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Review

# State of the Art Review of Reinforcement Strategies and Technologies for 3D Printing of Concrete

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**Abstract:** This state of the art review paper aims to discuss the results of a literature survey on possible ways to reinforce printed concrete based on existing reinforcement strategies. Just as conventional concrete, for 3D printed concrete to be suitable for large-scale construction, reinforcement is needed to increase the tensile capacity of concrete members and reduce temperature and shrinkage cracking. Despite efforts that are currently underway, the development of proper reinforcement suitable for printed concrete is still very active on the research agenda. As an initial step for designing suitable reinforcement for printed concrete, the existing reinforcement methods for printed concrete as well as conventional cast concrete from the literature are reviewed and summarized. Through the preliminary evaluation of the suitability and effectiveness of various reinforcement methods, guidelines are proposed to better understand possible solutions to reinforce printed concrete and inspire new practical ideas to fill the current technology void. The conclusions also include the possible improvements of the existing reinforcement methods to be considered in future applications.

**Keywords:** 3D printing of concrete; reinforcement; additive manufacturing; construction; reinforced concrete

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## 1. Introduction

Contemporary additive manufacturing, also known as 3D printing, has been shown to have great potential in many fields, such as mechanical engineering, medical practice, food-producing, and aerospace. The use of robots has made the automation of manufacturing process possible. Over the past two decades, efforts have targeted introducing this technology in building construction. One of these efforts concerns the additive manufacturing of concrete structures, also known as 3D Printing of Concrete (3DPC), which can significantly upgrade the conventional cast-in-place or precast approaches. The printing process starts with concrete mixing, pumping the fresh concrete from the mixer through hoses, and extruding the concrete in the form of filament through the nozzle attached to the robotic arm. The movement of the computer-controlled robotic arm determines the geometry of the printed concrete part.

Compared to conventional (cast concrete) construction, 3DPC needs less labor, shorter construction time, no disposable formwork, and can potentially provide increased freedom for building design, in particular curved surfaces. From the perspective of sustainability, the 3D printing process deposits the exact amount of material as needed and where needed, thus it leads to reducing the construction waste that could end up in landfills. This efficient construction process can also help companies significantly lower the overall cost for building homes, thus helping those in need of low-cost housing. The sources of cost-saving include material transportation, labor, and in particular, formworks, which costs about 40% of the concrete construction. With the limited construction waste and material transportation needs, 3DPC reduces the carbon footprint in building houses. Moreover, renewable and recyclable materials can be integrated into the printing process to make the house eco-friendly. For example, a few companies (e.g., WASP) that market 3D printing homes are trying to replace concrete with sustainable material, such as construction waste or locally available sand or clay, to reduce the amount of greenhouse gas emissions and maximize the energy efficiency of a home [1]. While, in general, it is true that 3DPC would require fewer traditional labor for concrete work, 3DPC would require some skilled workers to operate computer controlled mixer, pump, and robotic arm. Furthermore, given the general shortage of skilled construction workers, the traditional concrete labor can be easily absorbed in other sectors of construction industry [2]. Such transition will diminish the impact on the labor market and also protect the workers from a potentially hazardous construction environment.

Due to the lack of compaction, printed concrete may possess a lower density than conventional cast concrete. Furthermore, the interface between printed filaments may be prone to shear or tension failure depending on the bond quality between adjacent filaments [3,4]. Therefore, printed load-bearing concrete members need to rely more on reinforcement to increase the tensile capacity and reduce temperature and shrinkage cracking in order to ensure acceptable performance of large-scale building construction. Although various reinforcement methods have been proposed for 3DPC, none has gained wide acceptance, as they all have specific uses and limitations. The development of proper reinforcement suitable for printed concrete is currently still very active on the research agenda. Therefore, this paper aims to learn from the experience of general use of different reinforcement types in different materials and components and identify the need and opportunities for future development of reinforcement methods in printed concrete. The paper summarizes and evaluates existing reinforcement approaches used in different structures to explore the potential for implementation and appropriateness of those in printed concrete.

As an initial step for designing suitable reinforcement for printed concrete, this paper discusses the results of a literature survey on possible ways to reinforce printed concrete based on existing reinforcement strategies. Initially, however, a brief review of how reinforcement is used in conventional construction (foundation, walls, pavements, etc.) is presented, followed by a summary of existing reinforcement methods for printed concrete. In the end, the suitability and effectiveness of the various reinforcement methods are discussed. The main objective of this paper is to identify from the literature various reinforcement methods approaches that may be suitable for application to 3D printed concrete.

## 2. Review of Existing Reinforcement Concepts

### *2.1. Conventional Concrete Reinforcement*

Concrete has a much higher resistance to compressive stresses compared to tensile stresses. The ratio of concrete's tension capability to compression is about 10%, which requires adding reinforcement on the tension side of concrete members to resist tensile stresses, while concrete on the compression side resists compressive stresses. Besides the reinforcement for bending stresses, concrete also needs reinforcement for shear forces and to control temperature and shrinkage cracking. The following sections provide a brief review of effective reinforcement methods, including rebar, FRP sheets, fiber reinforcement, prestressed cable, and mesh reinforcement.

### 2.1.1. Rebar

Because of its main property to undertake tension, steel rebar is the most common reinforcement type used in concrete. The standard design code for steel rebars in concrete is covered in ACI 318 [5]. The general fabrication process involves placing rebars at designated locations inside the wood formwork before pouring concrete. Based on the material used, rebar can be categorized as steel rebar and non-metallic rebar.

Steel rebar is mainly used in conventional concrete to resist flexural, shear, and axial forces. Flexural reinforcements (longitudinal reinforcement) are placed in the longitudinal direction of slender concrete members, such as concrete beams, walls, and columns, on the side subjected to tensile forces. However, to increase the bending moment resistance of a beam, as we place more steel rebars on the tension side, the compression side will reach its maximum capacity. In such a case, either a deeper beam should be designed, or steel rebars should be placed on the compression side to prevent concrete crushing in the compression zone, a strategy referred to as doubly reinforced beam. The steel rebars on the compression side can also provide higher ductility and reduction of long-term deflection. Shear reinforcement (stirrups and ties) is placed perpendicular to the flexural reinforcement to resist shear forces and diagonal tensile stresses. In addition, stirrups can hold the longitudinal reinforcement in place in beams, while ties can brace the longitudinal reinforcement to prevent buckling failure, hence, increasing the bearing capacity of columns for axial loads.

Besides the steel rebar, other materials, such as bamboo and fiber-reinforced polymers, also have unique features to potentially be used in concrete as alternative reinforcement. The construction industry consumes abundant resources and contributes about 8% of global $CO_2$ emissions [6]. This has led to increasing concern about the damage current construction incurs to the environment and has created widespread demand to find a more environmentally-friendly substitute for the material. Ghavami [7] investigated the feasibility of using bamboo as reinforcement in concrete elements and mentioned that the energy used to produce steel is 50 times more than bamboo, which still possesses relatively high tensile strength in the direction parallel to the fibers. The mentioned research used bamboo shells as reinforcement in concrete beams, slabs, and columns. In concrete beams and columns (Figure 1a), bamboo segments were used as longitudinal reinforcement wrapped by steel wires. The amount of bamboo reinforcement is recommended to be about 3% of the cross-sectional area. In concrete slabs (Figure 1b), a row of half bamboo culm was first filled with fresh concrete, and then, after the concrete gained enough strength, they would serve as the tensile reinforcement at the bottom of the slab.


(**a**) (**b**)

**Figure 1.** Assembled bamboo reinforcement for (**a**) concrete column and (**b**) concrete slab [7].

Using untreated bamboo as the reinforcement, however, would cause some issues, such as insect attacks, water absorption, as well as swelling of the bamboo, which can lead to loss of bond between the bamboo surface and concrete. In order to increase the durability of bamboo-reinforced concrete, bamboo needs to be adequately treated prior to the start of construction. The treatments include drying to prevent mold attack, applying a thin layer of epoxy to the bamboo surface followed by a coat of fine sand to make it impermeable, and applying Sikadur 32-Gel to the bamboo surface to increase bond strength. According to Ghavami [7], compared to the steel reinforcement that may have severe corrosion after ten years, treated bamboo reinforcement maintains satisfactory performance when checked after 15 years.

Fiber-reinforced polymers (FRP) material has been proposed as a promising substitute for steel reinforcement, considering the following advantages: excellent corrosion resistance, good fatigue properties, damage tolerance, low specific gravity, lightweight, non-magnetic properties, low energy consumptions during fabrication, and the ability to offer an overall more economical option for construction applications [8,9]. The standard design code for FRP reinforcement in concrete structures is embedded in ACI 440 [10]. The inner structure of FRP rebar is formed with unidirectional fibers embedded in a resin matrix, which provides high tensile strength in the longitudinal direction. To illustrate the desirable characteristics of FRP rebars, Kudyakov et al. [11] compared the strength and deflection of steel-reinforced beams with those reinforced using FRP rebar, both reinforced on the bottom side and subjected to two-point loading at the top surface. Test results revealed that the FRP rebar-reinforced concrete beams experienced 5–10% more critical force and 4–5 times more deflection compared to steel-reinforced concrete beams under the same static load. However, this increased ductility of the flexural element reinforced by FRP rebars may not satisfy the serviceability requirement, and further research is needed in this regard.

