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The Application of 3D Printing Formwork Technology in Concrete Building Materials

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Abstract: - Concrete 3D printing technology is a prime example of contemporary digital manufacturing, showcasing its efficiency and automation in the realm of construction. Compared to traditional construction methods, the characteristics of labor-saving and formwork-free in 3D printing technology have brought changes to the construction personnel structure and forming process. Enhancing the flexibility of concrete materials and 3D printing technology are two major areas of concentration, along with promoting the wider application of 3D printing in the construction industry. An extensive review of the advancements in concrete 3D printing technology is given in this paper. The mechanical, printable, buildable, and rheological properties of concrete materials that are suitable for 3D printing are also discussed. The study also shows how 3D printing formwork technology is frequently used in decorative elements and atypically shaped projects. The goal is to offer informative analysis and practical tools for further research and advancements in 3D printed concrete technology. The study's overall findings emphasize how important it is to improve 3D printing technology's compatibility with concrete materials. By tackling essential performance criteria and exploring creative uses, we can unlock the complete potential of concrete 3D printing, which will result in notable progress within the construction sector.

Keywords: Concrete, Rheological Property, 3D Printing, 3D Printing Formwork, Concrete Building Materials.

I. INTRODUCTION

Since its invention, cement-based materials have become the most widely used building materials due to their superior properties, and continue to evolve with the development of the times [1]. With the progress of technology, society is gradually welcoming the thriving development of digital construction and smart construction. As a typical area of rapid prototyping, 3D printing has become an important production technology guiding the third industrial revolution [2], establishing a new path in architecture with success and encouraging the building sector to keep moving forward in the direction of automation, digitalization, and green ecology[3].

While additive manufacturing decreases waste generated during production, smart use of 3D printing technology in the building industry might boost traditional construction's level of automation, boost productivity, and free up labor force.[4]. Concrete 3D printing is an important component of architectural 3D printing. As research continues to develop, material rheology, extrudability, buildability, setting time, and mechanical properties have become the general consensus for evaluating concrete 3D printing material performance [5]. Furthermore, considering the concept of material molding, concrete is a typical molding material, and 3D printing is a new type of "demolding" additive manufacturing technology [6], which can replace formwork of special-shaped components. Consequently, creating bespoke 3D-printed formworks for building is one of the finest uses of 3D printing technology in the field of construction engineering.

Under the era background of promoting green construction and intelligent construction, concrete 3D printing technology has a good application prospect and huge potential development space. The history of the advancement of concrete 3D printing technology is first covered in this article. The next two main topics discussed are the design and use of 3D-printed concrete materials and the utilization of 3D printed formwork technology. This extensive analysis aims to offer a priceless resource for the research and development of 3D printing in architecture.

II. 3D PRINTING TECHNOLOGY

By layering materials, 3D printing technology uses digital control to turn a digital model into a tangible object. Towards the end of the 20th century, this idea independently developed in Japan and the United States. Following this, the United States witnessed the establishment of the world's inaugural 3D printing equipment firm, "3D Systems." This company embarked on comprehensive technical investigations, offering valuable insights for the broader exploration of 3D printing technology, thus initiating a phase of rapid advancement in 3D printing technology.

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Construction 3D printing originated from Pegna's [7], proposed method of constructing shaped components based on layer-by-layer addition of cement-based materials. With the continuous development of related technologies, construction 3D printing has gradually formed three main construction methods: contour process [8], D-Shape adhesive settlement molding process [9], and "concrete printing" technology [10]. The construction sector will undergo revolutionary changes as a result of the continuous 3D printing of concrete, which will have a substantial influence on cost reduction, energy efficiency, and design optimization. Meanwhile, a strong basis for the advancement of building 3D printing has been established by the maturity of printing material preparation technology and the intelligentization of printing equipment [11].

