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Interaction of reinforcement, process, and form in Digital Fabrication with Concrete

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ABSTRACT

Material, manufacturing process, and form are mutually dependent. In formwork-based concrete construction, the reinforcement must be positioned and fixed in the formwork, limiting material efficiency and freedom of form. In Digital Fabrication with Concrete (DFC), the formwork no longer limits the concrete forming process. Furthermore, the reinforcement no longer must be installed in advance, but can be placed before, during or after the concrete application. Therefore, the role of reinforcement and its interaction with processing must be fundamentally rethought in DFC. Furthermore, with reinforcement integration a concrete component expands from a contour-based shape into a structural form.

The current paper proposes a new so-called RPF-framework expressing the interaction of reinforcement, process and form in DFC. The application of this framework is illustrated using current examples of DFC, whose structural forms are critically discussed. Finally, the need for a holistic approach to material, process and form in DFC is emphasised.

1. Introduction

Building means to bring material into form, and processing is the technological link. In ancient times, only natural mineral and organic materials were available, and had to be processed manually. Greek and Roman structures were built of solid stone, while in other building cultures the granular mineral material was formed using clay as a natural binder. Due to the lack of sufficient tensile strength of the mineral materials, ancient buildings were designed as mass-active forms that only generate compressive forces. Based on these design principles, different building cultures and eras have produced a variety of architectural styles, all of which express the unity of material, process and form.

The age of industrialization brought new man-made materials, especially steel and concrete, to construction. And with these new materials, new processes and forms had to be invented [1]. In contrast to steel, with its high compressive and tensile strength, like natural stone concrete could hardly withstand tensile loads. It was only with the invention of the complementary behaviour of concrete and steel that these two mineral-based materials were combined to make a composite material: reinforced concrete. Now, the integrated reinforcement enabled the concrete to withstand tensile forces, making new elegant and

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material-saving structures possible, such as the Salginatobel Bridge in Switzerland by Robert Maillart (1930) possible [2]. However, as early as the beginning of the 20th century, two-dimensional system formwork and reinforcement grids, which were introduced for economic reasons, began to limit the formal freedom of design and structurally efficient use of materials. The resulting mass-intensive, geometrically simple constructions still dominate reinforced concrete construction today. As a result, materials and forms have been adapted to the manufacturing processes.

Nowadays, novel digital tools are available for design and manufacturing of reinforced concrete structures. In the field of Digital Fabrication with Concrete (DFC) there is a great potential to reinvent the unity of material, process, and form, and in particular, to adapt the manufacturing processes to materials and forms, again. Additive Manufacturing (AM) technologies offer the opportunity for a paradigm shift in designing reinforced concrete structures [3,4] The elimination of formwork opens up a new dimension for the efficiency of material, process and form. Especially, the reinforcement integration gains a new role as an integrative part of the DFC processes [5,6]. This is because the reinforcement no longer has to be placed and positioned - independently of the concreting process - into the formwork in advance, but can be digitally controlled placed in the areas subjected to tensile forces during the various phases of AM processes (before, during, and after). This makes reinforcement and concrete processing equal process partners that support each other [7]. While Digital Fabrication with Concrete was initially focussed only on digital concrete processes, this paper expands the understanding of DFC to include reinforcement integration as an integral part of DFC. Moreover, the digitally controlled reinforcement integration itself offers new perspectives for the role of reinforcement design in DFC: Through linearity and continuity, reinforcement elements provide clearly defined paths for forces that are fully determined by their alignment and continuity. Concrete, on the other hand, is massive and volumetric. Compressive stresses have to find their pathways within the entire concrete volume, depending on the boundary conditions, geometry of structure, and arrangement of reinforcement. Therefore, in DFC the precision of reinforcement integration plays a significant role in controlling the force flow in a material-efficient manner, and opens up completely new perspectives for the design of form-optimised reinforced concrete structures [8–10].

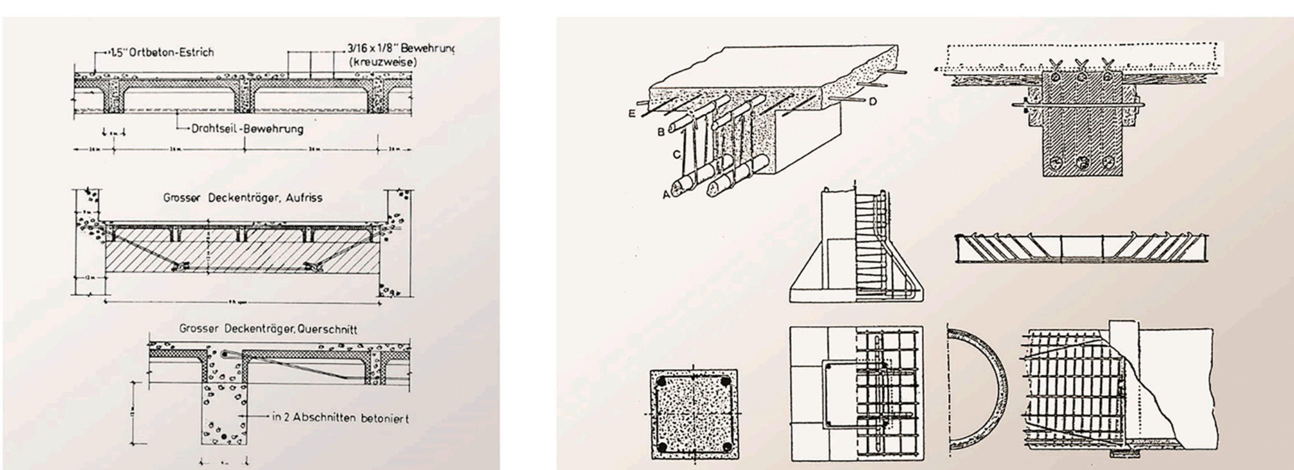
Based on these considerations, the aim of this paper is to identify the interaction of reinforcement, process and form in DFC, and especially to gain a new perspective on the role of reinforcement processing related to the concrete forming process. It is the integration of the reinforcement that gives a concrete component its structural form. Therefore, this paper sets up on findings from previous reinforcement papers, especially those focussing on material-process interaction [7,11,12] and extends them by the influence of reinforcement processing on the forming of reinforced concrete structures in DFC. After the introduction, a brief historical review on the beginnings of reinforced concrete construction is given, and the interaction of reinforcement, method, and form at those times are presented using selected examples. The core of the paper is built by the new systematic framework for the reinforcement, process, and form interaction in DFC, the so-called RPF-framework. Here, a distinction is made between two basic scenarios for an interactive reinforcement integration in DFC. Either concrete processing is the leading forming process, in which case reinforcement integration is primarily aimed at efficient local positioning to take up the tensile forces. Or the digitally controlled processing of reinforcement, in addition to taking tensile forces, is leading the forming. Finally, selected advanced demonstrators and their integration within the RPF framework are presented. Besides technological progress, understanding the interaction of reinforcement, process, and form in DFC is a great opportunity for structural engineers to expand creativity in structural design of reinforced concrete construction.

2. Historical retrospective on the development of reinforcement in concrete construction

2.1. Passive reinforcement

The first attempts to reinforce concrete with iron bars and wires date back to the 1850s [13]. While Joseph Louis Lambot used iron meshes to reinforce containers and boats, William Boutland Wilkinson and François Coignet already used iron bars and wires as reinforcement for concrete slabs, girders and columns, with layouts similar to those common today (see Fig. 1). As can be seen from the layout of girders, the reinforcement was mainly placed where the main tensile stresses occur, i.e., with a large lever arm at midspan and diagonal orientation close to the supports. Furthermore, the patent of Wilkinson (Fig. 1) shows stay-in-place formwork elements with in-situ cast concrete to produce ribbed slabs with low self-weight.

In the same period as Wilkinson and Coignet, Joseph Monier used iron meshes to reinforce planters and later (1878–1891) obtained ground-breaking international patents for reinforced concrete building construction. Monier's main patent was adopted in the following years by contractors, in particular François Hennebique who was a key person in the evolution and commercialisation of concrete construction with over 100 concessionaires spread over many countries.



a) b)

Fig. 1. Reinforcement systems proposed by a) William Boutland Wilkinson, 1854 [14], and b) François Coignet, 1855 [15].

In the early days of reinforced concrete, there were no standardised mass-produced reinforcing bars, but each system used different types of reinforcement. While François Hennebique combined longitudinal reinforcement consisting of smooth round bars with steel plate stirrups (Fig. 2a), Ernest Leslie Ransome used twisted wires and twisted bars with a square cross-section (Fig. 2b), and Julius Kahn employed "trussed bars" consisting of rhombic longitudinal bars with lateral steel plate flanges that were bent up at regular intervals (Fig. 2c) just like tension diagonals in a truss. This truss bar shows a common concept of early reinforcement application, with its placement inspired by the trajectories of the principle tensile stresses.

Ransome's bars can be seen as forerunners of modern reinforcing bars, as the twisting of the reinforcing bars causes an increase of the yield strength by cold-working to about 300 MPa (compared to roughly 500 MPa in contemporary reinforcing bars) and also enhances the interaction of concrete and reinforcement, commonly referred to as bond, of crucial importance for the load-bearing behaviour of reinforced concrete.

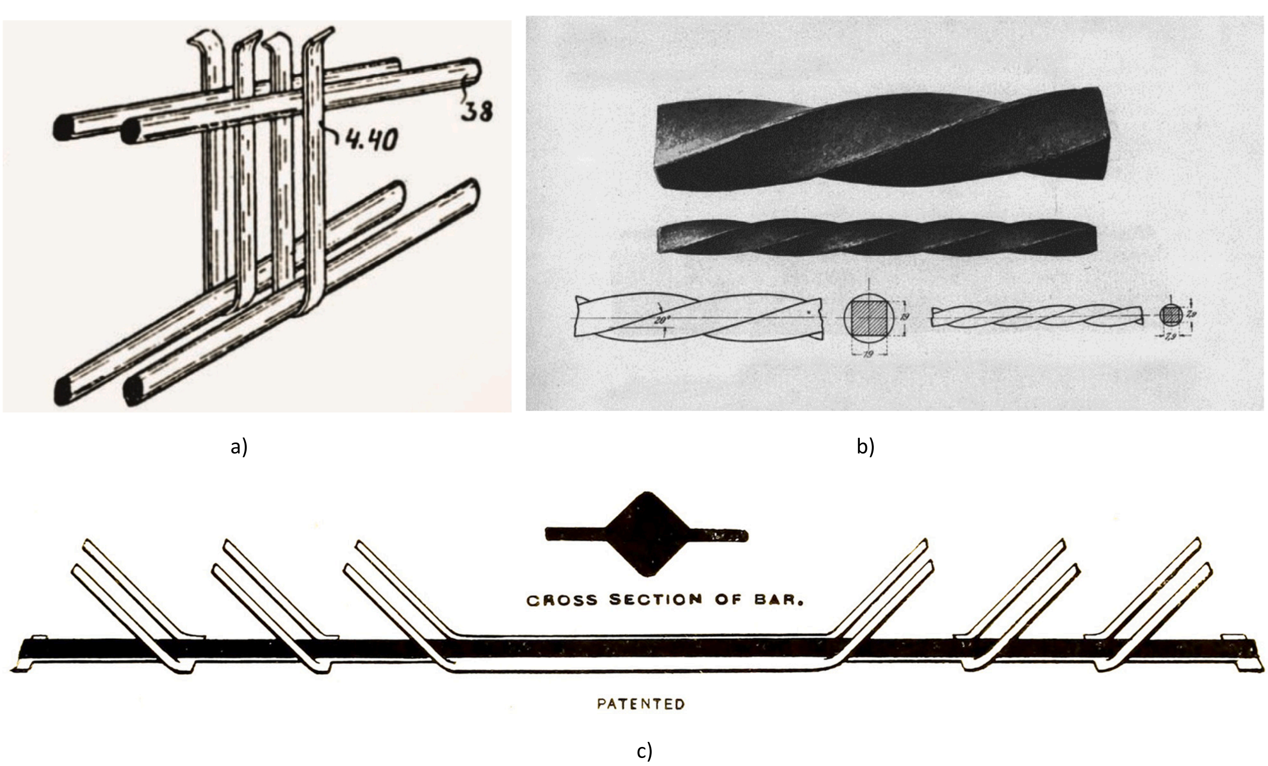
Modern reinforcement of concrete structures typically consists of hot-rolled, round reinforcing bars with ribs or indentations to ensure bond. While the bars were manually bent to the required shape for decades, the introduction of automatic reinforcing bar bending and standardised rebar shapes in the 1970s marked a significant step towards industrialised construction. Further developments that significantly increased productivity and ease of use were welded mats as well as a variety of reinforcement products including full-capacity rebar couplers, T-headed bar anchorages, standardised joint reinforcements and structural thermal breaks. While the industrialization of reinforcement production significantly reduced costs and increased productivity, it also reduced the design of concrete structures to simple and repetitive solid forms. Similar developments in formwork construction enhanced this trend, leading to today's low material efficiency concrete designs adapted for manufacturing efficiency.