The durability of FRP rebars highly depends on the type of fiber, interface bonding conditions between fibers and resin, and environmental conditions. Carbon fiber has the overall best performance compared to glass and aramid fibers because of its zero-water absorption and high resistance to acid, alkali, and organic solvents [12]. Glass fiber is highly prone to an alkali environment, yet widely used because of the low price. A strongly bonded interface between fibers and resin to resist environmental attacks can be achieved using a coupling agent on the fiber surface [12]. Furthermore, the most critical effect of the external environment on the strength of FRP rebar is the thermal condition, where the increase in the surrounding temperature would decrease the elastic modulus and strength of FRP rebar. Additionally, the difference between thermal coefficients of concrete and FRP rebars in the transverse direction would induce high tensile radial stresses, weakening the FRP rebar-concrete interface, further resulting in the longitudinal splitting of concrete cover. During construction, the spiral wrapping can be installed to restrict transverse strain and radial tension, while the thickness of the concrete cover can be increased to prevent splitting and improve fire resistance.

#### 2.1.2. FRP Sheet

High corrosion resistance makes the FRP material suitable not only to replace the inner steel reinforcement but also to serve as the outside concrete reinforcement for rehabilitation purposes, namely the FRP sheet, of which the standard design code is also specified in ACI 440 [10]. While FRP sheets have high tensile resistance, they lack the ability to resist compression, and thereby they are usually bonded to the bottom of beams or slabs for flexural resistance or attached to the sides of beams for shear resistance (e.g., [13]). By doing so, FRP sheets help concrete control crack width after crack initiation and, therefore, extend the service life under loading conditions. Additionally, because FRP sheets are very light, no heavy equipment is needed for on-site installation. Prestressed FRP sheets use the material more effectively as they can delay the crack initiation by counteracting the tensile force using the stored energy from stressing. There are three existing methods for prestressing FRP sheets. According to Saadatmanesh and Ehsani [14], FRP sheets could be bonded to the lower face of concrete beams after hydraulic jacks camber the positive moment region of the beam to form negative curvature, and then be stressed as the beam deflects back due to the removing of the jacking force (Figure 2a). Deuring [15] proposed a prestressing strategy where the stressing bed can be used to tension the FRP sheets before attaching them to the tension side of the beam. Weight et al. [16] prestressed multiple FRP sheets using a mechanical anchorage system that will be left in place after prestressing (Figure 2b).

The effectiveness of FRP reinforcement and prestressed FRP sheet reinforcement were also evaluated. The findings show that the FRP sheet can significantly improve serviceability and increase the ultimate strength of concrete beams. Such improvement can be further enhanced if more FRP sheets are used or prestressed.

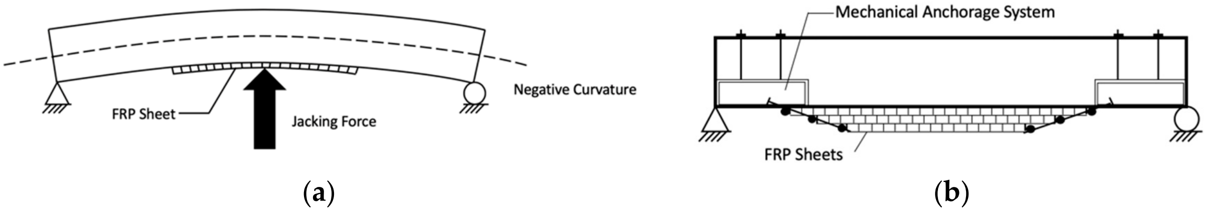


**Figure 2.** FRP prestressing systems for concrete beams developed by (**a**) Saadatmanesh and Ehsani and (**b**) Wight et al. [16].

### 2.1.3. Fiber Reinforcement

For those thin and complex concrete elements that are not suitable for reinforcement using rebars, fiber reinforcement sometimes becomes a desirable option. The standard design code for fiber-reinforced concrete can be found in ACI PRC-554.4-18 [17]. Fibers are added to the concrete during the mixing process so that they are dispersed and oriented three-dimensionally throughout concrete. Under loading conditions, when cracks appear in fiber reinforced concrete, fibers perpendicular to crack planes tend to hold the crack and prevent crack propagation. From this point of view, fiber reinforcement provides higher toughness and tension resistance to concrete elements, and like conventional steel rebars, they can only be functional after the crack initiation. Based on the material type, fiber reinforcement can be categorized as steel fiber, glass fiber, synthetic fiber (e.g., carbon fibers and polypropylene fibers), and natural fiber [18]. Song and Hwang [19] tested the compressive strength and tensile strength of steel fiber reinforced concrete. They summarized that tensile strength and modulus of rupture increase with more fiber attendance. The compressive strength has the same trend until the steel fiber volume fraction reaches 1.5%. Steel fibers are also effective in enhancing the ductility performance of concrete as they are commonly applied in reactive powder concrete (RPC) due to the dense microstructure that is prone to brittle failure [20]. Polypropylene (PP) fibers were tested to decrease the thermal conductivity further when added to foamed concrete [21], which was attributed to the increase of the percentage of porosity resulting from the drying of the water retained due to the nature of hydrophobic of the PP fibers. Moreover, PP fibers were proved to improve the fire resistance of the concrete [22].

More importantly, the unique feature and, in some cases, the main purpose of using fiber reinforcement is that they are instrumental in controlling plastic shrinkage cracking during concrete curing and hardening. Commonly, only a small number of synthetic fibers (e.g., 0.1% volume fraction) are needed in the mixture to reduce the plastic shrinkage cracking [23].

To achieve a more comprehensive improvement through fiber reinforcement, two types of fiber are used, micro-fiber and macro-fiber. According to Lawler et al. [24], a combination of micro-fiber (less than 0.022 mm diameter) and macro-fiber (0.5 mm diameter) is effective to restrain the crack growth at different stages for different types of failure. Both of these types of fibers can minimize plastic shrinkage at an early age. Macro-fibers can also be utilized to provide longer durability, higher toughness, and tension resistance after curing, which are not available from micro-fibers.

### 2.1.4. Prestressed Cables

Prestressing is the most common reinforcement method used in buildings and bridges to minimize the member depth and cracking when spans are large [25]. The standard design code for prestressed concrete can also be found in ACI 318 [2]. Steel cables are prestressed to develop internal stresses that tend to bend the concrete member to counteract the effect of applied loads. Prestressed cables not only increase the ultimate strength of concrete elements but also delays the crack initiation. That is, the external loads would first offset the moments resulting from the internal steel cables, and after the concrete elements recover to their original shape, the applied loads will impose further moments creating cracks on the tension side.

Two common prestressing methods are pre-tensioning and post-tensioning. Pre-tensioning refers to stressing the steel tendons before casting the concrete, as opposed to post-tensioning, which stresses the steel tendons after concrete sets. Pre-tensioning is suitable for prefabricated concrete elements, as the equipment for stressing is hard to move to the site. Additionally, it is economical to make repeated members with known loads. Post-tensioning is likely used for cast in situ concrete elements because such procedure is easily arranged and adjustable on site.

### 2.1.5. Wire Mesh Reinforcement

Due to features such as being economical, flexible, and lightweight, wire mesh reinforcement is typically used in thin concrete elements (e.g., thin concrete slabs and walls). It is also effective in reinforcing curved, hollow, and unsupported concrete members (i.e., domes, shells, and folded plates) as different forms can be designed to satisfy the geometry of reinforced concrete.

The most common wire mesh reinforcement is made of steel rebars welded or woven in two orthogonal directions with certain spacing. The design and construction specifications of welded wire mesh in concrete structures are mentioned in ACI PRC-439.5-18 [26]. The square wire mesh is placed on the ground, lifted, and supported at the designated height for the slab before pouring fresh concrete. Mesh reinforced concrete could be vulnerable to shear failure under concentrated loads applied between wires. Such shear failure is highly unfavorable and unpredictable as shear failure occurs with no sign of warning.

The wire mesh pattern does not necessarily have to be square; other shapes have also been experimented. Ibrahim [27] investigated and compared the ultimate capacity of concrete slabs reinforced by steel wire mesh in square and diamond shapes (Figure 3). According to the study results, the slabs reinforced by diamond mesh experienced ultimate load and deflection, respectively, 21% and 40% higher than slabs reinforced by square meshes.

**Figure 3.** Two shapes of wire mesh for concrete slab experimented by Ibrahim, square shape (**left**) and diamond shape (**right**) [27].

#### 2.1.6. Summary of Potential Use in 3DPC

Three-dimensional (3D) printing concrete is different from conventional concrete as the concrete mortar is extruded from a nozzle, printed layer by layer, and consolidates without tamping or vibration. Hence the reinforcement strategies mentioned before cannot be applied to 3DPC without significant change in the conventional process considering the 3DPC printing system features. Some possible approaches to apply conventional reinforcement in 3D printed concrete are provided in the following discussion.

