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Integrating reinforcement in digital fabrication with concrete: A review and classification framework

Viktor Mechtcherine[a], Richard Buswell[b], Harald Kloft[c], Freek P. Bos[d], Norman Hack[c], Rob Wolfs[d], Jay Saranjan[e], Behzad Nematollahi[e], Egor Ivaniuk[a], Tobias Neef[a]

[a] Institute of Construction Materials, Technische Universität Dresden, Germany

[b] School of Architecture, Building and Civil Engineering, Loughborough University, UK
[c] Institute of Structural Design, Technische Universität Braunschweig, Braunschweig, Germany
[d] Department of the Built Environment, Eindhoven University of Technology, The Netherlands
[e] Digital Construction and Concrete Laboratories, Swinburne University of Technology, Melbourne, Australia

Abstract

This article offers a comprehensive, systematic overview of the existing solutions for integrating reinforcement in digital concrete technologies with particular emphasis on Additive Manufacturing (AM) with concrete, also called 3D concrete printing (3DCP). While the functionalities of various types of reinforcement are briefly addressed, the major focus is on the integration process as such, i.e., on its technological aspects. On this basis a generic classification and process description outline has been developed for reinforcement integration, which is regarded as an extension of the RILEM process classification framework for Digital Fabrication with Concrete (DFC). In many instances, the integration occurs in a separate process step prior to or after concrete shaping. This holds true for all formative digital concrete shaping processes and for many 3DCP solutions. 3DCP approaches enable, however, integration of the reinforcement during concrete shaping as part of a single-step AM process in a simultaneous or contiguous manner, while placement of reinforcement is considered to be a sub-process.

Keywords: Digital fabrication; 3D concrete printing; additive manufacturing; reinforcement; review; classification

1. Introduction

The introduction of digital fabrication processes with concrete in a prefabrication facility or directly on the construction site is a decisive step towards the digitization of the entire value creation chain in the construction industry. Over the last five years, enormous progress has been achieved both in terms of establishing scientific fundamentals for the purposeful design of DFC processes; see, for example, [1]. And with respect to implementation of the new technologies into the practice of construction; see e.g. [2]. To date in most publications and pilot projects the greatest attention has been focused on concrete shaping processes, especially on Additive Manufacturing approaches (3DCP) while the solutions for incorporating reinforcement are still rudimentary in many instances. As such they lag the development of 3DCP technologies.

For any person familiar with concrete construction, it is clear that the use of reinforcement is mandatory in most structural applications in complying with key requirements such as load-carrying capacity, ductility, robustness, etc. While integrating reinforcement into formative digital shaping processes, one can usually reach back to established technological solutions. However, in the case of Additive Manufacturing, the challenges of introducing appropriate reinforcement have already been recognised since the initial developments of 3DCP technologies [3].

In early projects this challenge was circumvented by using 3D-printed concrete mostly as lost or integrated formwork for casting, conventionally reinforced structural concrete elements; see as an example [93]. Alternatively, the integration of mesh reinforcement between the layers and the application of post-tensioning to the print element were demonstrated at Loughborough University [94]. However, a multitude of further conceptual solutions has been explored and indeed some have been implemented directly into Additive Manufacturing processes. Developments are still very much ongoing. While the number of publications on the topic and corresponding application examples has been increasing exponentially over the last years, several review efforts have been made as well; see e.g. [4–6]. And initial classification schemes have been suggested [7]. These efforts are of high value in considering the wide range of options with respect to the choice of reinforcement material and geometry, the orientation of reinforcement related to concrete layers and point in time related to concrete deposition, the function of reinforcement, and possible technological manners of its integration, etc. They provide a clearer view of the advances in the field and sharpen the understanding of differences in the various approaches. However, the state of knowledge covered by previous reviews and classification efforts has been in many instances overtaken by the extremely dynamic developments and rapid growth in expertise and comprehension of different novel technologies among the professionals involved. Hence, the authors feel the need to develop a more systematic and more generic view of the subject by preparing a comprehensive review and suggesting a universal classification scheme.

Indeed, the first purpose of the article at hand is to provide a comprehensive, critical, state-of-the-art review of existing approaches to the integration of reinforcement into digital concrete technologies with particular emphasis on AM/3DCP processes. When presenting the various approaches, this review focuses on the technological aspects of the reinforcement integration and on the process-specific characteristics such as continuity of reinforcement, formal freedom, or automation capacity to name a few. In contrast, the functionality of different types of reinforcement as well as structural design and aspects of design for durability are addressed only briefly if at all. This is done mostly with respect to the general choice of the type of reinforcement according to its overall performance. While both functionality and durability of reinforcement are of major importance in structural design, these issues cannot be covered in the present article due to the high complexity of the topic. Another collaborative effort will be needed to offer a sound, interlinking scheme among related aspects of technological implementation, as covered here, and design requirements and solutions. Indeed, this is an exciting field of research and development since the optimal design solutions are likely to be very technology- or application-specific, contrary to the “one-size-fits-all” strategy of reinforcement bars in cast concrete.

Based on the analysis of the state-of-the-art as presented in the review and numerous comprehensive discussions among the authors, a generic, technology-oriented classification for integrating reinforcement into digital fabrication with concrete is suggested. The benefits of establishing such classification are obvious since it provides a basis for a) a clear, systematic description of processes and process chains, b) seamless communication between stakeholders in a highly interdisciplinary field, and c) comparative analysis of various approaches. Furthermore, comprehensive classification is essential in developing application guidelines and other technical or regulatory documentation as well as a reference for further purposeful advancements in DFC technologies. While developing the classification the authors did their best to follow both the spirit, systematic, and terminology of the RILEM process classification framework for DFC prepared by the RILEM Technical Committee 276-DFC “Digital fabrication with cement-based materials”.

2. State-of-the-art review

2.1 Review concept

For most applications of concrete parts, elements, and structures reinforcement is indispensable in attaining the required mechanical performance. While key features of concrete with respect to its use in construction are compressive strength and durability, the main functions of reinforcing material are to carry tensile forces and to impart structural ductility. The various reinforcements differ in terms of their capacity to carry tensile forces and their direction of action; see Figure 1. Certainly as the most widely used composite material there is more to say about the features and functionalities of reinforced concrete, i.e., about both structural and reinforcing materials’ obvious, very successful performance together. However, the focus of this review is on digital fabrication processes with concrete. From this technological perspective in the overwhelming majority of existing approaches and applications, concrete processes provide for the shape of a manufactured element independently if a formative shaping process such as casting or additive shaping process like, e.g., material extrusion is used. Only in rare cases does the arrangement of reinforcement create scaffolding for concrete deposition and “dictate” the shape of the element. Thus, the key question with respect to manufacturing with reinforced concrete is how to integrate reinforcement into concrete with minimum interference in the concrete shaping process.

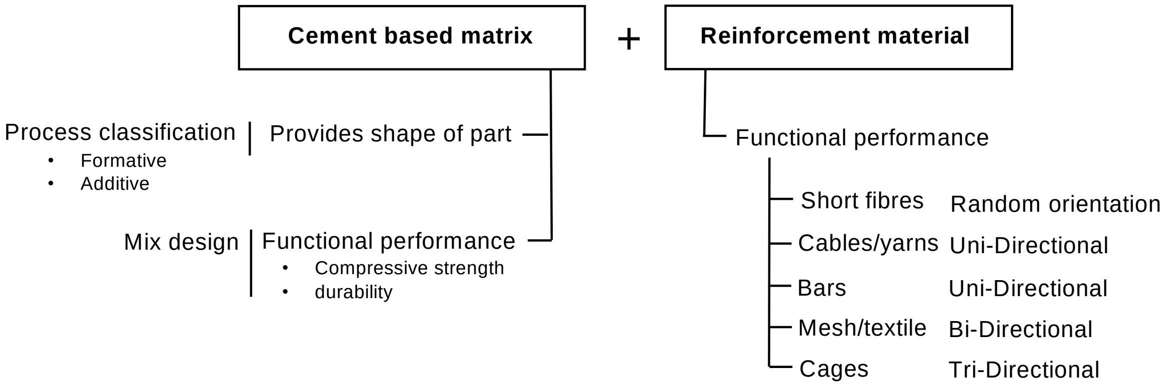


Figure 1. Reinforced concrete as composite material with the assigned main functionalities of the two components concrete and reinforcement.

This section provides an overview of different reinforcement integration approaches used in the context of extrusion-based and jetting-based 3D concrete printing technologies. Particle bed printing techniques are not explicitly considered in this review for three reasons: 1) at this stage this technique is applied very seldom at the common scale of concrete elements, 2) no reinforcement approaches requiring special attention exist specific only to this AM method, 3) the authors want this review to be concise and readily comprehensible.

The review is organised by reinforcement type: bars, grids/meshes, cages, textiles, cables, nails, and short fibres. A further differentiation occurs according to the reinforcing material: steel, carbon, glass fibre, etc. Rather than being exhaustive, representative examples are selected with the intention of covering all known relevant approaches. Section 2.2 briefly describes structural functions and process-specific characteristics to show the perspectives of both design and technology. The review of the existing approaches for integration of reinforcement in the context of Additive Manufacturing with concrete is presented in Section 2.3, while some general conclusions are given in Section 2.4.

2.2 Structural functions and process-specific characteristics of reinforcement integration in 3D-concrete-printing

2.2.1 Structural functions

Not every type of traditional reinforcement integration in 3D-concrete-printing can be used for static-constructive purposes. In this respect material characteristics, geometric dimensions, installation position, the bond with concrete, durability, etc. are decisive. When using steel it is possible to fall back on well-established material parameters. The material characteristics of yarns and textiles made of carbon, glass or basalt fibres are subject to greater scattering as these are composites whose behaviour depends on the materials used for impregnation; see e.g. [95]. Furthermore, the bond between the reinforcement and the concrete matrix is crucial to the effectiveness of the reinforcement. The bond is significantly influenced by the form fit using the surface condition of the reinforcement and its complete embedding into the matrix.

By using different types of reinforcement, the failure form of the components can be influenced. However, while the failure behaviour of reinforcement ranges from brittle, abrupt failure as, for example, in the case of carbon reinforcements, to good-natured, slow-onset failure as with steel reinforcements. Failure on the composite and component levels is affected by a number of additional parameters such as the degree of reinforcement and the geometry of the component. The ductility of components can be increased by the additional use of short fibre reinforcement.

2.2.2 Process-specific characteristics

While the structural functionalities of reinforcement are critical to structural design, they are indirectly relevant also in manufacturing processes. The choice of material and the position of reinforcement in an element to be printed certainly affects possible integration scenarios for reinforcement and associated process characteristics. Establishing the links between structural design and technological implementation is certainly essential from a general perspective. However, detailed deliberations are beyond the scope of this paper. Thus, the process characteristics are presented predominantly from the technological perspective.

