Existing Reinforcement Concepts for 3D Printed Concrete

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3D printed concrete (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). 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.

reinforcement 3DCP Additive Manufacturing 3D Printing

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.

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 1**a,b). The horizontal rebars and form ties can also be laid manually between layers or inserted into printed layers during the printing process (**Figure 1**c). 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 1**d). More applications of manually placed reinforcement combined with the CC printing method in on-site building constructions are shown in **Figure 2**a–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.

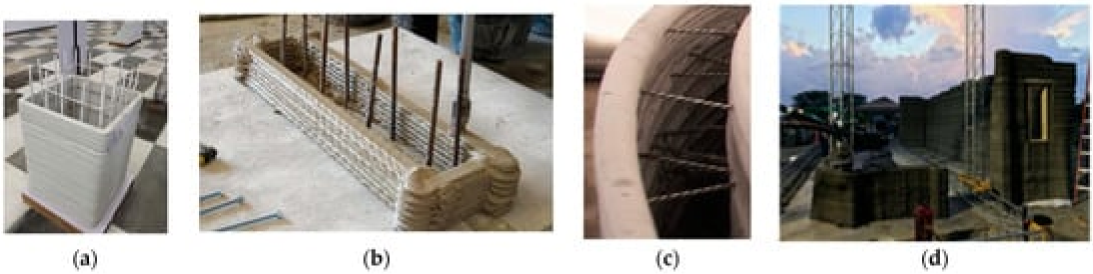

Figure 1. Reinforcement methods for printed concrete adopted by (**a**) WinSun [29], (**b**) CyBe [57], and (**c**) Apis Cor [58]. (**d**) Printed concrete building construction [56].

Figure 2. Reinforcement strategies for 3D printed concrete (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 3**). 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.

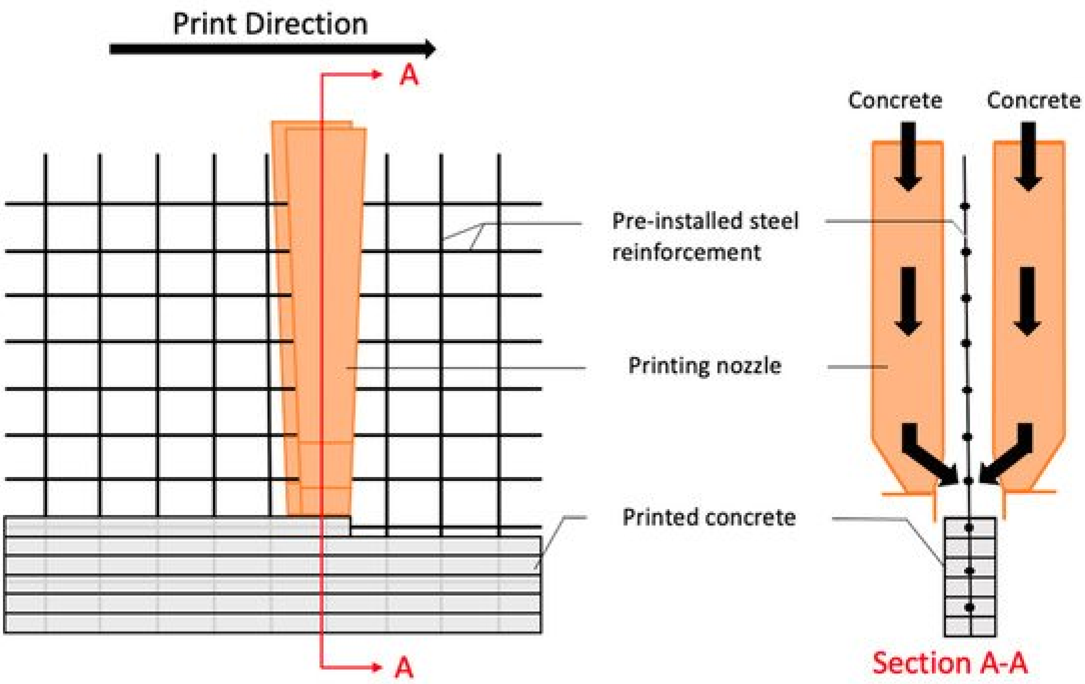

Figure 3. Concrete printing with vertical and horizontal reinforcement by HuaShang Tengda Ltd.

