

Application of 3D Printing Technology in the Construction Industry and Its Development Prospects

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ABSTRACT

The success of rapid industrialization around the world may be due to automated processes leading to faster and cheaper production methods. Over the past three decades, the method of mixing and pouring concrete on site has been gradually replaced by prefabricated construction techniques in some developed countries. The construction industry benefits from advanced technology, which also reduces labor requirements and construction time, saves costs, and improves project quality and reduces environmental impact. The article presents the current status of 3D printing research applications in the construction industry and provides an outlook and plan for its development.

Keywords: Construction Industry, 3d Printing, Application Status, Development Prospects

1. INTRODUCTION

The concept of 3D printing technology was first proposed and successfully patented by Professor Emanuel Sachs at MIT in 1989, and in the 1990s, Professor Charles developed and completed an additive manufacturing system capable of producing parts, which was an important milestone in the 3D printing development process [1]. 3D printing technology is based on a digital model, and through the use of automatic computer control technology, 3D solids are printed layer by layer with materials to achieve rapid prototyping. This technology is also known as "additive manufacturing". Additive manufacturing has technical features such as rapid free-forming without molds, full digitalization, and high flexibility. This technology can produce geometries of nearly infinite complexity and can be applied to the manufacture of most material types. In simple terms, 3D printing is the final manufacturing of three-dimensional physical objects by means of layered processing and overlay molding, without the need for the original embryo and mold.

2. 3D PRINTING BACKGROUND AND ITS ADVANTAGES

3D printing technology and industry is a strategic emerging industry leading the future innovation and development of manufacturing, which also includes the construction industry. At the same time, it is of great significance to the upgrading of the construction industry. 3D printing technology is also known as rapid prototyping technology, which is based on 3D data, based on the principle of point, line and surface cascading molding, it improves the traditional

construction process there are more difficulties. The concept of 3D printing technology first originated in the USA with the hope that the technology could change traditional manufacturing processes and facilitate social transformation. 3D printing technology has become the focus of attention around the world. The world-renowned magazine "The Economist" once mentioned that 3D printing technology will lead to the third industrial revolution [2]. 3D printing is a promising technology for buildings. Compared with traditional buildings, 3D building printing can save 50%-75% of the time cost, 50%-80% of the labor cost and 30%-60% of the material cost. According to experts' estimation, 3D building printing can save 30%-50% of the total cost.

The National Science and Technology Major Project and the National Natural Science Foundation of China (NSFC) have provided substantial financial and personnel investment in order to vigorously develop and promote 3D printing technology. In 2015, the state ministry of officially released for the first 3D printing special propulsion plan to increase material manufacturing industry development plan, it points out: encourage enterprises engaged in 3D with materials production advantage to print special material research and development and production work, for the aerospace, biomedical and other fields of major requirements, development of special 3D printing materials. 3D printing technology has the characteristics of high degree of automation and short industrial process, which is very consistent with China's current policy to reduce carbon emissions. The application of 3D printing technology plays a crucial role in China's greening and informatization construction.

At present, the advantage of China's demographic dividend is gradually disappearing, and the construction industry is changing from the labor-intensive industry to the technology-intensive industry. China's construction industry is now facing the dilemma of "labor panic", and not long ago, the state explicitly prohibited workers over 60 years old from engaging in manual construction

labor. The continuous development and improvement of 3D printing technology has provided an effective solution to this difficult problem. Compared with traditional construction methods, the application of 3D printing technology in the construction industry has obvious advantages, as shown in Table 1.

Table 1. Advantages of 3D printing technology in construction

Advantage	Expound
Resource conservation	<p>①Materials: 3D printed buildings can be formed in one time without supporting and removing molds, which reduces the waste of concrete materials and improve the utilization rate of materials.</p> <p>②Construction period: Compared with the traditional construction technology, 3D printing technology greatly improves the production efficiency, which can reduce the construction period by 50% and shorten the payback period of investment.</p>
Green environmental protection	The printing process produces little noise, dust and strong vibrations.
Accuracy	According to the preset computer program, layer by layer construction, to a large extent to avoid human error, to ensure the quality of the finished product.
Immediacy	3D printing can be done according to different requirements, thus reducing inventory, and can also be formed once, without assembly, realizing immediacy from printing to delivery.
Applicable to extreme conditions	Extreme conditions refer to the environment in which traditional manufacturing techniques are no longer applicable and external conditions make people's activities difficult, such as weightlessness or extreme cold. In some special cases, 3D printing technology can replace manual construction.