- **Continuity of reinforcement**
  The continuity of the reinforcing entities is of elementary importance to the global load-bearing capacity of a structural element or of an entire structure. In particular, achieving continuity of reinforcement either orthogonal or inclined to the deposited concrete layers represents a major challenge. Reinforcement strategies offering such reinforcement arrangements can – in addition to providing the necessary vertical reinforcement – also improve cross-layer force transfer and so make for less anisotropic mechanical behaviour.
- **Automation capability**
  Starting from the automation of the concrete shaping process, the automation of reinforcement integration is essential to the enabling of seamless digital fabrication in the future. To arrange the respective reinforcement elements in an automated process, the automation capability assesses the process engineering effort required. The automation of approaches in a single process step together with the shaping of the concrete seems particularly demanding.
- **Geometric freedom**
  The geometric freedom that additive concrete application allows can be limited by the choice of reinforcement technique. Thus, the technology of reinforcement integration exhibits some restrictions with respect to both structural and architectural design.

- **Process speed**
  An important criterion both for the technical applicability and economic viability of any reinforcement technique is the achievable process speed. This is particularly relevant for single step processes in which reinforcement is introduced simultaneously or congruously to the shaping of the concrete. In such cases an insufficient process speed or insufficient ease of the process – both together defining the overall process speed – can delay the concrete printing process, possibly leading to long time intervals between subsequent layers, which may result in insufficient interlayer bonds, generally leading to an undesired slowdown of the entire AM process. However, also in two-step processes, i.e., where the reinforcing process is decoupled from the concrete shaping, the production efficiency is of high relevance.
- **Robustness of the process**
  Various approaches to reinforcement implementation impose various levels of technical sophistication when being implemented. Generally, the robustness of a process tends to decrease with an increasing level of complexity, e.g., the number of necessary process sub-steps or high requirement on precision in timing or positioning. Some types of reinforcement require additional installation aids during their integration. These temporarily used devices increase the complexity of automation and in turn have an influence on the robustness of the entire process, increasing the infrastructural requirements. Additionally, the robustness of the reinforcement material as such plays a role with respect to range of its handling scenarios.
- **Technological maturity level**
  The technological maturity level is not really a process-specific characteristic, but rather the indicator of the current state of development for the given reinforcement type. This indicator is supposed to express the effort required to implement a new technology successfully, here a reinforcement approach. The assessment is based on the so-called Technology Readiness Level (TRL), which is defined in nine levels and ranges from “the observation and description of the functional principle" to "a qualified system with proof of successful use"; see, for example, [96].

Indeed, the quantification or at least comprehensive qualitative description of the process specific characteristics listed above are crucial for a comparative assessment of various approaches to incorporating reinforcement into digital fabrication with concrete. In the following review, however, the authors will not be particular in respect of these characteristics due to the very limited amount of available qualitative and quantitative information as yet.

2.3 Review of representative reinforcement concepts

2.3.1 Bars

Reinforcing concrete structures with conventional reinforcing bars is a standard method in construction. Not surprisingly this method is also being investigated for its applicability in Additive Manufacturing with concrete. The known concepts range from the placement of straight and pre-bent reinforcing bars in-between the printed layers, through techniques specifically developed for reinforcing also in the vertical direction, up to the drop by drop welding of individualised reinforcing bars using Wire Arc Additive Manufacturing (WAAM) processes; see Figure 2.

(a) (b) (c)

Figure 2. Reinforcement strategies using steel bars: a) placement of straight reinforcement bars in the print plane [8]; b) placement of reinforcement in horizontal as well as in vertical direction [9]; c) 3D-printed reinforcement bars using WAAM welding process [10].

In order to reinforce straight, 3D-printed walls, unbent reinforcing bars can be placed into the still fresh concrete parallel to the printing plane and then covered by a subsequent layer of concrete; see Figure a. This approach was, for example, demonstrated by [8] and the bond between reinforcement and concrete was analysed by [11]. For more complex geometries such as the Cohesion Pavilion at the University of Innsbruck [12], the reinforcing bars have to be pre-bent manually or automatically and positioned in the correct location between the layers, as was done in most of the 47 different parts that comprise the structure. Often this also required adapting the internal concrete filament structure to match the limited geometrical flexibility of the pre-bent bars.

The challenge of integrating reinforcement bars in both directions was tackled in a demonstrator from the TU Braunschweig using the Shotcrete 3D Printing technology [13]. For this purpose, a process-specific printing strategy involving a sequence of manufacturing steps was developed. In the beginning the input geometry is parametrically converted to contain slight horizontal undulations, which are later used to integrate the vertical reinforcement. Every 50 cm the printing process is stopped and pre-bent reinforcing elements are placed on the top layer. The undulations thus create tabs over the entire height of the wall, into which the unbent vertical reinforcement can be inserted; see Figure b. The now still external reinforcement is covered by another layer of shotcrete and subsequently trowelled under automation [9].

In the projects described above, the reinforcing bars were placed manually. In order to improve the accuracy of the positioning, the applicability of Augmented Reality was tested in the last example. An automation of the placement process is also possible, although with increasing bar lengths it is more challenging due to the long bars' sensitivity to vibration.

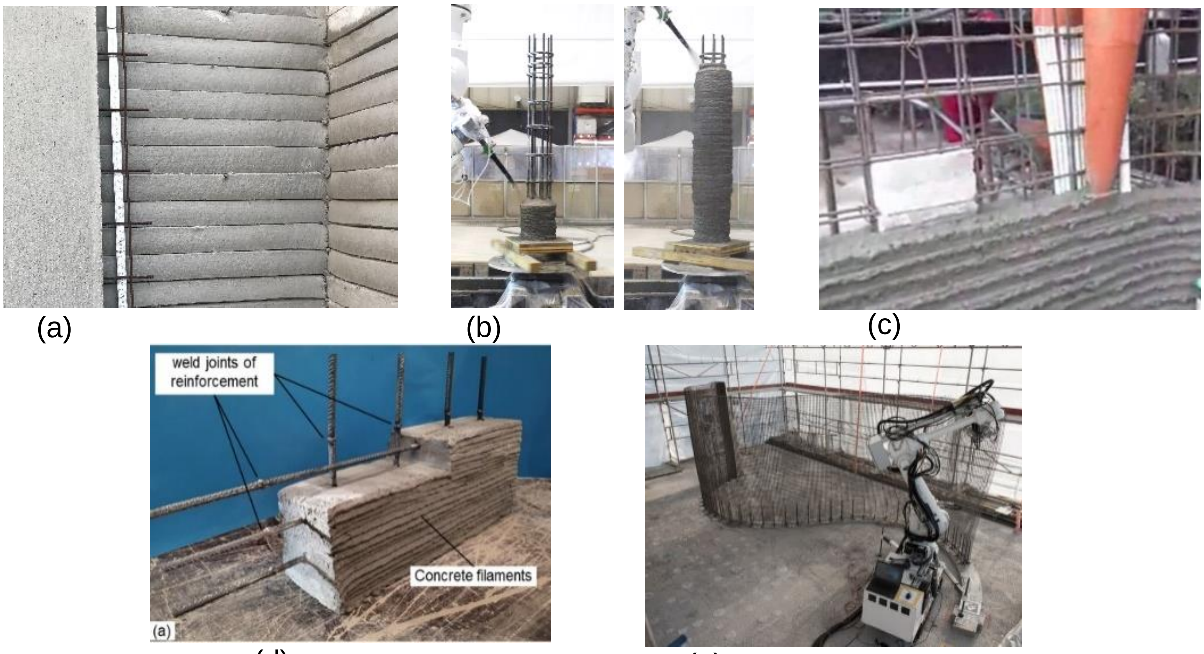
The possibility of avoiding some of the challenges mentioned above, i.e., pre-bending, two-way reinforcement, and automated placement, 3D printing using a parallel to the printing plane was suggested by Mechtcherine *et al*. [10] using Wire Arc Additive Manufacturing (WAAM); see Figure 2c. In the WAAM method, the reinforcing elements are built up in a drop-wise manner enabling a maximum of geometric flexibility, including the possibility of thickening the printed bars locally, so resulting in an improved bond between concrete and reinforcement. Tensile tests confirmed load-bearing behaviour comparable to conventional concrete steels as well as a ductile failure of the bars [10]. Hurdles in applying this concept are that: 1) the steel printing process is slower than the concrete printing process; 2) the steel printing generates very high temperatures, which could potentially damage the concrete, and 3) the WAAM welding process is so costly. The applicability of this process to digital fabrication with concrete is currently being investigated by several research groups [10,14,15].

2.3.2 Grids, mats and cages

Today reinforcement meshes are manufactured mostly of steel but in some cases from polymers reinforced with glass or carbon fibre as well. Mats are also used as semi-finished products to produce more complex reinforcing cages [16]. To cover a wide range of different stresses, reinforcing meshes are produced with different bar thicknesses and mesh sizes. Prefabricated meshes reduce the amount of work on the construction site, as individual bars no longer have to be laid out and connected. The use of prefabricated meshes and reinforcement cages in digital fabrication with concrete offers the advantage that the reinforcement is already arranged in two principal directions. However, approaches in assembling the meshes or cages automatically on site have been developed as well. Thus, different concepts for integrating mats and cases into the digital concrete technologies concentrate either on the challenges related to shaping the reinforcing meshes into the desired geometry, on the shaping of concrete for given mesh geometry, or sometimes on both cases.

2.3.2.1 Metallic grids, mats and cages

The most straightforward way of reinforcing 3D-printed concrete structures using steel mats was demonstrated at the TU Dresden. The wall shown in Figure 3a was printed as a monolithic structure using a nozzle with a width equal to the width of the wall, here 150 mm. Short steel bars were placed every couple of concrete layers perpendicular to the wall plane, so that their ends protruded from concrete. After concrete hardening, the steel grid was installed on the wall surface using protruding bars' ends as supports; see Figure 3a [17]. After that, the mesh was covered with a protective layer of concrete.



(a) (b) (c)

(d) (e)

Figure 3. Integration of steel mats and cages: a) steel grid installed on a 3D-printed wall after concrete hardening [17], b) Shotcrete 3D Printing around a preplaced reinforcement cage [18]; c) in-situ printing encasing a preplaced reinforcement mat using a split nozzle [19]; d) mesh created from welding short bars onto each other using a stud-welding process [20]; e) robotic in-situ fabrication of a double curved reinforcement cage [21].

In contrast to that, application of concrete on pre-configured and preplaced reinforcement cages using Shotcrete 3D Printing was developed at TU Braunschweig. In the experiment depicted in Figure 3b, a standard reinforcement cage for a column was placed on a computer-controlled turntable before Shotcrete 3D Printing was performed. A section through the column showed a good embedment of the reinforcement in the concrete without visible inclusion of air voids [18].