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 4**a,b) or steel bars through cutting, bending, and welding [63] (**Figure 4**c). 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 4**d) 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.

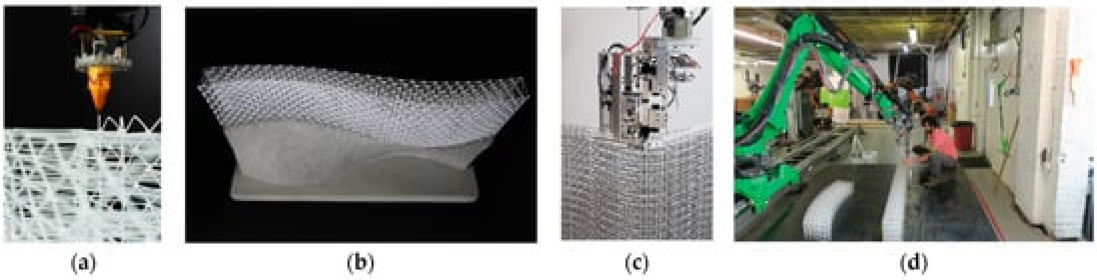

Figure 4. Applications of Mesh Mould concept: (**a**) polymer wire mesh extrusion [62], (**b**) polymer wire mesh reinforced concrete wall [62], (**c**) steel wire mesh fabrication [63], and (**d**) core fabrication of reinforced concrete wall from Branch Technology [65].

1.2. Other Methods Reported in the Literature

Asprone et al. [52] reinforced printed concrete beams using external steel rebars (**Figure 5**). 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 5. Printed hollow concrete units assembled and reinforced by external steel rebars [52].

Feng et al. [66] wrapped and looped printed concrete columns (**Figure 6**a) and beams (**Figure 6**b) 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.

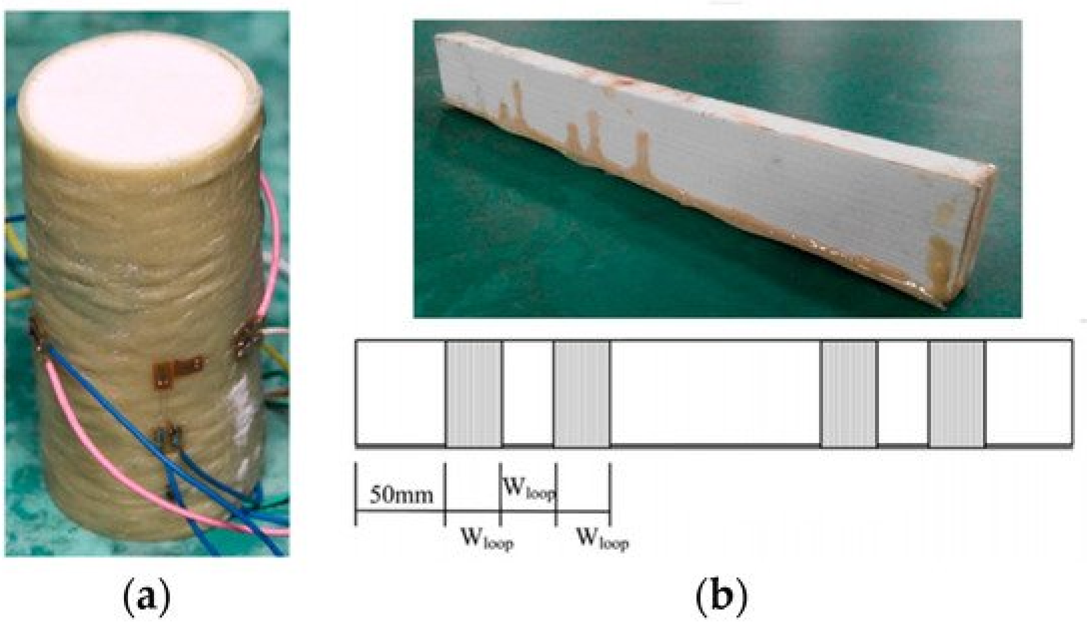

Figure 6. Applications of FRP sheet reinforcement in printed concrete members: (**a**) printed concrete column wrapped by FRP sheets and (**b**) printed concrete beam looped by FRP sheets [66].