Rebars can be used in 3DPC by burying it close to the surface of the concrete aligned with the filaments in the longitudinal direction or be inserted vertically into fresh concrete. However, among those methods, the vertical insertion of reinforcement deserves more attention, as it may cause the printed fresh concrete structure to collapse. Rebars can also be welded or tied as a framework or cage to reinforce printed concrete. In this case, first the concrete mortar can be printed inside the framework to fill the interior space, and then shotcrete can be sprayed on the outside to protect the steel. Alternatively, concrete mortar can first be printed as an exterior shell to function as the formwork and then pour concrete in the space created by that shell after placement of the steel framework. In fact, the latter approach, which was developed by Contour Craft [28], has already been used and implemented at construction scale by WinSun (Yingchuang Building Technique Co., Ltd., Shanghai, China) [29]. However, the limitation of this approach is that the printed concrete shell basically acts like the formwork in conventional concrete construction, which restricts the freedom of design for 3D printed concrete.

FRP sheets can be attached to cured concrete surfaces after the whole printing process as in conventional cast-in-place concrete, while maintaining the same effectiveness. For the fiber reinforcement, fibers are conventionally blended in the concrete mix to achieve uniform distribution after concrete sets. When fiber reinforced concrete is subjected to external loads, only the part of fibers that are not parallel to the crack plane and cross the crack width can effectively control its width. Different fiber orientations render concrete multidirectional cracking resistance. This reinforcement method has great potential to be applied to 3DPC since the orientation and the location of fibers are controllable during the printing process.

Pre-tensioning is not feasible in 3DPC since stressing cables in the printing area is difficult for a 3D printer to work continuously. On the other hand, post-tensioning seems quite possible and easily adaptable in 3DPC. Because tensile force is applied to tendons after curing of concrete, post-tensioning has no effect or only minor effect on the printing process. The steel tendons can be stressed in the duct space created as part of the concrete printing process. The toolpath design, however, would need to be more complicated for the sake of creating the space needed for the ductwork and placement of tendons.

Wire mesh is also suitable for use in 3DPC because the large steel surface area and, in particular, the interlocking of concrete within the grid benefits the bonding between concrete and steel wires. Furthermore, the lightweight property will significantly reduce the layer deformation during printing, when the printed concrete is still fresh and does not have enough strength to handle its weight and reinforcement.

### *2.2. Reinforcing for Other Materials*

Reinforcement is necessary to strengthen the construction material to improve its future behavior, including load resistance, durability, ductility, etc. Besides concrete, reinforcement is used with many other materials such as asphalt pavement, masonry, glass, wood, and ceramics. In the process of identifying some new ideas for reinforcing 3D printed concrete, it is essential to review existing reinforcing concepts used with other materials as well.

#### 2.2.1. Flexible Asphalt Pavement

Asphalt experiences different types of distress during its service life, including fatigue cracking and rutting. To delay crack formation and protect the subgrade, pavement needs reinforcement. The primary pavement reinforcement system is geogrid (Figure 4), which is popular because of its high-tension resistance and the ability to distribute loads. Geogrids are geosynthetic materials in the form of grids and are typically made of polyester, polypropylene, and glass fiber. The square or rectangular patterns (from 12.5 to 40 mm) can interlock soil and aggregates so that reinforcement can perform a composite behavior with a restricted lateral movement for aggregates and reduced possibility for shear. Before being placed on the ground, geogrids are coated with polymer to provide a better bonding condition with asphalt and to protect it from outside chemical reactions and corrosions. According to Nguyen et al. [30], such geogrids are buried between asphalt pavement layers to extend pavement fatigue life, followed by spraying tack coat at the surface to enhance interface bonding condition with the layer above.

**Figure 4.** Geogrid application on sprayed tack coat for pavement reinforcement [30].

The location of geogrid layers can affect the pavement service life. For example, geogrid can retard reflective cracking when paved above the cracked asphalt layer before the overlay construction. According to Button and Lytton [31], when the crack touches the geogrid, it grows along the geogrid until it runs out of energy because the geogrid is much stiffer than the surrounding material. Geogrids can also serve as a sealant between two asphalt layers to prevent rainwater and oxygen penetration that may cause corrosion and crack initiation. Furthermore, geogrids can be placed near the top of the pavement to resist stretching forces under traffic loads or near the bottom of the base layer to protect the subgrade from the punching of the granular base.

### 2.2.2. Masonry

Masonry is commonly used to construct residential and non-residential buildings and has historically been used in unreinforced form. The design of masonry walls is covered by the International Building Code (ICC IBC-2021, [32]) and Building Requirements and Specification for Masonry Structures (ACI 530.1-11, [33]). Unreinforced masonry buildings are generally composed of mortared bricks or hollow concrete blocks with no embedded reinforcement. Because of poor mechanical properties and lack of connection between walls and floors, unreinforced masonry buildings are highly prone to damage under both in-plane and out-of-plane forces generated under seismic loading conditions. According to building codes [32], unreinforced masonry buildings are only allowed in areas with a low chance of seismic activity. However, many unreinforced masonry buildings already exist in places that have experienced frequent seismic activities. For such existing buildings, some reinforcement should be added to enhance the seismic loading resistance of the building and fulfill the code requirements. According to the literature [34,35], there are several ways to reinforce masonry walls, including using steel reinforcement within the masonry wall and applying FRP reinforcement on the face of the wall.

In the first approach, hollow masonry units align in the vertical direction to allow steel rebars to pass through the vertical cavities. Steel rebars are also embedded horizontally across the masonry units and tied to the vertical rebars to form a steel grid. Furthermore, steel wire joint reinforcement (ladder-type, Figure 5a, and truss-type, Figure 5b) consisting of two longitudinal wires bridged by cross wires can be laid on the bed joint between masonry layers to control thermal cracking, horizontal bending, and expansion [36]. The mortar between concrete masonry units (bed joint and head joint) holds the units together and increases the flexural and tensile strength of the structure. After securing all the reinforcement installation, grout fills the voids and bonds the steel rebars to the concrete masonry units to make the structure whole. Various metal connectors are commonly used to join multiple wythes of masonry wall together or attach masonry veneers to a backing system, e.g., ties and anchors. Those reinforcements are functioned to build a connection, transfer lateral loads, and allow in-plane movement for minimizing differential movement [37].

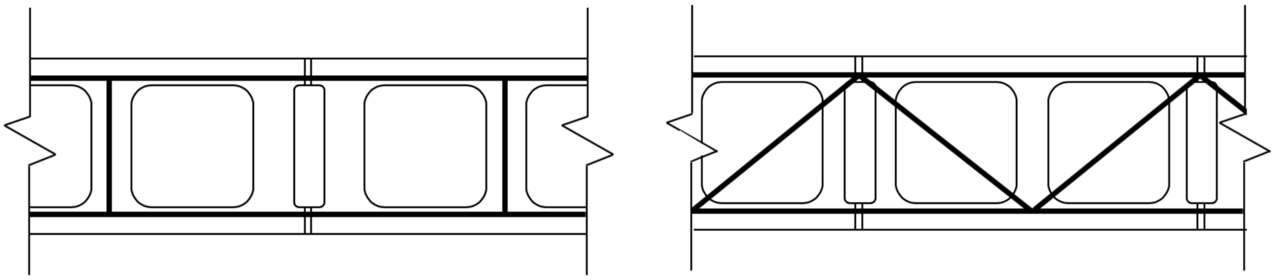

(**a**) (**b**)

**Figure 5.** Two types of joint reinforcement in masonry walls: (**a**) ladder-type and (**b**) truss-type.

The second approach is mainly utilized for retrofitting old unreinforced masonry buildings. It is based on the experience of using FRP bars for increasing the load-bearing capacity of a single structural element. One attempt to attach FRP bars to masonry walls was experimented with by Turco et al. [34], where the effectiveness of FRP bars to increase the flexural and shear resistance of masonry walls was evaluated. The FRP bars can be placed either in the vertical grooves cut at the surface of the member as the flexural reinforcement or in the horizontal mortar joints as the shear reinforcement. The study results showed that the rectangular and circular FRP bars are suitable for strengthening the flexural and shear capacity of masonry walls up to 26 and 2.5 times, respectively. Additionally, the overall performance of glass FRP bars is better than carbon FRP bars. Still, another method to apply FRP reinforcement is to adhere FRP sheets to the masonry or brick veneer wall surface (e.g., [38]).

### 2.2.3. Glass

Glass is brittle and vulnerable to breakage under force or impact, which may shatter it into many pieces (shards) and cause damage and injuries. Typical reinforcement for architectural glass material is the steel wire mesh [39]. During the manufacturing process, the steel wires are embedded in the glass at the middle thickness. Then in case of breakage due to external forces, such as concentrated loads and thermal expansion, such reinforcement helps keep the fragments together. Wired glass has no superior performance in terms of breakage resistance, in fact, it is even weaker on impact compared to the regular glass [40], but it can provide better fire resistance and impact resistance. Another method to increase impact resistance to glass is to apply a plastic-based film such as polyethylene terephthalate (PET) over the glass surface, which keeps glass shards adhered to the film [41].