III. Technological Development of 3D Printing in the Construction Industry

A. *Research on the Characteristics of Concrete 3D Printing Materials*

The foundation of construction 3D printing lies in dependable printing materials, playing a pivotal role in enabling the harmonious integration of feeding systems, fabric systems, and printing path control systems within the 3D printing construction process. Extensive study has been conducted on the rheology, extrudability, constructability, and mechanical characteristics of concrete materials in order to suit the demands of construction 3D printing technology. [12].

One of the secrets of printed concrete is good rheology. As soon as water is added to concrete components, they begin to hydrate and solidify. While the extruded layer must offer strength support for the successive printing layers in the formwork-free layer stacking construction method, the printing process necessitates that concrete materials maintain good workability for a specific amount of time.[13]. According to the findings of Roussel and colleagues, their research indicates that cementitious materials exhibit rheological behavior similar to that of a Bingham fluid when undergoing the printing process. In this context, the material will flow solely when subjected to an applied stress surpassing the critical yield stress threshold. They underscore the significance of an adequate yield stress, which serves as a defining characteristic setting 3D printed concrete materials apart from conventional concrete. Furthermore, researchers manipulate the thixotropy of concrete by adding mineral admixtures, nano powders, and other materials with a higher specific surface area. This enables them to modify the paste's yield stress, thereby attaining the preferred rheological characteristics of the mixture. In addition to material proportions, researchers have also utilized techniques such as adjusting the water-cement ratio and incorporating chemical admixtures to attain good rheological performance in concrete, as reported in previous studies.

Extrudability in the context of 3D printing concrete is commonly understood to be the capacity to convey new concrete in a continuous, lengthy thread to the extruder hopper's nozzle and deposit it smoothly via the print head nozzle [14]. Concrete 3D printing is a coordinated process of multiple systems, requiring coordination between materials and machinery. For this reason, researchers have extensively explored factors affecting the coordination of the concrete 3D printing process, such as aggregate particle size [15] and printing rate [16].In traditional concrete compositions, aggregate occupies the majority of the volume. However, from a materials science perspective, it is not difficult to conclude that larger aggregate particle size and higher content will increase the dispersion of printed concrete, thus reducing the controllability of material extrusion. Sufficient amount of slurry will enhance the lubricity of concrete in the printer [17], but increasing the amount of binder material or reducing the aggregate particle size in printed concrete will not only increase the printing cost but also increase the risk of matrix cracking.Malaeb et al. [18] found that when the maximum particle size (D_{max}) of the aggregate in the printing material is less than 1/10 of the nozzle diameter, the printing material can be smoothly extruded through the nozzle. Subsequently, Cheikh et al. [19] combined numerical simulation with experimental operations to systematically investigate the collaboration between slurry rheology, aggregate size, and printer nozzle diameter.Studies have shown that there is a proportional coefficient between the aggregate particle size and the printing nozzle diameter, which enables concrete to have good adaptability to the printer and achieve satisfactory extrusion and printing results.Nerella et al. [20] quantitatively characterized the extrudability of materials by defining a unit energy, which is the energy consumed per unit volume extruded. They found that the extrusion energy for finer sand was 1.62 times higher than coarser sand. In addition to material properties, research has shown that the matching degree between the extrusion rate of the printing head and the movement rate of the printing head during the printing process is critical in influencing the continuity, matrix density, and shape stability of the printed material [21].

If the stages of construction 3D printing are divided, rheology and extrudability are the basic foundations of early technology, while buildability and mechanical properties will be the practical test of this technology.People have carried out several exploratory research on the constructability of printed materials in accordance with the requirements for defining buildability, but the standards and testing protocols for assessing the buildability of 3D printing materials are still in the early stages of development [22]. And they summarized typical construction failure modes, such as single-layer deformation yield failure, bottom-layer deformation failure, uneven interlayer shape, and instability at supercritical heights [23]. Figure 1 is atypical form of extrusion breakage and different failure patterns.