3. CURRENT 3D CONCRETE PRINTING SYSTEM

3D concrete printing technology is based on modeling, using a special printer to spray material, and then continuously increase the material layer by layer printing. 3D printing technology is mainly divided into three categories: contour technology, D-shape and concrete printing. 3D printing technology mainly includes modeling, segmentation, printing, spraying and post-processing.

3.1 Brief Introduction to 3D Concrete Printer

From the point of view of the situation, there are three main types of 3D concrete printers available. As shown in Figure 3, they are gantry system, robot system and crane system, and there have been excellent cases of using these printers. Gantry is a typical crane, as shown in Figure 1(a). As shown in Figure 3(a), the gantry is a very common crane, and its height is generally fixed. However, the crane system shown in Figure 3(c), which is adjustable in the vertical direction, offers some flexibility. Gantry printers and crane printers are usually used because they are easily scalable in size. In contrast to these two printers, robot printers usually have a fixed

size, which makes it difficult to go to scale. Therefore, the relative advantage of a 6-axis robot allows it to do tasks that a 4-axis gantry printer cannot do. In addition, gantry printers are superior to robotic printers if the design of the print target is not complex. This is because the robot costs more and the load on the robot arm is usually lower than that of a gantry printer. Figure 1(a) shows a four-axis gantry system with adjustable printing envelope, it is reported that Wen Sun has built many houses by using this technology (gantry printer). The printing method is similar to that of inner and outer beads in a layered manner, and honeycomb-like internal structures (Fig1(c)). In some cases, during printing, steel bars are manually placed between layers. The mixture of concrete materials used by Wensun contains fiberglass, steel, cement, hardener and recycled construction waste. However, Wen Sun built many houses are not completely 3D printed. The structural elements are segmented in the factory and then shipped to the site for assembly [4]. In the current research, 3D printed concrete technology is mainly applied to build low-rise buildings. For high-rise buildings with complex structures, currently only prefabricated parts can be printed one after another and then finally encapsulated according to the assembly principle, thus losing the advantage of 3D printing itself for rapid prototyping.

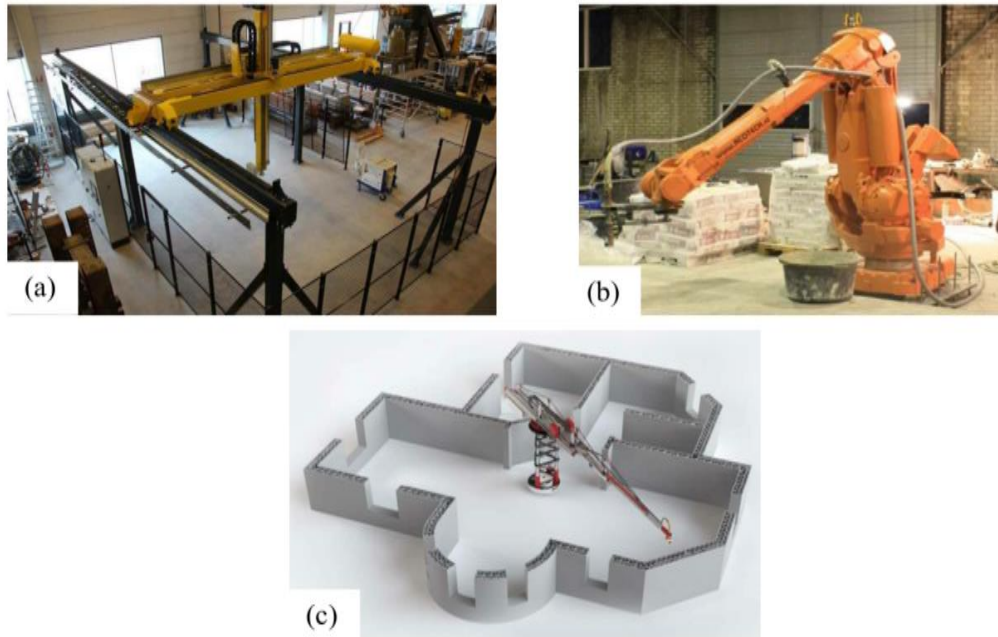


Figure 1. Current 3D concrete printer (a) 4 axis gantry printer (b) 6 axis robot (c) crane printer