### 2.2.4. Wood

Wood has a long history of being used as a building material. However, due to the extra work and economic reasons, not much reinforcement has been developed for wood elements for commercial purposes. Still, several studies [42–44] have investigated possible ways to enhance the strength of wood for structural use purposes. Such studies can be mainly categorized based on the use of steel reinforcement or FRP reinforcement. Bulleit [42] summarized that steel reinforcement in the form of plates, wires, and strands had been used to improve the bending strength of wood beams. To be more specific, steel plates have been used to reinforce wood members by placing them between laminated wood in the tension zone. High-strength steel wires surrounded by epoxy matrix have also been placed on the tension side of wood beams. Furthermore, prestressed steel strands have been anchored at the two ends of wood beams on the tension side. However, corrosion is still the primary concern for using steel as the reinforcement material, but such a concern can be avoided by using FRP reinforcement. FRP sheets (Figure 6) bonded to the tension side of the wood beams strengthen the member by either restricting crack propagation or delaying the crack initiation if it has been prestressed. Plevris and Triantafillou [43] proposed that even a skinny FRP sheet bonded at the tension side of wood beams can significantly increase strength, ductility, stiffness, and shear resistance to the beam. The use of prestressed thin FRP sheets can give the same reinforcing level as thicker FRP sheets, but at some additional cost for prestressing [44].

**Figure 6.** FRP sheet reinforced timber beam [45].

### 2.2.5. Ceramics

Superior physical properties, including high melting point, high stiffness and hardness, lightweight, and chemical inertness, make ceramic material suitable as cutting tools, refractory material, and thermal insulators. The major disadvantage of ceramics is brittleness. Once the ceramic material experiences external shock, cracks will grow along the gain boundaries. Several reinforcement strategies have been proposed to improve the cracking behavior of ceramics. Continuous-fiber-reinforced ceramics manufactured by embedding fibers in a ceramic matrix has higher stiffness, shock resistance, and reliability than unreinforced ceramics [46]. Bowen et al. [47] proposed that after using 40% of carbon fiber to reinforce ceramics, its stiffness, strength, and fracture energy are increased by a factor of three, seven, and three, respectively. Moreover, discontinuous-fiber-reinforced ceramics fabricated by mixing short fibers or whiskers with powered matrix material possess similar fracture resistance as continuous-fiber-reinforced ceramics but have less pullout length [48].

The increase in whisker size, strength, and modification of interface properties will further increase the fracture resistance of whisker-reinforced ceramics [49]. Furthermore, carbon nanotube reinforced ceramics have a unique microstructure, which results from dispersing nanotubes in the ceramic matrix to increase the fracture toughness and strength [50]. In that case, the homogeneous distribution of carbon nanotubes is crucial for ceramics to gain satisfying mechanical properties. Last but not least, metal reinforcements are used to increase the fracture toughness and the impart behavior of ceramics. Metal reinforced ceramics are fabricated by using pressure filtration to pack powder within a network followed by intruding metal into a channel formed by pyrolyzing the network [51].

#### 2.2.6. Summary of Potential Use in 3DPC

The reinforcement strategies discussed can be summarized in three main categories: steel wire mesh, fiber reinforcement, and FRP or steel rebar reinforcement. While these strategies may apply in 3DPC, the use of metal reinforcement in ceramics is certainly not for use with 3DPC technology.

Steel wire mesh is frequently used in relatively thin materials such as flexible asphalt pavement and glass. The grid structure enables it to cover a broad area and increases interlocking by stacking aggregates in the grid cell (the open area between grid lines). Additionally, the high surface area provides a well-bonded interface between steel wire mesh and the surrounding material. Based on these features, steel wire mesh can easily find its application in printing thin and flat concrete elements such as slabs and domes.

Fiber reinforcement is also applied in ceramics. Because fibers are usually added during the mixing process, the use of fiber reinforcement is limited where mixing is not a part of the manufacturing process. Concrete needs mixing, and it is therefore favorable to have fibers in any type of printed concrete if there is a suitable way to disperse fibers uniformly throughout the concrete.

FRP reinforcements in the form of sheets and rods, and steel reinforcements in the form of plates, rebars, strands, and wires are mostly bonded to the tension side to strengthen the bending resistance of flexural members, such as beams. Such reinforcement concepts can also be applied to 3DPC by attaching to the surface as external reinforcement after concrete setting or embedded in the tension side of concrete beams during printing.

## 3. Existing Studies on Reinforcement in 3DPC

3DPC technology is relatively new, and it still has many challenges to overcome if it is going to replace, at least in part, conventional concrete construction. One of the difficulties is the lack of proper reinforcement for printing building scale structures. Different ideas proposed to reinforce 3D printed concrete can be categorized based on the material (e.g., steel, thermoplastic, FRP, and other materials) or stage to place reinforcement (pre-installed, in-process, and post-installed reinforcement) [52,53]. However, limited available test data and even fewer examples of the use of the proposed reinforcement concepts in actual construction have retarded the development of this advanced technology. Before developing some novel concepts, looking back to review what has been achieved in this regard is a necessary step to move forward. This section will discuss the recent attempts to reinforce 3D printed concrete based on different stages to place the reinforcement.

### *3.1. Pre-Installed and Post-Installed Reinforcement Methods*

Pre-installed and post-installed reinforcement methods eliminate the need to integrate the reinforcing system in the printing process and provide greater freedom in the placement of reinforcement, thus some of these methods have been adopted by companies, as discussed in the next section. However, due to the need for additional time and labor, these methods are preferred not as the original and primary reinforcing option; instead, they are better employed as further strengthening to satisfy higher strength demand.

### 3.1.1. Reinforcement Methods Adopted by Companies

Contour Crafting (CC), developed by Khoshnevis [54], is one of the major concrete printing techniques, which consists of printing the concrete shell as the formwork and then casting the concrete in the core. Vertical rebars or tied steel meshes can be combined with the CC printing method by installing them inside the printed formwork before casting the concrete (Figure 7a,b). The horizontal rebars and form ties can also be laid manually between layers or inserted into printed layers during the printing process (Figure 7c). This method has been applied by several 3D printing concrete building companies, including Contour Crafting Corp. (USA), ICON (USA), TotalKustom (USA), WinSun (China), CyBe (Netherlands), and Apis Cor (Russia) [55]. Kreiger et al. [56] also implemented this method to reinforce 3D printed concrete walls in the process of building construction (Figure 7d). More applications of manually placed reinforcement combined with the CC printing method in on-site building constructions are shown in Figure 8a–d. Although these companies use the 3D printing technology only to print the stay-in-place "formwork" and not the core, the approach seems effective and suitable to make vertical concrete components such as walls and columns. However, when the walls have vertical curvature, such an approach will have its limitations.

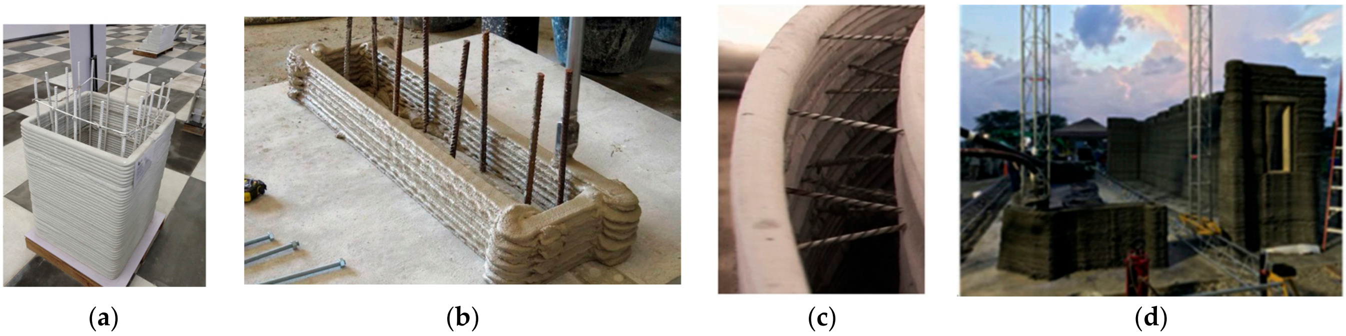

(**a**) (**b**) (**c**) (**d**)

**Figure 7.** Reinforcement methods for printed concrete adopted by (**a**) WinSun [29], (**b**) CyBe [57], and (**c**) Apis Cor [58]. (**d**) Printed concrete building construction [56].


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

**Figure 8.** Reinforcement strategies for 3DPC used in on-site building constructions: (**a**) vertical rebars tied by a curved horizontal rebar in a curved wall element (ICON [59]), (**b**) vertical rebars with form ties in a wall element (CyBe [57]), (**c**) concentrated reinforcement in a wall element (Apis [58]), and (**d**) concentrated reinforcement connected by rebar couplers in a column element (WinSun [60]).