The Chinese construction company Huashang Tengda developed and patented a process for integrating preplaced conventional steel reinforcement meshes in the 3D printing process based on layered extrusion by encasing them with concrete one layer after another. The concrete is deposited from two sides around reinforcement using a split nozzle as shown in Figure 3c. The split-nozzle is capable of printing around meshes of about 1.5 m height [19]. To produce walls at full room height, a second or possibly third series of mats with appropriate overlap, have to be mounted as the concrete printing progresses.

While the reinforcement described in the examples above was manually pre-configured and pre-placed in position, there are attempts to automate these processes and integrate them into the printing process. In a concept from RWTH Aachen and KU Leuven, the fabrication of a freeform mesh structure and the printing of concrete around this structure are envisioned to take place simultaneously. The fabrication of the mesh is based on a stud welding process in which pre-cut reinforcement bars of 8 mm in diameter and approximately 25 cm in length are butt-welded in both the horizontal and vertical directions. In the demonstrator depicted in Figure 3d, however, the mesh was welded manually [20]. Concrete was printed around the structure using a split nozzle, generally similar to the process depicted in Figure 3c, however, with the advantage that the nozzle does not require the excessive height of the technology in which preinstalled meshes are used. For a distance between the nozzles of 1.5 times the reinforcement diameters, good inclusion of the rebar was observed. However, the small leeway made the process prone to collisions of the nozzle with the reinforcement.

The Mesh Mould process, developed by researchers of ETH Zurich, involves the bending and welding of 6 mm steel reinforcement by a mobile robot *in situ* for creating geometrically complex reinforcement structures; see Figure 3e. After the entire mesh structure has been fabricated, it is filled with concrete in more or less conventional fashion. In the demonstrator at the DFAB HOUSE on NEST, this was done by laterally pumping concrete into the mesh [21]. Automated concreting, similar to the extrusion-based approaches followed by Huashang Tegna or the Shotcrete 3D Printing, seem to be feasible in future applications in conjunction with the automated fabrication of reinforcement cages.

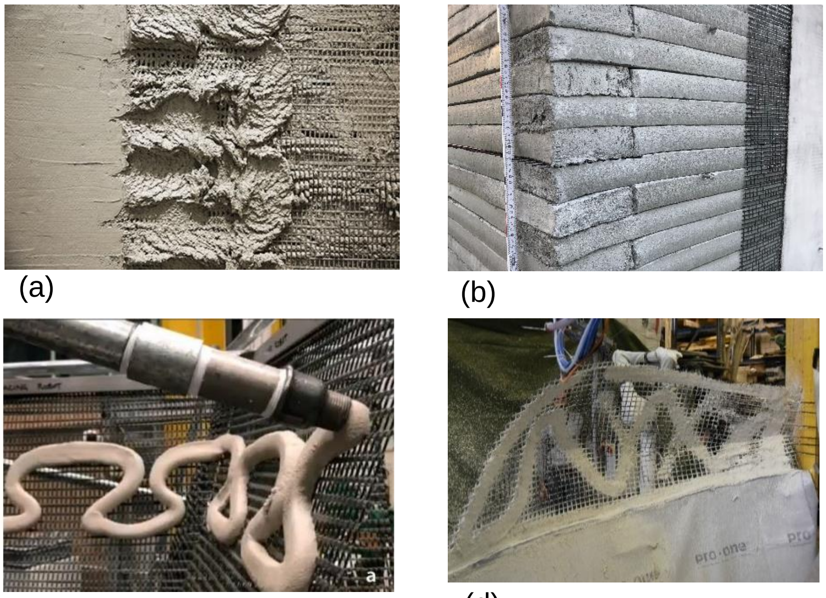
The examples given indicate the potential of the combination of automated grid production and automated concrete application, but due to the high complexity of such combination, full automation has not yet been proven.

2.3.2.2 Carbon grids and mats

Due to their higher flexibility in comparison to steel mats and their narrower mesh size, the suitability of carbon fibre mats for additive manufacturing with concrete is being presently investigated in several research projects. In these experiments different methods of concreting, i.e., by extrusion and spraying, as well as different sequences of concrete placement, i.e., before or after placing the mat, have been investigated.

One way of reinforcing construction elements is to press a carbon fibre mat into the still fresh concrete, directly after the core has been printed. This approach was demonstrated using Shotcrete 3D Printing in [22]. Subsequently the core and the mesh are covered with another layer of concrete; see Figure 4a. This method is particularly suitable for single curved components, as the commercially available carbon reinforcements can only adapt to single curvature.

Carbon grids also can be used for the reinforcement of already hardened 3D-printed concrete structures as presented by TU Dresden in the context of CONPrint3D technology; see Figure 4b [17]. The carbon mesh was incorporated using a laminating technique known from application of carbon reinforced concrete for strengthening or repair; as an example see [23].



(a) (b)

(c) (d)

Figure 4. Carbon grids: a) placement of the mesh onto a freshly printed concrete element with subsequent application of a cover layer [22]; b) carbon grid laminated on a 3D-printed wall after concrete hardening [17]; c) extrusion-based printing on a pre-positioned carbon fibre mesh [24]; d) shotcreteing on a preplaced carbon-fibre mat using glass-fibre reinforced concrete [25].

Whereas in the two approaches presented the reinforcement is supported by the previously printed concrete core, the inverse strategy is also subject to investigations. In those cases, the reinforcement mats are pre-placed and concrete is printed onto the pre-defined geometry. In the Sparse Concrete Reinforcement in Meshworks (SCRIM) research project, this is done by extruding concrete from one side onto the previously positioned mesh as depicted in Figure 4c [24]. A similar approach has been followed by the Robotic AeroCrete project of ETH Zürich. However, instead of extruding concrete onto the mesh, the material is sprayed using a shotcreting process; see Figure 4d [25]. In order to avoid the concrete from flying through the mesh, a special spray-gun application is used, adding chopped glass fibres to the concrete right at the nozzle orifice.

2.3.3 Pre-stressing strands (steel, stainless steel, CRP)

An early adopted reinforcement strategy for 3D-printed concrete is the application of pre-stress to eliminate any tensile stresses occurring in the concrete. Generally, the type of ‘post-tensioning without bond’ is utilised. This principle has been applied in a 3D concrete printed bicycle bridge in the Netherlands; see Figure 5a [26]. The designers opted to press six printed elements together perpendicular to their print plane using a common commercially available system with strands anchored in cast concrete end blocks and running through the open inner structure of the printed parts. The design enables counteraction of any prestress loss in the tendons, as the shrinkage characteristics of the printed concrete were not well known beforehand. Large 1:2 scale four point bending tests showed that the element integrity was not lost in several un-/reloading cycles until well beyond the crack moment [27]. Nevertheless, this should remain a point of attention when designing a structural element that relies on unbonded tendons for its structural integrity.

Figure 5b shows a post-tensioned dry joint column manufactured by the Institute of Structural Design at TU Braunschweig in 2019. In this case, column segments were Shotcrete-3D-printed, leaving a central integrated channel. The efficient integration of channels by AM technologies allow the integration of post-tensioning elements after printing. In a subsequent step the joint surfaces were subtractively machined and then joined and reinforced via post-tensioning [28].

(a) (b) (c) (d)

Figure 5. Pre-stressing with hardened 3D-printed concrete components: a) conventional prestressing strands in a printed bicycle bridge [26]; b) post-tensioned dry joint column of shotcrete-3D-printed segments [28]; c) post-tensioned girder consisting of several segments produced using 3D concrete printing [29]; and d) external reinforcement system with tightened bars [30].

In the example of this bridge, the geometry of the printed elements was still fairly straightforward. However, more recent case studies have shown the potential of the use of this reinforcement strategy in combination with structural optimization methods to obtain more elaborate and minimalised geometries [27]. The post-tensioned girder with a span of 4 m and consisting of several segments produced using 3D-concrete printing was developed at Ghent University; see Figure 5c. By means of topology optimisation techniques, not only was the concrete distribution optimised, but the optimal shape and curvature of the post-tension cable were also determined.

Another example for reinforcement systems applied to form a segment structure is external reinforcement for a 3D-printed truss component developed at the University of Naples "Federico II" [29]. The patented system uses tightened steel bars. In a first manufacturing step, only the printing elements of a truss are printed. Then, cavities for reinforcement anchors are cut out and the reinforcement anchors are inserted and monolithically cast. Eventually, prefabricated diagonal tension elements are attached to the reinforcement anchors and tensioned.

2.3.4 Cables and yarns

In 2017 a method was presented at TU Eindhoven for reinforcement of an extrusion-based 3D-printed concrete, longitudinal filament by directly entraining a high strength steel cable into the filament [32]. Actively fed from a spool by a small servo motor with an appropriately flexible cable, this allows a fully automated process that does not reduce the geometrical possibilities of the 3DCP technology. This technology is clearly only effective in one direction, i.e., longitudinal to the filament. Besides several studies that have been published, this concept has been applied in the bicycle bridge discussed in Section 2.3.3 as secondary reinforcement to act, in about 10% of the layers of each element, transversely internal to the bridge. Although initial studies have shown the potential of this technology, several issues remain before it can be used generally. Besides further development of the equipment to allow fully automated processing, the minimal reinforcement ratio in an application should be considered because the maximum tensile force in the applied cables is limited due to their small section size, which in turn is the consequence of the requirement for sufficient lateral flexibility. Another important issue is the bond between cable and matrix. As the concept relies on the cable acting as conventional reinforcement, this bond has to exceed the cable strength. A recent study [33] showed that the bond quality is highly dependent on the chemical interaction between cable surface and matrix mortar as well as the flow behaviour of the matrix around the cable upon introduction. Inspired by the work at the TU Eindhoven, other research groups have dedicated research efforts on use of thin steel cables in extrusion-based 3D concrete printing; see [34,35].

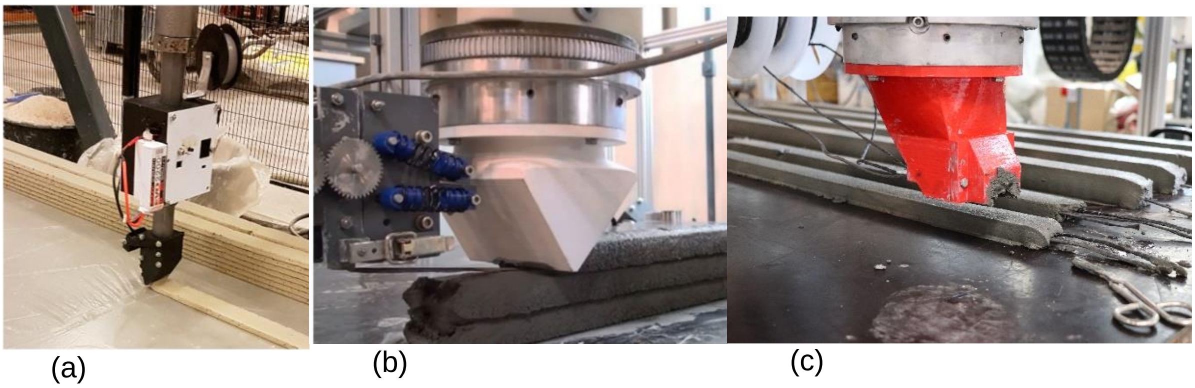


Figure 6. Introduction of linear reinforcement through or at the printhead nozzle: a) high strength steel cable introduced into extruded filaments [36], b) mineral-impregnated carbon yarns with feeder for placing reinforcement between concrete layers [37]; c) mineral-impregnated carbon yarns introduced into extruded filaments [38].