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 7**a). The world's first 3D printed reinforced concrete bridge (**Figure 7**b) 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 7**c) and girders (**Figure 7**d) 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.

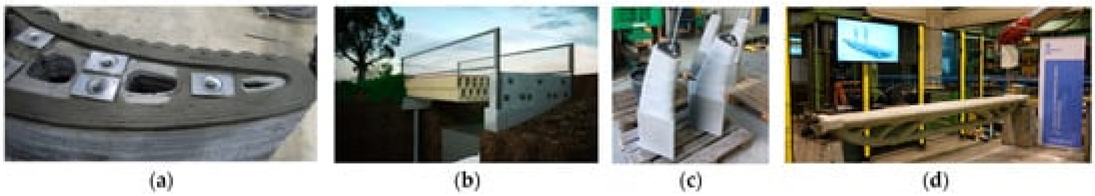

Figure 7. Printed concrete members reinforced using post-tensioning: (**a**) concrete bench (Lim et al., 2011), (**b**) conceptual design of concrete bridge deck by BAM [69], (**c**) concrete column [70], and (**d**) concrete girder [71].

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 8**a). 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 8**b). 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.

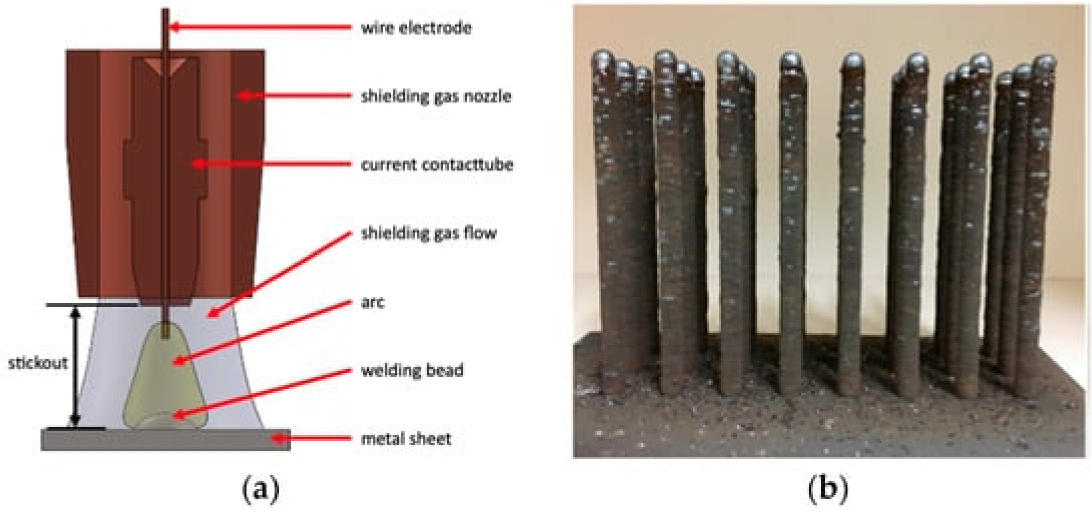

Figure 8. Steel printing concept of generating steel rebars automatically while printing the concrete: (**a**) gas-metal arc welding system and (**b**) printed steel [55].

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 9**), 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.