Figure 1: Typical Forms of Extrusion Breakage and Different Failure Patterns

Perrot and colleagues established a criterion for evaluating structural strength failure. They compared the critical stress responsible for initiating plastic deformation in early-age concrete printing materials to the vertical stress acting on the previously printed layer. Through practical printing outcomes, they verified that, with a reasonable construction pace and a robust structural foundation, it is feasible to ensure that the vertical stress remains below the critical stress threshold, ensuring a stable and dependable construction result.

In a similar vein, Kazemian and associates devised two assessment methods, namely "layer settlement" and "cylinder stability," with a focus on measuring variations in height to evaluate the structural integrity. Their objective was to quantitatively characterize the constructability of concrete materials. Figure 2 shows the experimental setup for these tests. Yuan et al. also considering the deformation of building materials, evaluated the constructability of concrete 3D printing materials by monitoring the deformation between each printed layer during the stacking process.

Figure 2: Cylinder Stability Test

With the deepening of research, it has been discovered that optimizing particle gradation can achieve coordination between material extrusion and material construction. At the same time, good gradation also provides assurance for the post-service performance of printed components. Weng et al. compared the effects of FullerThompson gradation, uniform gradation, Gap-Gradations gradation, and natural river sand gradation on the extrudability and constructability through printing cylindrical layers. Figure 3 shows the experimental process. The results showed that materials based on FullerThompson gradation exhibited the best performance, allowing printing of up to 40 layers without collapsing or deforming. This proves that Fuller Thompson gradation is an effective method for preparing cement-based materials with good constructability for 3D printing.

Currently, many achievements have been made in the research of constructability. However, factors such as the printing window period, printing regime [24], cycle time between layers , and physical and chemical reactions of materials are all important factors that affect the constructability of 3D printed concrete in construction.

Therefore, continuous exploration and accumulation are still needed to obtain scientific and standardized testing methods and specific evaluation criteria.

Reliable printing materials are the cornerstone of construction 3D printing; they are essential to the smooth operation of feeding systems, fabric systems, and printing path control systems in the 3D printing construction process. Among them, the early mechanical properties are closely related to the buildability of concrete 3D printing materials. The characteristics of formwork-free construction make early-age mechanical properties particularly critical. Therefore, extensive research has been conducted on the early-age strength, stiffness, stress-strain curve, deformation characteristics, and other aspects of concrete printing materials [25]. Wolfs et al. used mathematical modeling to develop a consistent failure criterion for early-stage 3D printed concrete. Through actual testing that included direct shear tests and uniaxial compression, they were able to verify the model's efficacy. The study found that during the first 0 to 90 minutes after 3D printing, the concrete's Young's modulus, compressive strength, and shear strength all exhibited a direct relationship with time, rising in direct proportion to the concrete's freshness. The Tongji University team systematically conducted experiments on the mechanical attributes of freshly printed 3D mortar using unconfined compression tests. Additionally, they conducted a thorough examination of the 3D printed mortar's early-stage stress-strain characteristics, vertical load-displacement relationship, lateral deformation, and failure mode after 2.5 hours. This offers a wealth of reference material for investigating the mechanical characteristics of concrete 3D printing materials in early life.

(a) (b) (c)

Figure 3: A Method for Evaluating Print Material Buildability by Printing Layer Height

In contrast to conventional concrete structures, 3D printed concrete structures have anisotropic mechanical characteristics due to the stacking of layers that produces a high number of interface structures[26]. During experimental investigations, it has been found that a key factor affecting the strength anisotropy is weak interface bonding. Researchers have conducted a series of explorations from the perspectives of printing regime and printing materials to address this issue. In terms of printing parameters, researchers have found that the printing time interval significantly affects the interface. Longer printing time intervals can result in "cold joints" and more defects, leading to poor interlayer bonding [27]. Panda and colleagues introduced the concept of a "window period" as an optimal printing interval, which they employed to assess the effect of time intervals on bond strength. Their findings indicated that when the printing occurs within this window period, the interface exhibits superior performance. Beyond just printing parameters, Nerella and associates examined how the presence of volcanic ash minerals influences the interface in relation to printing time intervals. They observed that volcanic ash minerals could mitigate the impact of printing timing on interlayer bonding at the interface. Currently, one method to enhance the bonding at interlayer interfaces in 3D printed materials involves the use of admixtures. Another common method, as shown in Figure 4, is to add additional layers at the interface to optimize the interface effect.