Researchers at the TU Dresden developed an alternative reinforcement material, Mineral-impregnated Carbon-Fibre (MCF) composites, which are particularly suitable for integration into digital fabrication with concrete. In comparison to steel cables or polymer-bound carbon-fibre reinforcement, MCF bonds more effectively with concrete, and in the case of MCF, sufficient bond strength was measured even at temperatures up to 500 °C [39]. The new reinforcement is also less expensive and environmentally friendlier in comparison to the polymer-bound version. However, of major interest is a very high technological flexibility of new reinforcement, since it can be processed and shaped easily in the fresh state and that fully automated [40].

Various approaches for introducing MCF into 3D concrete printing were suggested. In the first approach, the MCF reinforcement is placed between subsequently printed concrete layers. The MCF yarn is operated by a feeder attached to the printhead so that reinforcement is deposited in front of the nozzle just before it passes the same spot[37,41]. While the MCF reinforcement is being placed, the previously printed concrete filament acts as a substrate; then the roving is immediately covered by the following printed concrete layer extruded by the printhead; see Figure 6b. The main advantage of this approach is that the MCF can deposited indeed independently of the concrete. This facilitates the manufacture of elements with complex geometries and the specific reinforcement arrangements; see[37]. The entire process is flexible, especially if a nozzle with a vertical discharge direction is used. On the negative side, a weaker bond between reinforcement and concrete is to be expected in comparison to the solution in which the yarn is integrated into the concrete filament [37,38].

Figure 6c shows an alternative approach, called ProfiCarb, which currently enables the integration of up to six MCF yarns simultaneously into the concrete filament through the printhead before concrete deposition. The bond in the joint between the concrete layers is not disturbed by the reinforcement, which is an advantage of this technology [38]. Flexible reinforcement is inserted into a nozzle through an opening on the reverse side of the printhead while the obverse side of the nozzle shapes the concrete filament with the integrated reinforcement. There are also limitations on such a setup: 1) deposition of the reinforcement without concrete is problematic, and 2) placement of the reinforcement is possible only in parallel with the printed layers.

Mechtcherine *et al*. [37] pointed out that additional requirements within both approaches can be 1) the free start and stop of MCF supply and integration into concrete and 2) an adjustable degree of reinforcement. Quite clearly these requirements increase the level of sophistication of the printing system and increase its flexibility and overall efficiency in the purposeful use of the reinforcement.

2.3.5 Textiles

Few studies have investigated the application of textiles made of different materials such as carbon, glass or basalt fibres for reinforcing DFC. Wang *et al*. [42] at the Loughborough University placed plane glass fibre textile on a print concrete layer and covered it then by printing the next concrete layer; see also Figure 7a. Mechtcherine and Nerella [43] proposed an 'in-process' reinforcement method to place a special 2.5D textile between individual concrete layers to counteract the possible formation of 'cold joints' between printed layers; see Figure 7b. The aim of this method is to stitch each of the two adjacent layers together by the protrusion of individual fibres in the vertical direction. Obviously, a specific print head needs to be designed for accurate automatic placement of the textile. Apart from prevention of cold joints, concrete layers are reinforced in the printing direction as well.

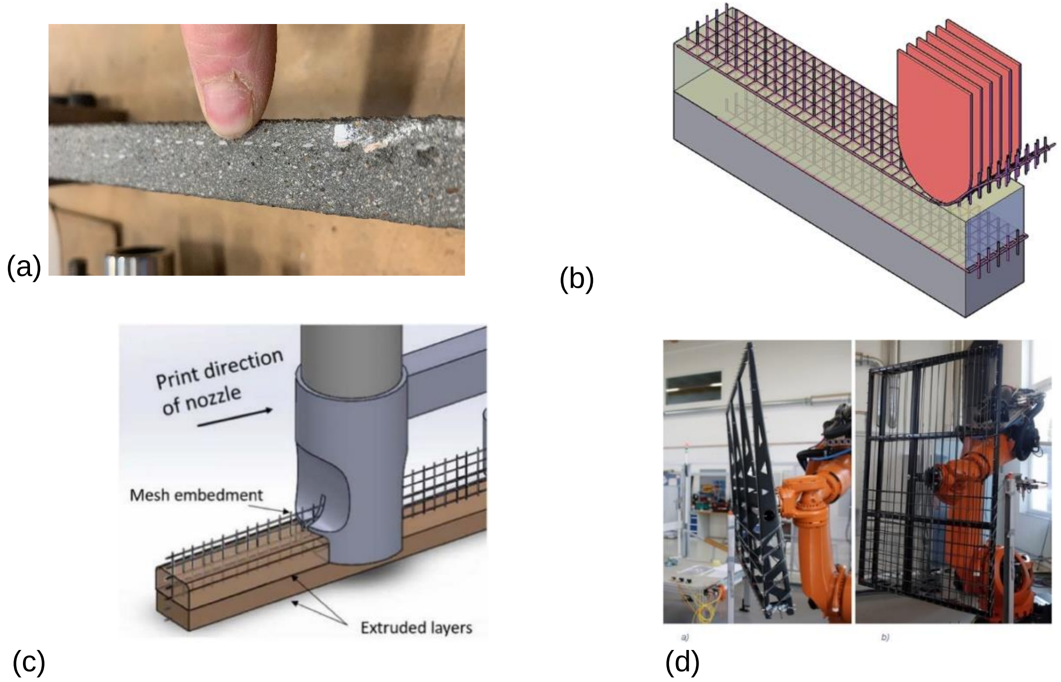


Figure 7. Reinforcement strategies using textiles: a) print concrete specimen reinforced with a planar, glass fibre textile [42]; b) placement of special 2.5D textile between two adjacent layers in the printing plane [43];c) in-process placement of galvanised steel wire mesh in the interlayer direction (across the layers) [44]; d) automated manufacturing of 3D reinforcement structure for a balcony using a robot-based wrapping process for mineral-impregnated carbon fibre composites [40].

Recently, Marchment and Sanjayan [44] proposed an 'in-process' reinforcement method called Mesh Reinforcement, in which a galvanised steel wire mesh was placed in the middle of each printed layer while the concrete layers were being printed to provide reinforcement in the interlayer direction, i.e., across the layers; see Figure 7c. The embedded mesh in each layer was overlapped in the vertical direction of the interface transverse to the layer to ensure continuity of reinforcement. A special nozzle was designed to allow the insertion of the continuous reinforcing mesh in the middle of the layers' being printed. The reinforcing mesh should have appropriate rigidity, diameter, and aperture of the grids to provide adequate bond and anchorage within the printed layer, accommodate the mobility of the nozzle during deposition, and allow placement and feeding through the nozzle system. While the proposed method proved effective in providing a continuous 'in-process' reinforcement for lab-scale 3D-printed straight walls, the process still needs to be automated, and further testing should be done on larger scale components and curved structures. In addition, the method may be optimised by autonomous stitching together of mesh via rebar ties to reduce/eliminate the overlap length and chance of collision during the process.

Mechtcherine *et al*. [40] used Mineral-impregnated Carbon Fibre composites (MCF) for automated manufacturing of 1D- (bars and strips), 2D- (mats), and 3D- (e.g., shells) reinforcement elements. Figure 7d shows a robot-based wrapping process for manufacturing a 3D reinforcement for a balcony, where a supporting frame was mounted at one single point to the robot, and the wrapping process was conducted by moving the supporting frame around the impregnated yarn, guided by a fixed shaping nozzle.

2.3.6 Dispersed short fibres

Several studies investigated the application of various short fibres made of polymer, carbon, glass, steel or stainless steel as disperse reinforcement for DFC [1]. They can be premixed into the dry mortar, added during concrete mixing, or introduced into the mortar/concrete just prior to deposition. The former two cases have the distinct advantage that no custom equipment is needed, allowing easy integration into the printing process. The latter, on the other hand, may be required due to pump-fibre incompatibility and would need specific equipment [45]. However, this still means that the printing itself is unencumbered by additional process steps.

During printing fibres do not take a random orientation, but mostly one that globally corresponds to the direction of the printing path. The actual fibres' orientations are the result of a complex interaction between matrix material properties, e.g., viscosity, fibre properties, e.g., aspect ratio and transverse stiffness, and the print facility, e.g., pumping pressure and nozzle geometry). Generally, fibres will only provide reinforcement in the print plane because they do not cross filament interfaces. However, a study showed this might be overcome by providing a tongue-and-groove type of surface accentuation of the filament; see [46].

Hambach and Volkmer [47] reported on the mechanical properties of cement paste reinforced by different types of 3- to 6-mm-long fibres, including carbon, glass, and basalt fibres. The inclusion of the fibres resulted in high flexural strength of the printed specimens, up to 30 MPa. ESEM micrographs of fractured specimens confirmed a pronounced alignment of fibres in the printing direction; see Figure 8a.

(a) (b) (c) (d)

Figure 8. Examples of the use of dispersed short fibres: a) a sample containing aligned reinforcement fibres and corresponding ESEM micrographs showing fibre orientation (perpendicular and parallel to the fracture surface of the specimen) [47]; b) printed specimen reinforced by short steel fibres and sawn parallel to the printing direction [48]; c) 3D-printing process with UHPFRC reinforced by short steel fibres [49]; d) 3D-printing process with SHCC containing PE fibres [50].

Bos *et al*. [48] investigated the effect of the inclusion of short, straight steel fibres on the performance of 3D-printed specimens, and the results were compared with the counterpart cast specimens. A strong alignment of fibres in the printing direction was observed; see Figure 8b. Still the results showed that the fibre-reinforced specimens exhibited significantly higher flexural strength as compared to the specimens made of plain mortar. However, all specimens exhibited deflection-softening behaviour after reaching peak load.