One of the main drawbacks of reinforcing steel is corrosion. It was believed in the early days that concrete eternally protects the reinforcement from corroding. Today we know that this is not generally true, mostly due to carbonation and chloride ingress. Recognising corrosion of steel reinforcement as the main cause of deterioration of concrete structures caused increase interest in use of alternative materials, including stainless steel and carbon- or aramid fibre reinforced polymers.

2.2. Fibre reinforced concrete

Another reinforcement solution proposed decades ago is fibre reinforced concrete (FRC) [18]. Here, short fibres made of various materials, e.g., steel, polymer, or carbon, are added to the concrete matrix, resulting in a theoretically random dispersion and orientation of the fibres. The content of fibres was long limited by the workability of the concrete. It resulted in softening behaviour as the crack-bridging capacity of fibres is lower than the tensile strength of the concrete, and the fibres are gradually pulled out of the concrete matrix. These limitations were overcome by changing the cementitious matrix composition and adding short and thin fibres, resulting in strain-hardening cement-based fibre reinforced composites (UHPFRC, SHCC, CRC), see [19,20].

The efficient use of strain-hardening fibre-reinforced material imposes new methods of designing lightweight and thin-walled structures [21,22] as well as dry-joint connections, inspired by steel elements [23,24]. On one hand it helps in limiting the scatter of fibre orientation, on the other hand in employing the high compressive strength through



a) b) c)

Fig. 2. Reinforcing bars: a) François Hennebique [16]; b) Leslie Ransome [17]; c) Julius Kahn, 1904, ©Library of Congress.

reduction of sectional area. It further allowed for innovative developments, such as robot-guided magnetic alignment of steel fibres to increase resource efficiency [25]. The continuous reinforcement, in form of bars or prestressing, is used only in the direction of main forces.

2.3. Prestressing

Resourceful engineers had already tried to prestress concrete in the early days of reinforced concrete. However, their attempts failed as the prestressing was almost completely reduced by the long-term deformations of concrete (shrinkage and creep) and reinforcement (relaxation) due to lack of high-quality material. Accordingly, the breakthrough of prestressing came in the 1930s with the availability of high-strength (by the standards of the time) steel, which would typically result in losses of around 35 % of the initial prestressing force (comparing to the range of 10 % nowadays). Soon, multiple patents of various prestressing systems, including tendons, jacks, anchorages and processes followed in the 1930s–1950s.

These systems can generally be categorised as pre- or post-tensioning. In pre-tensioning the force is applied to strand before application of concrete, and to concrete when it hardens sufficiently. Due to nature of the process based on timing, it is usually carried out in prefabrication plants, and straight geometries of tendons are preferred limiting the form of elements. Post-tensioning allows for alignment of ducts before concrete application to respect the force-flow coming from bending moment distribution. The force can be applied to tendons and concrete long after casting – even to existing structures as external prestressing. As the tendon alignment, concrete application, and prestressing are to a certain extend temporally independent, it can be applied both on site and in prefabrication, allowing for more complicated geometries and forms. In both cases, prestressing allows for shifting the force-flow relation between reinforcement and concrete, resulting in more slender and lightweight spanning structures.

2.4. Ferrocement

While in the above examples the reinforcement primarily has the function of bearing tensile forces and is arranged correspondingly in the concrete, there are also historical examples in which the reinforcement is the forming material, such as the Monier's planters reinforced with metal wire mesh or the 1848 Joseph-Louis Lambo's boat. While these were small-scale experiments rather than classic construction elements, Pier Luigi Nervi took up the concept of form-defining reinforcement in the 1940s and developed the ferrocement.

In ferrocement, several layers of fine metal mesh are placed on top of each other and are then bent into an arbitrary, usually organically shaped form. This wire structure is then coated with a fine mortar to produce very thin walled, form active components such as shells. The high rigidity of the form active components and the partially disordered overlapping of the metal grids allows for employing geometry for strength, reducing the need of material resources. This however comes with the large amount of 'artisanal' labour, preventing its widespread in post-war Europe. This material-efficient construction method is nevertheless still used today for the construction of organic architecture where freedom of form plays an outstanding role, as well as increasingly in developing countries where labour is cheap, but materials are expensive (see Fig. 3).

3. Development of the interaction of material, process and form

Designing a structure means to unify material, process and form. The manufacturing processes are the link between material and form. New developments in materials, construction techniques and moulding methods require continuous adjustment and refinement of the unity of material, process and form. In natural stone construction, the material properties were dictated by nature, and it took more than a thousand years of formal development from the Roman arches to the filigree vaults of the Gothic period. As the new man-made materials with defined properties became available at the beginning of the industrial age, they acted as a driver for innovation in the construction industry. The design of structures using iron, steel, and later reinforced concrete was initially based on known forms and construction principles. And so, the first cast iron bridge, the Coalbrookdale Bridge, realised in England in 1779, was designed like an arched stone bridge but without stones, and the joining principles were adapted from timber construction [1]. It took decades of continuous research and development to create the knowledge of how material, process, and form can be harmonised in steel construction.

In reinforced concrete construction, the search of the unity of material, process and form was guided by the arrangement of concrete and reinforcement according to their strength. Here, the expression of the 'logic of form' culminated in remarkable shell and spatial structures of famous structural engineers, including masters such as Robert Maillart, Eduardo Torroja and Pier Luigi Nervi (see Fig. 4). In his book 'Philosophy of Structures' Eduardo Torroja described reinforced concrete as an 'organically constituted stone in the mass of which the tensional function of the reinforcement is effectively distributed and arranged in such a way that the concrete at every point will resist tension in accordance with the existent network of stresses' [26].

Development of the unity of material, process and form is however not only determined by engineering logic, but also by the social context. At the beginning of the 20th century, the design of reinforced concrete structures was guided by expensive materials and low labour cost. These boundary conditions led the engineers to design and build structures with as little material as possible. A structure designed in that time appears natural, with material-efficient elegance (see Fig. 4). The concrete and reinforcement were placed exactly where needed, often with complicated and labour-intensive arrangement. While the material and

Fig. 3. Ferrocement building of Art of Living, Triveni Ashram, Pune, India; placing of mortar on steel mesh (left) and finished structure (right), ©Studio Acrobat.

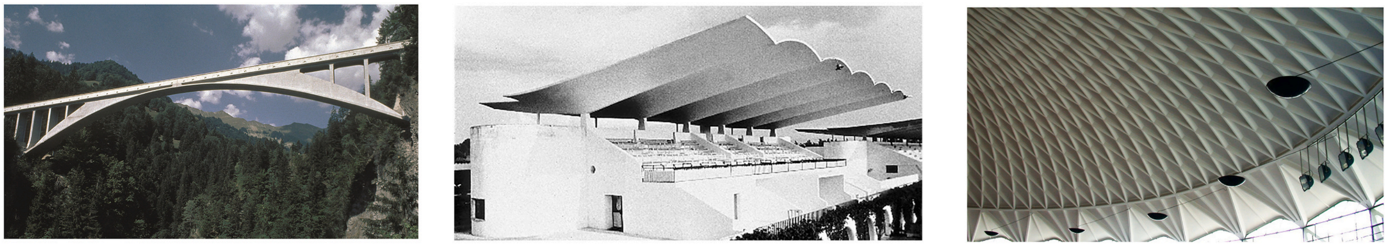


Fig. 4. Material-efficient reinforced concrete structures: a) Salginatobel Bridge, 1930, Robert Maillart (©Monsch, Institut für Baustatik und Konstruktion, ETH Zurich); b) Roof for the Zarzuela Hippodrome, 1935, Eduardo Torroja et al. (©Instituto Eduardo Torroja); (c) Palazetto dello Sport, 1957, Pier Luigi Nervi (©H. Kloft).

form were structurally in harmony, the processing time was inefficient, but due to the low labour costs the overall manufacturing was economical [27]. Later, labour costs increased steadily and since the 1970s, in order to reduce manufacturing time, reinforced concrete structures evolved from outside to geometrical simple, uniform and mass-intensive shapes. But also inside the installation and arrangement of the reinforcement developed from material-efficient linear tensile force arrangements to manufacturing-efficient orthogonal surface layouts.

While new materials were the driving force behind innovations in construction in the industrial age, digitally controlled processes are the drivers of change at the beginning of the 21st century. DFC offers the chance to reinterpret the principles of material-efficient reinforced concrete construction from the past. Similar as at the beginning of the industrial age, today we find ourselves in the time of searching for the unity of material, process and form. DFC has its origins in concrete printing. By printing concrete paths, one define the shape of structures by its outer contours (contour crafting) [28]. But it is only with reinforcement integration that DFC unfolds its full potential, and the manufacturing opportunities extend from realizing shapes to entire forms. By integrating reinforcement as a digitally controlled interactive part of DFC, the reinforcement can be used both externally as a contour-forming element, and internally for the targeted guidance of tensile forces. This, together with aligning print paths to principal stress trajectories and functional integration [29–32], opens up new possibilities in form-optimised structures.

4. A framework for the interaction of reinforcement, process and form in DFC

4.1. Reinforcement in DFC

Understanding reinforcement integration as an integral part of DFC has the potential to introduce a new mindset in reinforced concrete construction. While in formwork-based concrete construction the reinforcement must be set and positioned in advance, in DFC it is performed as an interacting process that can take place at different times – before, during, or after deposition of concrete. This freedom in processing time opens up new possibilities, either to adapt existing reinforcement techniques or developing new customized solutions. On one hand, standard industrial reinforcement products, such as reinforcing bars or mats, are cost-effective and widely available; nevertheless, they limit the flexibility of the process and of the resulting element. On the other hand, tailored reinforcement solutions, such as robotically prefabricated reinforcing cages [5] or in-situ fabricated continuous fibre reinforcement [33] provide more freedom in terms of defining the form of an element, and allow introduction of new materials and methods [34–36].

While the placement of reinforcement can generally be performed manually, automated placement allows for breaking away from the symmetry and repeatability imposed by the need for simplicity. With proper programming and organisation, the diameter and spacing of reinforcement can be of large variation, without additional difficulty in execution. Furthermore, non-orthogonal alignments can be formed with high precision, especially if combined with, already available, digitally controlled bending of reinforcement bars, or in-situ reinforcement fabrication [33].