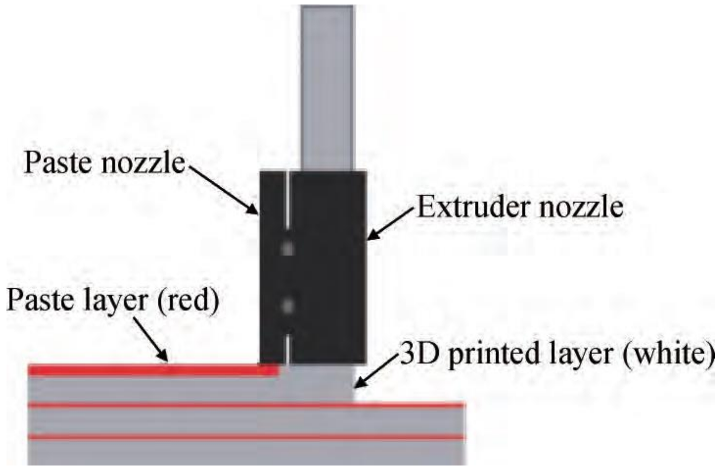


Figure 4: A Form of Printing with an Intermediate Bonding Layer

Construction 3D printing technology, as an important manifestation of intelligent construction, is always moving forward in development despite facing huge challenges in complex material and structural design. At present, the commonly used construction 3D printing material is cement mortar, which is prone to cracking in actual applications. To improve the status quo and meet the 3D printing construction of large buildings, large particle size aggregate 3D printing concrete and 3D printing fiber-reinforced concrete are researched and applied.

Ma et al. prepared interface materials using cellulose fibers and limestone as fillers. They conducted interlayer tensile strength tests, shear bond strength tests (as shown in Figure 5), and microscopic experiments to verify that the added water-retaining components can reduce early shrinkage caused by water loss and achieve good internal curing effects, thereby enhancing interface performance. At present, while there are numerous methods to enhance the mechanical characteristics of construction 3D printing materials, research in the realm of interfacial bond strength, mechanical properties, durability, and their interconnected aspects remains relatively scarce. Moreover, there is a lack of standardized evaluation methods, especially regarding standardized procedures or protocols for early-age compression conditions. Establishing a more systematic experimental exploration and a scientific standard system will provide better support for construction 3D printing.