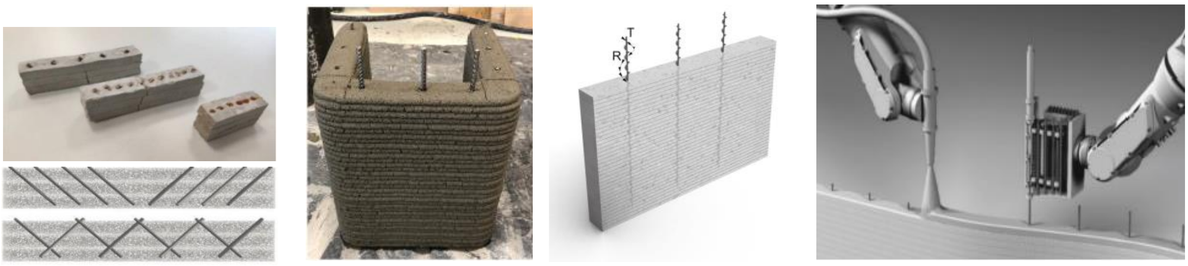
Arunothayan *et al*. [49] recently reported the systematic development of a non-proprietary, 3D-printable ultra-high performance fibre-reinforced concrete (UHPFRC) reinforced with 2% by volume of 13 mm long steel fibres; see Figure 8c. The printed UHPFRC exhibited high flexural strengths (up to 39.5 MPa) along with deflection-hardening behaviour. The modulus of rupture of the printed UHPFRC specimens was significantly higher than that of the mould-cast specimens, due to the alignment of short fibres in the printing direction during the extrusion process.

Ahmed *et al*. [45] presented a device to introduce generic particles, which could be different types of fibres, into the mortar in an extrusion-based 3D concrete printing facility just before printing, thus circumventing potential compatibility issues of, for example, aggregates with the main pump of the system. Amongst others, 24-mm-long glass fibres were introduced, which resulted in semi-plastic failure behaviour and high deformation capacity.

To date few studies have reported the development of 3D-printable, strain-hardening cementitious composites (SHCC) reinforced by short polymeric fibres such as polyvinyl alcohol (PVA) and high-density polyethylene (HDPE) fibres. Li *et al*. [46] recently provided a state-of-the-art review on 3D printing with SHCC. 3D-printed SHCC exhibits tensile ductility comparable to that of cast SHCC. Ogura *et al*. [50] reported that printed HDPE-SHCC specimens exhibited pronounced strain-hardening behaviour in uniaxial tension for fibre concentrations as low as 1%; cf. Figure 8d. Chaves Figueiredo *et al*. [46] presented a quantitative methodology based on rheological parameters for development of printable SHCC reinforced by PVA fibres. In another study, Zhou *et al*. [51] reported the development of printable SHCC reinforced by different percentages of PE fibres, exhibiting very high tensile strength and tensile strain capacity of up to 5.7 MPa and 11.4%, respectively. The results of several of the abovementioned investigations showed that the printed specimens exhibited superior tensile performances to cast specimens, which was attributable to the strong fibre alignment caused by the extrusion process. However, for a mixture with PVA fibres, Chaves Figueiredo *et al*. [52] reported that the fibre orientation was not simply parallel to the longitudinal direction, but rather seemed to be influenced by differential flow between the in- and outside of the filament, too. In order to address the lack of effectiveness across the interfaces, it was shown by Li *et al*. [46] that a tongue-and-groove type of surface accentuation to the printed filament can significantly improve the post-crack strength of a notched beam in three-point bending, thereby suggesting the issue of lack of out-of-plane ductility might be solved.

2.3.7 Penetration reinforcement

A few studies have introduced an ‘in-process’ reinforcement method in which nails, screws and conventional steel bars are driven through a predefined number of freshly printed layers of concrete. The aim of these methods is to provide reinforcement across the concrete layers. Although in the available studies, as presented in the following, the reinforcements manually penetrated the concrete layers, in practice the placement of reinforcement can and should be automated. Penetration of the reinforcement causes different levels of disturbance to the printed layers, depending on the penetration depth among other parameters, specifically, if conventional steel bars are used. Obviously, the bond between reinforcement and printed concrete should be adequate to ensure the composite action. Therefore, the number of layers into which the reinforcement can be driven while yielding sufficient bond strength is limited.



(a) (b) (c) (d)

Figure 9. Reinforcement approaches using penetration: a) penetration by steel nails with different spacing and orientation through freshly printed concrete [53]; b) penetration of 350 mm long steel bars through printed concrete [54]; c) inserting screws by a combination of translational and rotational movement into freshly printed concrete [55]; d) vision for penetration of short reinforcement bars into Shotcrete-3D-Printing process using an automated, robot-guided process [56].

Perrot *et al*. [53] used nails of 30 mm length and 1.8 mm diameter with different spacing of 10, 15, 20 and 30 mm and various orientations, i.e., vertical, inclined and crossed, to the printed concrete layers. Specimens consisted of three or ten layers; see Figure 9a. For the 3-layer specimens tested perpendicular to the layer’s direction, the vertical nails did not contribute to the bending capacity, while the inclined and crossed nails increased the bending capacity by up to 50% as compared to the unreinforced specimens. For the 10-layer specimens tested parallel to the layer’s direction, the nails, irrespective of their orientation (vertical or inclined), increased the bending capacity by up to 50%. The comparison between the smooth and rusty nails showed a negligible effect of the nails’ surface roughness on bending capacity but had a significant effect on post-peak behaviour. For the smooth nails, the load post peak dropped to zero due to slippage, while for the rusty nails the load did not drop to zero, but to a constant residual value.

Recently, Marchment and Sanjayan [54] introduced a method in which a deformed steel bar of 7 mm diameter was penetrated manually through a number of freshly printed layers; see Figure 9b. Pullout tests were conducted to characterise the bond between the bar and the printed concrete along the penetration depth. It was found that the bond was higher at the bottom of the penetrated depth and gradually decreased towards the top. The bond between the bar and printed concrete specimen near the bottom of the penetrated depth was similar to that of the cast specimen. A strong correlation was found between the penetration length and reduction in bond strength.

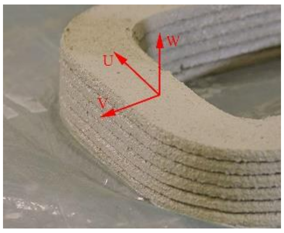
Hass & Bos [55] presented a new reinforcement method in which screws are inserted into freshly printed concrete. The combination of translational and rotational movement provided very good bonding and few defects between the screw and the freshly printed concrete, which is a major downside characteristic of merely translationally pressing any sort of element into the relatively rigid mortar. This was confirmed by the results of pull-out and three-point bending tests, in which premature pull-out failure of the screw was not recorded, but rather failure was observed in the printed concrete itself. Although manually applied in this study, the technology could be automated and can be effective in any direction except longitudinally to the print filament. It requires an additional, intermittent sub-process during printing, of which it may therefore influence efficiency negatively. There will be a time window in which the technology can be applied and related to the setting rapidity of the print mortar in use.

Freund *et al*. [56] investigated three different methods for placement of a short bar, of diameter 12 mm and made of steel or carbon, into the Shotcrete-3D-Printing process; see Figure 9d. These methods include a) direct insertion, b) insertion into a grouting mortar, and (c) screwing the bar into the printed concrete. Pull-out test results and evaluation of computer tomography images confirmed that method (a) resulted in a reduced bond as compared to the other two methods due to a process-related cavity formed between the bar and the surrounding concrete. On the other hand, methods (b) and (c) resulted in a significant enhancement of the bond between the bar and concrete.

2.4 Summary of the reviewed reinforcement approaches according to their advantages and limitations

Based on the above review, which is organised according to reinforcement types and materials, reinforcement approaches and their key features can be identified. These approaches are listed in Table 1 and some of their perceived advantages and limitations are described. The concepts with similar advantages and limitations are listed together, based on the process and the type of reinforcement that have been developed and demonstrated so far. The directions in which the reinforcement can be provided are defined with regards to the fabrication rather than the product. The fabrication direction u is defined as the direction of the layer along the layer or print direction; v is the interlayer or layer stacking direction; and w is the out-of-plane direction. See also the small sketch internal to the table. The product being fabricated may have a different coordinate system such as x, y and z, e.g., x and y being horizontal and z being vertical).

Table 1. Approach listed according to their advantages and limitations

Reinforcement approach	Advantages	Limitations
Post-installed reinforcement • reinforcement bars placed and grouted [57–64] • prestressed reinforcements [26] • external reinforcement [65]	Structural requirements such as robustness, ductility and tensile strength, shrinkage, creep, and crack width limitations can be satisfied with these reinforcements. These types of reinforcements have been used in reinforced concrete for many decades and are technologically mature with regard to design and implementation.	Require post-processing. Coordinates used in this table: 

Pre-installed reinforcement - Print around the reinforcement [66,67] - Mesh Mould [68,69] - Print over reinforcements [11,70]	These approaches can satisfy most of the structural requirements mentioned above. Pre-installing reinforcements before casting concrete is a traditional method. However, printing concrete is a relatively new concept.	Require pre-processing.
Cable entrainment in the filament [32,34–36,71,72] Continuous fibre entrainment [35,71]	In-process reinforcement method.	Only in u-direction. Bars cannot be used.
Overlapping mesh reinforcement [44]	In-process reinforcement method; u- and w-directions can be reinforced.	Not in v-direction; bars cannot be used.
Penetrating reinforcement [53–56,74–76]	In-process reinforcement method; cross-layer (w-) direction can be reinforced.	u and v directions have not been attempted; in-process, but two separate parallel processes are required.
Dispersed short fibres [45,46,81–84,48,49,51,52,77–80]	Easy to implement without additional equipment; in-process method; effective for preventing plastic shrinkage cracks, reducing crack widths, and increase in toughness.	Mainly for non-structural purposes, structural member ductility and structural robustness cannot be achieved due to discontinuities of the fibres.
Welded bars [10,14,15,20,85,86]	In-process method; u-, v- and w-directions are possible.	Quality and steel property control need to be monitored carefully; process speed and cost considerations may outweigh the technical benefits.
Printed polymeric reinforcement [87–89]	Complex shaped reinforcements in all u-, v- and w-directions are possible; it can be used for special arrangements of structural reinforcements.	Non-structural reinforcement only; limited tensile strengths.

3. Previous reviews and classifications

The great variety of approaches for integration of reinforcement in digital fabrication with cement material calls for a classification. The available framework to build such a classification on is fairly limited. Conventional structural concrete engineering guidelines hardly provide a handhold. In the vast majority of concrete structures, reinforcement is provided by linear elements, generally made of steel: normal strength steel for passive reinforcement, and high-strength steel for active reinforcement, i.e., prestressed. The use of other materials for such bars, e.g. glass fibre reinforced polymer (GFRP) and carbon fibre reinforced polymer (CFRP), is possible but remains limited to special cases, since these types of reinforcement are not covered by major codes such as the Eurocode 2 [90]. In a limited number of applications, the use of short fibres as reinforcement is allowed to obtain the required functional tensile strength and hence a reduction in conventional reinforcement. In a few situations, such as industrial floors, short fibre reinforcement can even be used without reinforcement bars. Occasionally, alternative reinforcements such as textile fabrics are applied, but altogether the options in conventional concrete are limited to such an extent that an explicit classification has not emerged.