The physical and mechanical laws guiding reinforced concrete remain the same in DFC: the assumptions behind the safe application of the theory of plasticity, the need of proper reinforcement anchorage, or the requirement of a continuous flow of forces. However, the flexibility of forms and processes provided by the automated integration of reinforcement opens up new possibilities for the reinforcement's role, either as a forming element for the fresh concrete or as an optimised reinforcement that follows the possibilities of the DFC process. Understanding the limitations and opportunities is necessary to change our ways of thinking and to explore anew the unity of material, process, and form for digitally fabricated reinforced concrete structures.

4.2. Interaction of reinforcement and concrete processing in DFC

The term Digital Fabrication with Concrete encompasses a large number of processes, techniques and methods. One of the first attempts to discuss how the DFC material and process interplay with reinforcement integration and structural performance was made by Asprone et al. [11]. They have grouped approaches to reinforcement integration by 1) the structural principle, i.e., ductile fibre-reinforced printing material, composite with passive reinforcement, compression loaded structures due to pre-stress or form, or hybrid of those; and 2) the stage of the reinforcement manufacturing process, i.e., before, during, or after the DFC manufacturing process. Importantly, they argued that the fundamental mechanical behaviour of digitally fabricated concrete elements will not differ from conventional concrete elements. Nevertheless, they added that it is crucial that new reinforcement concepts in DFC will incorporate an integral approach to the development of design, material and application processes [11].

As new DFC processes were developing, Buswell et al. [37] attempted to classify them, in particular with respect to the method of digitally controlled concrete manufacturing. Their classification was based on the previous attempts and at-the-time available digital concrete fabrication methods. In particular, it differentiated between the DFC process, understood as giving the shape through fabrication and assembly, and other 'indispensable' sub-processes, such as material control or reinforcement integration. The main objective thus was to understand, demonstrate, and classify the concrete fabrication process itself, treating the cementitious material and reinforcement integration methods as boundary conditions, rather than as an integral part of the digital processing. Kloft et al. [7] were the first to attempt to illustrate the interaction of DFC and automated reinforcement integration in a descriptive

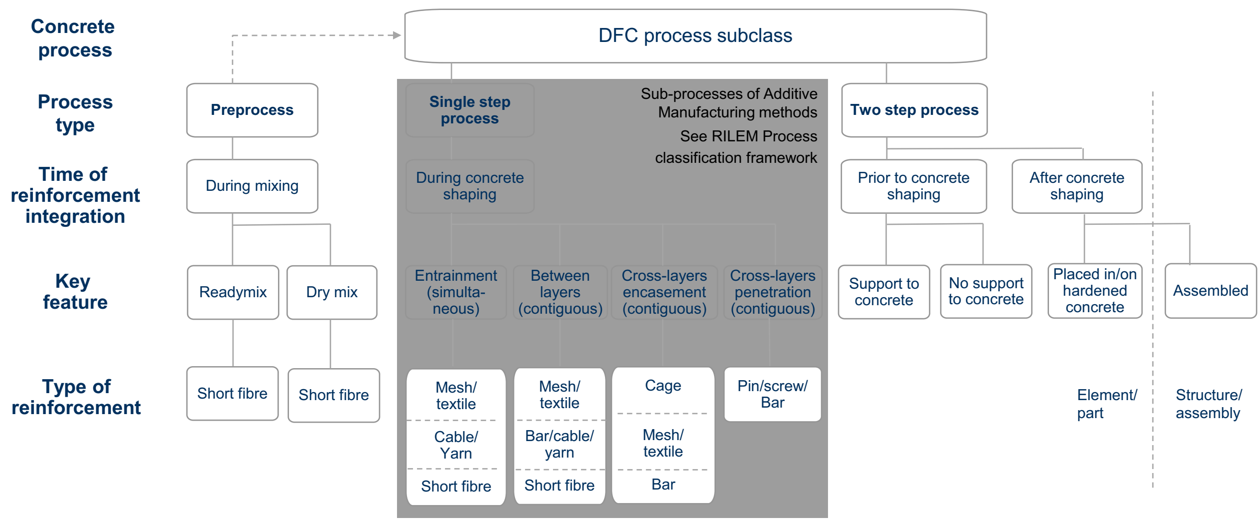


Fig. 5. The process classification framework for integration of reinforcement into DFC technologies, adapted from [12].

framework. In particular, the possibilities of reinforcement integration in interaction with the sequence of process steps were presented: either the concrete is printed first and then provides a support for the reinforcement integration, or the reinforcement is prefabricated and in turn provides the support for the automated application of the concrete matrix.

This work was brought further by Mechtcherine et al. [12]. It became obvious that the precise tuning of the material to automated manufacturing processes is essential, to establish a successful digitally fabricated reinforced concrete. Furthermore, it is both reinforcement and concrete, which interact with the fabrication process and determine the scope of applicability. As such, the reinforcement integration is an integral part of DFC. Therefore, this classification (Fig. 5) explicitly determines the time of reinforcement integration, and the key feature of the process in terms of reinforcement-concrete interrelation. In particular, the framework focusses on so-called single-step process, i.e., when concrete and reinforcement are fabricated within the same process, and hence both influence the fabrication method. Contrary, in two-step processes, concrete fabrication and reinforcement integration are separately controlled, leaving much more freedom regarding the type of reinforcement to be integrated.

4.3. Interaction of reinforcement, process and form in DFC (RPF – framework)

Based on the previous findings on the interaction between reinforcement and concrete processing in the DFC, the influence of reinforcement processing on the forming of reinforced concrete structures is newly elaborated in this work. Knowledge of reinforcement, process, and form is the key to a holistic change in designing reinforced concrete structures from the outer shape, as well as the guidance of the inner force-flows. This will allow to incorporate material and manufacturing efficiency, as well as environmental considerations, into optimised designs for DFC in the future.

The aim of the novel RPF-framework presented in Fig. 6 is to unify previous classifications on the reinforcement-process interaction with the new perspective on reinforcement-form interaction. The upper part of Fig. 6 considers reinforcement-process interactions and is adapted from [12]. Minor modifications were made, to reflect the advancement of DFC technologies, and to underline the fact that the various methods of reinforcement integration are stemming from the process type. The reinforcement – process interaction largely defines the boundary conditions for reinforcement integration.

The lower part of Fig. 6 continues with the reinforcement – form interaction. It considers reinforcement as equally important to concrete in DFC processes. The classification follows the principle that the material, either concrete or reinforcement, is creating the form. The form should be differentiated from the shape of an element. Whereas shape is representing the outer contour, the form is understood as the comprehensive three-dimensional expression of an object. In the context of reinforced concrete, form-optimised structure means geometrical-efficient outer shape and material-efficient guidance of the inner flow of forces. In addition to structural issues, a form can also include surface qualities and patterns as well as additional functions or architectural features. Even when the reinforcement is the forming material, the DFC process has the formal freedom to complete the final object for architectural or value-adding reasons.

Furthermore, the reinforcement arrangement with respect to the layer-based concrete application, as well as the geometric composition of reinforcement are considered. In order to be functional, reinforcement needs to provide a continuous and unobstructed flow of forces within the element. Therefore, its dimensionality, whether it is limited to a line, extends in both direction as a plane, or is a spatial and three-dimensional composition, determines the efficiency of the form in serving its purpose.

The complete Fig. 6 forms the Reinforcement-Process-Form interaction in DFC; it should be read in vertical columns. It needs to be understood that the process type and time of reinforcement integration determine the possible range of mutual interrelation between reinforcement and concrete. This, in turn, defines a possible geometric composition of reinforcement within the element. Likewise, the choice of forming material determines the applicable processes range.

For sake of better understanding, the type of reinforcement is listed at the bottom, along with exemplary illustrations. The type of reinforcement not only needs to be compatible with the process and form, but defines the geometric composition of reinforcement within the element. However, e.g., the planar arrangement can be formed by linear bars arranged appropriately during element forming and processing.

5. Classification of selected examples within the RPF framework

In this section, an overview of relations between reinforcement, process, and form in DFC is demonstrated using multiple examples. They are grouped according to the category they fit in, see Fig. 7. Examples in

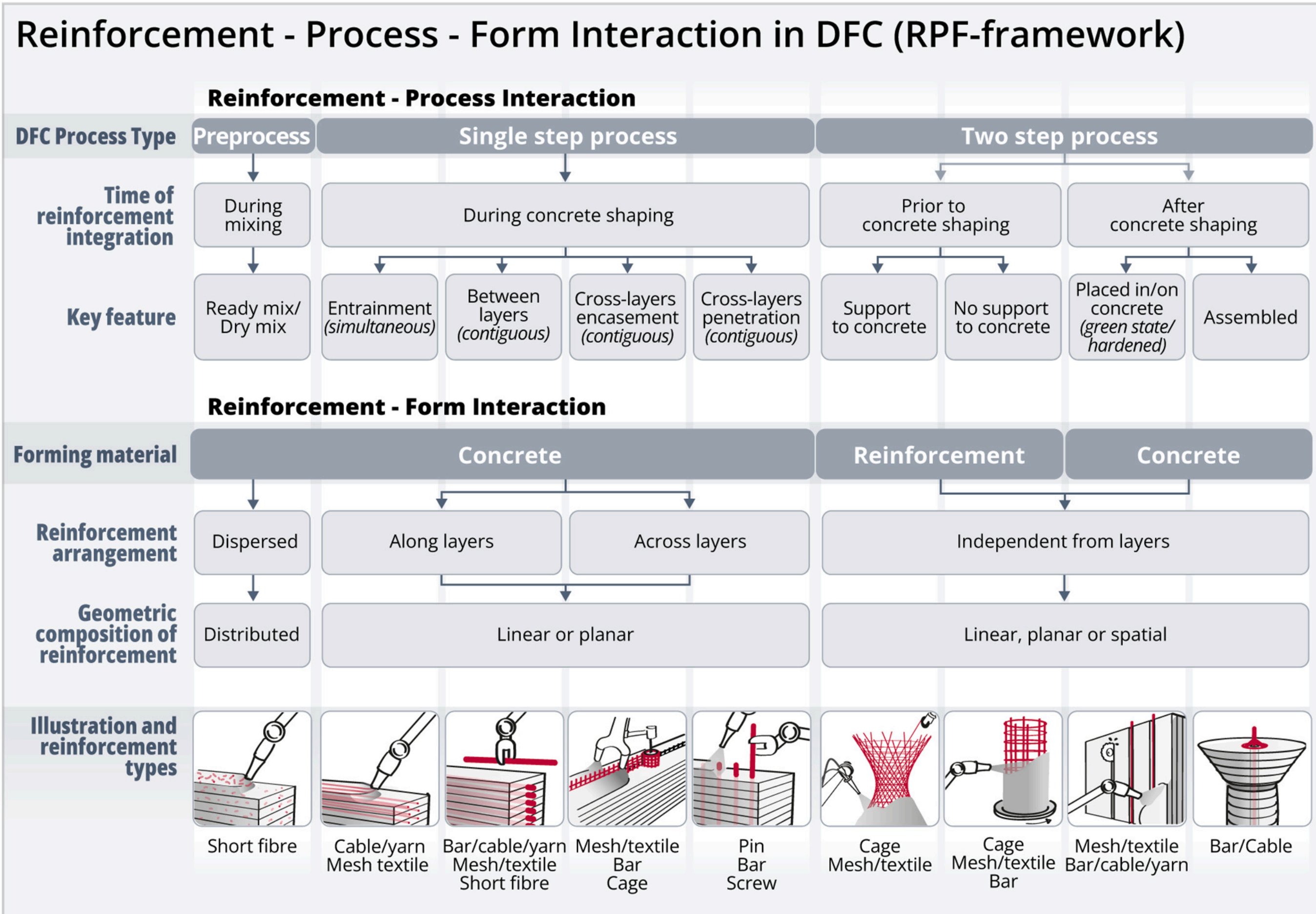


Fig. 6. The RPF-framework: A framework for reinforcement, process and form interaction in DFC.

