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3D printed concrete components and structures: an overview

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Abstract: This paper aims to present an overview and explore components or structures suitable for 3D printed concrete. Most traditional structural forms are not well suitable for 3D printed concrete. To be more specific, it cannot fully consider the characteristics and advantages of 3D printing such as individualization and digitalization. Several 3D-printing-specific structure forms (including hollow form, tree form, arch form, and structure-functional form) are classified and the relevant successful cases are demonstrated. Moreover, the application potential of 3D printed concrete structures is illustrated and the limitations as well as the solutions for the application of 3D printed concrete in practical projects are also summarized. Based on the classification of different reinforcement materials, several reinforcement methods are intensively discussed for 3D printed concrete including steel bars, fibers and other reinforcement materials. The comparison of economic and environmental benefits between 3D concrete printing technology and traditional construction method is discussed respectively. Finally, the expected evolution of 3D printed structures is put forward and recommended.

Keywords: 3D printed concrete; component form; structure; reinforcement method; application

1 Introduction

In recent years, 3D concrete printing technology has achieved rapid development and become a research hotspot worldwide [1-3]. The most popular 3D concrete printing technology in the construction industry is Contour Crafting, proposed by Khoshnevis [4], which manufactured smooth flat and free-form surfaces by computer control. Computer 3D modeling combined with formless construction can theoretically achieve the various complex curved surface shapes. Therefore, 3D concrete printing technology has brought new development opportunities for the construction industry. For example, the application of manufacturing architectural ornaments of complicated geometries, demonstrating the potential for complex and personalized construction [5]. Besides, 3D concrete printing technology can integrate parametric programming and optimized evaluation of architectural design proposals [6], displaying the advantages of digital construction.

However, there is still a long way from the point view of practical engineering applications, which is due to limited research involving 3D printed concrete components and structures. It is difficult to guarantee the safety of 3D printed concrete structures without proper structural design and analysis. To explore the potential of 3D concrete printing technology, 3D-printing-specific design of components and safety design of structures are required. For 3D printed concrete components and structural forms, although traditional structural forms can provide a reference for 3D printed concrete structures to some extent, the characteristics and advantages of 3D printing such as individualization and digitalization cannot be fully considered.

In addition to 3D printed concrete components and structural forms, the safety design of components and structures is also necessary. Generally, steel reinforcement is essential in traditional concrete structures because concrete cannot ensure the safety of the structure by itself in terms of bearing tensile stress and seismic performance. The mechanical properties of 3D printed concrete are not as good as cast-in-place concrete due to the interfaces between the filaments [7]. The experimental results of Le et al. [8, 9], Ma et al. [10] and Ding et al. [11] all indicated that the compressive strength of 3D printed concrete was lower than that of cast-in-place concrete. Obvious anisotropy and discreteness in the hardened state were also noticed. This is mainly because printing parameters such as nozzle size and printing speed are different in different tests [7]. The size of the nozzle will affect the number of interfaces inside the specimen, while the printing speed and other parameters will affect the bond strength of interfaces. Taking the printing interval parameter as an example, it was observed that the tensile strengths of these interfaces were sensitive to the change of time intervals [8, 12-14]. Therefore, the reinforcement of 3D printed concrete is related to the safety of components and structures, as well as the popularization and application in civil engineering.

In addition to analyzing the anisotropy and discreteness of 3D printed concrete, the components, and structural forms, as well as reinforcement methods, are also unresolved problems. Some scholars have found the solutions inspired by the nature [15]. Plants and animals in the nature present numerous excellent structures with beautiful shapes and high strengths that can enlighten the design of structures [16], such as a hexagonal honeycomb [17] or a conch-like structure [18], which have been optimized to adapt to various environments through years of evolution. These structures are not adopted in buildings for various reasons, for example, the shape and structure system of the buildings are limited by calculation theory, construction technology, and economic issues. Concrete structures tend to use standardized beams and columns that are easy to manufacture while they have clear force transmission paths. However, with the improvement of design and calculation ability, the design and calculation of complex structural shapes are rapidly developing. The progress of materials, calculation, and construction will promote the development of architecture towards aesthetics. Meanwhile, the emergence of 3D concrete printing technology helps buildings break through the limitations of traditional construction technology.

