# Research Progress of 3D Printed Concrete

Yongxin Chen[a,*], Huanhuan Hou[b], Yancun Chen[c]

Kezhijie New Materials Group Henan Co., Ltd., Xinxiang, China

[a]732692115@qq.com, [b]1062688783@qq.com, [c]1030716410@qq.com

**Abstract.** In recent years, the rapid development of 3D printing concrete technology has become a worldwide research hotspot. This article aims to explore the structural characteristics, performance, and potential application areas of 3D printed concrete, and analyze the challenges faced in applying 3D printed concrete in practical engineering projects.

**Keywords:** 3D printing, concrete, structure

## 1 Introduction

The construction industry is one of the pillar industries of the national economy, which has long been plagued by common problems such as high waste of building materials, low degree of automation, and aging population. The development from traditional extensive construction to automation, intelligence, and digitization is the trend of high-quality and sustainable development in China's construction industry. Since its formation in the early 21st century, 3D printing technology for architecture has rapidly emerged in fields such as construction, bridges, and infrastructure due to its advantages of modularity, speed, and flexibility. According to data from the National Bureau of Statistics, the production of 3D printing equipment in the first half of 2024 increased by 51.6% year-on-year, reflecting the strong growth momentum of the 3D printing industry in recent years. 3D printing technology is based on precise 3D data models and constructs complex structures by stacking materials layer by layer, completely breaking the limitations of traditional subtractive manufacturing models. This technology not only greatly expands the entrepreneurial space and flexibility of design and manufacturing, but also significantly reduces the manufacturing cost and time of complex shapes and high-precision products.It is an innovative technology that promotes the development of prefabricated buildings and intelligent construction.

With the rapid development of technology, the application of 3D printed concrete technology in the field of construction is becoming increasingly widespread, attracting many researchers to conduct in-depth research and exploration. In the construction industry, the most popular 3D concrete printing technology is "contour machining" proposed by Khoshnevis, [1] which utilizes computer control to produce smooth flat and free-form surfaces. This technology, combined with computer 3D modeling, theoreti-


Y. Zhang et al. (eds.), *Proceedings of the 2024 10th International Conference on Architectural, Civil and Hydraulic Engineering (ICACHE 2024)*, Advances in Engineering Research 259,
https://doi.org/10.2991/978-94-6463-658-1_47

cally can accurately print various complex shaped concrete structures, bringing unprecedented changes to the construction industry.

## 2 Research Status of 3D Printed Concrete at Home and Abroad

The research focus of the initial stage of 3D printing construction is in the field of mechanical equipment and material technology, which has received less attention from architects. With the application and popularization of this technology, the connection between architects and 3D printing has become increasingly close. In the past, due to the lack of systematic consideration for the form and force analysis of buildings in most research results, many experimental results were difficult to integrate with actual construction, and the shortcomings in modeling also limited the promotion of 3D printing construction technology to the public. In recent years, with the cooperation of professionals in mechanics, materials, architecture, and other fields, 3D printing construction has been able to achieve more complex building systems.In order to ensure the safety of 3D printed concrete structures, researchers need to conduct specialized printing designs for the components and conduct detailed safety assessments of the overall structure. Although traditional structural forms can provide theoretical references for designing 3D printed concrete, they cannot fully meet the personalized and digital requirements of 3D printing technology.

In traditional concrete system structures, in order to improve the load-bearing capacity of components to tensile stress and the safety of seismic performance, it is necessary to embed steel bars in the system. However, 3D printed concrete cannot use steel bars due to its inherent characteristics, resulting in relatively poor mechanical properties. [2] The printing process is a digitally controlled additive method capable of manufacturing architectural and structural components without formwork, unlike conventional concrete construction methods. Le et al. [3] Li et al. conducted research and analysis on the hardening performance of high-performance fiber-reinforced fine aggregate concrete extruded materials, and the results showed that 3D printed concrete has low strength, high density, and can retain the inherent high performance of the material.The team led by Xu Weiguo from Tsinghua University used a robotic arm and concrete materials to print maze like art pieces. The pieces have a three-dimensional curved surface shape, and the multi-directional printing of the robotic arm achieves printing in the three-dimensional dimension. At the same time, the layered staggered method is used to solve the defect of insufficient strength at the joint position in 3D concrete printing.