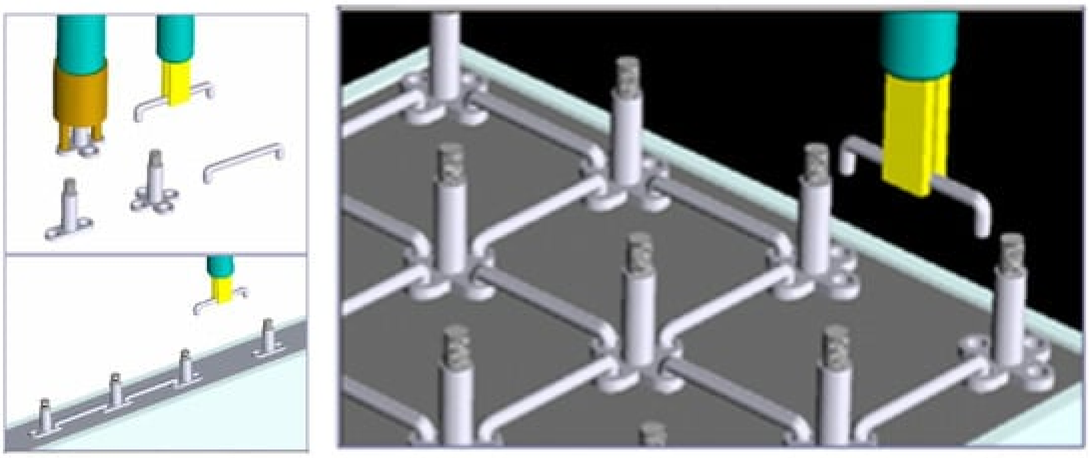

Figure 9. Steel elements reinforcement for printed concrete developed by Khoshnevis [28].

Another method that can combine printing and reinforcing processes in 3DPC is fiber reinforcement (**Figure 10**a), 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 10**b) 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.

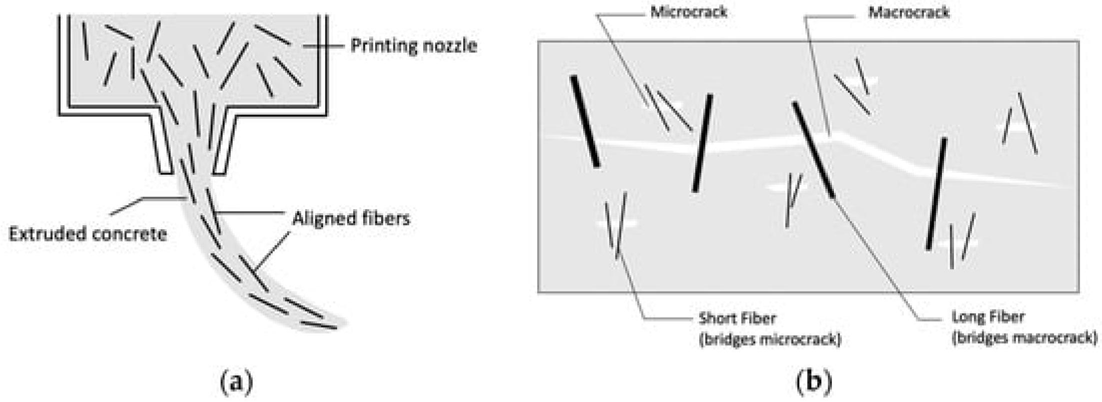

Figure 10. Fiber reinforcement for printed concrete: (**a**) schematic diagram of printing concrete with fibers and (**b**) functions of fibers in different lengths.

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 11**a). 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.