This paper focuses on an overview of 3D printed concrete components and structures. Firstly, this paper analyzes the advantages and disadvantages of adopting the traditional concrete structure system for 3D concrete printing in Section 2. Then several components and structural forms suitable for 3D printed concrete based on successful research cases are summarized in Section 3. Finally, the application potential of 3D printed concrete is analyzed while the limitations and solutions of the application of 3D printed concrete are also summarized in Section 4. The sustainability and carbon emission reduction potential of 3D printed concrete structures will be discussed in Section 5. This paper aims to provide a reference for future studies on 3D printed concrete to develop new forms of sustainable concrete components and structures.

2 Traditional structure form for 3D concrete printing

The traditional concrete structure system includes frame structure, shear wall structure, and so on. Taking the frame structure as an example, the frame structure mainly consists of components such as beams, columns, slabs, and foundations, forming a load-bearing structure [19]. 3D printed concrete buildings with frame structures can be divided into on-site and prefabricated 3D printed buildings according to the construction methods. On-site 3D printed buildings are those concrete structures printed on the construction site, while prefabricated 3D printed buildings are those beams or walls printed in a factory and assembled on site. Prefabricated 3D printed buildings can save the time of on-site printing, but increase the cost of transportation and hoisting. In actual engineering, on-site or fabricated 3D printed buildings can be selected according to the requirements of the building project. While the printing problem of horizontal components cannot be solved by on-site printing, which needs additional support such as precast lintels [20].

When applying the traditional structure system to the design of 3D printed concrete structure, the force transmission path and internal force distribution between the 3D printed structure components do not change significantly. The analysis and calculation methods of the framework and other structural systems can be used for reference. This is conducive to the promotion and application of 3D printed concrete in engineering to a certain extent. However, compared with traditional construction technology, although 3D printing technology saves labor, it also greatly increases the cost of construction equipment due to the use of concrete printers and other equipment. Besides, due to the requirements of extrudability and buildability of 3D printed concrete, many admixtures need to be added to adjust the properties, so the material cost also increases significantly. The mechanical properties of 3D printed components are sometime not better than those of cast-in-place components. The eccentric loading test result of 3D printed concrete columns taken by Ge et al. [21] showed that the ultimate bearing capacity of 3D printed concrete columns was lower than that of cast-in-place concrete columns. Furthermore, it is still difficult to arrange the steel bars in 3D printed concrete, and the tensile behaviors of the components are not easy to be guaranteed.

In summary, when 3D printed concrete adopts the traditional structural system, the construction efficiency is lower than the traditional construction method, the construction cost of materials and equipment increases significantly, and the safety of the building is also difficult to be guaranteed. It is worth noting that the purpose of this paper is not to compare the quality of 3D printed structures with traditional concrete structures, which covers many aspects, such as economy, efficiency, and safety, but aiming to explain that the traditional structural system is not suitable for 3D printed concrete structures. Therefore, the traditional structural system should be improved and some components or structural forms suitable for 3D printed concrete need to be proposed.

3 3D-printing-specific structure

At present, few researches on the components or structural forms can be found from the literature. The review of Plessis et al. [15] on the advancing biomimetic research of 3D printed concrete is inspiring. However, not all bionic concepts can be applied for engineering. Many factors need to be considered as a whole, such as reasonable structure design, aesthetics, convenient construction, function, and economic factors. Therefore, based on full considerations to the digital and individualized advantages of 3D printing technology, four types of components or structural forms suitable for 3D printed concrete are classified, which are hollow form, tree form, arch form, and structure-functional form.

3.1 Hollow form

(a) (b)

Fig. 1 (a) The Manufacturing process of post-tensioned 3D printed concrete girder [24]; (b) Steel reinforced 3D printed components [25].

The hollow form component refers to the component section contour being formed by 3D printing with cavities inside the section. Hollow form components are applied widely not only because of material savings, but also because of the requirements of the functions such as heat preservation [22] and sound insulation. For 3D printed hollow form components, the internal holes also leave space for steel bars and other reinforcements. For example, Salet et al. [23] and Vantyghem et al. [24] made full use of the cavities of the cross-section and adopted the assembly construction method, including printing the segments, assembling all parts, and filling the inner cavity with a grouting mortar. The use of prestressed tendons on hollow form components increases the application potential of 3D printed concrete, as shown in Fig. 1 (a). In addition to the longitudinal steel bars, Assaad et al. [25] tried to add the transverse steel bars such as stirrups during the printing process as well, as shown in Fig. 1 (b).