Sections 5.1 to 5.5. demonstrate cases when reinforcement is integrated before or during concrete processing, and concrete is the forming material. The examples in Sections 5.6 to 5.9 involve two-step processes, where reinforcement and concrete are processed in separate stages. There, either concrete, or reinforcement is the forming material.

Many processes are in the conceptualisation phase, or demonstrated as a small and not yet scalable proofs of concept. In order to present the applicability of RPF-framework, only the processes on the Technological Readiness Level (TRL) 3 or higher are considered here. Importantly, the holistic approach to the reinforcement integration method is taken for TRL assessment, i.e., encompassing the reinforcement fabrication and integration, concrete deposition, and structural verification by means of testing and design methods. As a results, relatively low TRLs are presented, as compared to e.g., concrete extrusion only, estimated to be on the TRL 7–8 [38].

5.1. Mixed short fibres within concrete

5.1.1. Process description

Short fibres can be used as reinforcement by integrating them into the printed material [39,40], either to the dry fractions, during concrete mixing, or prior to extrusion or spraying. In the first two cases the pumping process is challenging, while the latter case requires special equipment [41]. The fibres can be made of materials such as polymer, carbon, glass, or steel. It is even possible to obtain printable Strain-Hardening Cementitious Composites (SHCC) reinforced by short polymeric fibres [42], presenting stable tensile strain-hardening response. The 3D printing process causes fibres to orient in the printing direction. Typically, the fibres do not protrude beyond the printed filament, although some minor intermixing between layers may occur when they are pressed together.

Several studies have been devoted to the use of short fibres for 3D concrete printing, as discussed e.g. [42] The use of short fibres for structural reinforcement has been demonstrated in laboratory conditions, thus the technology can be attributed to TRL 3. For example, SHCC was used to 3D-print modules of a sphere-like demonstrator with a diameter of ca. 1.7 m, see Fig. 8. The demonstrator consisted of 24 modules connected to each other using metal fittings embedded in the modules by placing them between 3D printed layers. The use of SHCC for printing modules allows them to withstand not only quasi-static compressive and tensile forces, including concentrated loads from contacts with neighbouring modules, but also dynamic forces acting during transportation and assembly [43].

5.1.2. Reinforcement, process, and form interaction

The integration of short fibres into the printed material enables printing of reinforced structures without imposing restrictions on their geometry. Use of short fibres seems to be the easiest method of integration of reinforcement, once the pumpability challenge is solved. However, the subsequent phases of the print process can negatively impact the effectiveness of fibres, which in turn can be detrimental to the performance of printed elements [44]. The variation in equipment can also cause significant differences in performance of fibre reinforced specimens from different printing facilities [45] It is also worth noting that short fibres usually cannot fully cover the reinforcement demand, in particular across the layers of concrete, but often need to be combined with other types of reinforcement in the main direction as well [46]. In

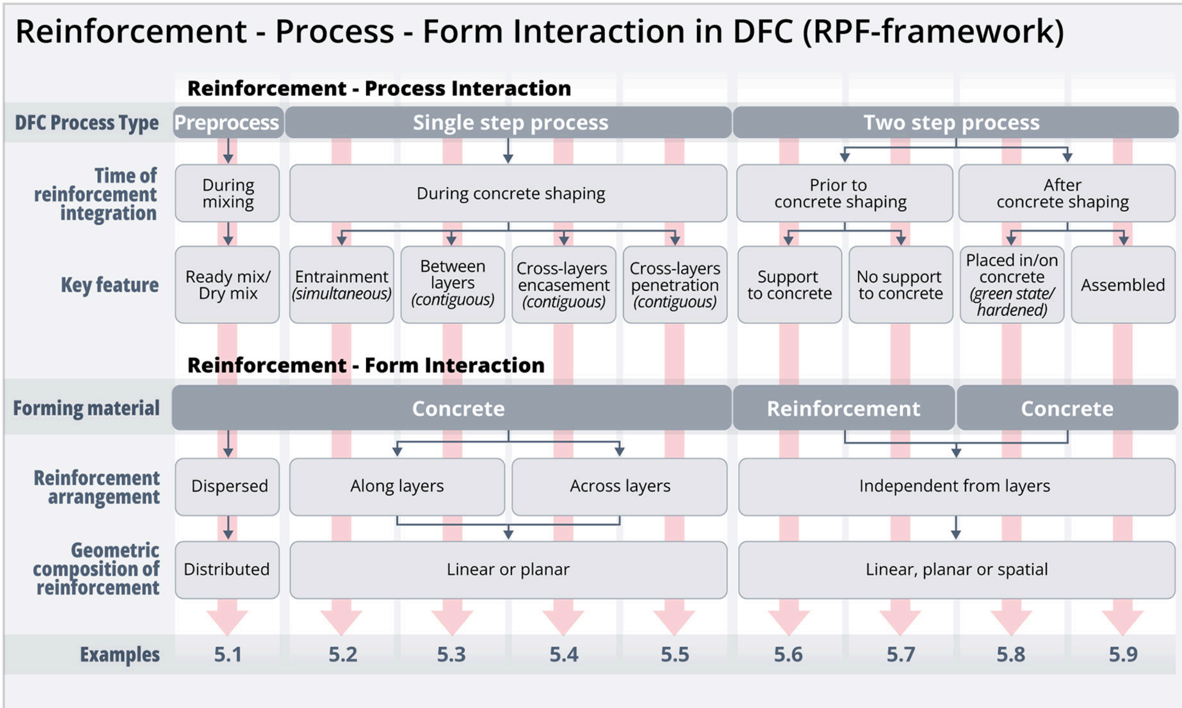


Fig. 7. Classified Examples of reinforcement, process and form interaction in DFC, with numbers of sub-sections they are presented in.

the future, more detailed studies on the effect of short fibres on the properties of concrete in fresh and hard states are required, in particular concerning pumping and deposition of the material.

5.2. *In-layer entrained reinforcement*

5.2.1. *Process description*

DFC is often characterized by its layered nature, and, depending on the method of deposition, interfaces can be weaker than the deposited material. Thus, the incentive is therefore to embed the continuous reinforcement within the layers, rather than between them. Bos et al. [34] used steel cables and chains as an entrained reinforcement, deposited through a modified extrusion nozzle. A further example is the continuous carbon yarn integration inside extruded filaments [47] (see Fig. 9). For this sake, a previously impregnated carbon yarn is fed into the modified concrete extrusion nozzle from the spool attached to the printhead. An additional feeder rotates the spool to assure that the velocities are aligned, and no damage of interface between the yarn and deposited concrete takes place due to tensile forces on the yarn. Following the same concept, multiple yarns can be fed simultaneously [48].

The strategy of embedment of impregnated yarn was tested in laboratory, including material and bond testing, also in elevated temperature [49], therefore this method is of TRL 4. The steel wire embedment was applied as transverse reinforcement in the bicycle bridge in the Netherlands [50], setting this technology at TRL 7.

5.2.2. *Reinforcement, process, and form interaction*

Integration of continuous reinforcement in form of cables or yarns within the layer of concrete provides continuous reinforcement aligned with the concrete strands without influencing layer-to-layer joint. It is particularly important in case of extrusion-based methods inherently vulnerable in the interlayer zones. Therefore, embedment within concrete layers, rather than between them, often results in better reinforcement-to-concrete, and interlayer bond [51]. This, in turn, results in better structural properties of fabricated elements. Obviously, the main limitation of this reinforcement strategy is that the reinforcement can be placed only along the concrete printing direction, and with constant position with respect to the layer.

Fig. 8. Extrusion 3D printing of Strain Hardening Cementitious Composite (SHCC) panels (left) and assembled spherical structure (right) [43]; ©E. Ivaniuk.

Fig. 9. Extrusion-based printing of concrete reinforced with embedded steel cable (left, courtesy TU Eindhoven) and cross-section of layer reinforcement with carbon fibre (right, courtesy of TU Dresden).

5.3. Interlayer inserted reinforcement

5.3.1. Process description

In this process, the reinforcement is placed between concrete layers in the form of continuous filaments, rebars, or short fibres. For continuous filaments, such as carbon fibre yarns, the yarn can be deposited from the spool onto just printed concrete, and immediately covered by another layer of concrete [35]. This results in a continuous reinforcement in the direction of the concrete layers. Furthermore, short fibres can be placed between the concrete layers to provide longitudinal reinforcement [52], see Fig. 10. Separation of the placing process from concrete printing process allows for alignment of fibres in the required direction. Additionally, the fibres which are partially embedded in both preceding and following concrete layers improve the shear resistance of the joint [53]. The successful application of short fibres between the layers is governed by the bond to concrete, which in turn depends on rheological properties of the concrete during fibre placement and subsequent layer deposition, as well as on the amount and position of fibres, allowing embedment in the concrete material.5.1.

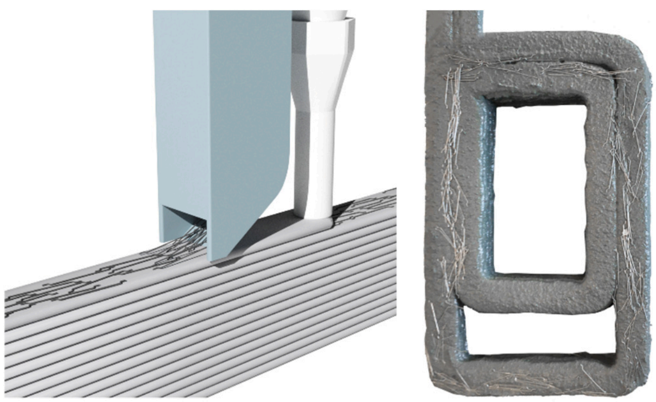


Fig. 10. Schematic concept of fibre placement between layers (left), and hollow cross-section with visible fibres (right); ©L. Gebhard.

When the concrete strand is wider, embedment of continuous steel reinforcement bars becomes possible. The Shotcrete 3D Printing (SC3DP) method, with a strand width in the range of 10–15 cm depending on printing parameters, provides such an opportunity. It was used to fabricate steel reinforced beams, and a ribbed 16 m^2 slab [54]. A smaller 5.6 m^2 ribbed slab was also fabricated using extrusion-based process, demonstrating universality of this reinforcement integration method [9]. In both cases the conventional pre-bent reinforcing bars were manually placed between subsequent layers of concrete. The optimisation of form can be achieved, for instance, by control of the lateral printing velocity and/or concrete volume flow to achieve variable static height (Fig. 11 a and b), or by printing path alignment, as in case of ribbed slabs (Fig. 11 c and d). In both cases, continuous reinforcement is provided along the direction of concrete printing.

When multiple strands are produced next to each other (see [32]), a levelled transversal section is obtained, which can be used to freely orient the reinforcement, as on Fig. 12. This method was used to integrate bent steel reinforcement bars providing bending reinforcement at mid-span, and shear reinforcement towards the supports of a beam [31]. This was made possible by rotating the element by 90° after fabrication. This example shows that the orientation of interlayer reinforcement, despite being limited to the concrete layers' plane, does not need to be co-axial with the printing direction, allowing for more complex arrangements.