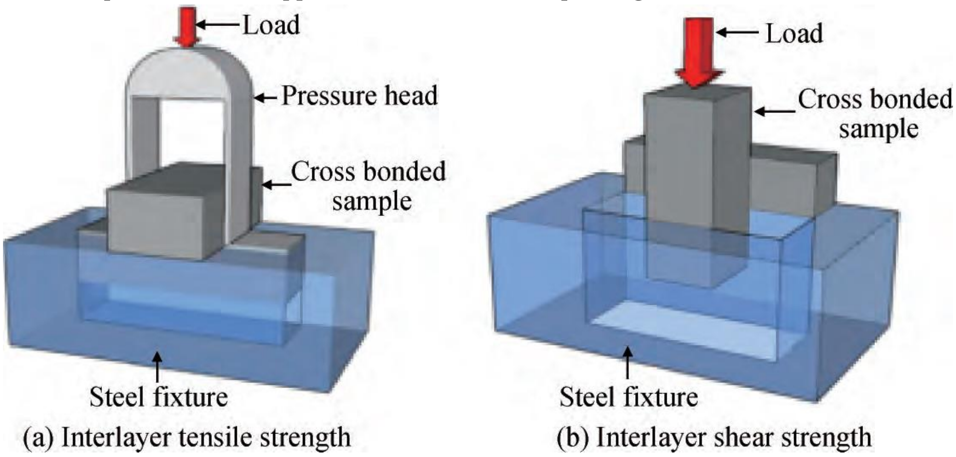


Figure 5: Schematic Illustration of Test Setup for Interfacial Mechanics

As an important manifestation of intelligent construction, architectural 3D printing technology continues to advance despite facing significant challenges in complex material and structural design. Cement mortar is commonly used as a construction 3D printing material but is prone to cracking in practical applications. To address this difficulty and meet the needs of large-scale architectural 3D printing construction, research has been done on materials such as fiber-reinforced 3D printed concrete and large-aggregate 3D printed concrete.Moreover, in the context of green and ecological development, the material system in architectural 3D printing is constantly being enriched and innovated. Various types of mineral admixtures, geopolymer materials, desert sand, tailings [28], and others can be used as excellent architectural 3D printing materials. On the other hand, materials such as engineered cementitious composites (ECC), ultra-high-performance concrete (UHPC), and novel composite additives have also been applied in architectural 3D printing technology to enhance overall performance and contribute to the flourishing development of future architecture.

B. Development of Concrete 3D Printing in Construction Technology

The applications of 3D printing technology in the construction sector are growing as it advances. Due to the great degree of creative flexibility offered by 3D printing, a diverse range of beautiful landscapes and architectural miniatures were produced in the early stages of the technology's development. With the advancement of technology and the maturity of material design, 3D printed structures have evolved from purely artistic creations to innovative buildings that combine both artistic and practical value. Figure 6 shows an example of 3D printed concrete. As shown in Figure 6, during the gradual development and deepening of architectural 3D printing, researchers have added reinforcement and poured concrete into the printed hollow walls to accommodate the printing of large-scale architectural structures.

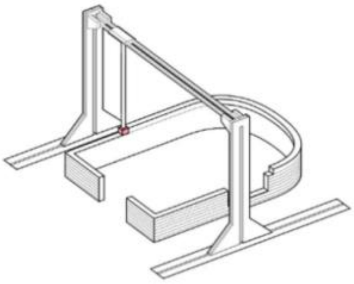


Figure 6: Examples of Concrete 3D Printing

Construction 3D printing originated overseas but has achieved a series of developments and achievements in China in recent years. Several enterprise units such as China Construction Co., Ltd. Technical Center, and Yingchuang (Shanghai) Construction Technology Co., Ltd. have carried out a large amount of exploration in the equipment, materials, and developmental applications of construction 3D printing.

Researchers are increasingly focusing on harnessing the benefits of 3D printing technology for intricate architectural component designs that are challenging to produce using conventional templates.Figure 7 shows 3D printed reinforced concrete beams and slabs, indicating that architectural 3D printing is gradually being integrated into various key structures of buildings. Simultaneously, architectural 3D printing technology encompasses the convergence of materials, programming, and mechanical equipment. To meet construction operations under different conditions, there is continuous enrichment and development of related supporting software, hardware, and other components [27].

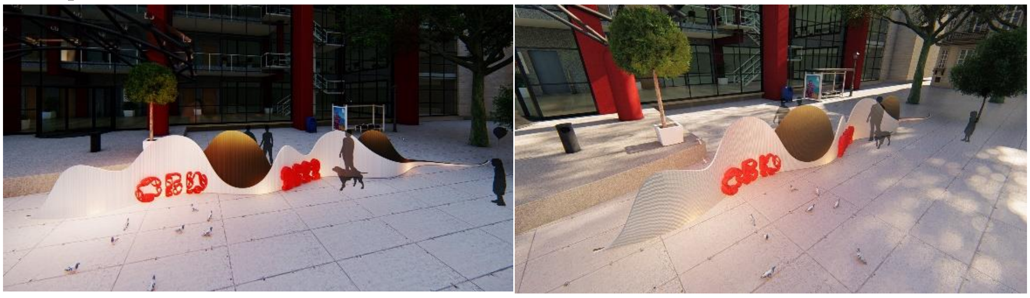


Figure 7: 3D Printing Reinforced Concrete Beams and Panel.