The inner truss can also effectively improve the bearing capacity of the components. Uniaxial loading tests on a hollow wall with an inner truss were carried out by Daungwilailuk et al. [26], which show that the inner truss of the flat wall had a supporting effect, mitigating the bending and preventing the buckling failure. Besides, a structure with the size of 2.5m×2.5m×3m designed by Xiao et al. [27] consisted of the contour and the inner truss. Meanwhile, four cavities with steel bars and pouring concrete were reserved to improve the seismic performance of the structure. To investigate the failure performances of hollow concrete structures, Wang et al. [28] compared the mechanical behaviors of four different hollow forms by compression and flexure tests. Results showed that the truss-like hollow prism displayed the best flexural bending behavior. It will be feasible to design 3D printed structures through topological optimization algorithms.

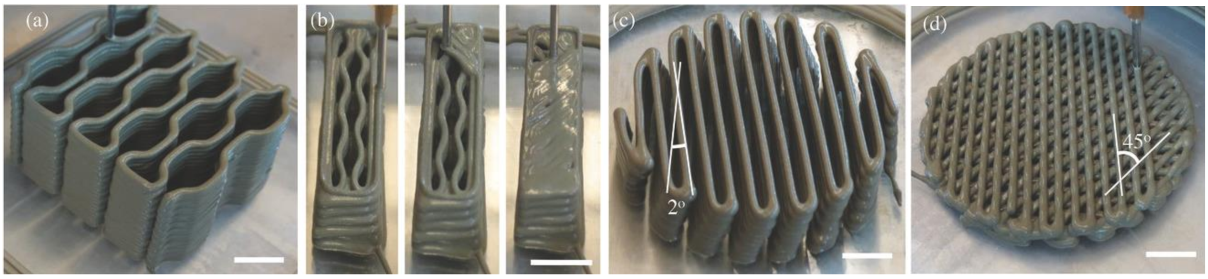

Fig. 2 Various 3D printed structures [30]. (a) honeycomb, (b) cellular sandwich panel, (c) and (d) Bouligand architecture with pitch angles 2° and 45°.

Inspired by biological structures in nature, Nguyen et al. [29] designed three different hollow structures including primitive cellular blocks, gyroid cellular blocks and lattice blocks, and compared the mechanical behaviors under uniaxial compressive loading by experiment and finite element analysis. As shown in Fig. 2, Moini et al. [30] focused on utilizing the interfaces by applying bioinspired structures and analyzed the unique damage mechanisms and flaw-tolerant properties of these structures.

3.2 Tree form

Fig. 3 Completed Future Tree pavilion [33]

Fig. 4 Branching Column [31]

Although trees are ubiquitous in our daily lives, the mechanical principles that exist inside trees are rarely applied to structures. If a tree is regarded as a structure, the trunk is a vertical component and the branch is a horizontal component. The size of each section of a tree is closely related to the stress on that part. Thin branch ends and thick branch roots are evolved because branch roots bear the fixed bending moment, which is similar with the variable section cantilever beam in the structure. Such buildings are novel and beautiful in shapes, such as the columns of the buildings [33] presented in Fig. 3. This type of structure is not popular in previous architectural designs because of the difficulty of design calculation and the complexity of construction. However, with the improvement of structural calculation ability, the calculation of complex structure is no longer a problem. Besides, the emergence of 3D printing technology also makes such structures more available in constructions. The tree form component refers to the component that applied this shape and its mechanics. Burger et al. [31] presented a novel construction process that integrates fused deposition with simultaneous casting of concrete, as shown in Fig. 4. Compared with other printing methods, it adopts synchronous concrete pouring, and the installation of the steel cage does not affect the printing process, which greatly enriches the shape of the building. The columns printed by Anton et al. [32] are also similar cases.

3.3 Arch form

Arches are common in architecture such as bridges [34] and vaults [35, 36]. When concrete is applied for horizontal components, cracks may appear due to tensile stress because of the low concrete tensile strength. However, arch forms can reduce the tensile stress and bending moment by diverting a part of the vertical load into horizontal force, which will take advantage of concrete properties and increase the capacity of the structure. Compared to traditional construction technology, 3D printing concrete technology saves many formworks and provides more design space for arch structures. The arch form components not only refer to the curvilinear components but also to curved surfaces. For example, Lim et al. [37] printed a doubly-curved sandwich panel, which presented the advantages of 3D printing technology in the construction of complex curved surface structures. A solution to improve surface finish quality was proposed by Lao et al. [38], which combined the artificial neural network model with the printing parameters.

To optimize the design of 3D printed structure, a finite element analysis using the maximum stress criterion was carried by Feng et al. [39], which showed that the bearing capacity of the structure was affected by printing directions. Li et al. [40] designed and optimized arch beams and spiderweb-like structures according to stress distribution and transfer modes, as shown in Fig. 5. The bending test results showed that the bending capacity of the arch beam was enhanced by cables.