Another company that uses inner and outer beads to print in a layered way is the Seby Additives Industry Company, founded in the Netherlands. They printed a mortar to reach an acceptable strength in 5 minutes. Some researchers have experimented by attaching the print head to an imprecise 6-axis manipulator (Fig 1(b)), which takes into account the diversity of printer speeds and heights. The additional rotational axis of the robot on the gantry printer gives the designer more freedom to design complex shapes. With a diameter of up to 6 meters, this robotic printer is capable of printing larger components in a short period of time. A Russian company has developed a crane-type printer (Figure 1(c)) capable of printing large areas of up to 58 m², which has almost no height limitation [5].

3.2 Pumping and control system

The pumping of concrete material is important in 3D concrete printing system because of its need for fast delivery and the inability to separate particles. The pump must be able to convey the concrete material with the specified requirements, which is a challenge. This is because of the large size of the aggregate particles and the wide range of w/c. Freshly mixed concrete needs to retain its shape even after printing to ensure its high viscosity, which requires relatively high pumping pressures, in the range of 1 to 4 MPa. The mixing of concrete materials needs to be adjusted to avoid segregation under these pumping pressures and to form a thin coating layer for good pumpability. The separation during high pressure pumping may lead to the loss of the smear layer and lead to material blockage in the pipeline. For better printing, a balance is needed between the feed system, nozzle and material

characteristics. The pump speed needs to be adjusted according to the size and shape of the print object. When the angle of the printing path changes, the deposition of materials should be controlled to avoid higher material deposition. Print heads (nozzles) can usually change direction fairly quickly. However, the perfection of geometry requires a reduction in pump speed at particularly sharp curves or discontinuities. Therefore, it requires a proper control system to adjust the speed of the printer to accomplish the job of nozzle rotation and pumping the material.

4. 3D CONCRETE PRINTING CONSTRUCTION TECHNOLOGY AND MATERIALS

Dry mortar is commonly used as printer "ink" in 3D printed buildings. The material requirements of 3D printing construction dry-mix mortar are similar to those of printing concrete, both of which require it to have good plasticity and other properties. Its performance requirements are very strict. Dry mixing mortar is cement, sand, mineral admixture and functional additives according to the relevant proportion, by professional manufacturers in the dry state of well-proportioned mixing, mixing into a granular or powdery mixture. The next is to dry mixed mortar with dry powder packaging or bulk transported to the site, according to the provisions of the ratio of water mixing can be directly used. Dry-mixed mortar is favored by engineering circles because of its convenience, flexibility and other excellent properties, and has been more and more widely used in recent years.

4.1 3D Concrete Printing Construction Process

The construction process of 3D concrete printing is mainly divided into 5 steps. It is concrete mix

proportion design, concrete preparation, concrete transportation, cloth printing molding and finished product maintenance these steps. Figure 2 shows the steps of 3D concrete printing.