A similar steel rebar reinforcement strategy but with a different printing system has been used by the Chinese building company HuaShang Tengda (HuaShang Tengda Ltd., Beijing, China). (Figure 9). In their approach [61], vertical and horizontal steel rebars are held in position while a customized two-nozzle printing system deposits the concrete on each side of the reinforcement, layer by layer. During the printing process, two nozzles sandwich the vertical rebars and, therefore, keep the vertical reinforcement straight limiting the design freedom of the wall shape.

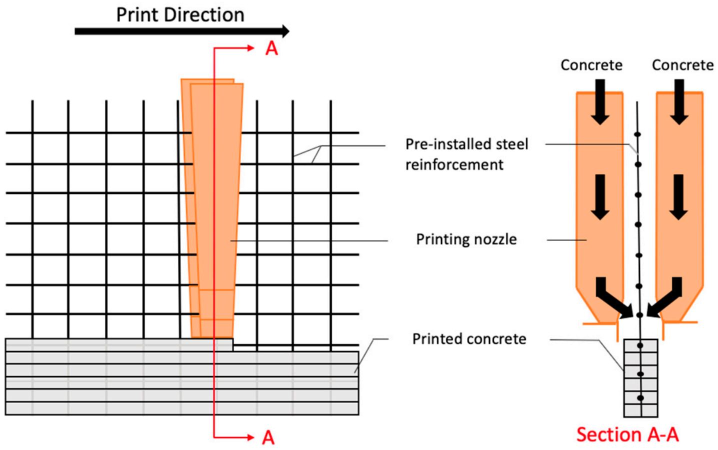


**Figure 9.** Concrete printing with vertical and horizontal reinforcement by HuaShang Tengda Ltd.

The Mesh Mould concept developed at ETH Zurich uses three-dimensional mesh structures to reinforce concrete. In this method, concrete is sprayed over a perforated formwork that is either made of polymer through extrusion [62] (Figure 10a,b) or steel bars through cutting, bending, and welding [63] (Figure 10c). This prefabricated mesh structure acts as both the reinforcement and stay-in-place formwork, thus saving material, as no disposable formwork is needed. However, because this mesh structure is not strong enough to resist structural loads, its application is limited to non-structural components. This technology was used by Sika Chemical Company (Baar, Switzerland) and Branch Technology (USA) [64]. Branch Technology's approach (Cellular Fabrication) to building interior walls (Figure 10d) follows the Mesh Mould concept but uses carbon fiber reinforced thermoplastic polymer as the core [65]. After mesh fabrication, the matrix is filled with spray foam insulation and then covered by the concrete.

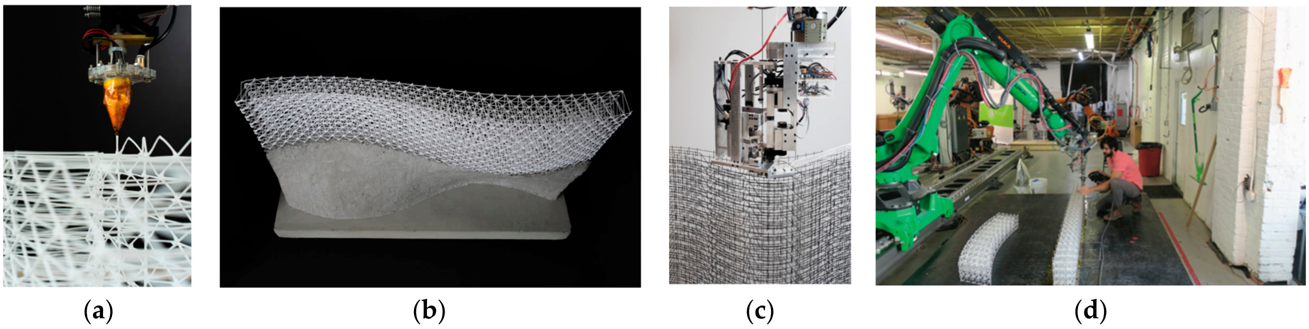


**Figure 10.** Applications of Mesh Mould concept: (**a**) polymer wire mesh extrusion [62], (**b**) polymer wire mesh reinforced concrete wall [62], (**c**) steel wire mesh fabrication [63], and (**d**) core fabrication of reinforced concrete wall from Branch Technology [65].

### 3.1.2. Other Methods Reported in the Literature

Asprone et al. [52] reinforced printed concrete beams using external steel rebars (Figure 11). In this study, hollow segments of the concrete beams were printed independently in the thickness direction. Then, the hollow concrete blocks were assembled and tied by steel rebars to form the beam structure. In this case, rebars play two roles: holding each segment in place and providing external reinforcement under loading conditions. The two ends of the rebar were bent to insert in holes made in the concrete, and then filled with mortar to anchor the rebars in their position. Because of the bend bars, such reinforcement can provide in-plane and out-of-plane resistance to the beams. In the study, the printing process allows the topology optimization of beam elements, which saves material compared to conventional construction techniques. Moreover, because of variable locations and orientations, the external steel rebars contribute to improving compression, tension, and shear behavior of printed concrete beams rather than just increasing tension resistance as in conventional concrete. However, the extended work of anchoring the rebars and filling the holes eliminates any advantage over conventional concrete in terms of construction time.

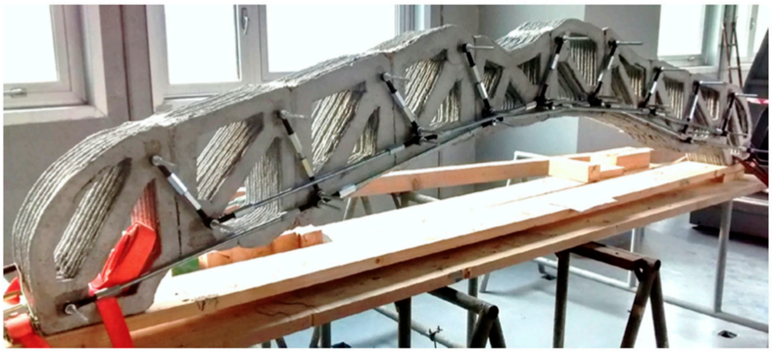
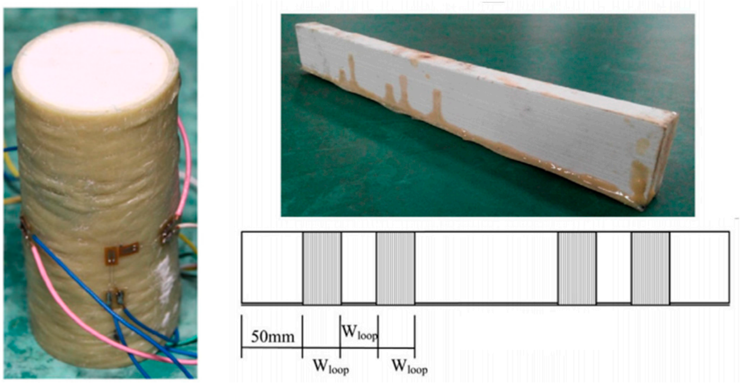


**Figure 11.** Printed hollow concrete units assembled and reinforced by external steel rebars [52].

Feng et al. [66] wrapped and looped printed concrete columns (Figure 12a) and beams (Figure 12b) by glass fiber-reinforced polymer (GFRP) sheets using a hand-lay-up procedure after the printing process, similar to the application of FRP sheet (wrap) to conventional concrete discussed earlier. According to the results of uniaxial compression and flexural tests, this reinforcement method changed the failure mode of concrete columns from brittle to ductile and concrete beams from brittle flexural failure to less brittle shear failure. The GFRP sheets reinforced concrete elements are more ductile, as they can deflect more before failure and thus resist more load before cracking. Although this method requires extra labor, its effectiveness is verified based on the reported data.



(**a**) (**b**)

**Figure 12.** Applications of FRP sheet reinforcement in printed concrete members: (**a**) printed concrete column wrapped by FRP sheets and (**b**) printed concrete beam looped by FRP sheets [66].

The post-tensioning method discussed earlier, as applied to conventional reinforced concrete, is also used in 3DPC after printing. Based on structural optimization, concrete members can be printed as hollow structures using less material. Those cavities created as part of the printing process can function as ducts that will be grouted after the tensioning of steel cables. As early as 2011, this reinforcement method was used at the Loughborough University, UK, to print a concrete bench [67] (Figure 13a). The world's first 3D printed reinforced concrete bridge (Figure 13b) printed at TU/e also used prestressed steel cables applied longitudinally and anchored to the reinforced cast concrete blocks [68,69]. This reinforcement strategy has also been applied to printed concrete columns (Figure 13c) and girders (Figure 13d) by Silva et al. [70] and Vantyghem et al. [71], respectively. In these studies, the concrete members were printed with layers normal to the longitudinal direction in segments and assembled by aligning the center holes. Post-tensioning cables were then threaded through the holes, which function as ducts. The feasibility of applying post-tensioning to 3DPC seems promising. However, more experiments need to be conducted to evaluate the effectiveness of this reinforcement method in printed concrete.