Fig. 5 Failure patterns of cable reinforced arch beam [40]

3.4 Structural-functional form

3D printing technology has brought the tremendous potential for integrating various functions such as structural, architectural, and environmental functions. For example, a 3D printed vertical green wall system was designed by He et al. [41] to improve the building's energy efficiency, as shown in Fig. 6. The simulation results from the thermal network model indicated that the building with the system exhibited excellent potential for saving energy and improving thermal comfort. Gosselin et al. [42] embedded additional functions such as thermal insulation and soundproofing in the components. Besides, Nguyen et al. [29] suggested that the 3D printed cellular structure has extensive application prospects such as coastal protection blocks, noise insulation panels and so on. To compare the fire performance of varying 3D printed concrete walls, the finite element analysis was carried by Suntharalingam et al. [43] and the results showed that 3D printed non-load bearing cavity walls had superior fire resistance. To create an energy-saving and comfortable environment, a guideline was presented by Alkhalidi et al. [44] by investigating the thermal comfort of 3D printed structures.

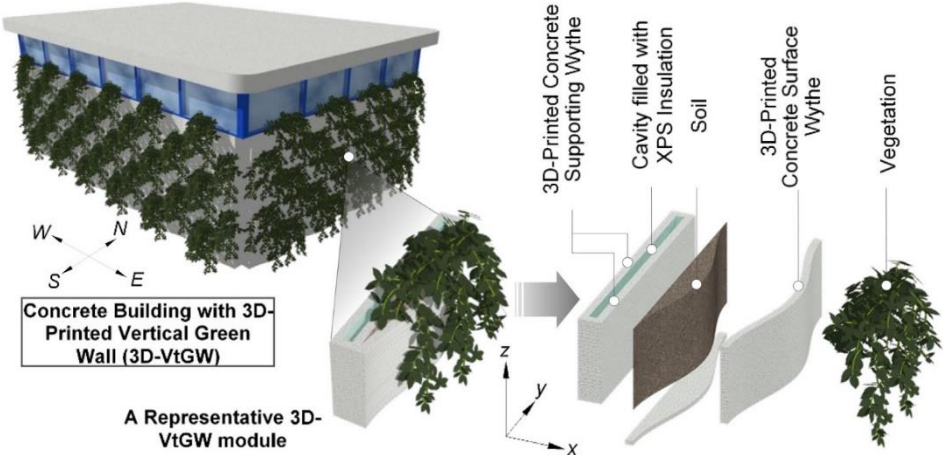

Fig. 6 3D printed vertical green wall module [41]

3.5 Summary

In summary, each of these four types of components or structural forms has its own characteristics and it is hard to say which structure is more suitable for 3D printed concrete. The characteristics of the four components or structural forms are comparatively listed in Table 1. When choosing the components or structural forms, one or the integration of several forms should be chosen according to the actual needs. For example, the self-supporting curvilinear pavilion designed by Prasittisopin et al. [45] integrates the hollow form and arch form, which has smooth curves and is easy to be assembled.

Table 1 The characteristics of the four components or structural forms

Structural forms	Characteristics
Hollow form	Saving materials; Easy to be assembled and reinforced by steel bars.
Tree form	Enriching the shape of vertical components; Reasonable force conditions because of variable sections.
Arch form	Enriching the shape of horizontal components; Reasonable force conditions because of the arches.
Structure-functional form	The integration of structure and function; Low carbon, energy saving and emission reduction.

4 Limitations and solutions of the reinforcement of 3D printed concrete structures

3D printed concrete technology provides the potential for various novel components and structural forms, at present however, these components cannot be applied in practical engineering due to the unsatisfactory performance, especially the tensile capacity. Concrete is quasi-brittle material with low tensile strength. The traditional concrete structure needs to be reinforced with enough steel bars to satisfy the tensile requirements. However, since 3D printing technology uses a layer-by-layer forming method, it is unable to tie and embed steel bars like traditional construction methods. Therefore, many reinforcement methods are proposed for 3D printed concrete. Several literatures had reviewed the reinforcement methods. Lu et al. [46] classified the reinforcement into two methods according to the order of placement of reinforcement materials. Marchment et al. [47] divided the reinforcement methods into post-installed reinforcement, short fiber reinforcement, in-layer direction reinforcement, pre-installed reinforcement, and reinforcement welding method. The classification proposed by Mechtcherine et al. [48] is according to reinforcement types and materials, reinforcement approaches and their key features. In this paper, we hope to simplify the classification, and only take the reinforcement materials as the classification standard, and divide them into steel bars, fibers, and 3D printed reinforcement materials.