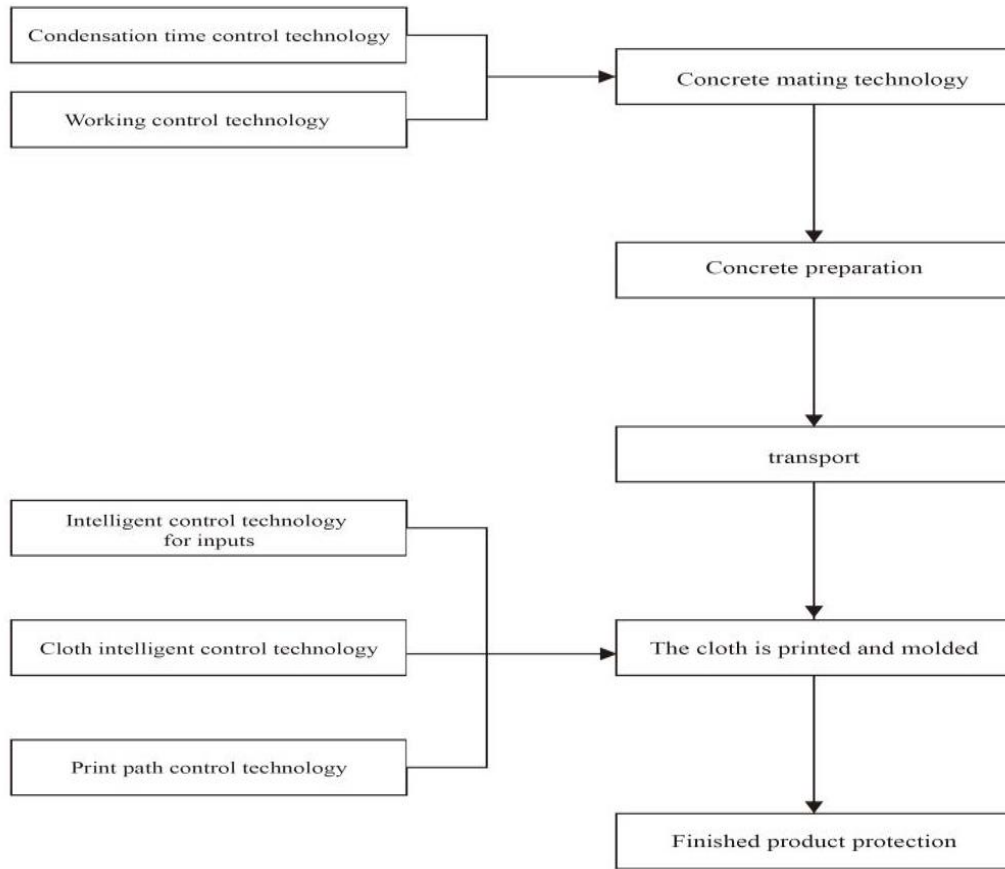


Figure 2. Steps of 3D concrete printing

4.2 Building Materials

Building 3D printing technology for concrete materials can be divided into: working performance, mechanical performance and durability. Among them, the working performance can be divided into extrudability, bonding ability, molding ability, setting time and printing strength control. The first step in preparing materials that can be 3D-printed is to select constituent materials, namely raw materials. The raw materials of 3D printed concrete studied by scholars at home and abroad mainly include cement, fly ash, silica fume, limestone powder, metakaolin, fine sand, nano silicon, superplasticizer, retarder, early strength agent, viscosity modifier, water and different kinds of fibers. Among them, cement in addition to the most widely used ordinary Portland cement, there are sulfur aluminate cement and so on. 3D printing is very demanding and requires concrete with excellent durability. In order to ensure durability, the material's resistance to seepage and frost must be taken into account. In general, the use of admixture-doped concrete or high-quality cement as the base layer of 3D printed products ensures a certain degree of insulation

and impermeability, but the actual printed concrete products are brittle and prone to fracture [6]. Therefore, for 3D concrete printing technology to make a breakthrough, this requires concrete materials with excellent printing performance, structural performance and hardening performance.

Since no support formwork was used in the printing of 3D concrete, so ordinary concrete could not be used. To ensure little or essentially no deformation of the mat, concrete with up to zero slump needs to be used, as shown in Figure 3. To facilitate pumping, low-viscosity concrete can be used, which requires intervention by adding a chemical accelerator at the nozzle for fast setting after printing. The production of low-slump concrete requires special attention to the granularity characteristics of fine particles. In this respect, the particle shape has great influence on the compacting performance and the strength of the green. Thixotropic properties are ideal, so materials with high static viscosity can undergo microstructural changes and become less viscous by removing flocculation during agitation or stress. But once squeezed out and stopped, it reforms or re-flocculates and becomes highly viscous. Thixotropic materials subjected to rheological testing

require a higher torque (static torque) to flow when they are at rest. Over time, the torque required for a specific angular velocity in rheological testing decreases, which is referred to as dynamic torque. We can learn from the experience of previous concrete applications where

water/binder ratios (w/b) and chemical additives were successfully used to adjust flocculation processes or microstructure thinning (anti-flocculation) and reconstruction (re-flocculation) depending on the aggregate gradation [8].