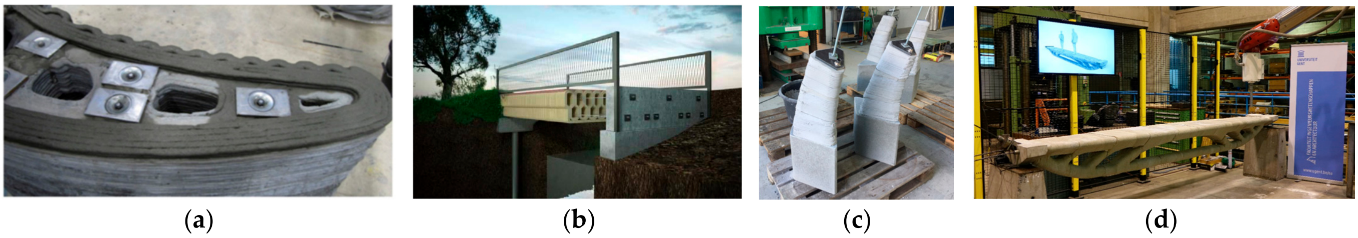
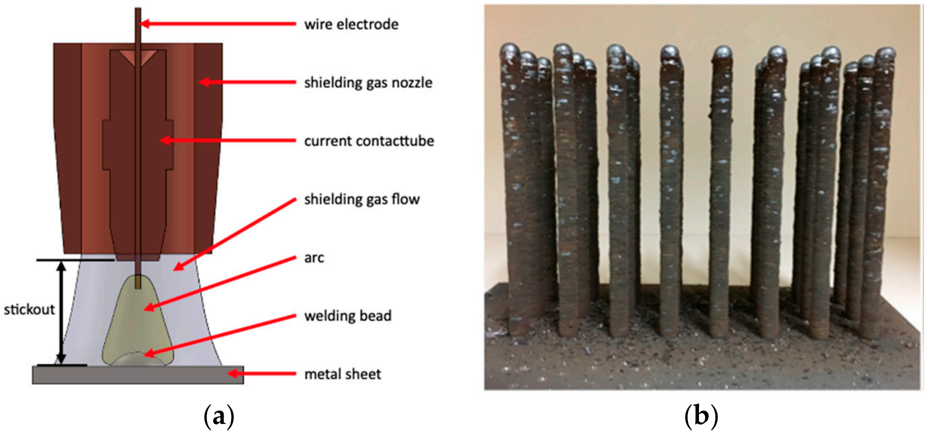

(**a**) (**b**) (**c**) (**d**)

**Figure 13.** Printed concrete members reinforced using post-tensioning: (**a**) concrete bench (Lim et al., 2011), (**b**) conceptual design of concrete bridge deck by BAM [69], (**c**) concrete column [70], and (**d**) concrete girder [71].

### 3.2. In-Process Reinforcement Methods

In-process reinforcement method refers to a reinforcement strategy that allows printing and reinforcing steps to carry on simultaneously and automatically. This highly automated printing system brings benefits to the construction process, for example, by saving the time of applying reinforcement manually. In this way, 3DPC can reach its full potential over conventional concrete construction. However, many of these innovative methods are stagnated at the research stage because they lack the ability to provide high strength improvement to printed concrete, which will be further discussed in the following section.

Steel rebar is the preferred and commonly used reinforcement method in conventional concrete construction. Accordingly, it is reasonable to develop strategies for automatic generation and application of steel rebars in the 3D printing of concrete. Mechtcherine et al. [55] proposed an autonomous system to print steel rebars, a process referred to as gas-metal arc welding (Figure 14a). In this process, an electric arc between continuously fed wire electrodes and the metal base sheet causes the wire electrode to melt and turn into steel beads, which as it accumulates along the length produces a rebar (Figure 14b). However, the rationale and the approach of integrating the printing process to include both printed concrete and printed steel rebars are still unsolved. Moreover, the effect of the cooling system required by steel printing on printed concrete and the nature of the interaction of the cooling system with the printing system still need to be determined.



(**a**) (**b**)

**Figure 14.** Steel printing concept of generating steel rebars automatically while printing the concrete: (**a**) gas-metal arc welding system and (**b**) printed steel [55].

Khoshnevis [28] designed a novel reinforcement method to add reinforcement during the Contour Crafting printing process. The steel reinforcement used here consists of many small steel elements (Figure 15), which can be assembled to form different shapes (strip and mesh). The printing process is operated by a gantry system that contains a nozzle for printing the shell, a robot for assembling steel elements, and a feeder for filling the formwork with concrete. However, the complexity of this expensive and intricately detailed printing system makes it a challenge to apply in actual construction.

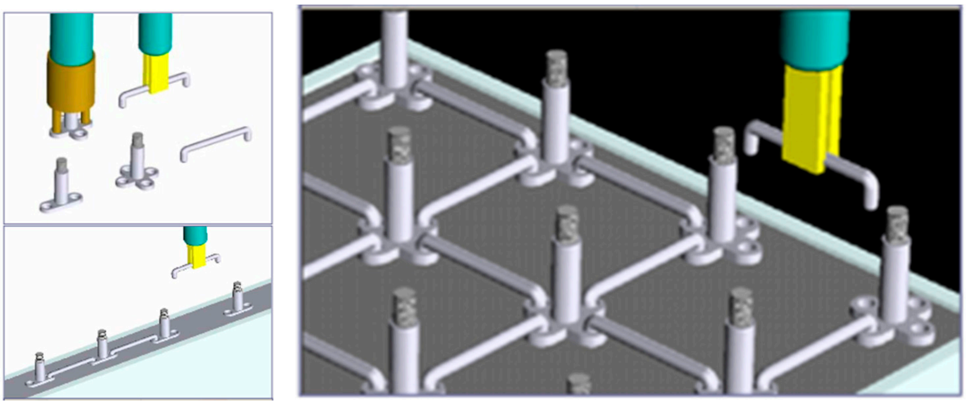


**Figure 15.** Steel elements reinforcement for printed concrete developed by Khoshnevis [28].

Another method that can combine printing and reinforcing processes in 3DPC is fiber reinforcement (Figure 16a), also called discontinuous reinforcement. Short fibers that will easily flow through the pump's stator and nozzle with concrete are mixed with other ingredients until reaching uniform consistency throughout and then extruded as fresh concrete to generally enhance shear, compression, and tensile resistance of the printed and cured concrete. Hambach and Volkmer [72] reinforced 3D printed concrete in small scale (specimen size is about a few centimeters) using carbon, glass, and basalt fibers (3–6 mm in length, 7–20 µm in diameter). The diameter of the nozzle was adjusted to be 2 mm, which is smaller than the lengths of fiber to make sure the extruded fibers aligned with the printing direction. Such a small diameter nozzle is not commonly used to print concrete, but it is feasible to do this without mixing aggregate in the cement mixture. The high degree of aligned fibers increases the flexural and compressive strength of printed concrete, reported to reach 30 MPa and 82.3 MPa, respectively, as the maximum value among tested specimens. A similar concept but with different materials was used by Bos et al. [73] where steel fibers (6 mm) with 2.1 vol% were added to the wet concrete mix and extruded with concrete parallel to the nozzle travel direction. The experiment recorded a significant increase in the flexural strength of printed concrete after adding steel fibers (from 1.1 to 5.95 MPa). Additionally, adding multiple lengths of steel fibers (6 mm and 13 mm) in the concrete mix (Figure 16b) has been considered and experimented with at Technical University at Eindhoven (TU/e), Netherlands, to improve the mechanical properties of printed concrete under loading conditions [74]. Accordingly, 6 mm fibers can bridge microcracks increasing tensile strength, and 13 mm fibers can hold the macrocracks, increasing the ductility after cracking. Although this printing system seems useful to help 3D printing reach its full potential for automation, there is still room for improvement. The highest level of strength achieved using this approach is still not enough to build large-scale concrete elements without additional reinforcement, which may be feasible with some of the other types of reinforcement, thereby pushing the strength limit further. The orientation of fibers need not necessarily be aligned with the nozzle as multi-directional fibers can become feasible by enlarging the nozzle diameter, which is more suitable to increase the overall performance of concrete, including but not limited to flexural, compressive, and shear resistance.

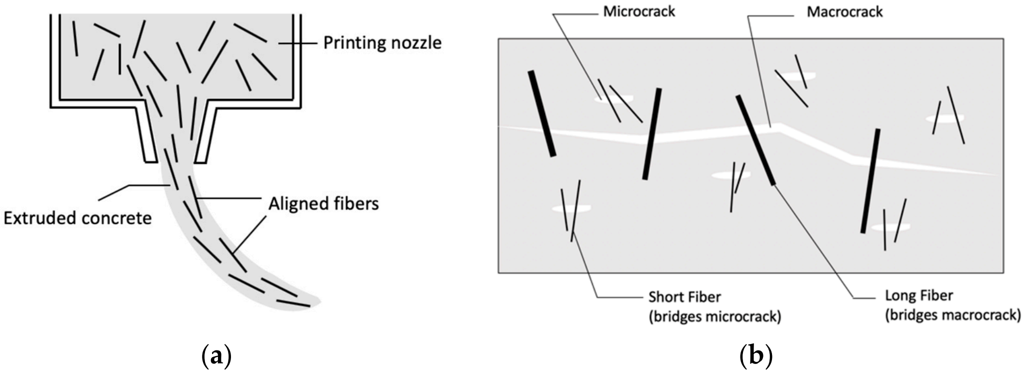


**Figure 16.** Fiber reinforcement for printed concrete: (**a**) schematic diagram of printing concrete with fibers and (**b**) functions of fibers in different lengths.