4.1 Steel bars

Reinforced concrete structure with steel bars is the most common selection. According to the sequence of steel bar reinforcement, it can be divided into post-installed reinforcement and pre-installed reinforcement. In the post-installed reinforcement process, 3D printed contour serves as the formwork, and the steel bars are installed later and filled with concrete such as the post-tensioned 3D printed concrete beam [49], and the building by WinSun [50], as shown in Fig. 7(a). While in the pre-installed reinforcement process, the steel bar meshes are installed on the 3D printed filaments and later the next layer is printed, for example, the construction of the power distribution substation [51], as shown in Fig. 7(b). Marchment et al. [47] tried to reinforce the 3D printed concrete during the placement of the layers by designing the nozzle to allow the insertion of continuous reinforcement mesh in the middle of the filament, as shown in Fig. 7(c). Liu et al. [52] verified the effectiveness of steel mesh reinforcement through experiments. Similar practices such as Hack et al. [53] producing non-standard curvilinear architecture by applying the shotcrete and steel mesh. Besides, there are some exceptional cases. For example, Asprone et al. [54] proposed a method to divide the reinforced concrete component into different concrete segments, print separately and then assemble them together with steel bars.

(a)

(b)

(c)

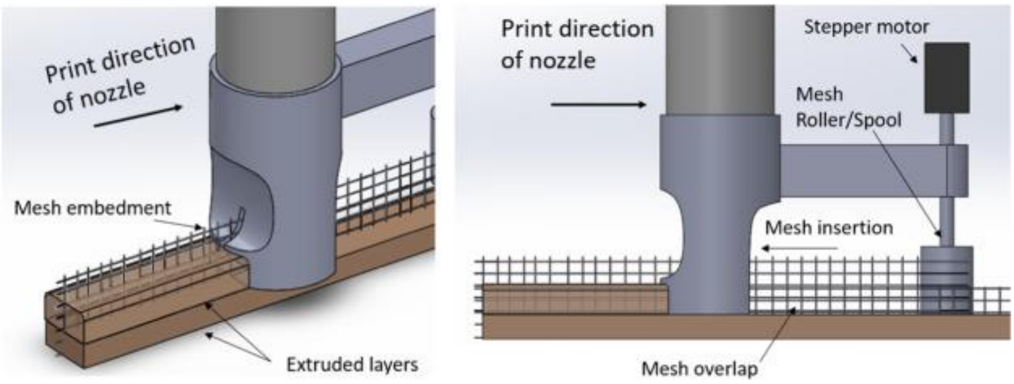

Fig. 7 Several steel bar reinforcement method: (a) Post-installed reinforcement [50]; (b) Pre-installed reinforcement between the layers [51]; (c) Pre-installed reinforcement in the middle of the filaments [47]

Different from the traditional reinforced concrete structure, the interfaces existing in the 3D printed concrete, and the bond properties between the steel bar and the 3D printed concrete are affected by the relative direction of the steel bars. Taking the orientation of the layers into consideration whether parallel or perpendicular to the steel bar, the bond properties between concrete and steel bars were tested by Baz et al. [55, 56] and Marchment et al. [57] through a series of pull-out tests. The results tested by Baz et al. [55] showed that the strength reduced 13% and 22% respectively when the filaments are parallel and perpendicular to the steel bars. For 3D printed concrete structures, the bonding between steel bars and concrete is more complicated due to the deposition of filaments and the existence of interfaces. Besides, different reinforcement methods will also affect the bond properties. For example, in the pre-installed reinforcement process, the presence of steel bars may affect the bond strengths of interfaces. In addition to the bond properties, there is little relevant test data available to evaluate the reinforcement efficiency.

At present, the actual 3D printing engineering mostly adopts the method of steel bar reinforcement and grouting, which is feasible and effective. The addition of steel bars helps to increase the tensile capacity of the components and structures, while the grouting ensures the effective connection of the steel bars to the 3D printed contour. However, this method also has its limitations. Considering that the steel bars cannot be rolled or bent like the steel cables, it is necessary to place the steel bar manually in the printing process, so it is difficult to realize the synchronous printing of the concrete and the steel bars in practical engineering. Besides, appropriate reinforcement anchorage or lap length should be considered to ensure a reliable connection between steel bars and concrete.