When compared to traditional construction methods, 3D printing technology offers noteworthy advantages, including digital construction (industrial advancement), streamlined construction (simplification), sequential construction (process simplification), expedited construction (enhanced efficiency), additive construction (waste reduction), and precise construction (improved quality). With continued progress and experience, 3D printing technology is poised for more extensive adoption within the construction industry.

IV. Application of 3D Printing Formworks in Decoration and Special-shaped Buildings

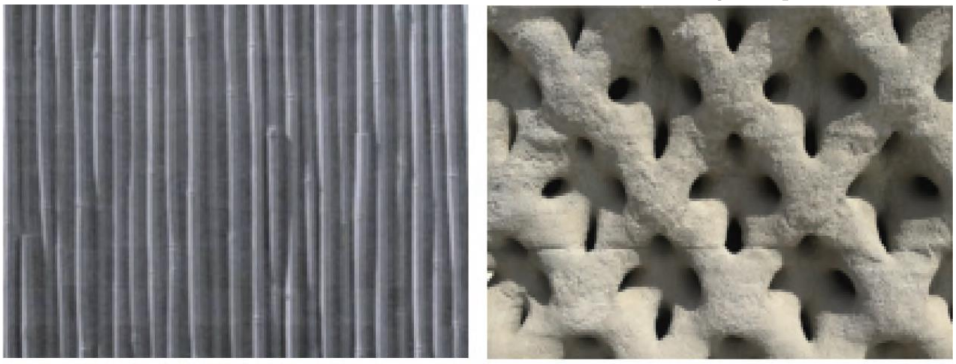
High formwork cost and massive construction waste are two major challenges faced by traditional concrete construction. Researchers have specifically studied the cost of building formworks, with results indicating that, in concrete construction projects in the Sydney CBD (Central Business District), formwork costs account for 80% of total costs. Another local survey in the UK found that garbage generated from construction and dismantling activities accounts for more than 30% of all waste in the country, with approximately 32% of landfill waste and 25% of used raw materials coming from the construction industry.

The substantial volume of construction waste not only represents a significant resource wastage but also poses the risk of environmental pollution, which contradicts the contemporary principles of eco-friendly and sustainable development. The additive manufacturing characteristic of concrete 3D printing ensures its own formwork-free construction and can serve as a permanent formwork for traditional concrete. At this time, the entire structure retains a high degree of freedom in shape design, and the additive manufacturing mode based on computer model design minimizes material waste. It's this stark advantage that has made 3D printed formworks promising in their application to architectural decoration and special-shaped building construction.

Depending on the field of application, current formwork-free 3D printing technologies in architecture can be mainly divided into four aspects.

A. 3D Decorative Modeling Formworks

Concrete materials have excellent plasticity; after hardening, their surface texture, feel, and color are closely related to the formwork, theoretically creating any shape. And 3D printing formwork technology provides good technical support for concrete architectural art. 3D decorative modeling formworks can be divided into organic material-type 3D decorative modeling formworks and inorganic material-type 3D decorative modeling formworks. As shown in Figure 8, Figures 8(a) and 8(b) are decorative panels manufactured by organic formwork demolding and direct 3D printing, respectively. Organic material-type 3D decorative modeling formworks usually have better tensile strength, tear strength, and bond strength, and they are alkali-resistant, oil-resistant, and easy to demold. At the same time, the organic material-type 3D printed decorative modeling formworks recreate clear shapes and have a higher service life. The inorganic material-type 3D decorative modeling formwork serves as a permanent formwork that exhibits excellent artistic effects while demonstrating exceptional structural use.



(a) Imitation of bamboo texture (b) Relief modeling

Figure 8: Concrete Decorative Board

The application of 3D decorative formworks to shape concrete can achieve integration of concrete structure decoration, including any shapes such as stone-like, wood-like, etc., and concrete can achieve a highly realistic effect similar to the original object. Figure 9 is a concrete 3D printing decorative formwork. 3D decorative formworks can also create large curved surfaces, hollows, and other special shapes, satisfying the specific geometric space shaping needs of concrete, thus elevating the level of concrete decorative art and beautifying architecture (as shown in Figure 9).