Within the field of DFC itself, the attempts at classification have also been scarce. This is mainly due to the sheer novelty of the reinforcement technologies; most of them have been developed only in the last five years. Several review papers discuss the state of affairs with regard to the development of reinforcement for DFC, but they usually do not provide more than a list of more or less logically ordered methods. Wangler *et al*. [1], in Section 3.2, provide an extensive state-of-the-art review of reinforcement strategies but do not present a specific organising scheme. Similarly, several reinforcement solutions are discussed by Mechtcherine and Nerella [43]. Menna *et al*. [91] extensively discuss structural engineering of DFC structures, thereby inevitably touching on the issue of reinforcement. Amongst others, they discuss a number of realised DFC projects in depth, including the issue of reinforcement and how that has been addressed in each project. While the article provides an interesting angle from the perspective of actual use of reinforcement, it does not offer a comprehensive basis for classification, especially not with respect to the manufacturing processes in the context of DFC.

To date the most complete discussion can be found in Asprone *et al*. [92]. The authors present a two-parameter classification based on the moment of application of the reinforcement respective to the manufacturing process on the one hand, and the structural principle on the other. In the manufacturing stage, they recognise the substages before, during, and after the concrete deposition. ‘Before’ and ‘after’ should be understood as being at a moment in time independent of the moment of deposition of the concrete; i.e., the time between the shaping process of concrete and the placement of reinforcement exerts significant influence neither on the performance nor on the manufacturing process.

As structural principles, ‘ductile material’, ‘DFC composite’, ‘compression loaded structures’, and ‘hybrids’ are identified. The former generally translates into the application of short fibres, as the intent is to provide a ductile material that for the purpose of structural calculation can be treated as homogenous, albeit possibly anisotropic. The DFC composite is a combination of distinguishable components to which distinct compressive and tensile properties can be assigned for structural calculations of the constituted sections. Compression-loaded structures such as arches or domes avoid the need for reinforcement by eliminating tensile stresses, while hybrids could be a combination of any of the three previously described structural principles.

Using the moment of application and the structural principle as two parameters, Asprone *et al*. [92] classify a number of studied cases. Although this classification enables a clear positioning of individual solutions, it does not cover more detailed aspects regarding manufacturing processes or directional dependency.

Kloft *et al*. [18] also attempted an organization of reinforcement strategies for DFC; see Figure 11. Like Asprone *et al*. [92], they organise the various methods into a matrix, but one that is based on quite different parameters. The columns represent the primary organisational principle. Distinction is made between cases in which concrete supports reinforcement, meaning that concrete is placed first, and those in which reinforcement supports concrete, i.e., the reinforcement is positioned first and acts as a (semi-open) formwork or scaffolding for concrete. The further distinction within each of these two groups is made according to specific processes: putdown rods, unrolled filaments/pressed-on textiles, interspersed fibres/inserted short rods are identified in the concrete-supports-reinforcement group, while weaving rods, winding filaments / rovings, and welding/gluing short rods/printing reinforcement are the sub-categories of the other group.

The horizontal orientation of the matrix is reserved for an indication of the effective direction of the proposed reinforcement solution: parallel, orthogonal, and inclined. So seen, this classification addressed directional dependency although it ignores the orthogonal direction in the horizontal plane. Furthermore, some categories are hard to distinguish; particularly, the ‘put down rods’ and the ‘insert short rods’ are very similar. An advantage might be that this classification effort is less abstract than the one proposed by Asprone *et al*. [92] and that it includes directionality of reinforcement’s effectiveness.

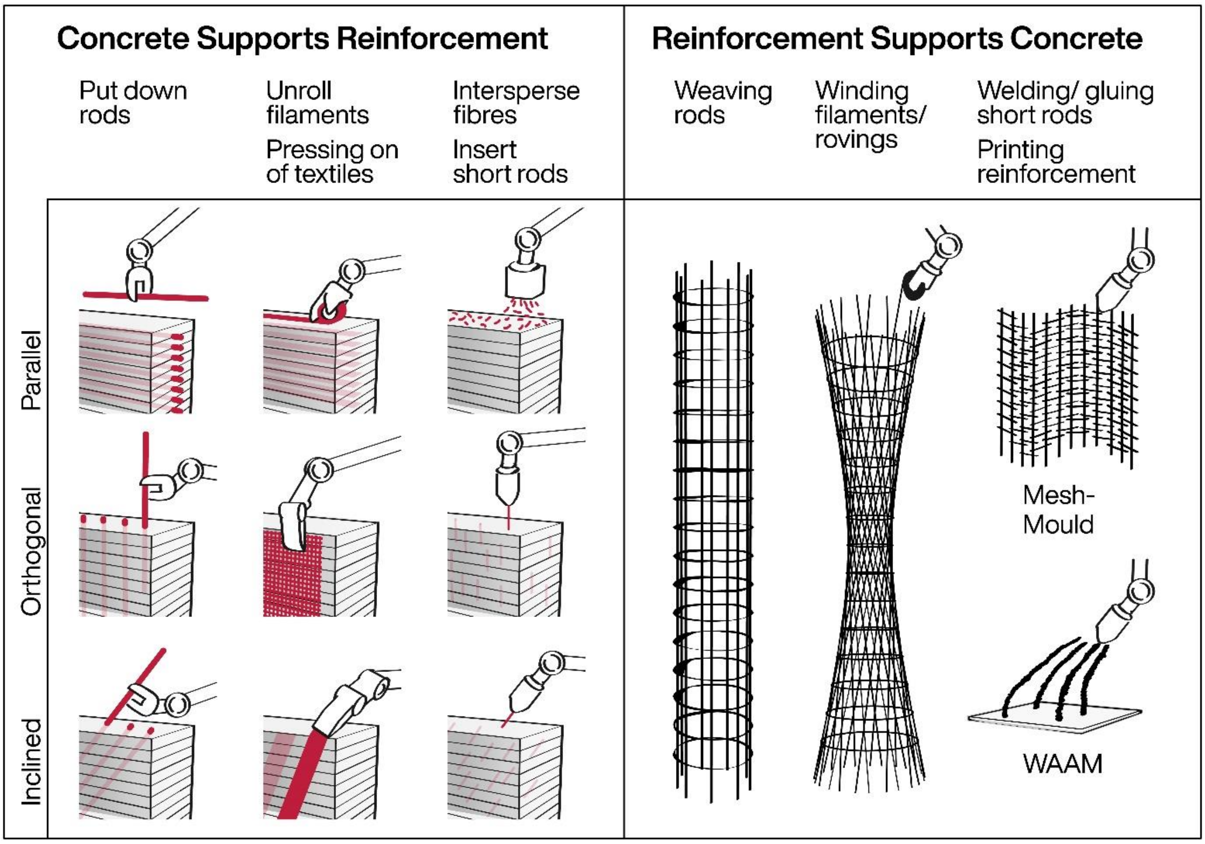


Figure 11. Organizational scheme of DFC reinforcement strategies, adapted from Kloft *et al*. [18].

Taken in sum, these early attempts purport to show that there is a need within the field to develop a solid basis to discern and position individual solutions within the wide variety of options being developed. In doing so, however, it is not straightforward as many variables, timing, application method, structural principle, directionality, and so forth, can be used as organizing principles, but it is not yet clear which ones are the most suitable.

4 The classification framework and process description

The review of existing approaches on integration of reinforcement into digital fabrication with concrete as presented in Section 2 as well as previous reviews and classification efforts as outlined in Section 3 show a great range of relevant parameters and features to be considered when designing both reinforced structures/elements and fabrication processes. The authors of this article believe that it is neither possible nor necessary to accommodate all the parameters in one classification. The classification framework suggested here focuses on the processes for integration of reinforcement into DFC, and it is designed as an extension of the RILEM process classification framework for DFC technologies [7]. The RILEM framework is an over-arching scheme that helps to define, describe, and classify DFC processes using well-defined intersection terms in interdisciplinary field where construction meets manufacturing and automation; see Figure 12.

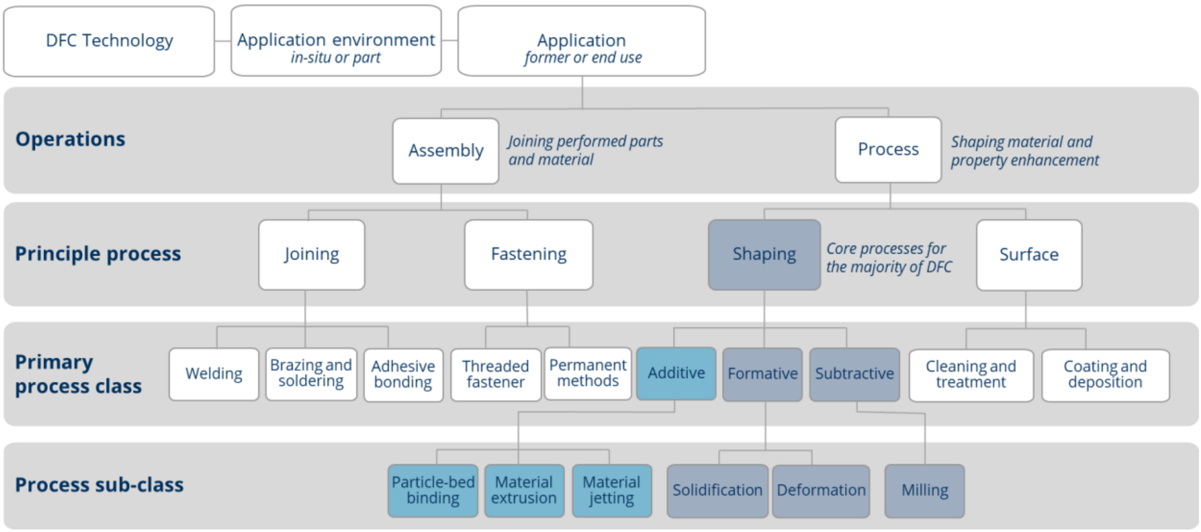


Figure 12. RILEM Process Classification Framework for DFC, adapted from Buswell *et al*. [7].

It is important to note that the RILEM framework in many instances provides description of a single process step. While DFC uses many different manufacturing operations methods and approaches to shape the material into the form it maintains in its hardened state, often more than one process step is required to manufacture an end-use product such as a structural element. It holds especially true with respect to the integration of reinforcement. Identifying these steps helps to define boundaries and so helps in clearly defining the principal operations involved in a process. Figure 13 depicts four cases that relate to the introduction of reinforcement to the mortar/concrete: 1) where the reinforcement is created in one step, and then the concrete is shaped in another; 2) where the concrete and reinforcement are added as part of a combined process, typically Additive Manufacturing; 3) when post tensioning is used on a hardened part; and 4) when post-tensioning is used to assemble multiple parts into a structure.