Another method to achieve a force-flow optimised reinforcement

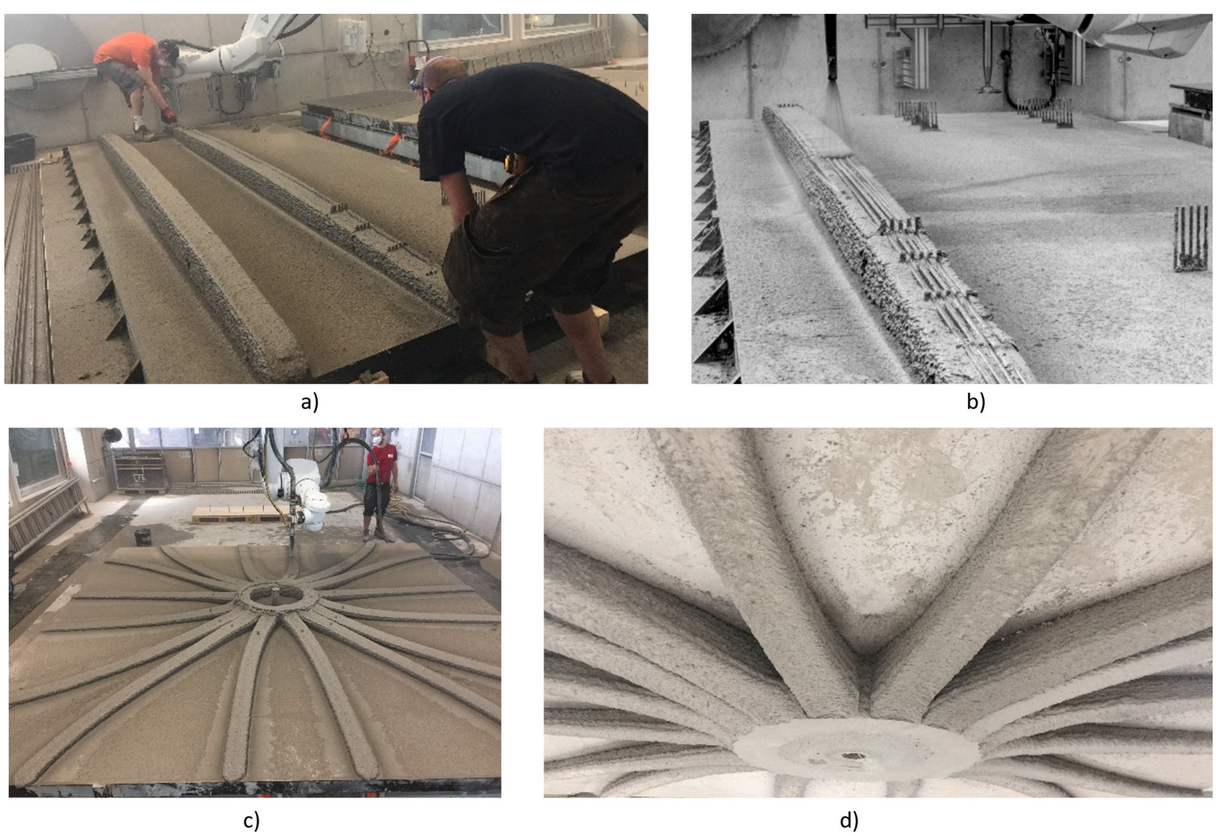


Fig. 11. Examples of continuous interlayer reinforcement integration in SC3DP; a) Manual placing of reinforcing bars between layers in beams; b) Deposition of subsequent layers of concrete; c) Fabrication of ribs with integrated longitudinal reinforcing bars; d) Finished slab with cast deck and SC3DP ribs with interlayer reinforcing bars; ©ITE, TU Braunschweig.

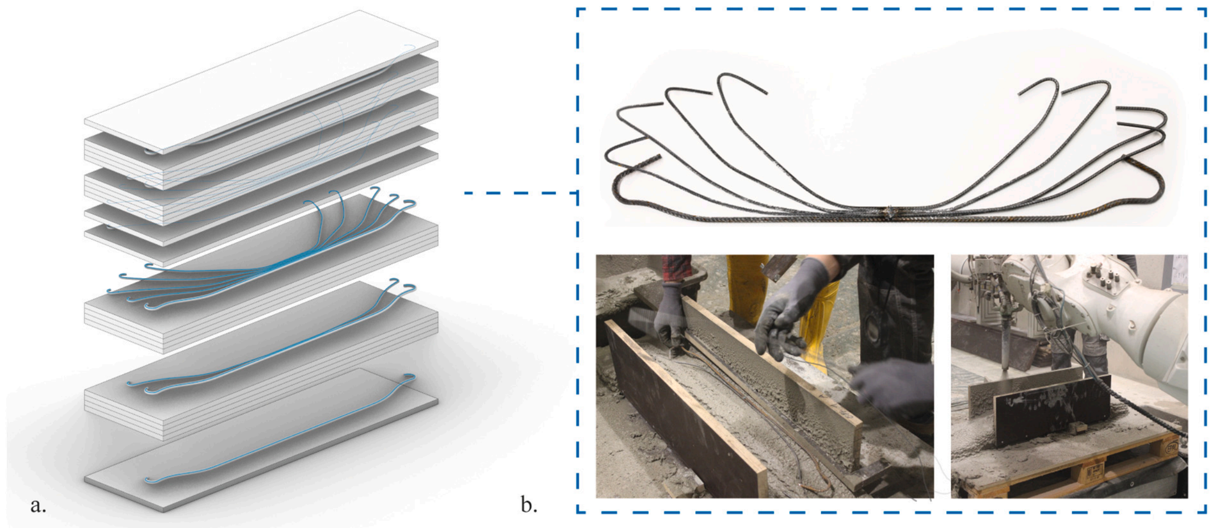


Fig. 12. a) A scheme of reinforcement placed between SC3DP layers; b) Pre-bent reinforcement (top), manual reinforcement placing (bottom left), and spraying of subsequent layer of concrete (bottom right); © ITE, TU Braunschweig.

arrangement is to place the reinforcement between non-planar concrete layers, see Fig. 13 a) and [32]. Using SC3DP and a complex concrete deposition path, layers arrangement in a beam was chosen to allow for force-flow oriented placing of a carbon fibre mesh placed between them [55]. First, the height of element over supports was build, and later force-compliant concrete layers were fabricated to host the reinforcement mat. The mat was placed manually and slightly pressed down for sake of initial bonding. The immediate spraying of subsequent layers further improved the bond, as concrete embeds and penetrates through opening of the mat to bond with the previously deposited layer. In such a way, a monolithic reinforced element is created. Subsequently, the surface of the 2.4 × 0.18 × 0.36 m^3 beam was milled to achieve the rectangular shape.

The beam with force-flow compliant concrete layer arrangement and carbon mesh in-between (Fig. 13) was fabricated, but not proven structurally, thus holding TRL 3 [55]. All the other examples discussed here were tested in scalable and representative structural elements, therefore can be assigned to TRL 4.

5.3.2. Reinforcement, process, and form interaction

As demonstrated by the variety of examples, despite the fact that the interlayer reinforcement is bound to follow the plane of the concrete layers, it provides multiple possibilities of reinforcement encasement.

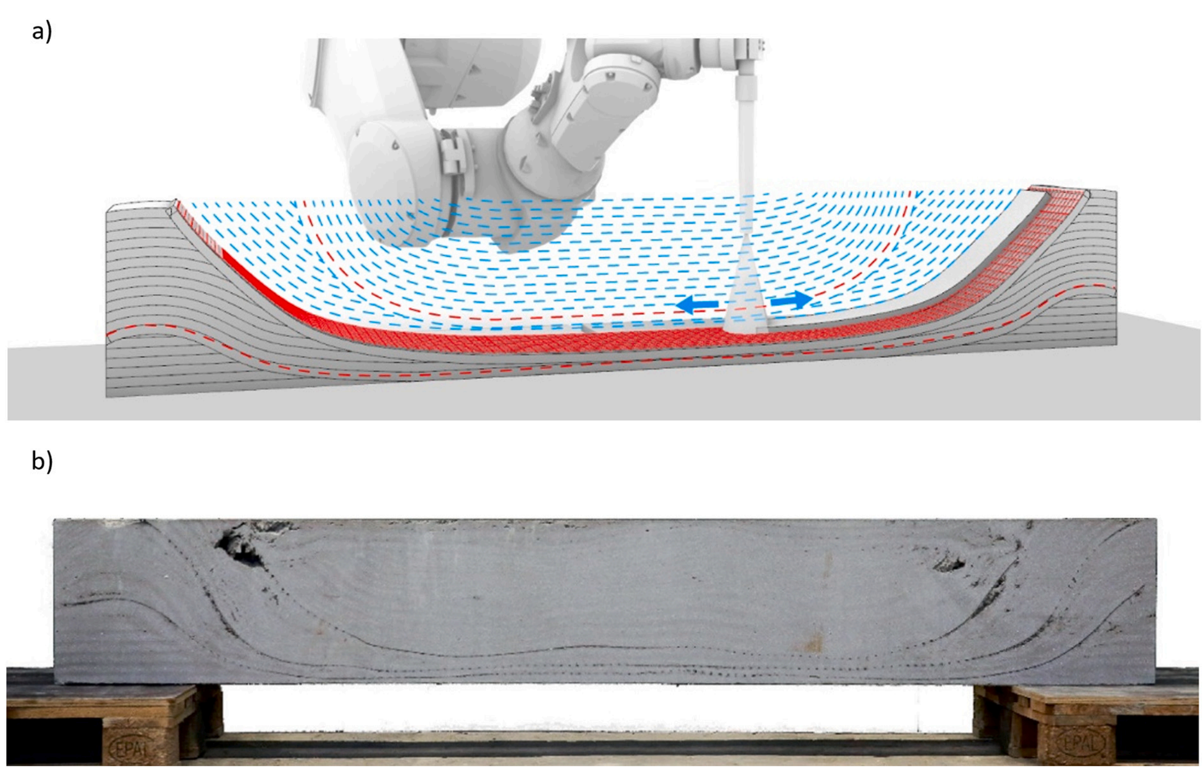


Fig. 13. Force flow compliant robotic path planning with carbon mesh reinforcement layers: a) fabrication concept, and b) executed element; © ITE, TU Braunschweig.

Such arrangement facilitates integration of continuous reinforcement aligned with the concrete layers, virtually unlimited in its longitudinal direction thanks to placing in alternation with concrete deposition. Probably the simplest approach is when the fibre yarn, bar, or fibres are placed along the horizontal concrete strands. Such a simple reinforcement alignment can provide longitudinal reinforcement, e.g., for beams or walls, and additional improvement of interlayer strength, e.g., in shear. It can be further extended to placing mats over multiple strands printed one next to another, in order to achieve wider elements. The strands can be of varying height, e.g., non-planar layers, as in case of SC3DP beams (Fig. 11). In all these cases the reinforcement follows closely the concrete printing geometry.

For sake of structural optimisation, a much more complicated concrete printing path can be created (Fig. 13). In this case again the reinforcement follows closely the printing geometry, but this geometry is modified for sake of, e.g., structural efficiency of an element. This approach requires much more design and fabrication effort, which can be solved using semi-automated or automated routines based on, for example, finite element modelling [55]. It can be envisioned that the results of modelling can be in an automated way translated into the printing path, rather than employing cumbersome semi-manual programming.

The third presented approach is the combination of a simple arrangement of concrete layers, with more complex reinforcement geometry (Fig. 12). From the point of view of material-form interaction, this solution is similar to the traditional reinforced concrete approach, where the simple volumetric concrete mass hosts more complex reinforcement alignment. Obviously, contrary to conventional concrete casting, the arrangement of reinforcement is restricted by the planes of the printed concrete strands – hence, its complexity can be realised only in two dimensions.

5.4. Cross-layer encased reinforcement

5.4.1. Process description

The method of cross-layer reinforcement encasement assumes simultaneous or alternating placement of reinforcement, and subsequent enveloping by concrete. Several methods have been proposed in literature, but only few were successfully demonstrated.

One of such is based on use of the special split nozzle [56]. A steel galvanized 26 mm wide mesh oriented vertically is unrolled from a spool attached to the printing head and fed in the opening in the middle of the nozzle. The concrete is deposited from both sides of the mesh simultaneously. A small part of mesh is protruding from the top of deposited layer, to overlap with the following mesh and concrete layers. A small-scale element of height of 9 layers was produced and tested.