Figure 9: Concrete 3D Printing Decorative Formwork

B. 3D Printed Landscape Miniatures and Public Facilities

Figure 10 shows concrete 3D printing landscape pieces and public facilities. As shown in Figure 10, public facility buildings in cities have characteristics of being small and diverse; urban landscapes and cultural propaganda generally have special shapes, which may be difficult or costly to complete through customized formworks. However, concrete 3D printing technology can meet the rapid manufacturing requirements and realize the connotation requirements of designers' special shapes and cultural information. In the pursuit of creating aesthetically pleasing and people-centric cities, the utilization of 3D printing techniques can showcase innovative advancements in construction technology. This approach helps curtail the environmental pollution associated with traditional stone carving, thus fostering the growth of eco-friendly and socially conscious construction practices.

Figure 10: Concrete 3D Printing Landscape Pieces and Public Facilities

C. 3D Printed House Buildings and Building Components

Achieving 3D printing of houses and other large buildings is an important application direction for concrete 3D printing technology. Among them, direct printing of the solid wall with rebar or using 3D printed concrete to form prefabricated mold shells, and forming assembled 3D printed buildings through combination are several important concrete displays of 3D printing in architecture. Figure 11 uses 3D printed concrete to form the wall's outside in accordance with the architectural 3D model. The printed hollow structure serves as a strong formwork that makes it possible to fill the inside later with insulation or concrete.

Figure 11: Field application of Concrete 3D Printing Formwork

Large-scale construction 3D printing displays are progressively becoming more common, as Figure 12 illustrates, thanks to advancements in technology and shifting public perceptions.In addition, more and more individuals are utilizing architectural 3D printing technology in their spatial building design plans.

Figure 12 shows the first domestic two-story office building printed based on "contour process". Its extremely high construction efficiency fully demonstrates the technical advantages of architectural 3D printing.

Figure 12: 3D Printing Buildings

D. 3D Printed Bridges and Components

Concrete 3D printing has also demonstrated outstanding potential application value in bridge, municipal track, and other engineering projects.

A few concrete 3D printing application examples for bridges are shown in Figure 13. The prefabricated 3D printed mold shell is filled with concrete as part of the arch bridge construction process.

In addition, Figure 14 shows potential application forms of concrete 3D printing in special-shaped bridge piers. While satisfying structural support, the printed pier not only eliminates the cost brought by traditional formworks but also provides good artistic effects.

Figure 13: 3D Printing Bridges

Figure 14: Comparison between Traditional Bridge Pier and 3D Printing Bridge Pier

V. OUTLOOK ON CONCRETE 3D PRINTING TECHNOLOGY

Concrete 3D printing additive manufacturing and its formwork-free process characteristics significantly reduce the generation of construction waste while increasing construction efficiency, aligning well with the current direction of construction development. In addition to significantly increasing architectural design freedom and offering practical solutions for the real construction of intricate concrete structures, the widespread use of 3D printing technology can also release architectural design from the limitations imposed by conventional formwork procedures. Under the demand for development and transformation of engineering technology, architectural 3D printing will move towards a longer future. Meanwhile, architectural 3D printing technology is a multi-disciplinary cross-border integration involving architectural modeling, structural design, material optimization, system integration, etc., the complexity. The relationship between 3D printing architectural materials, structures, and performance needs to be strengthened. The core research topic is how to elevate 3D printed buildings to have the structural properties of reinforced concrete or fiberglass structures. Ensuring the seismic performance of buildings is a challenge for 3D printing architecture, materials, processes, and equipment. Only reinforced concrete structures can effectively guarantee the seismic performance of buildings. At the same time, based on clarifying the direction of development, the stability of printing materials, the innovativeness of process equipment, and the normalization of standard system construction are still the important directions that need attention in the future.

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