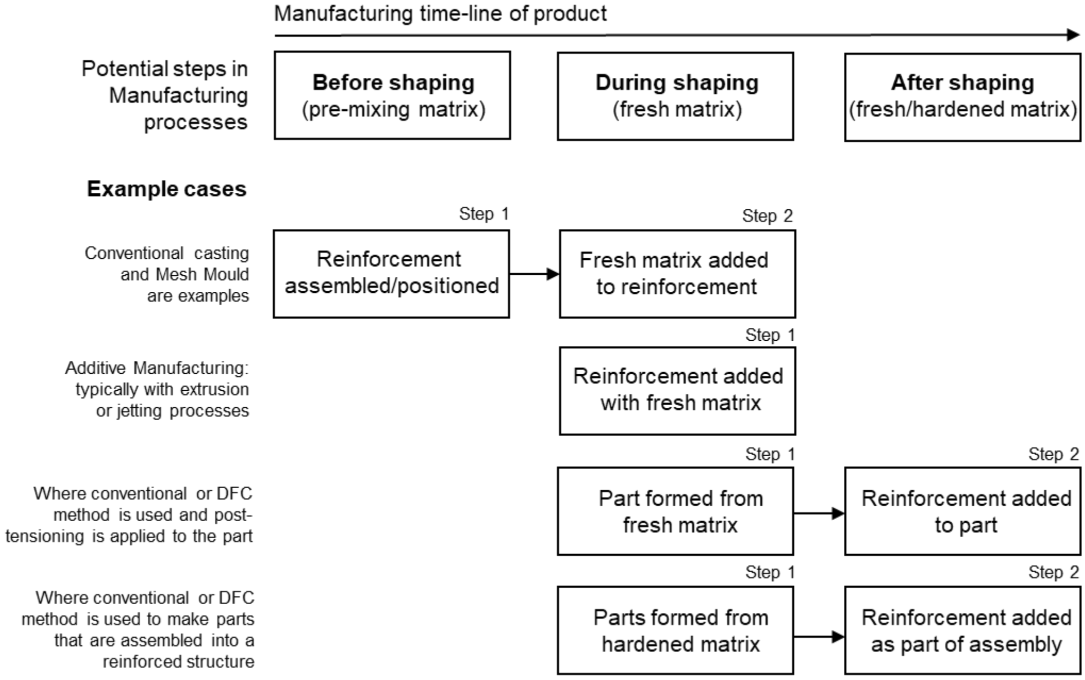


Figure 13. Combining mortar/concrete shaping and the placement of reinforcement.

The classification suggested here considers the sequence of distinct processes according to the manufacturing timeline of product as a starting point; see Figure 14. While building upon the RILEM framework, the classification also provides a link to structural design issues by naming corresponding options for the choice of reinforcement according to the following primary categories: cage, mesh/textile, bar, cable/yarn, and short fibre. Indeed, the proposed classification begins right there where the RILEM framework ends, i.e., at the level of the DFC process subclass for shaping concrete either additively, i.e., particle bed binding, material extrusion, material jetting, or formatively, i.e., solidification, deformation; cf. Figure 12.

For Additive Manufacturing methods with concrete, reinforcement can be integrated within a single process step as a sub-process occurring during concrete shaping. This is not feasible for formative processes. However, the integration of reinforcement prior to or after concrete shaping, i.e., in a separate step, can be performed both with additive and formative concrete processes in a similar manner. These options are indicated in the classification as two-step processes. Additionally, concrete mixing is defined as a pre-process preceding any concrete shaping process. During mixing short fibre may be added as dispersed reinforcement to produce either ready mix or dry mix for further use in both single-step and two-step DFC processes. A prominent example for AM processes is material extrusion with SHCC; for example, see Figure 8d. Here and further in this section references to the figures presented in Section 2 will be made for the sake of clarity.

There are four categories for integration of reinforcement during the concrete shaping process; see Figure 14. The first is entrainment into concrete bulk before material deposition. For extrusion-based processes entrainment of cables, in Figure 6a, and yarns, in Figure 6c, can be realised as a part of printhead process. Short fibre and textile/fine mesh can be entrained as well. Note that the dispersion of short fibre requires energy for intermixing with the concrete matrix, which can be done both in the material extrusion process, mixing of fibre as a part of the printhead process, and in the material jetting process, in- or outside the nozzle.

The second category is the placement of reinforcement between layers of concrete. In contrast to the entrainment where the deposition of concrete and the entrained reinforcement occur simultaneously, the process is contiguous in this case. Examples are given in Figure 7b for textile, in Figure 2a for bars, in Figure 8b for yarns, all positioned horizontally in the longitudinal direction of concrete filaments arranged vertically one over another. However, other arrangements are technically possible as well, e.g., deposition of a yarn or stripe of textile on the vertical face of a concrete filament and depositing the next filament laterally onto the yarn or textile and previously deposited concrete filament. This applies also for short fibre, which can be sprinkled on both horizontal and vertical concrete surfaces. The deposition of reinforcement between horizontal layers can be used in all three subclasses of AM incl. particle-bed binding.

Cross-layer encasement is also a contiguous process. Vertical or inclined fragments of reinforcement as well as the attendant horizontal components are placed before the next concrete layer is deposited. The concrete layer encases the fragments but still does not cover their tops, since further reinforcement fragments will be attached there and / or in order to establish cross-layer reinforcement. Vertical or inclined stripes of mesh/textile can be used in this category as in Figure 7c as well as vertical or inclined bars or little cage fragments locally assembled as in Figure 3d or additively produced as in Figure 3d. The fourth category also addresses cross-layer arrangement of reinforcement; however, the key feature here is that the reinforcement is induced by penetration while the concrete is still in the fresh/plastic state. Typically, straight, one-dimensional pieces of reinforcement are used for the purpose, either pins (see Figure 9a) or screws (see Figure 9c). They can be placed perpendicular to the layers' plane or inclined to it.

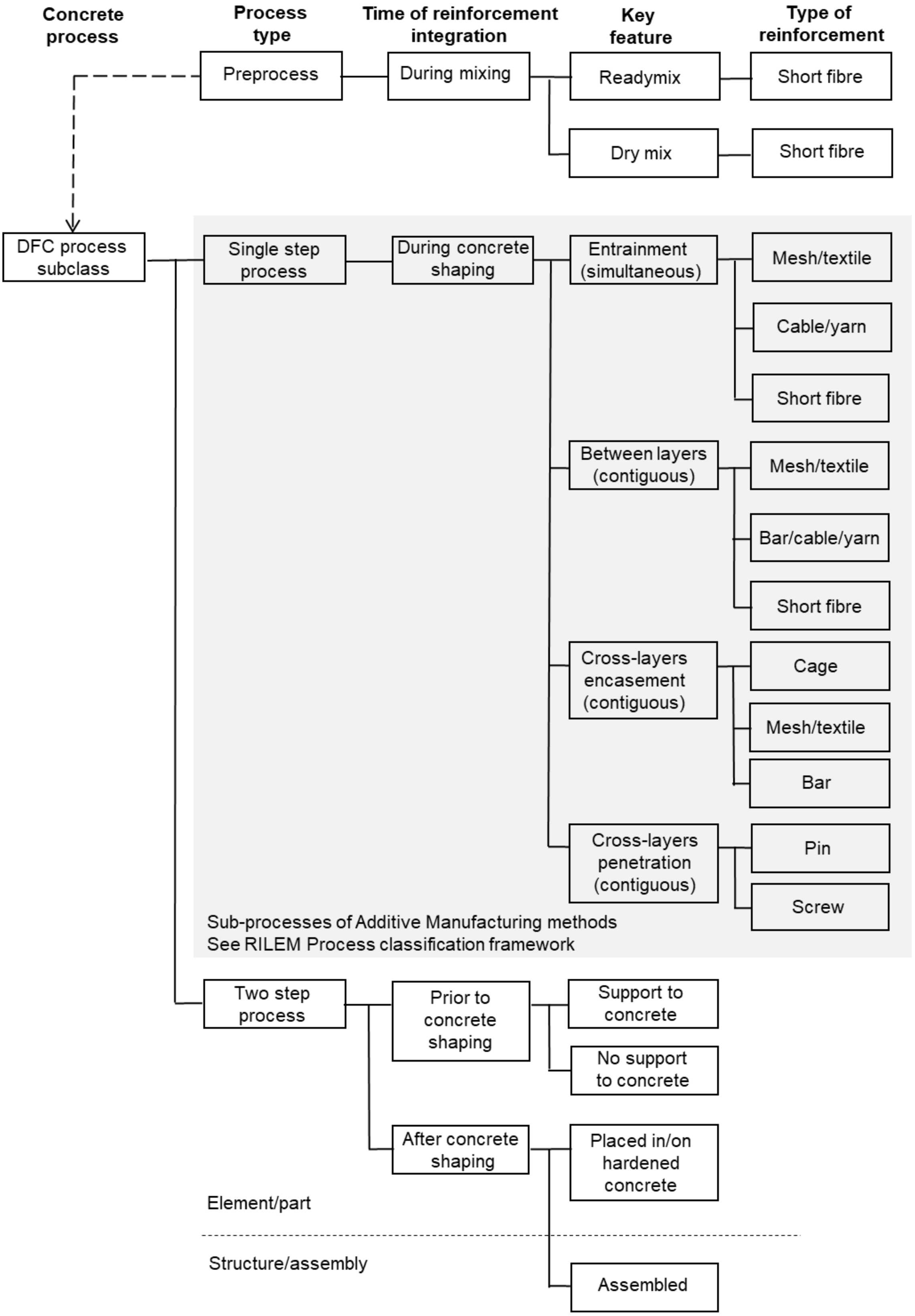


Figure 14. The process classification framework for integration of reinforcement into DFC technologies (PC4IR-DRC)

The two-step processes are subdivided into two categories according to the time of the reinforcement integration, i.e., prior to or after concrete shaping. The key feature of reinforcement placed prior to concrete shaping is its support for the concrete or the absence of such support. If reinforcement provides support to concrete, the concrete shaping process is a formative one since the shape of the element is defined by the supporting reinforcement, which acts as a mould or sheathing; cf. Figure 4c, -d. In the no-support-case, both formative and additive concrete shaping approaches are applicable. Finally, in the category 'after concrete shaping' we distinguish between 1) placement of reinforcement in or on hardened concrete as a process step to complete a structural or non-structural element; see, for example, Figure 3a or 4b and 2. Assembling elements/parts to a structure are illustrated in Figure 5a. In the latter case, post-tensioned cables have been used efficiently.