Another demonstrated method, rivet reinforcement [57], allows for the orthogonal bridging of filament layers. Modified male-female blind rivets are fixed into one another, via an automated pneumatic rivet tool and nosepiece that allows for contiguous reinforcing and printing, to form a continuous vertical spent rivet string, see Fig. 14. Deposition of concrete follows immediately after fixing of a rivet to the rivet string, thus constituting a contiguous process. Rivets are encased in concrete, leaving their top surface free and ready to host successively fixed rivets. A rivet-to-rivet connection is, on average, made in 0.29 s. This is combined with flexible wire rope entrained by a split nozzle inside of the concrete layers, wrapping around the vertical rivet strings, and acting as longitudinal reinforcement. Not only do the vertical rivet strings act as orthogonal reinforcing, but simultaneously provide increased anchorage to the longitudinal wire ropes.

The two methods discussed here achieved an early TRL 3, and further development and scaling of the process is required.

5.4.2. Reinforcement, process, and form interaction

Cross-layer encasement of reinforcement aims towards integration of reinforcement and deposition of concrete within one contiguous process. The main motivation in development of this class of processes is to achieve DFC elements of virtually unlimited height, and with continuous vertical reinforcement with good bond to concrete. This reinforcement method could be particularly interesting for fabrication of walls. To encase reinforcement within the structure, its prior installation is crucial. However, the dimensions of the installed reinforcement are constrained to allow clearance for the nozzle and the subsequent concrete deposition. Concurrently, a significant challenge arises in achieving a continuous reinforcement structure composed of small segments. For this sake, many concepts consider welding of short metallic elements or WAAM fabrication of reinforcement [58]. This however generates large amount of heat, which can damage already deposited concrete [59]. Furthermore, it is time-consuming, potentially causing the formation of cold joints in concrete. In contrast, the two methods presented before utilise lap splicing and mechanical connection.

5.5. Cross-layer penetrating reinforcement

5.5.1. Process description

A further method to insert the reinforcement across the concrete

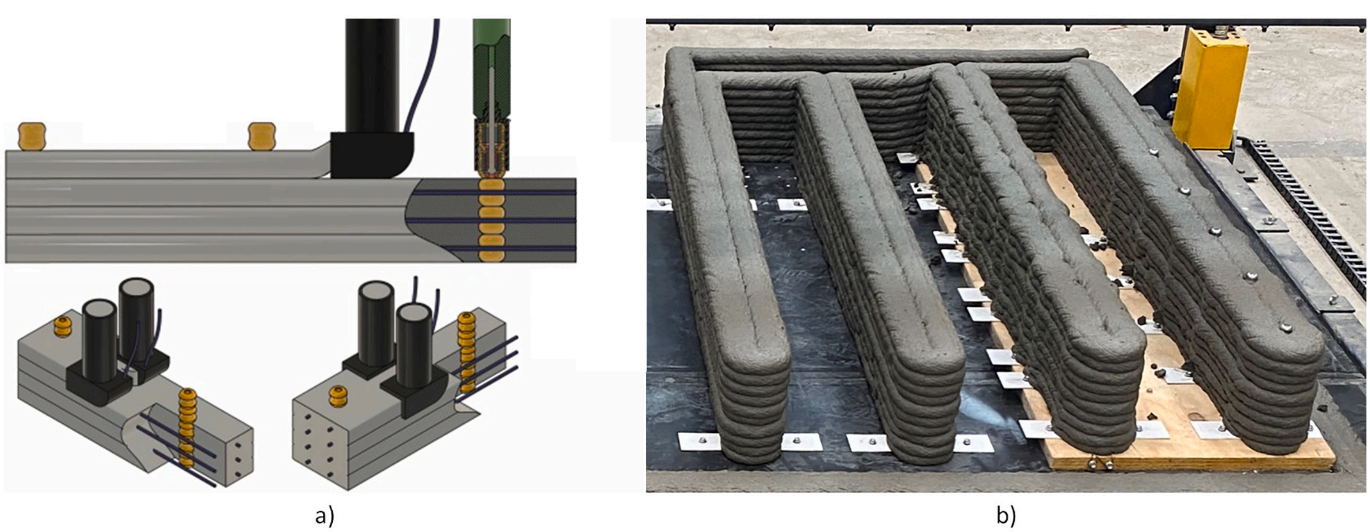


Fig. 14. Rivet reinforcement - multiple rivets installed on top of each other during concrete deposition (left) and the demonstrator (right); adapted from [57].

layers is by penetrating the freshly printed layers, for example by pushing or screwing in the reinforcement elements, optionally in combination with a bonding mortar or vibration energy.

A first example of such process is the automated integration of short reinforcement elements, such as Short Rebar Insertion, see Fig. 15 [60]. This reinforcement strategy is carried out alternately with the concrete printing as a contiguous single step process. Reinforcement bars of various types are inserted using fitting methods, such as direct insertion [61–63], integration into a grout [61,64], rotational integration synchronised with the thread pitch of reinforcing bars [61,65] and vibrated insertion [66] into the concrete. Subtractive auxiliary processes, such as drilling, are possible but not mandatory. The reinforcement is partially or fully inserted, and subsequent layers of concrete are applied. Depending on the selected reinforcement material, integration length, and technical limitations, the printing strategy is adjusted and the changeover between printing and inserting is set precisely and repeated until the desired height of element is reached. The method allows a variation of insertion angle with respect to deposited concrete layers, which enables a wide variety of reinforcement arrangements.

Another interesting method to integrate reinforcement across layers is “sewing”, see Fig. 16 [67]. Various reinforcing patterns are possible, and the cavity created by the sewing action can be filled with grout immediately after sewing the yarn. In addition, the sewing needle measures the torque required to penetrate the concrete layers, therefore offering a quality-control index to ensure material homogeneity. The sewing device comprises an oscillating hollow needle that facilitates penetration and sewing, a pump that facilitates grout injection into the sewn yarn cavity, and a command panel for controlling the automated contiguous reinforcement process parameters, e.g., the sewing frequency and penetration depth. Various yarn types can be used, ranging from synthetic to bio-based, braided or non-braided, stranded or metal applications. A single continuous yarn therefore is sawn multiple times through layers, and in-between the penetration points deposited on the concrete layer. Subsequently, further layers of concrete are deposited.

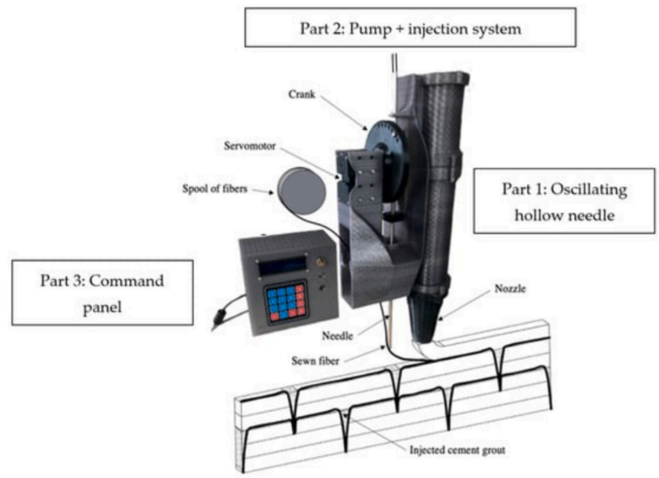


Fig. 16. Sewing method for cross-layer penetration reinforcement, adapted from [67].

For short rebar insertion, a 1:1 scale demonstrator has been fabricated, and pull-out tests performed on reinforcement [61], the method is thus of TRL 3. In case of sewing reinforcement, a small-scale fabrication and mechanical testing was performed in laboratory environment [67], setting it at TRL 3.

5.5.2. Reinforcement, process, and form interaction

This type of reinforcement integration is characterized by the penetration of several layers of concrete. In case of insertion of short reinforcement elements, the reinforcement itself is used for penetration, and therefore it remains in the position and direction of introduction.

a) b)

Fig. 15. Robotic Short Rebar Insertion method in combination with SC3DP; a) Automatic insertion of reinforcing bars, b) Element ready for spraying of subsequent layers of concrete; ©ITE, TU Braunschweig.

The insertion angle can be normal to the deposited layer, or within certain angles, limited only by the stability of concrete structure during insertion and process limitations. As a result, the insertion of short reinforcement elements provides the possibility to orient it according to the force flow in an element, to some extend irrespective of the orientation of concrete layers. Nevertheless, the limited length of the reinforcement elements imposed by the stability of already printed concrete prevents this method from integration of continuous, long reinforcement elements, e.g., continuous reinforcement bars. For sake of continuity of flow of forces, it is necessary to provide sufficient lap splicing [60,68]. Additionally, this method limits the utilisation of non-linear elements, as the introduction of such elements during insertion results in the accumulation of voids and weak bonding zones. As a rule, the limits of the reinforcement arrangement are given by the contour of the concrete structure, so that concrete defines the form of the manufactured element. To sum up, this reinforcement integration method is structurally effective within a certain angle from the normal to the concrete layer orientation.

In case of sewing, the needle penetration takes place in direction perpendicular to the deposited layers of concrete. However, due to certain flexibility of the deposited yarn and the width of the opening, the reinforcement is at an angular orientation. Furthermore, between the sewing points, the reinforcement is aligned with concrete layers, similarly to interlayer reinforcement (see Section 5.3). Therefore, the primary effective direction of reinforcement is along the direction of deposition of concrete. In normal direction, no continuous reinforcement is developed, unless with overlapping, which was however not investigated in detail.

5.6. Pre-processed reinforcement supporting concrete

5.6.1. Process description

This integration method is characterized by a prefabricated reinforcement structure that is subsequently encased with concrete in a digital fabrication process. Here, the reinforcement, aside from its structural functions, can also provide the support to concrete during the fabrication process, and define the form of the fabricated element. The method holding probably largest similarities to traditional reinforced concrete is Mesh Mould process, where a robotically bent and assembled reinforcing structure composed of steel reinforcement bars is provided [5] This reinforcement is later filled with concrete by spraying or extrusion. Such a reinforcing structure could also be prefabricated by WAAM [69].

Another method to fabricate reinforcement defining the form of an element is frame winding [70]. It is based on the robotic winding of continuous fibre yarns onto an auxiliary frame to create a mesh structure, onto which concrete is subsequently deposited, compare [32]. The winding points where yarn is attached to the frame, and the strategy of yarn deposition, can be optimised to create complex double-curved shapes, see Fig. 17. The yarn is continuously produced using the Dynamic Winding Machine [71], where a glass fibre reinforcement strand is impregnated with epoxy resin. Additionally, a smaller yarn can be wound around the main strand, in order to create a helix providing mechanical bond to concrete – similar to ribs in reinforcing bars. The freshly produced continuous fibre is flexible for sake of installation. It subsequently hardens as resins sets, providing a stiff support for concrete to be deposited. In the discussed example, a mesh was deposited together with the continuous fibre, in order to provide better support for concrete during fabrication.

A similar process was also demonstrated with prefabricated orthogonal carbon fibre mesh [72], where auxiliary structure can be used to provide the requested shape, and then concrete deposited to solidify it. The reinforcing mesh can be also tailored, for example using CNC knitting, as in the KnitCrete technology [73]. Thanks to CNC fabrication of textile formwork, the shape of the final element, as well as mesh density can be fabricated as requested, allowing or not for partial passage of concrete for better bond [74]. Additionally, high-strength inlays, e.g. aramid, can be added, where more reinforcement is needed [6]. This method was to date combined with robotic shotcrete for digital concrete fabrication [75], see Fig. 18.

Mesh Mould is the most advanced technology among those discussed here, with real-case structural application [76], however with manual sprayed concrete deposition. It sets the reinforcement method to TRL 7. The closed-form KnitCrete element has been structurally tested, setting it to TRL 4. Other methods are on TRL 3 level, and more research is required on the structural performance level.