Figure 3. Slump-free 3D printable concrete

4.3 Support Materials

Many people think that 3D printing should be automatic. As soon as you press a button, the building is automatically printed. But the reality is not so, from the printer out of the print often have to go through a variety of surface treatment before it can be used. The most important step in these steps is the treatment of the supporting material, which is the post-processing we mentioned earlier. 3D printing works by adding layers of cross sections together to form a three-dimensional object. This forming method has certain limitations on the shape of the object. If a top level outstanding structure object, up from one layer at the bottom of the printing, print to objects above a sudden need to print the cross section of a large, more than all the bottom of the print head at this time or in accordance with the need to print the trajectory of motion, but not after extrusion due to below materials can support its structure, material will fall under the influence of gravity. The minor consequence is the accuracy of the print, the serious consequence is to become a messy ball, which is a complete failure of the print. A similar problem occurs

when printing objects with hollow structures inside them.

The use of supporting materials is a solution to this situation. Support materials come in many forms. The most common is the use of the printing material itself, by creating a fine lattice or columnar structure under the overhanging form, so that the overhanging part of sufficient support, at the end of the printing with a file and sandpaper to remove the support structure.

5. REINFORCEMENT IN 3D CONCRETE PRINTING

To ensure better structural performance of the building, it is often necessary to add suitable reinforcement to the concrete structure. Figure 4 illustrates the previous study of SH inner and outer beads extruded by steel bars in a layered manner.

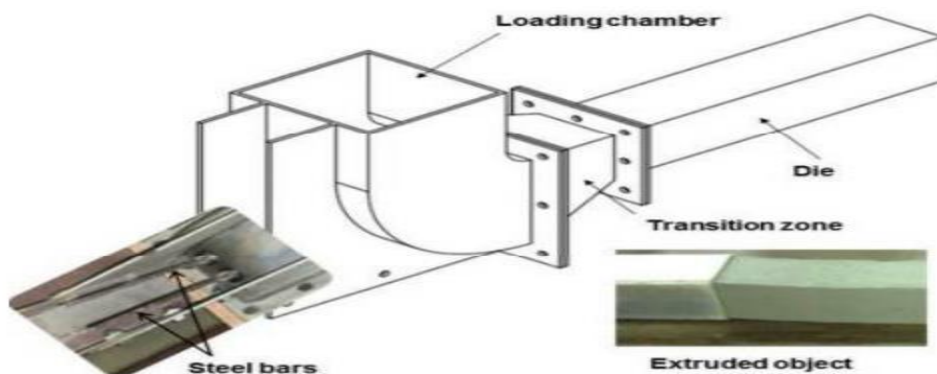


Figure 4. SH Extrusion of steel bars printed in layers with inner and outer beads

In fact, installing rebar in the 3D concrete printing process is a challenging task. Using current printing technology. The placement of vertical steel bars and the connection between steel bars are not simple. In order to strengthen the structural strength of 3D concrete printing, we can try to introduce some alternative reinforcement methods. Examples include composite fibers in mixed concrete, carbon fibers, or fiber-reinforced polymers, but this requires thorough research and innovative adaptation of 3D concrete printing technology. Preliminary studies have shown that 3D prestressed concrete can significantly increase the load-bearing capacity of structures. We can try to

develop a hybrid printing system that can respond to different needs and thus greatly enhance the structural strength. According to experiments, it is possible to manually place reinforcement bars, as shown in Figure 5, in the intermediate layers (Figure 5a), or between the fiber layers (Figure 5b and Figure 5c), or by directly extruding the concrete through the sides of the manually pre-tied reinforcement cage (Figure 5d). The elimination of this intervention allows for a basic automation of the printing process, with the advantages of geometric accuracy, reduced manufacturing time, and reduced labor costs [9].