Note that the suggested classification for the integration of reinforcement does not cover the step of assembling or shaping of reinforcement either in a conventional or digital manner. Indeed, it would be a separate process step to be considered and described. However, this can be done by using RILEM Classification Framework for DFC as basis. For example, the manufacturing process of Mesh Mould reinforcement can be described by operation assembly, with joining as the principal process step and welding as the primary process class. Certainly, not in every case is the process allocation is so straight forward since the scheme is very generic on purpose and does not exclude its extension in the future. For example, the WAAM process for manufacturing of steel reinforcement can be classified as an additive shaping process, a kind of extrusion as a process sub-class in which the printing nozzle deposits moulded material on given coordinates upon which steel phase change occurs due to cooling.

Finally, some examples of applying the new classification to describe digital fabrication processes with reinforced concrete should be provided in form of simple process flow charts; see Figure 15. The first example is a single-step process in which reinforcing cable is entrained into the concrete filament and thus deposited simultaneously with concrete shaped by extrusion. The purely digital process continues until the printed part/element is finished, while the sub-process of the cable entrainment able can be interrupted on demand by cutting the cable and stopping its feed; and the entrainment can be eventually resumed by restarting the feed. In such a way the segments of the bicycle bridge in Gemert were produced. Note that for this single-step process the segment is the end product.

Example 2 shows the entire multi-step process of the bridge fabrication. The first process step is equivalent to Example 1 with the difference that not a single part / segment is produced, but a number n of segments are printed consequently. The second process is assembling of the parts / segments. The final, third process is placing of prestressing strands and post-tensioning them. Note that the second and third processes a) were performed in a conventional manner in the given example but can in principle be digitised and automated, and b) do not depend on the process of segment production, i.e., if it is additive or formative. The final product of the process chain is the bridge itself.

Example 3 illustrates the single-step process which concrete is shaped additively by extrusion and cross-layers reinforcement is introduced contiguously. First several layers of concrete are deposited one upon the other followed by nailing layers of fresh concrete with steel pins. After distinct number of pins is inserted, the concrete printing is resumed to deposit further several layers before this procedure is interrupted again to give way to penetrating pins. Such alteration can be repeated numerous times until the printed product is completed. In the given example it is a wall-like demonstrator.

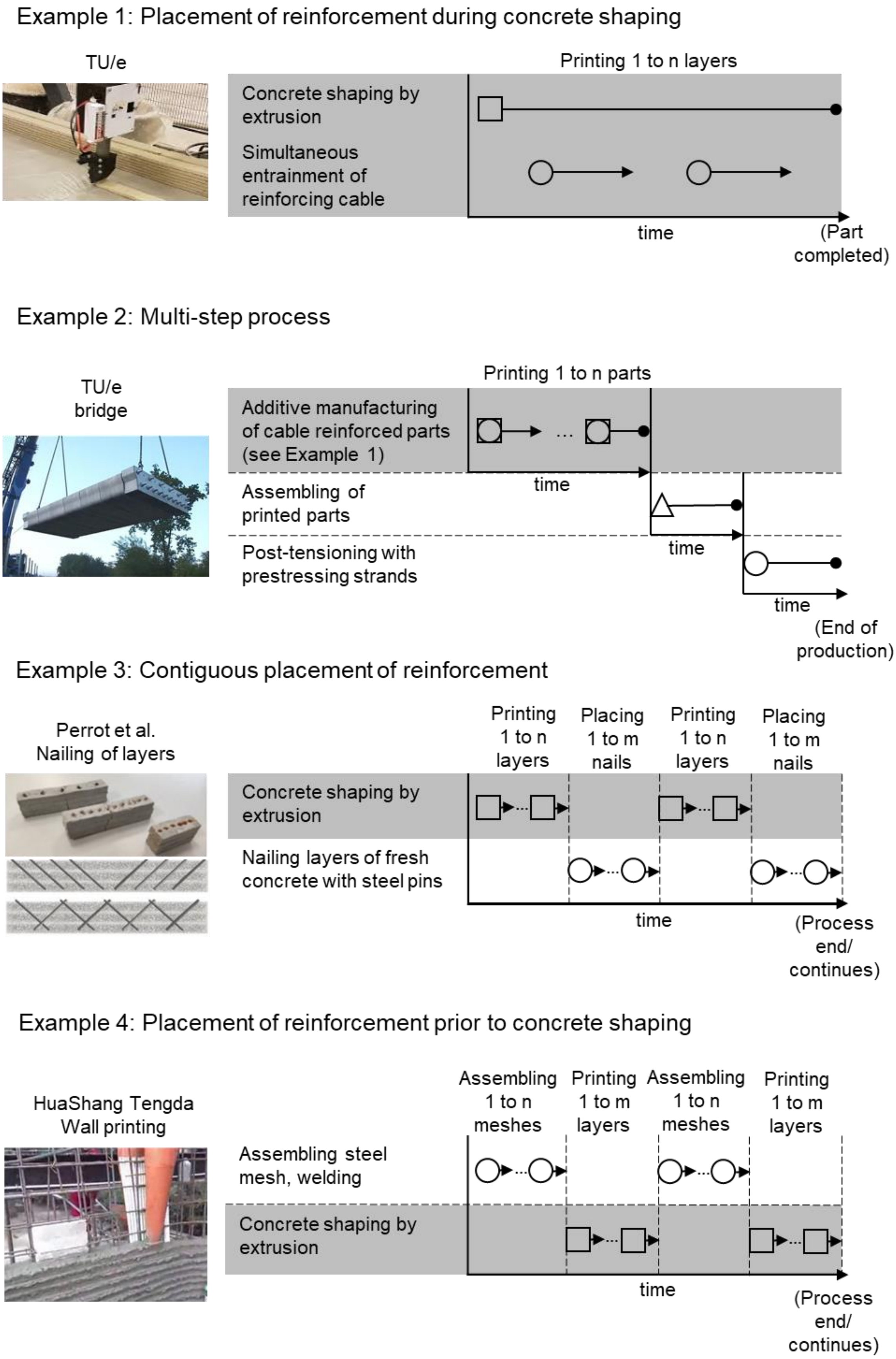


Figure 15. Examples for application of the new classification (Photo references: example 1 – [36], example 2 – [19], example 3 –[53], example 4 – [66]).

Example 4 presents a relatively rare case, where reinforcement is produced first in a distinct process step by assembling steel mats and bars. This step is followed by progressing encasement of reinforcement mats or cage with concrete in an additive extrusion-based shaping process. Since the printhead dimensions limit the height of the reinforcing elements, which can be encased in the approach under consideration, several repetitions of this sequence, i.e., assembling reinforcement/concrete printing, are required before the product, here an *in-situ* printed wall is finished. In this way Huashang Tengda fabricated a two-story villa in Beijing. Note that in the given example the assembling of reinforcement was performed in conventional manner, but this process step can be potentially automated and digitised as well.

5. Conclusions and outlook

The ongoing development of digital fabrication with concrete has led to an increasing number of projects appearing in practice over the course of the past few years. With the aim of realising structural applications, the need for reinforcement integration in DFC is obvious and thus, is increasingly being addressed by industry and academia across the globe. Although the functional requirements for reinforcement in DFC are similar to those in conventional concrete construction, the particular process characteristics of DFC render traditional reinforcement solutions unsuitable. As such, a new range of reinforcement solutions is being developed, targeting specifically the integration in DFC, presented in various stages of development.

To facilitate comparison between solutions and indicate the performance and suitability of each reinforcement method, a common language is desirable. To this end this paper presents a classification framework for reinforcement in digital fabrication with concrete, focused on additive digital concrete technologies.

First, the state of the art in reinforcement strategies for extrusion- and jetting-based 3D-concrete-printing methods has been presented and discussed. The review, organised by reinforcement type, and differentiated by material, presents various reinforcement concepts including their advantages and limitations. The following potentials and research requirements can be summarised from the review according to the reinforcement approaches:

- The application of straight or pre-bent reinforcement bars covers most of the structural performance requirements but is challenging in terms of automation. In most of the presented solutions, this type of reinforcement is still placed manually prior to concrete shaping, or during in an alternating process. To address these issues, WAAM has been proposed, although the alignment of the two AM processes is challenging.
- Alternatively, prefabricated grids and mats provide the desired reinforcement in two directions, and can be applied either before concrete shaping, or afterwards. These reinforcement solutions can provide a support to the fresh concrete during shaping, but full automation has yet to be proven. The geometric freedom is moreover limited by the geometry of standard mats, unless more advanced reinforcement fabrication (e.g. Mesh Mould) is adopted.
- Pre-stressing 3D-printed elements provides continuous reinforcement along the entire length of the object and has practically no limits in size or prestress force. This principle obviously imposes additional process steps, which may be difficult to automate. In any case, the location and shape of the pre-stress system should be incorporated in the design process, for instance through the use of advanced optimization algorithms.
- The entrainment of cables, yarns, or meshes directly into or in between filaments allows for a fully automated processes of both concrete shaping and reinforcement. The common challenge in these methods is that they provide reinforcement mainly in

the printing direction, and thus, require additional attention in the direction perpendicular to the printed layers.

- The dispersion of short fibres, premixed into the dry mortar, added during mixing, or introduced just prior to deposition, allow for an excellent integration into the automated printing process. First results on fibre reinforced mixtures, including SHCC's, are promising although a strong fibre alignment may occur. Moreover, fibres generally do not cross the filament interfaces.
- To provide reinforcement in the interlayer direction, penetration reinforcement strategies may provide a solution. Although presented examples are still based on manual application, these solutions have the potential to be automated. The main challenge for penetration reinforcement is to acquire sufficient bond across layers.

The review provides the basis for the process classification framework for integration of reinforcement into DFC technologies. As such, it connects with a previous publication in which DFC technologies themselves have been classified. Firstly, a distinction is made between process type, i.e., a pre-process, a single step process or a two-step process.

- For pre-process applications, reinforcement is typically integrated *during mixing*. This concerns mainly short fibres, added into the ready mix or during dry mixing of the printable composition.
- In single-step processes, reinforcement is integrated *during concrete shaping*. Here, reinforcement is either entrained simultaneously with concrete, or placed between or across layers. For single-step processes, a wide variety of reinforcement types is available, spanning from bars and meshes to cables and yarns.
- Finally, for two-step processes a distinction can be made between reinforcement placed *prior to concrete shaping* and *after concrete shaping.* In the first case, the reinforcement solution can provide a support to the fresh concrete. In the latter, the reinforcement is placed in or on the hardened concrete member or used to assemble multiple parts into a reinforced structure.

To support the ongoing growth of DFC and bring applications beyond merely showcase character, reinforcement strategies will have to be addressed. The classification framework presented in this manuscript provides the means effectively to compare solutions and can form a basis for further development and standardization in this rapidly expanding field.

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