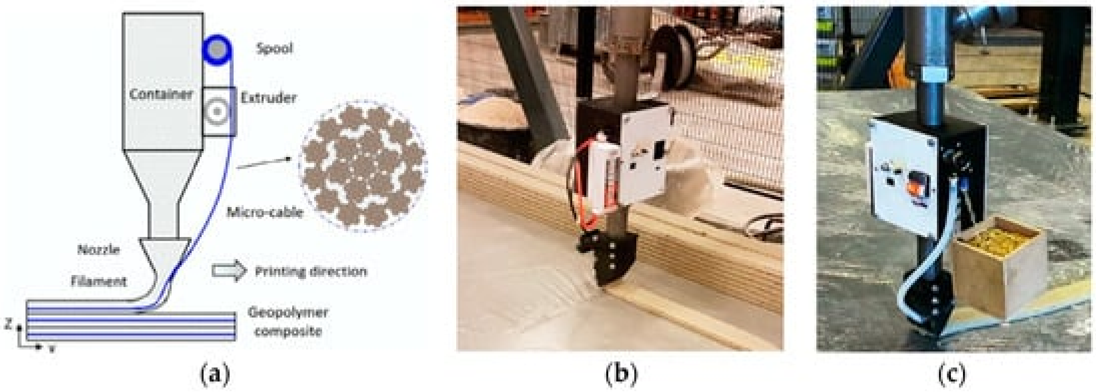

Figure 11. Concrete printing systems for different types of continuous reinforcement: (**a**) continuous steel cable [75], (**b**) wire rope [77], and (**c**) steel chain [77].

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 11**b) is more suitable to use as a reinforcement than steel chain (**Figure 11**c) and steel wire because it has high flexibility in the transverse direction, making it easier to work with, in particular for curve-shaped walls.

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 12**a,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 12**b) 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.

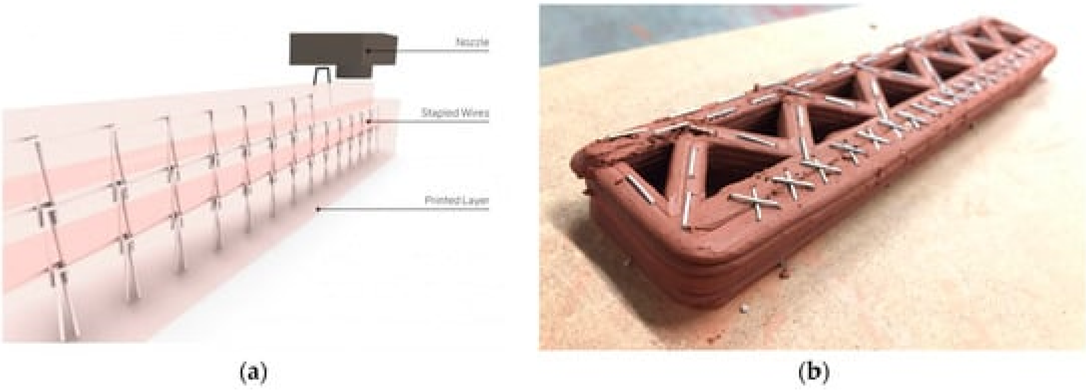

Figure 12. Applications of steel wire profile reinforcement in printed concrete: (**a**) aligning with printing direction [78] and (**b**) applied in "X" shape [79].

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 13**a). 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 13**b). 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 13**c). 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.

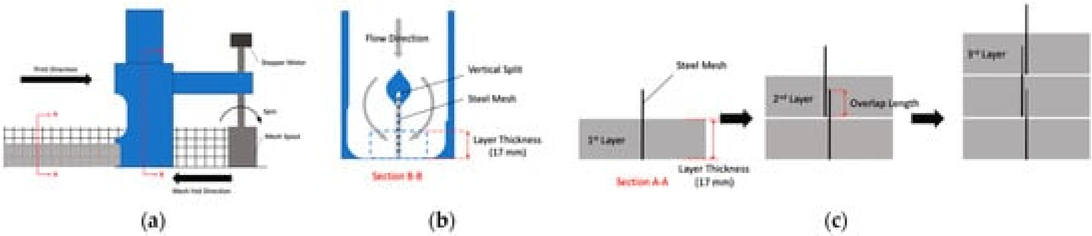

Figure 13. Vertically placed steel wire mesh reinforcement for printed concrete: (**a**) placement of vertical steel mesh reinforcement, (**b**) cross-section of nozzle head, and (**c**) overlapping of vertical steel mesh between printed layers.