4.2 Fibers

As the addition of fibers can reduce shrinkage and deformation in the plastic state, it has been widely used in 3D printed concrete. The specific method is to add fibers to the concrete mix, and then print with the fiber reinforced concrete. Different kinds of short fibers are applied to reinforce 3D printed concrete, such as short polymer fibers by Soltan et al. [58], Li et al. [59], Zhu et al. [60], Ding et al. [61], and Ogura et al. [62], basalt fibers by Ma et al. [63], steel fibers by Pham et al. [64] and Bos et al. [65]. The addition of fibers can improve the tensile strength of concrete. For example, the tensile strength of 3D printed concrete designed by Soltan et al. [58] has reached 6 MPa and the tensile strain 4%. Ding et al. [61] suggested that fiber length had no obvious effect on the peak stress, but had a significant effect on the post-peak behavior. Ogura et al. [62] characterized that fiber contents of 1% and 1.5% by volume are suitable for 3D printed concrete. The results tested by Ma et al. [63] showed that the more fiber employed, the higher flexural strength but the lower flowability of the cement composite and the higher risk of blockage. Pham et al. [64] obtained that the length of steel fibers has a positive effect on compressive strength, which are negligibly affected by fiber volume fractions. Besides, the extrusion process has a crucial impact on fiber reinforced concrete, because it changes the final fiber orientation. It is generally noted that the nozzle enables fiber to align with the filament during the extrusion process [61-65], which is important for enhancing the performance of fiber reinforced concrete. As the scanning electron microscope (SEM) images were taken by Ma et al. [63] shown in Fig. 8, some fibers are pullout from the cement matrix.

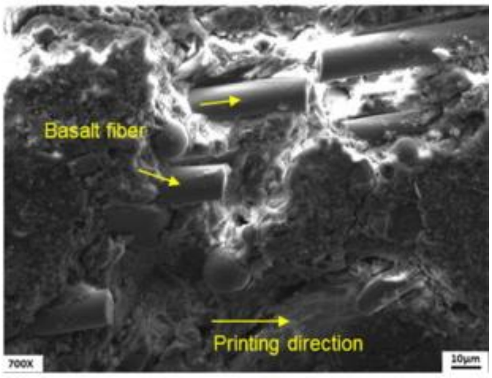

Fig. 8 Micro-scale investigation on mechanical enhancement of fiber alignment based on 700 × SEM images [63].

The addition of fibers can improve the tensile strength of 3D printed concrete, thus improving the ductility of the components, which allows 3D printed concrete to get rid of the need for steel bars and have greater design freedom. On the other hand, the addition of fibers will affect the flowability of 3D printed concrete, and then affect the extrudability. 3D printed concrete with a high fiber content has higher requirements for the nozzle design such as the extrusion power of 3D printer and extrusion screw design.

4.3 3D printed reinforcement materials

Another method is to print the reinforcement materials together with the concrete and the reinforcements are embedded in the filaments or between the layers. At present, the materials of this reinforcement include steel or other cables, and polymer materials. For the reinforcement of cables, the key is to realize the synchronous printing of cables and concrete filaments. The schematic diagram of printing process is displayed in Fig. 9 (a). The cables are continuously fed into the nozzle and extruded simultaneously with the deposition of the filaments. Some scholars have tried to reinforce 3D printed concrete with steel cables. For example, Bos et al. [66] analyzed the printability and mechanical behavior of 3D printed concrete reinforced with steel cables by pull-out tests and bending tests. Ma et al. [67] tested the effect of different printing paths on the flexural strengths of 3D printed specimens reinforced by steel cables, which showed that the flexural strength of the reinforced specimens is respectively 5.1, 5.6 and 2.1 times higher than the non-reinforced ones varied with printing paths. Li et al. [68] found that the confining action of the cables plays an important role in increasing on the peak compressive stress and strain. The typical failure mode is shown in Fig. 9 (b).

Li et al. [40] also tested the reinforcing effect of cables in 3D printed structures such as arch beams. And Lim et al. [69] analyzed the flexural performance of reinforced specimens by experiments. Rather than using steel cables, Mechtcherine et al. [70] reinforced 3D printed concrete with carbon fiber cables, which demonstrated the feasibility of this reinforcement method. The advantage of using steel cables or other cables for reinforcement lies in that the cables are located inside the filaments, and their layout and filament printing are carried out synchronously. The automation level of the reinforcement method of cables is relatively high.