Different from discontinuous reinforcement, continuous reinforcement is input at the nozzle. Continuous steel micro-cable reinforcement has been applied in 3DPC by Ma et al. [75] (Figure 17a). The dual printing system consists of a nozzle for printing concrete and an extruder for placing steel micro-cable driven by a step motor that can continuously feed the steel micro-cable (1.2 mm diameter) to the printing nozzle. The feeding speed is adjustable to print concrete and lay steel micro-cable synchronously and to embed steel micro-cable into concrete beads while printing. The maximum flexural strength of the steel micro-cable reinforced concrete is reported to be 30 MPa, which corresponds to the maximum flexural strength of the short fiber reinforced concrete (30 MPa) based on Hambach and Volkmer's research [72] mentioned in the previous paragraph. This similarity implies the range of flexural strength of printed concrete reinforced by filament reinforcements, i.e., fibers and micro-cables. Additionally, it highlights the need for multiple reinforcements and the need for new reinforcement strategies.

A similar printing system but with different continuous reinforcement has been discussed by Jutinov [76] and Bos et al. [77]. Jutinov claimed that wire rope (Figure 17b) is more suitable to use as a reinforcement than steel chain (Figure 17c) and steel wire because it has high flexibility in the transverse direction, making it easier to work with, in particular for curve-shaped walls.

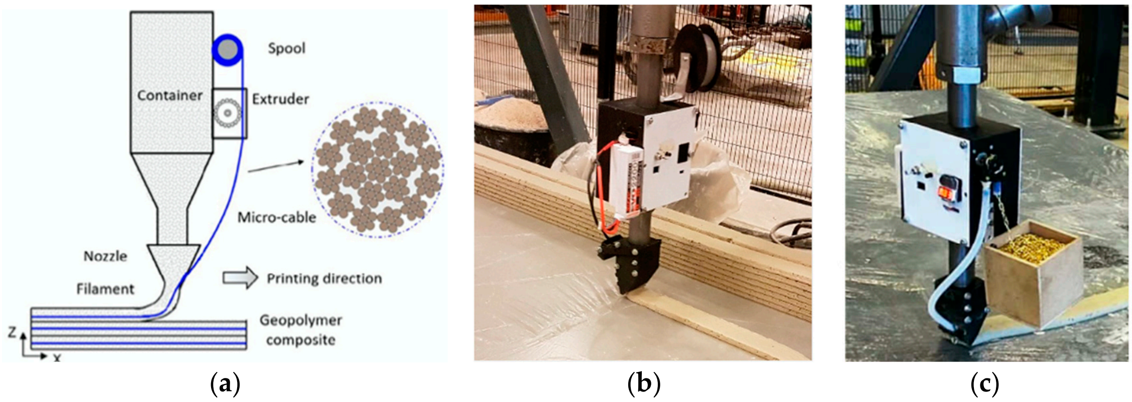
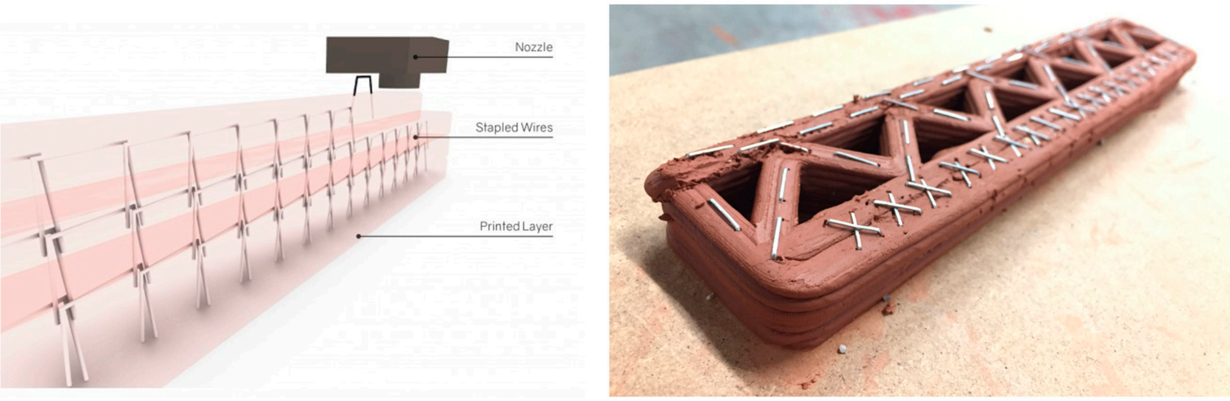


**Figure 17.** Concrete printing systems for different types of continuous reinforcement: (**a**) continuous steel cable [75], (**b**) wire rope [77], and (**c**) steel chain [77].

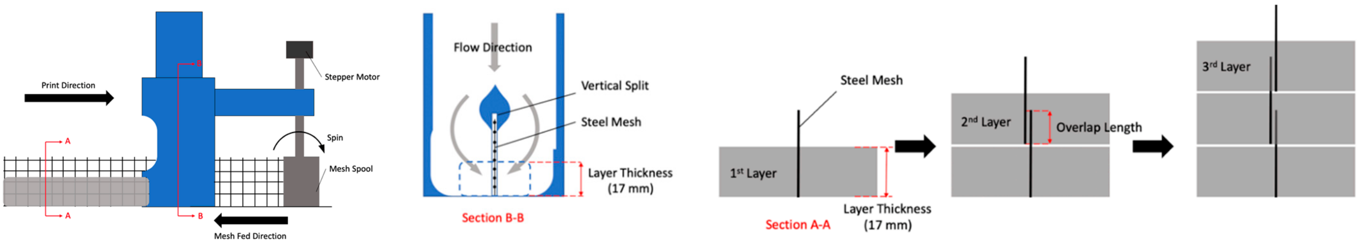
Instead of being printed together with fresh concrete, steel reinforcements can also be stapled into printed concrete. Geneidy and Kumarji [78,79] experimented with this innovative idea where the refitted electrical staple gun bonded to the robot arm inserts staple-like steel wire profiles (Figure 18a,b) into fresh concrete in designed locations. The stapling process is continuous with the movement of the robot arm and is accomplished simultaneously with concrete printing. Different shapes of steel wire are available for different geometric situations. After printing, the staples are embedded in concrete to form a 3D wire mesh, which not only enhances the bonding between printed layers but also increases the whole structural integrity. Accordingly, the most significant advantage of this printing system is that steel profiles can be stapled in different patterns by the staple gun with a switch that triggers the firing mechanism during the printing process. To be more specific, steel wire profiles can be inserted and overlapped to each other as an "X" shape (Figure 18b) between parallel beads to provide interlocking force or applied at the corner to strengthen that weak area. As suggested by the authors, future work includes using machine learning to simplify the process of locating weak points, identifying proper reinforcement types, and developing an optimized printing process. Although the amount of reinforcement based on this technique is still much below the steel rebar, high flexibility and controllability make it worth considering for reinforcing 3D printed concrete.



(**a**) (**b**)

**Figure 18.** Applications of steel wire profile reinforcement in printed concrete: (**a**) aligning with printing direction [78] and (**b**) applied in "X" shape [79].

Steel mesh reinforcement commonly used in conventional concrete is typically embedded horizontally at mid-depth of the concrete slab. Marchment and Sanjayan [80] proposed a novel way to embed steel wire mesh vertically in 3DPC while printing concrete walls. Accordingly, the steel wire mesh is rolled and placed vertically onto a spool, from which it is fed as the nozzle travels controlled by a stepper motor (Figure 19a). The nozzle head has a vertical split in the middle and is positioned after the spool along the travel direction to allow the placed vertical mesh to pass through the vertical split (Figure 19b). Inside the nozzle, the flow of fresh concrete is separated by that split but merged in the middle when the concrete is printed on both sides of the mesh. With these settings, a vertical mesh can be applied simultaneously with concrete during printing and sided by concrete beads on both sides to keep it vertical. The mesh is higher than the layer thickness (17 mm) but lower than two layers (34 mm) to overlap in the vertical direction among layers and achieve continuity in the vertical direction (Figure 19c). After the failure test (flexural bending test), steel yielding occurs before bond failure, which proves the existence of enough bond strength between the concrete and the steel wire mesh and that the embedded steel mesh contributes to the flexural bending resistance. This printing system has great potential as it is the first method to add vertical mesh automatically along with concrete printing. On the other hand, because the steel wire mesh segments are not welded or tied in the vertical direction and the customized feeding system limits the rigidity of the steel mesh, the increased flexural strength using this reinforcement method will be much less than applying a whole piece of welded wire mesh manually. Additionally, the author recommends cutting the mesh for different layer printing, but after cutting, it would be hard to align the wire to the nozzle head notch without manual interference. Furthermore, the mesh should be very flexible to roll in the spool, which has less stiffness than the steel rebar. These concerns need to be further addressed and improved to reach the full potential of this printing system.