In addition to the issues mentioned above, there is still no good solution found for the structural form and reinforcement methods of 3D printed concrete components. Domenico Aspron et al.[4]proposed a method for manufacturing reinforced concrete components based on concrete 3D printing technology, which strengthened the printed form beyond the material. Specifically, the reinforced concrete components are divided into different concrete segments, and then each printed unit is combined with external steel bars to form a system. This method helps promote free-form structural optimization, save concrete and steel usage, and manufacture lighter structures.[5]It is worth mentioning that some scholars draw inspiration from nature when exploring solutions. Animals and plants in nature have diverse structures with high stability and strength, which provide direction for structural designers.[6] For example, hexagonal honeycomb and conch structures have evolved over many years to be highly adaptable to various complex environments.

## 3 Traditional Structural Forms

The traditional architectural structural system, such as frame structures and shear wall structures, occupy an important position in the construction industry. However, in the context of 3D printed concrete technology, these traditional structural systems need to be adjusted and optimized accordingly. According to different construction sites, 3D printed concrete includes two types: integral printing and prefabricated printing. Integral printing is carried out directly at the construction site, while prefabricated printing involves printing some components in the factory before transporting them to the site for assembly. The advantage of 3D printing prefabrication method is that it can significantly reduce on-site construction time, but at the same time, it increases transportation and installation costs. Therefore, in actual construction, the construction method with higher cost-effectiveness can be selected based on the specific situation of the project.

When applying traditional structural systems to the design of 3D printed concrete structures, there is no significant change in the transmission and distribution of forces within the two systems. In this way, the analysis and calculation methods of 3D printing can refer to traditional structural systems. This is to some extent conducive to the rapid promotion of the widespread use of 3D printed concrete in construction projects. Different from traditional construction methods, 3D printing technology relies more on mechanical equipment, greatly freeing up labor costs, but its equipment costs are relatively high. In addition, due to the construction characteristics of 3D printed concrete, it is difficult to arrange steel bars inside it, and the tensile performance of the components is slightly inferior to traditional concrete components.

As can be seen from the above, due to the differences between 3D printed concrete and traditional structural systems, directly using traditional structural systems for construction will bring negative impacts such as low construction efficiency, high production and application costs, and reduced building safety. Therefore, a new structural system for 3D printed concrete should be designed and developed.

## 4 3D Printed Specific Structures

At present, there is little research on components or structural forms. Plessis's biomimetic advances in 3D printed concrete are exciting. Some researchers have begun to explore specific structural designs suitable for 3D printed concrete technology based on its characteristics. These designs fully utilize the advantages of digitization and personalization, mainly in the form of hollow structures, tree structures, and arch structures.

### 4.1 Hollow Structure

Hollow forming parts refers to forming the outline of the cavity in the section of the part by 3D printing. Hollow shaped parts are widely used, not only because of the material savings, but also because of its advantages in thermal insulation and sound absorbing. [7] In addition, the hollow structure provides sufficient space for steel bars or other reinforcement materials.

Daungwilailuk et al. [8] conducted uniaxial loading tests on hollow walls with internal trusses, and the results showed that the internal trusses of flat walls had a supporting effect, reducing bending and preventing buckling failure. In order to study the mechanical properties of hollow structures, Wang et al. [9] compared and analyzed different structural samples through compression tests and four point bending tests. The results indicate that the bending performance of the truss prism structure is significantly better than that of other structures.

### 4.2 Tree Structure

The tree structure simulates the growth form of trees in nature, combining the vertical and horizontal parts to form a unique structural form. The size of this structural form is closely related to the pressure it bears, similar to a variable cross-section cantilever structure. Due to the complexity of its construction, it is not commonly seen in traditional architectural design, but the emergence of 3D printing technology has provided possibilities for its widespread application in architecture. Burger et al. [10] proposed a new construction process, known as "Eggsell," which combines melt deposition with synchronous concrete pouring. Compared with other processes, the concrete printing process of this method does not affect the embedding of steel bars.

### 4.3 Arch Structure

In traditional structures, due to the low tensile strength of concrete, cracks are prone to occur in horizontal areas. Arched structures enhance the load-bearing capacity of the structure and reduce tensile stress and bending moment by converting some vertical loads into horizontal forces, which can effectively improve this defect. Due to the fact that 3D printed concrete does not require the use of templates, it provides more possibilities for the application of arch structures. Lim et al. [11] developed an unconventional additive manufacturing method - surface layer printing technology, and applied it to large-scale construction. Prior to this, although many scholars had studied the curved layered melt deposition model, there were few practical applications. They used the commonly used Grasshopper by architects as a single development environment to generate curved layered printing paths. The results indicate that compared with existing flat printing paths, this method has three advantages for large-scale construction applications: better surface quality, shorter printing time, and higher surface strength. Researchers optimized the 3D printing structure design and parameters of the arch beam based on stress distribution. The experimental results indicate that arched structures can exhibit superior bending resistance.

