance, i.e. graded concrete (see Figure 3) [22].

4. Digital fabrication of reinforcement

4.1 Functional formworks

While using digitally fabricated formworks (see Section 3.1) is a straightforward solution to ensure compliance with structural requirements, the fabrication possibilities of the reinforcement limit the geometric flexibility. Moreover, producing a formwork that only has a moulding function is highly non-ecological unless it can be easily reused or recycled. Several digital technologies have been explored to produce geometrically complex stay-in-place formwork that can be activated as reinforcement. Integrating non-corrosive high-strength fibrous materials within weft-knitted fabrics extends the KnitCrete lightweight, flexible formwork technology [23] into a functional formwork which is activated structurally [24–26]. An extensive study on the structural performance of this system shows the importance of providing straight structural inlays [24] and interlocking the textile reinforcement and the concrete (e.g. with spatial ribs, see Figure 4a) to avoid delamination issues [27]. While textile materials are non-corrosive and enable very slender sections, their brittleness requires measures to ensure a ductile structural response by providing ductile reinforcement that governs the load-bearing capacity [11] or using double-curved structures with a high degree of static indeterminacy [26].

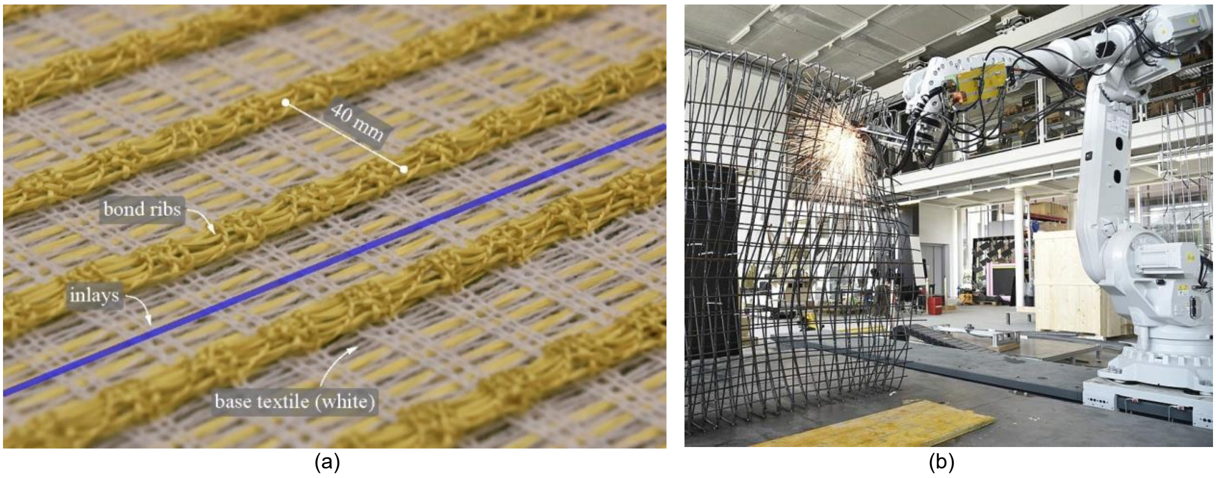

Figure 4: Digitally fabricated formworks with integrated reinforcement: (a) weft-knitted fabric with structural inlays and connectors before casting [27]; (b) steel reinforcement assembling process for the Mesh Mould Prefabrication technology [28].

The use of dense reinforcing steel cages that work as permeable moulds and structural reinforcement is a concept already used by Pier Luigi Nervi within the Ferrocement technology. The Mesh Mould technology automates this laborious process using robotically assembled reinforcement cages. Mesh Mould has been used for fabricating in a lean manner double-curved structural members that show similar structural performance to conventionally fabricated elements [28,29]. However, filling the permeable formworks efficiently is still challenging.

4.2 Reinforcement for non-standard shapes

Although digital fabrication of reinforcement has mainly been explored in the context of functional formwork, it also has great potential for producing conventional reinforcement for bespoke, non-standard shapes. Reinforcement cages for complex geometries could be very valuable in combination with the digital concrete processes presented in Section 3. They are also ready for use in combination with conventional formwork processes. However, even with straight bar elements, geometric complexity can be reached by applying geometrical principles such as ruled surfaces [30].

5. Conclusions

This paper has summarised the investigations conducted in the NCCR Digital Fabrication at ETH Zurich about the structural integrity of digitally fabricated concrete structures. The integration of reinforcement was a central part of the technological development in all investigated approaches, as these strategies are essential to ensure compliance with existing design guidelines and ease of mass-market adaptation.

Steel reinforcement cages can be combined with conventional casting processes using digitally fabricated temporary or stay-in-place formworks. While this approach leads to structural members complying with traditional structural design provisions, the great geometric flexibility offered by non-conventional digitally fabricated formworks is limited by the difficulty of manufacturing reinforcing cages for complex geometries within the required tolerances. Digital assembly processes of reinforcement are very promising to overcome these limitations.

Bespoke material-optimised concrete structures produced with temporary or stay-in-place digitally fabricated formworks might have difficulties competing in sustainability with conventional solutions because the formwork footprint is significant unless it can be easily reused or recycled. Therefore, using formworkless processes (e.g. 3D concrete printing or spraying) to produce entire reinforced concrete components or activating the stay-in-place formwork structurally as reinforcement is usually required to exploit the maximum environmental potential offered by digital fabrication with concrete. A wide range of reinforcement concepts can be used in 3D printed structures: printing around steel cages, post-installing the reinforcement or adding the fibres on top of the printed layers. Each approach has different advantages, and their combination might be required to ensure ductile structural behaviour while keeping a high degree of geometric freedom.

The presented results highlight that there are many different fabrication technologies and reinforcement approaches in digital fabrication with concrete, and so far, there is no one-fits-all solution. As mentioned above, each approach comes with its advantages and drawbacks, also compared to conventional production methods. Therefore, the area of application as well as the resulting environmental impact cannot be generalised but need to be evaluated on a case-to-case basis. The vast number of solutions makes the decisions challenging. While conventional deformed steel reinforcing bars remain the most straightforward and ready-to-implement reinforcement solution for most technologies, there is also great potential for combining them with fibre or textile reinforcement solutions that enable a higher degree of geometric freedom.

Going forwards, this area of research requires further development in (i) the automation of the reinforcement approaches, (ii) application to large scale demonstrators and real-life projects, and (iii) the assessment of the long-term behaviour and the resulting service life.

Data availability statement

This publication presents a conceptual study in which no data was generated.

Author contributions

Jaime Mata-Falcón: Conceptualization, Methodology, Supervision, Funding acquisition, Writing – original draft. Lukas Gebhard: Methodology, Investigation, Writing – original draft. Minu Lee: Methodology, Investigation, Writing – review & editing. Patrick Bischof: Methodology, Investigation, Writing – review & editing.

Competing interests

The authors declare that they have no competing interests.

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