(**a**) (**b**) (**c**)

**Figure 19.** Vertically placed steel wire mesh reinforcement for printed concrete: (**a**) placement of vertical steel mesh reinforcement, (**b**) cross-section of nozzle head, and (**c**) overlapping of vertical steel mesh between printed layers.

## 4. Evaluation

### 4.1. Effectiveness of Current Reinforcement Ideas on 3DPC

To choose an appropriate reinforcement option for 3D printing, it is important to match the structural needs to the characteristics of the reinforcement type/method. Table 1 is developed to summarize the attributes, drawbacks, and complexity and energy consumption of various types of reinforcement methods discussed. Although the method of printing steel with concrete and the method of assembling small steel elements while using CC method to print concrete presented additional interesting possibilities to reinforce printed concrete, such methods seem too elaborate and hard to achieve at this stage of technological development for practical use, and thus, are not considered here.

**Table 1.** Attributes, drawbacks, and complexity and energy consumption of different reinforcement methods for printed concrete.

| | **Reinforcement Methods** | **Attributes** | **Drawbacks** | **Complexity and Energy Consumption** |
|---|---|---|---|---|
| Pre-installed reinforcement | Prefabricated steel or thermoplastic polymer mesh structure (e.g., Mesh Mould) | Increase structural integrity and stability | Application is limited to non-structural components (e.g., interior walls) when thermoplastic polymer mesh is used | Requires long time and equipment to fabricate mesh structure |
| Post-installed reinforcement | Vertical steel rebar (e.g., Contour Crafting) | Increase flexural strength | Not suitable for vertically curved wall | Easy to operate with extra labor need |
| | Post-tensioned steel cable | Increase flexural strength and delay crack initiation | More test results are needed to evaluate its effectiveness | Requires long time and equipment to tension cables |
| | External steel rebar | Increase flexural, compressive, and shear strength | Requires long time for post-processing | Requires heavy labor work to assemble external reinforcement system |
| | FRP sheet | Increase flexural strength and ductility | Requires extended fabrication time especially for large concrete members | Requires labor work |
| In-process reinforcement | Discontinuous reinforcement (e.g., steel, carbon, glass, and basalt fibers) | Increase flexural, compressive, and shear strength. Increase post-cracking stiffness | Not enough strong on its own to use in large concrete members | Easy to operate |
| | Continuous reinforcement (e.g., wire rope, steel chain, steel wire) | Increase flexural strength, ductility, and post-cracking stiffness | Not enough strong on its own to use in large concrete members | Requires customized printing system |
| | Staple-like steel wire profile | Increase structural integrity, stability, bonding between adjacent printed filaments, and strengthen the weak area | Needs further development in the future in combining with machine learning to locate weak area | Requires customized nozzle system |

**Table 1.** *Cont.*

| | Reinforcement Methods | Attributes | Drawbacks | Complexity and Energy Consumption |
|---|---|---|---|---|
| In-process reinforcement | Vertical steel wire mesh | Increase flexural strength in two directions on the wall plane | Provides limited flexural bending resistance | Requires customized printing system |
| | Steel rebar and steel wire mesh (manually embedded immediately after the printing of each layer) | Increase flexural and shear strength and deflection capacity | Requires labor work during the printing and may not be efficient due to human errors | Easy to operate with extra labor need |

Based on the defined features, the existing reinforcement methods for printed concrete can be categorized for their suitability to be applied in different types of construction elements, as shown in Table 2. Discontinuous reinforcement, continuous reinforcement, and staple-like steel wire profile are not included in the table specifically because they are very flexible and can be used in conjunction with the methods in Table 2.

**Table 2.** Existing reinforcement methods categorized based on the suitability of use in different construction elements.

| | Construction Elements | Existing Reinforcement Methods |
|---|---|---|
| Horizontal Element | Slab | Post-tensioned steel cable<br>Steel/FRP rebar and steel wire mesh |
| | Beam | Post-tensioned steel cable<br>FRP sheet<br>Internal and External steel/FRP rebar |
| Vertical Element | Column | Post-tensioned steel cable<br>Steel/FRP rebar |
| | Wall | Post-tensioned steel cable<br>Vertical steel/FRP rebar<br>Vertical steel wire mesh<br>Prefabricated steel or thermoplastic polymer mesh structure |

The chosen method from the above that will be suitable for a given project should depend on the overall requirement and performance of the method, including labor, cost, and enhancement level. The most favorable and suitable reinforcement method should possess the following features: minimal labor and time needed for applying the reinforcement, ease and affordability of fabrication process, and providing a high level of strengthening for specific construction elements.

As discussed earlier, predominant reinforcement methods typically used in conventional cast concrete consist of steel rebars, FRP sheets, and post-tensioned steel cables. Although these methods are characterized by providing high strength and deflection capacity to concrete members, they are also considered labor-intensive. Thus they are not able to exploit the full potential of 3D printing technology. In-process reinforcement methods tend to be more focused on providing fully automated approaches that can reduce labor and construction time but could also result in compromising high levels of strengthening and deformability characteristics. Therefore, none of the existing reinforcement methods can cover all the favorable characteristics, which suggests the need to explore more innovative reinforcement methods for printed concrete.

### *4.2. Implementations of Reinforcing Idea for Other Than Concrete in 3DPC*

The choice of reinforcement depends largely on the shape and properties of the reinforced material. For example, steel wire mesh reinforcement is suitable for thin and flat components such as pavement and slab on grade. Rebar reinforcement is suitable for flexural members subjected to high bending stress, e.g., beams, slabs, and walls. Fiber reinforcement is suitable for components that need extra crack control and ductility, e.g., beams, slabs, walls. A more targeted reinforcement strategy will increase the effectiveness of reinforcing. For example, printed concrete domes and folded plates or thin shell structures will greatly benefit from steel wire mesh to strengthen large surface areas, printed beams need rebars to resist bending forces on the tension side, and fiber reinforcement added during concrete mixing is beneficial to all shapes of printed concrete.

### *4.3. Shortcomings and Possible Improvements*

Although many existing reinforcing attempts have already shown great potential to enhance the mechanical properties of printed concrete, the broad application is still lacking due to limitations of the proposed reinforcement, which reflects the difficulties of achieving a fully automatic printing system with in-process reinforcement while providing high strength to printed concrete. In this context, the mechanism of applying continuous and stiff reinforcement during printing and maximization of strengthening from discontinuous or flexible reinforcement in printed concrete become crucial to achieving. Accordingly, a novel printing system with multiple robots working separately to print concrete and place reinforcement simultaneously seems to be one of the solutions for a completely automated printing process incorporating the placement of continuous and stiff reinforcement. Additionally, combining multiple reinforcement methods is beneficial to higher strengthening levels compared to a single reinforcement approach. Moreover, the reinforcement method should be consistent with the corresponding load cases. In the future, the transition between different printing styles needs to be explored for automating the whole building construction.

## 5. Conclusions

This paper reviewed the existing reinforcement methods for conventional cast concrete, printed concrete, and other materials (e.g., asphalt pavement, masonry, glass, wood, and ceramics). In addition, a preliminary evaluation including the characteristics (Table 1), recommended applications (Table 2), and shortcomings and possible improvements for each reinforcement method was provided. The summarized reinforcement methods and proposed guidelines can help better understand potential solutions to reinforce printed concrete and inspire new practical ideas to fill the current technology void. As a result of this study, the following findings and conclusions are drawn:

- The favorable characteristics for reinforcement used in printed concrete include (a) less extra labor work and time needed for applying the reinforcement, (b) being easy to fabricate and use at a low cost, and (c) providing a high level of strengthening for specific construction elements.
- No reinforcement method is suitable for all types of construction elements. A more targeted reinforcement strategy will increase the effectiveness of reinforcing.
- Possible improvements for existing reinforcement methods include (a) a novel printing system with multiple robots working separately to print concrete and place reinforcement simultaneously and (b) a combination of different reinforcement methods.
- In future work, the development of suitable reinforcement strategies for printed concrete should follow either of the two directions, (a) applying continuous and stiff reinforcement using robot during printing and (b) maximizing the enhancement of structural performance from discontinuous or flexible reinforcement in printed concrete.
- For the large-scale adoption of 3DPC in the future, design standards for printed concrete as well as code recognitions and/or guidelines to establish equivalency to reinforced concrete through testing is vital. Guidelines are also needed to illustrate applicable analytical equations to calculate structural capacities and standard testing procedures for safety-related performance and serviceability-related expectations. Additionally, the development of 3D modeling software for structural topological optimization is also crucial for using material more effectively.

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