5.6.2. Reinforcement, process, and form interaction

Reinforcement as forming process, fabricated and assembled before concrete application, fully utilises the freedom of DFC. Automated fabrication methods, in particular when combined with digital design workflow and form-finding methods, lead to optimised solutions, opening path to reduced material consumption. The reinforcement can be placed exactly where needed. Regarding the final form, two strategies can be differentiated: where the reinforcement fully determines the form and shape of an element, and where it defines the form, but not the shape.

The first case is Mesh Mould [77] and KnitCrete used as a closed formwork [6]. Once a spatial reinforcement Mesh Mould cage is fabricated, it is filled with mortar or concrete using spraying or extrusion. The concrete extends outside the reinforcement cage only to provide necessary cover. KnitCrete, in turn, can be shaped as a traditional

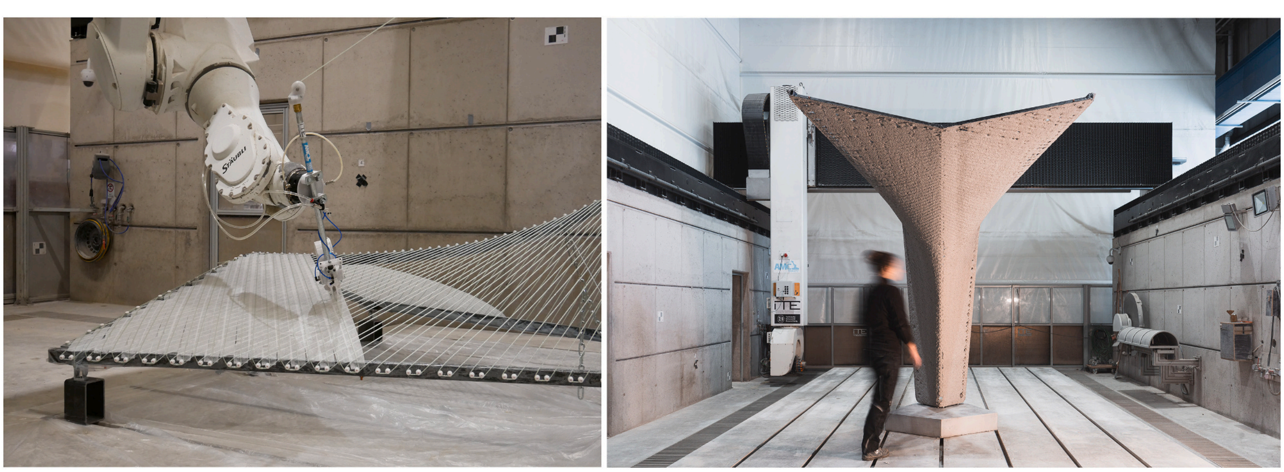


Fig. 17. Frame fibre winding process with visible white layer of mesh deposited simultaneously with the second layer of fibre yarn (left), and finished demonstrator with concrete applied through spraying (right); ©ITE, TU Braunschweig.

Fig. 18. KnitCrete bridge; application of the first layer of robotically sprayed concrete (left, ©ITE, TU Braunschweig), and the final demonstrator (right, © J. Bergmeister/TUM).

formwork and filled with cast concrete. Therefore, the shape of an element is defined by the reinforcement.

The second case is represented here by frame fibre winding [70] or a plane formed by the KnitCrete [75,78]. The form of a structure is defined by reinforcement layer, onto which the concrete is deposited. However, with the same form, different shapes are possible depending on the thickness of added concrete layer. It can be thin, forming a lightweight shell [78]. It can be however deposited as much thicker, possibly hosting more reinforcement layers and types, and providing a volumetric structure [75].

It is worthwhile to mention an important difference between serial mass-produced reinforcement, such as orthogonal fibre mesh, and tailored reinforcement, such as KnitCrete and fibre winding. The former allows for form definition, but only for limited reinforcement orientation and density adaptation to structural requirements of an element. Contrary, the latter can be placed and oriented to follow the main tensile forces of a structure, or even additional stronger material can be interwoven for sake of additional reinforcement where needed [76].

5.7. Pre-processed reinforcement not supporting concrete

5.7.1. Process description

Another possibility when reinforcement defines the form, is when it does not provide support to concrete. Obviously, as both materials interact during fabrication, it does provide a certain stabilisation to the applied concrete. The key criterion is, however, whether the same DFC process could successfully take place without the presence of reinforcement. Three examples of such a process are presented.

Smart Dynamic Casting, developed at ETH Zurich, advances slipforming technology by introducing either a freely slipping trajectory or adaptable actuated formworks, enabling the creation of diverse cross-sections and geometries [32,79] In this technology, fresh concrete is cast into a mobile formwork considerably shorter than the final element, see Fig. 19 a). The concrete has an adapted rheology to be workable when slipping through, yet at the base of the formwork it reaches a hydration state adequate for self-support. This technique facilitates continuous casting around a pre-installed layout of preformed steel bars. It has been used to produce several 3 m tall mullions for the DFAB HOUSE in the NEST building at Empa in Dübendorf, Switzerland. Exploiting the tailor-made fabrication possibilities offered by Smart Dynamic Casting, the variable cross-section of each mullion was optimised to withstand the wind loads acting on the façade without excessive structural reserves [80].

Another method is using SC3DP and classical reinforcement [81]. A concrete cage fabricated from steel reinforcing bars is prepared beforehand, and then concrete sprayed around it. Due to need of access from around the element for concrete placement, and no access from the above due to presence of reinforcing bars, a rotary platform, turntable, or similar device can be used, see Fig. 19 b) and c). The reinforcement provides no essential support to concrete – it was demonstrated that a

Fig. 19. Smart Dynamic Casting fabrication process with embedded reinforcement (left); and SC3DP of reinforced columns during (middle) and after (right) fabrication (©ITE, TU Braunschweig).

similar non-reinforced column can be fabricated, as well [81]. Therefore, the reinforcement alignment can be fully optimised towards its function, rather than fabrication – with the limitation of rebar spacing, to allow efficient concrete penetration and encirclement. The discussed demonstrator was a reinforced concrete column with diameter of 25 cm and height 1.25 m. The reinforcement alignment was chosen in accordance to DIN EN 1992-1-1. The spraying nozzle was inclined at angle of 60°. Analysis of cross-section revealed no significant shadowing or voids, with except of minor void at the axis of column. It can be therefore assumed that a good bond is achieved. In subsequent steps, the surface of an element could be robotically finished, or dry connections to assembly the segments milled [81].

The third example is use of traditional reinforcement bars pre-installed in the location of wall, and then extrusion of concrete from both sides using a split nozzle [82]. The size of the nozzle limits the height of pre-installed reinforcement; in the discussed example it was around 1.5 m.

Mesh Mould is the most advanced technology among those discussed here, with real-case structural application [76], however with manual sprayed concrete deposition. It sets the reinforcement method to TRL 7. Other methods are on TRL 3 level, and more research is required on the structural performance level.

5.7.2. Reinforcement, process, and form interaction

The two first examples discussed here concern vertical elements, mullions and columns respectively, of different structural functions. Mullions act mainly in bending, providing support to glazing of façade against wind loads. To achieve optimal performance, the cross-section varies along the element, following the bending moment distribution. Contrary, columns act mainly in compression, providing vertical load path between the stories. Their form could be optimised against buckling thanks to variable cross-section, and by use of transverse reinforcement providing confinement, as well. Both examples nevertheless have similar form: elongated in the longitudinal axis, and much smaller in cross-section. The form is hence in the accordance with the fabrication method, allowing virtually unrestricted continuous reinforcement in one direction, but limiting the lateral dimensions. In case of Smart Dynamic Casting, it is limited by dimensions of the slip formwork; in case of SC3DP by reachability of the sprayed concrete cone and penetration up to the centreline of the element. Both methods allow for variable cross-section dimensions along the element for sake of optimised structural performance.

The third example, concerning walls, can be considered similar to the previous two. The axis along the wall can be theoretically infinitely long, the thickness is limited by the concrete penetration, and the height is limited by nozzle size. It can be therefore considered equivalent, with one lateral dimension (length of wall) extended almost to infinity thanks to special design of the nozzle.

5.8. Post-processed reinforcement placed in or on concrete

5.8.1. Process description

To overcome difficulties and limitations coming from respective orientation of concrete layers and reinforcement, a set of strategies has been developed to first fabricate non-reinforced concrete element, and integrate the reinforcement in or on the concrete afterwards. The big advantage of this methods is that they are virtually compatible with any concrete 3D printing method.

Two strategies can be distinguished: 1) First the non-reinforced element is fabricated, and reinforcement is inserted with or without auxiliary steps, such as drilling of holes, and 2) After fabrication of non-reinforced element, the reinforcement is installed on the surface, and subsequently the thin concrete cover layer is applied.

The first strategy can be realised through insertion of short reinforcement elements into a concrete element, as described for cross-layer penetrating reinforcement insertion, compare Section 5.5. This strategy was successfully used for the reinforcement of stair steps [46]. The elements were first produced by extrusion-based concrete 3D printing. Next, before concrete hardened, helical reinforcement was robotically screwed in, providing the main longitudinal and continuous reinforcement. Inserted reinforcement can be partially protruding, allowing for subsequent fabrication of another part of structure. Such a strategy was also demonstrated during the fabrication of a wall element using SC3DP and subsequent insertion of short reinforcing bars providing protruding reinforcement for console fabrication [60], see Fig. 20. This method is applicable only in green state, i.e., when the material is hardened enough to keep its shape and stability, but gives way under applied pressure. It is therefore possible within a given open time defined by material, process, and environmental parameters.

The second strategy, i.e. installation of reinforcement on the surface of a previously fabricated concrete volume, can be realised by subtractive post-processing like milling or scraping grooves into the fresh applied concrete component, see Fig. 21 [83]. First, a non-reinforced concrete core is fabricated. Next, continues grooves are milled. They are slightly larger than the reinforcement to be hosted. After installation of reinforcement, and temporary fixing e.g., using pneumatic stamping gun, the cover layer of requested thickness is applied, for example using SC3DP. Since the reinforcement integration is performed before concrete hardens, bonding between concrete applied in the first step and reinforcement is still possible. Therefore, contrary to traditional shotcrete process where a certain gap is required between substrate and reinforcement for sake of fresh concrete penetration, here the

a) b) c)

Fig. 20. a) Automated Short Rebar Integration method in green state; b) reinforcement waiting for later fabrication of subsequent part of an element; c) fabrication of a console; ©ITE, TU Braunschweig.

a) b)

Fig. 21. Integration of force flow reinforcement through green state milling on SC3DP beam: a) robotic milling of force-flow optimised grooves, and b) integration of vertical and horizontal reinforcing bars; ©ITE, TU Braunschweig.

reinforcement can be installed in grooves. It is, in fact, slightly pressed into the supporting concrete. As a result, the reinforcement follows precisely the groove.

The second strategy can be realised also by use of reinforcing meshes made of carbon fibre or steel bars installed on the non-reinforced concrete core element [84]. During the printing process, short transverse reinforcing bars protruding from the core are placed between subsequent layers. After completion of the core of element, a reinforcing mesh is installed on them. Finally, a cover layer is applied encasing the reinforcing bars and forming the external surface of the element. This method was used so far with extrusion-based core printing and manual cover layer application (Fig. 22 a).