(a) (b)

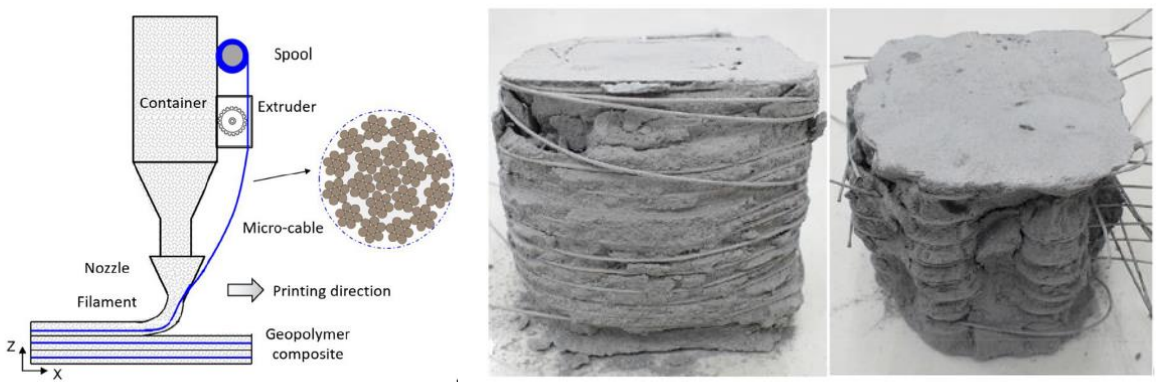

Fig. 9 (a) The schematic diagram of printing process of steel cables [67]. (b) Typical failure mode of 3D printed specimens reinforced by steel cables [68].

Another option is to lay out 3D printed polymer materials between the layers. These reinforcements can be printed in a variety of shapes according to mechanical or other requirements. For example, Fan et al. [71] applied carbon-nanotube-shaped reinforcement which was 3D printed to concrete specimens. The compressive strength of reinforced specimens increased 60-109%. Katzer et al. [72] suggested that concrete beams can be effectively reinforced by spatial 3D printed polymer elements. There are also various 3D printing reinforcement elements, such as the reinforcement elements designed by Lin et al. [73], the printed meshes based on triangular lattices designed by Xu et al. [74] and 3D woven textiles designed by Mishra et al. [75].

The current technology, though, involves printing the reinforcements and placing them manually between layers of 3D printed concrete. However, as the technology evolves, it may be possible for concrete and its polymer reinforcements to be printed simultaneously, in other words, using a device with a multi-printhead that prints one layer of concrete and then switches the nozzles to print the reinforcements such as polymer materials above the concrete layer.

4.4 Summary

Indeed, there are many reinforcement methods that are not discussed in this paper, such as the reinforcement by wrapping GFRP sheets [76], the reinforcement by U-nails [77] and so on. The reinforcement methods summarized in this paper are some representative methods in the existing literature. In summary, each of these reinforcement methods has its own advantages and limitations, which were summarized in Table 2. The reinforcement is the main limitation to the application of 3D printed concrete in engineering at present. Not only the reinforcement method but also the bearing capacity, failure mode and mechanism of the reinforced components also remain to be investigated. At present, there are relatively few literatures about the bearing capacity of 3D printed components, but the potential has been demonstrated. For instance, Zhu et al. [78] conducted the four-point bending test of 3D printed ECC beams with the size of 500 mm × 100 mm × 100 mm, and compared it with cast-in-situ unreinforced ECC beam and reinforced concrete beams. The results show that the bending capacity and ductility of 3D printed ECC beams are better than those of cast-in-situ ECC beams, which are equivalent to those of reinforced concrete beams with 2.36% reinforcement ratio, but the deformation capacity is better than reinforced concrete beams, confirming the application potential of fiber reinforced method. Besides, the automation of reinforcement, the coordination of reinforcement and printing are also the research directions in the future.

Table 2 The characteristics of the three reinforcement methods

Reinforcement materials	Advantages	Limitations
Steel bars	Conducive to large-scale construction; Better reinforcement effect.	Difficult to realize automatic construction.
Fibers	High level of automation; Increasing the tensile strength; Reducing shrinkage and deformation in the plastic state.	Reinforcement can only be achieved within the filaments, not between layers.
3D printed reinforcement materials	High level of automation; Reinforcement materials are printed synchronously with concrete.	Reinforcement can only be achieved within the filaments, not between layers.