## 5 Limitations of 3D Printing Concrete Structure Reinforcement

Although 3D-printed concrete technology offers possibilities for various new components and structural forms, the performance of these components currently remains inadequate, particularly in terms of tensile strength. Concrete, by nature, is a quasi-brittle material with relatively low tensile strength. Therefore, effectively reinforcing 3D-printed concrete structures has become an urgent problem to solve. However, due to the layer-by-layer manufacturing method employed by 3D printing technology, traditional methods of steel reinforcement binding and embedding cannot be directly applied.Therefore, many reinforcement methods are proposed for 3D printed concrete.The tensile strength of 3D printed concrete materials is insufficient and the printing process is limited, so reinforcement technology is used to address these issues. Steel bars, fibers, composite materials, and waste materials are used to enhance the performance of 3D printed concrete, making it meet higher performance requirements. Maurya et al. [12]embedded flexible steel cables in the extruded interlayer, and compared the flexural strength of 3D printed concrete with steel cables with diameters of 1.0 and 1.5 mm. They found that the flexural strength increased with the increase of the diameter of the embedded steel cables.Domenico et al. [13]enhances 3D printed concrete by introducing different fibers, which can work together to suppress the development of cracks when the concrete is under stress, thereby effectively improving the performance of 3D printed concrete.

## 6 Conclusion

In summary, 3D printing technology has made significant progress in engineering applications. The combination of 3D computer modeling and intangible architecture can, theoretically, realize various complex curved surface shapes, breaking through the constraints of traditional construction technologies. However, due to the generally poor mechanical properties of 3D-printed concrete components, limited methods of reinforcement, and high production equipment costs, their actual production and application have been hindered.

## References

1. Khoshnevis B. (1998) Innovative rapid prototyping process makes large sized, smooth surfaced complex shapes in a wide variety of materials. Materials Technology; 13:53-56. 10.1080/10667857.1998.11752766
2. Xiao J, Liu H, Ding T. (2020) Finite element analysis on the anisotropic behavior of 3D printed concrete under compression and flexure. Additive Manufacturing; 10.1016/j.addma.2020.101712
3. Le TT, Austin SA, Lim S et al. (2012) Hardened properties of high-performance printing concrete. Cement and Concrete Research; 42:558-566. 10.1016/j.cemconres.2011.12.003

4. Asprone,Domenico,Auricchio,et al.(2018) 3D printing of reinforced concrete elements: Technology and design approach.Construction & Building Materials；48(08)218-231.10.1016/j.conbuildmat.2018.01.018
5. du Plessis A, Babafemi AJ, Paul SC et al. (2021) Biomimicry for 3D concrete printing: A review and perspective. Additive Manufacturing; 38. 10.1016/j.addma.2020.101823
6. Ha NS, Lu G. (2020) A review of recent research on bio-inspired structures and materials for energy absorption applications. Composites Part B: Engineering; 181. 10.1016/j.compositesb.2019.107496
7. Oliveira RG, Rodrigues JPC, Miguel Pereira J et al. (2021) Experimental and numerical analysis on the structural fire behaviour of three-cell hollowed concrete masonry walls. Engineering Structures; 228. 10.1016/j.engstruct.2020.111439
8. Daungwilailuk T, Pheinsusom P, Pansuk W. (2021) Uniaxial load testing of large-scale 3D-printed concrete wall and finite-element model analysis. Construction and Building Materials; 275. 10.1016/j.conbuildmat.2020.122039
9. Wang L, Jiang HL, Li ZJ et al. (2020) Mechanical behaviors of 3D printed lightweight concrete structure with hollow section. Archives of Civil and Mechanical Engineering; 20. 10.1007/s43452-020-00017-1
10. Burger J, Lloret-Fritschi E, Scotto F et al. (2020) Eggshell: Ultra-Thin Three-Dimensional Printed Formwork for Concrete Structures. 3d Printing and Additive Manufacturing; 7:48-59. 10.1089/3dp.2019.0197
11. Lim S, Buswell RA, Valentine PJ et al. (2016) Modelling curved-layered printing paths for fabricating large-scale construction components. Additive Manufacturing; 12:216-230. 10.1016/j.addma.2016.06.004
12. Maurya S , Dey D , Panda B ,et al. (2023) Inline reinforcement of steel cable in 3D concrete printing.Materials Today: Proceedings;133:1-6. 10.1016/j.matpr.2023.04.092.
13. Domenico A , Costantino M , Bos F P ,et al.(2018) Rethinking reinforcement for digital fabrication with concrete.Cement and Concrete Research;112:111-121.10.1016/j.cemconres.2018.05.020.