A similar concept is used for Core Winding Reinforcement (CWR) [33], allowing for automated, continuous, and force-flow aligned reinforcement installation (Fig. 22 b). After fabrication of non-reinforced core, continuous fibre strand is attached to the surface by a robotic end-effector with integrated stapler, and then the cover layer is applied. So far, it was used with SC3DP. The yarn is fed from the Dynamic Winding Machine [71] where impregnation with resin and helical secondary yarn application takes place. Therefore, it is flexible during installation, but hardens soon afterwards. A certain space is left between the yarn and concrete core, so that concrete applied as cover layer can penetrate end encircle the reinforcement, providing bond and structural integrity.

The green state milling was verified in laboratory by structural testing granting it the TRL 4. The remaining methods discussed here are on TRL 3.

5.8.2. *Reinforcement, process, and form interaction*

As demonstrated, the integration of reinforcement after shaping of concrete is performed using two principal strategies: 1) insertion of short reinforcement while material is still sufficiently fresh (in green state), and 2) placement of reinforcement on the surface of an element, and further integration using the cover layer. The largest asset, common for the two strategies, is its independence on the method of concrete processing, and layer orientation.

The insertion methods, although allowing for free orientation of reinforcement in the volume, are however limited in principle to straight and short segments, limiting its structural continuity and optimisation possibilities. Furthermore, the integration time depends on open time of concrete in green state, imposing the need of timing of the process. This will surely influence negatively its applicability, especially in case of large elements executed on-site.

On the other hand, when the reinforcement is applied on the surface, it can be continuous and tensile stresses-aligned, allowing for optimised structural solution. Either prefabricated mats and bars, or in-situ digitally fabricated reinforcement can be integrated this way. The integration can take part either in green state, or in hardened state, making these strategies less time-dependent. Nevertheless, for sake of integration with concrete and bond assurance, additional steps are required, usually involving deposition of additional concrete cover layer. Finally, this strategy limits presence of reinforcement only to the vicinity of the surface of elements, liming the applicable reinforcement ratio; it could be however combined with other reinforcement strategies when heavily reinforced elements are produced.

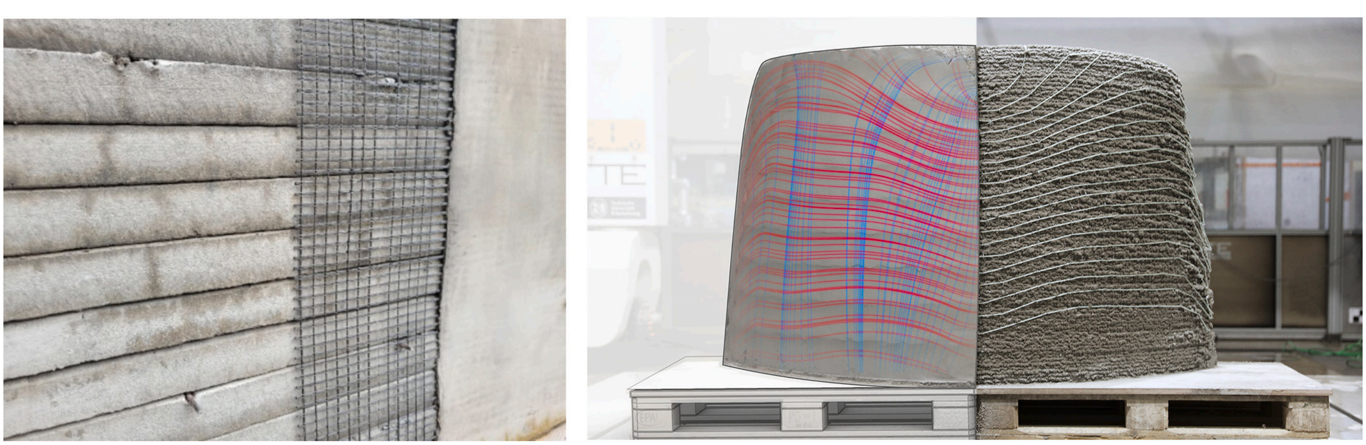


Fig. 22. Reinforcing carbon fibre mesh installed and cover layer applied (left) (©E. Ivaniuk), and Core Fibre Winding (right) (©S. Gantner).

5.9. Post-processed assembled reinforcement

5.9.1. Process description

Post-tensioning can serve two roles simultaneously: 1) of structural reinforcement, and 2) as a method of assembly of smaller elements to form structure [85], see Fig. 23. It has been used multiple times in DFC. First, the continuous open channels are left in fabricated elements. Then, the elements are, assembled, and tendons are led through them and post-tensioned [86]. If needed, grout can be further injected, however in most current cases, unbounded posttension is used. A few pedestrian and bicycle bridges using this reinforcement method has already been built, in particular in the Netherlands [50,87,88]. Accordingly, this technology is of TRL 9, as there already exists a market for post-tensioned DFC bridges in the Netherlands.

Post-tensioning can be also used solely for assembly process, without serving structural role to the element. The cables are then arranged to introduce uniform compressive stress on the contact surface of smaller elements, to create a larger structure. [81,89].

5.9.2. Reinforcement, process, and form interaction

The integration of prestress cables does not strongly compromise the geometric freedom of the digital fabrication process, although continuous openings for the cables should be present throughout the structure (e.g., along the span of a beam or over the height of a wall). This does, however, align well with the potential of material reduction offered by digital fabrication, where concrete structures no longer consist of solid, monolithic parts due to ease of manufacturing. Therefore, no ducts need to be pre-installed before concrete deposition.

As post-tensioning generates large stress concentration at anchorage points, often DFC only forms contour of an element in these regions, where conventional reinforcement and cast concrete are later applied. Another challenge lies in the materials used for DFC, with often larger tendency to shrinkage and creep, due to absence of large aggregate and higher cement content comparing to classical concrete. This can provoke relaxation of prestressing, which needs to be taken into account in form finding.

5.10. Remarks

The main purpose of the RPF framework is to facilitate the discussion of different examples and to give architects and engineers a common language. However, it does not aim to restrict their creativity in any way. Already today, some of the examples fall into more than one category, not only in terms of process but also in terms of the material that drives the form.

A double curved wall fabricated with SC3DP is such an example (Fig. 24) [10]. There, in principle, two reinforcement integration methods were combined. The horizontal reinforcement was integrated as an interlayer reinforcement made of steel stirrups installed manually during the printing of the core of the wall. After reaching the final height and width of the wall, long vertical reinforcement bars were installed, and cover layer applied, falling into category of post-processed reinforcement applied on concrete. The form and final shape were therefore defined by concrete. The intermediate shape, however, was dictated by reinforcement: the surface of the concrete core was undulating, in order to provide space for vertical reinforcement.

As the DFC is developing, it can be only expected that more complexity and processing steps will be added, in order to achieve optimised, efficient, and tailored forms. This underlines even further the importance of classification of the reinforcement integration steps and methods, for efficient communication in the research environment and on the construction sites.

Fig. 23. Topology optimised 3D printed post-tensioned bridge assembled from smaller elements [90].

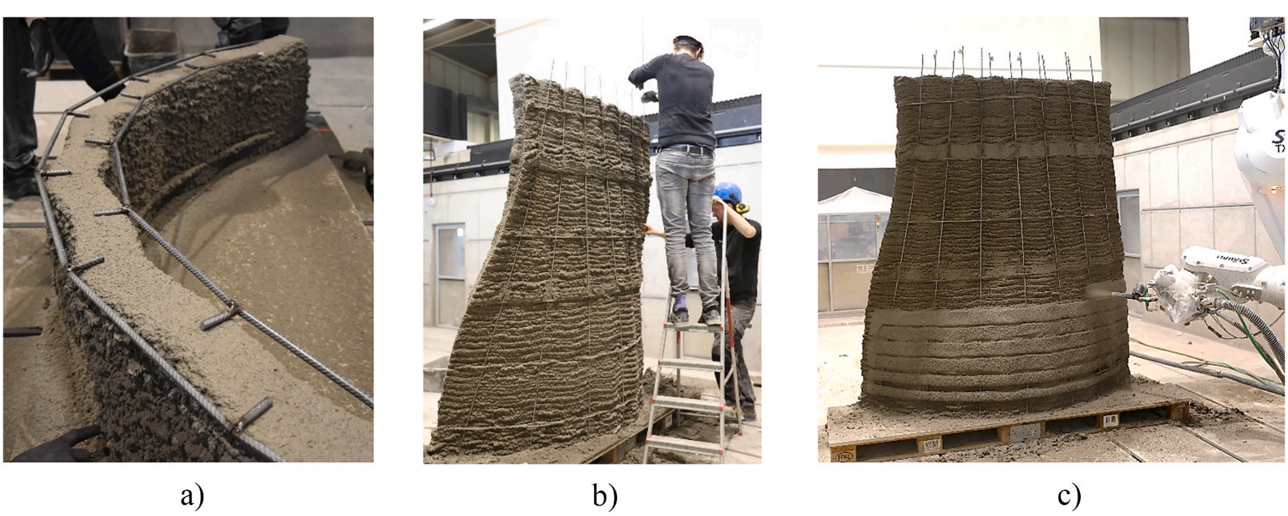


Fig. 24. Fabrication of the double curved wall with SC3DPL a) Placing of interlayer horizontal reinforcement, b) Placing of vertical reinforcement on concrete, c) Application of cover concrete layer.

6. Conclusions and outlook

Balance and unity of material, process, and form is depending on technological progress as well as social advancements, and requires a continuous development. At the beginning of the digital age, there is a great opportunity to fundamentally rethink the logic of form in reinforced concrete construction. The reinforcement integration can take place before, during and after the concrete application, and thus the reinforcement processing becomes an interactive process partner in DFC with its own influence on the form of reinforced concrete structures, i.e., the external shape, as well as the internal guidance of the force-flows. In particular, in DFC we can post-process the concrete directly after 3D printing, while it is still in a green state and can freely integrate the reinforcement in and around the printed volume. This opens up completely new freedom for guiding forces within reinforced concrete. In interactive concrete-reinforcement automation, ideally both materials can be positioned precisely in the areas subject to relevant stresses, and support each other during processing. Additional reinforcement to keep it in place, as in formwork-based construction, can be dispensed with. Therefore, knowledge of the reinforcement, process, and form interaction is essential.

The paper illustrates that the fundamental knowledge of reinforcement, process, and form interaction in DFC are already available. The presented new systematic RPF-framework aims to initiate the next step in DFC: to design and realize form-optimised and material-efficient reinforced concrete structures, which derive their natural beauty and elegance from the outer and inner logic of form. Furthermore, DFC has the potential to bring about a paradigm shift in the construction industry, namely to put the value of the material back in the foreground, and to adapt processing to the efficient use of materials. Therefore, future automated DFC processes will lead to customized reinforced concrete structures surprising with new forms, which will be both economical and sustainable. And, it offers engineers the opportunity to return to the origins: structural design being the synthesis of material, process, and form.

CRediT authorship contribution statement

Harald Kloft: Writing – original draft, Visualization, Methodology, Conceptualization. **Bartłomiej Sawicki:** Writing – original draft, Investigation, Conceptualization. **Freek Bos:** Writing – original draft, Investigation. **Robin Dörrie:** Writing – review & editing, Investigation. **Niklas Freund:** Writing – review & editing, Investigation. **Stefan Gantner:** Writing – review & editing, Investigation. **Lukas Gebhard:** Writing – original draft, Investigation. **Norman Hack:** Writing – original draft, Investigation. **Egor Ivaniuk:** Writing – review & editing, Investigation. **Jacques Kruger:** Writing – review & editing, Investigation. **Walter Kaufmann:** Writing – review & editing, Resources. **Jaime Mata-Falcón:** Writing – original draft, Investigation. **Viktor Mechtcherine:** Writing – review & editing, Resources, Methodology. **Ammar Mirjan:** Writing – review & editing, Investigation. **Rob Wolfs:** Writing – review & editing, Investigation. **Dirk Lowke:** Writing – review & editing, Methodology, Conceptualization.

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Data availability

No data was used for the research described in the article.

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