5 Discussion

The successful completion of structures such as the bridge [23, 24], the printed room [27,79], the power distribution substation [51], the Barracks Hut [80] and the bus stop shelter [81] demonstrated that unique structure designs can be achieved by 3D concrete printing technology. However, there are still many problems that need to be solved before the application of 3D printed concrete for practical engineering project. Besides, the design of structures should take full consideration to the digital and individualized advantages of 3D printing technology. Reasonable force, aesthetics, convenient construction, function, safety, economic factors, and life cycle analysis also need to be considered. The lack of research on the bearing capacity and failure mode of 3D printed concrete components and structures as well as the lack of structural safety design greatly limits the promotion and application of 3D printed concrete in engineering. It has been mentioned that most studies at present still follow the traditional structure system, without reflecting the advantages of 3D concrete printing technology. It is believed that the form and structure system of components suitable for 3D printing should be further developed and built. The novel shape of the structure should be adapted to the construction pattern of 3D printing, which can be optimized by topology and so on.

3D concrete printing technology also has great potential in reducing environmental impacts such as global warming and acidification [82]. The application of 3D concrete printing technology can largely save the formwork and labor costs [83]. However, the current construction method of 3D printed concrete has no significant economic and environmental benefits compared with the traditional construction method, which can be attributed to the following reasons. Firstly, compared to traditional construction, the environmental impact of 3D concrete printing technology is generally higher because of the high cement content as the dominant factor [83, 84]. The mix of 3D printed concrete needs to be optimized to reduce the environmental impact. Besides, some sustainable materials such as recycled materials [27, 85, 86] and other materials [87-90] makes 3D printed concrete a huge potential for reducing carbon emissions. Secondly, as mentioned above, current structural systems do not perfectly match 3D concrete printing technology. Besides, the more complex shape of the structure, the more the advantages of 3D concrete printing can be exploited.

For the components and structural forms, the concept of composite concrete structures which was proposed by Xiao et al. [91] and hybrid construction integrated with 3D concrete printing, prefabricated construction and on-site construction may be adopted when the project cannot be accomplished by 3D concrete printing alone. The combination of 3D printed ECC beams and 3D printed concrete beams is an available solution. ECC is placed at the bottom of the beam for tension and concrete at the top for compression.

For reinforcement methods, it is believed that the FRP mesh reinforcement has great application potential. Compared with the reinforcement method with steel cables, FRP mesh can achieve the reinforcement in two directions in the plane, which is equivalent to the effect of steel cage in traditional concrete structure. Compared to steel mesh, FRP mesh can be easily bent and rolled, which has the potential to be printed synchronically with concrete. Besides, the combination of several reinforcement methods is also a good choice, such as steel cable printed in the interior of the filament, and steel nails inserted in the deposition direction of the filament, so as to form a spatial network of reinforcement.

Currently, 3D printed concrete is still in the preliminary stage, limited by materials and technologies, but it still shows great potential. The digital features of 3D concrete printing technology would be applied to construct some personalized buildings. Besides, in some extreme environments, such as high temperature, low temperature and humidity or even on the moon [92], the advantages of automation will come to the fore.

6 Conclusion

3D printed concrete has gained rapid development in the construction industry in recent years. However, there are still many unresolved problems for research and application. According to the current literature, this paper classifies four types of components or structural forms suitable for 3D printed concrete, which are hollow form, tree form, arch form, and structure-functional form. The application potential of 3D printed concrete structures is demonstrated, and limitations as well as solutions of the application of 3D printed concrete in practical projects are also summarized.

The components or structural forms of 3D printed concrete should fully consider the digital and individualized advantages of 3D printing technology. Biomimetic concepts can be introduced into 3D printed concrete such as hollow form and tree form. The aesthetics of architecture is also an important factor that needs to be considered. It facilitates the manufacture of complex shapes, such as arch forms. Besides, reasonable force, function, safety, and sustainability also need to be considered.

The reinforcement is the main limitation to the application of 3D printed concrete in civil engineering. In this paper, based on the classification of different reinforcement materials, several reinforcement methods have been summarized for 3D printed concrete including steel bars, fibers, and 3D printed reinforcement materials. The automation level and reinforcement effect of these three methods are different, which can be selected according to the requirements of the project. In general, the automation levels of fibers and 3D printed reinforcement materials are relatively high while the reinforcement effect of steel bars is better.

Although limited by many factors such as reinforcement methods currently, 3D printed concrete structure presents great potential. The key of engineering application is mix optimization, reinforcement methods, and safety design of components and structures. The aim of the mix optimization is to reduce the carbon emissions of 3D printed concrete by introducing other admixtures to reduce the amount of cement, using light-weight aggregates or recycled aggregates. Reinforcements are critical to guarantee the safety of 3D printed structures. Besides, component and structure design method based on bearing capacity and reliability is also an important research direction in the future.

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Conflict of interest

The authors declare that they have no conflict of interest.

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