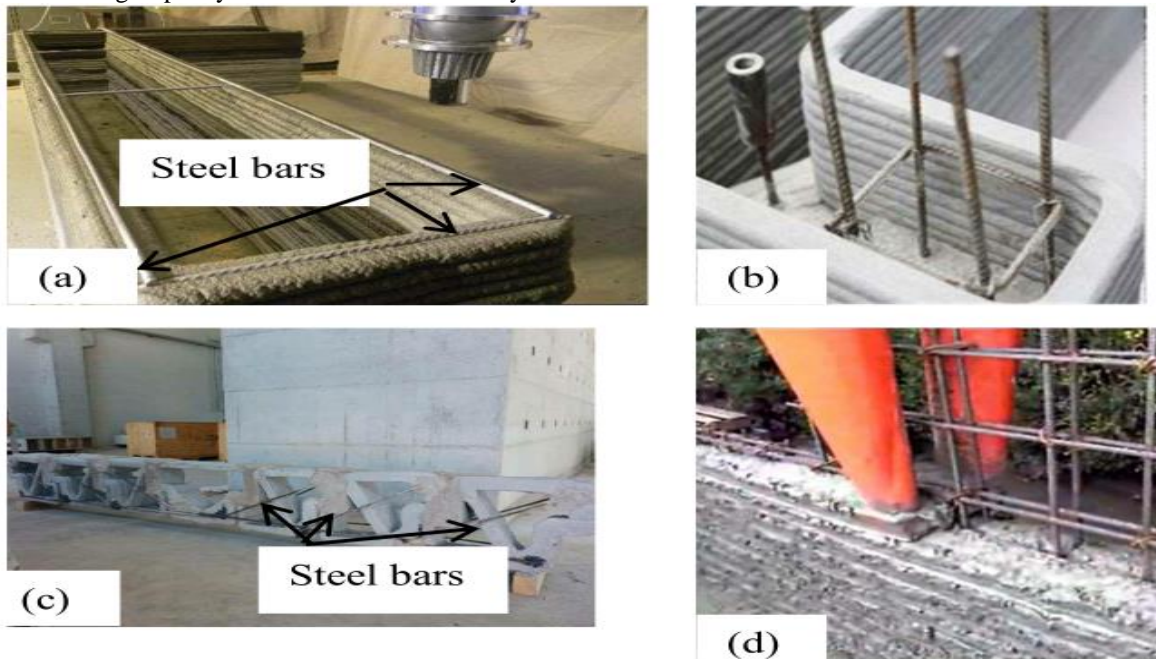


Fig 5. Steel reinforcement in 3D concrete printed buildings

In addition to these methods, researchers from Singapore are working on two other ways to install steel bars in 3D concrete printing. In the first scenario, the researchers designed a nozzle system that squeezes steel wire with the material. In this approach, the flexibility of wire reinforcement must be appropriate for the process, especially when the nozzle needs to be rotated with a geometric curve or climbed from one layer to the next. In the second method, before depositing the next layer, the hybrid printing system requires the robot to automatically inject steel fibers into the existing 3D concrete printing layers and these methods are still in the initial stage, a lot of research is needed before successful adoption in 3D Concrete Printing.

6. 3D CONCRETE PRINTING TECHNOLOGY WILL LARGELY AUTOMATE THE CONSTRUCTION INDUSTRY

3D printing technology is an important means to lead the development of future innovation in manufacturing. Furthermore, since the printer only prints where needed, contrary to the color-reducing method structure, the 3D printing principle of adding the structure can eliminate or significantly reduce the waste of materials. Concrete printing can improve current manufacturing methods by automating, thereby reducing dependence on labor and improving accuracy. However, considering these challenges, intelligent system design and advanced material development are needed to achieve environmentally friendly and affordable construction. Finally, the specific construction process may result in anisotropy, i.e. different performance in different directions. Therefore,

this standard test method for layer by layer construction is also very important.

In the case of assembled buildings, this technology has been around for many years in the construction industry. 3D concrete printing technology offers this alternative to prefabricated assemblies, which also suggests that prefabricated construction will expand from the factory to the construction site. In some areas of construction, particularly in underground buildings, the removal of formwork is both time consuming and costly. While innovative solutions have been developed for automated reinforcement with 3D concrete printing, a potential short-term application is 3D concrete printed permanent formwork. 3D concrete technology can provide an efficient automated production process for thin-walled formwork in which a reinforcement cage is placed and the internal concrete is subsequently poured in situ to form composite structural elements. Finally, each 3D concrete printing technology uses different materials and processing methods, so each has its own potential and direction for development.

7. CONCLUDING REMARKS

This paper presents the current development of 3D printing technology in the construction industry. With gantry, robot and crane systems, 3D printing technology has been successfully applied in a number of exemplary construction projects that have received extremely high ratings. Options for improving shape retention and constructability of sub-layers include developing thixotropic concrete materials or using low-viscosity concrete that can be easily pumped and then chemically treated at the nozzle to speed up its setting rate. However, limited data on the structural properties, safety and economics of the materials do not allow for an in-depth presentation. However, through the comprehensive analysis, we believe that the future direction of 3D printing technology in the construction industry are as follows:

(1) In order to achieve proper engineering design and construction, the mechanical properties of 3D of concrete printed elements must be characterized by standardized material testing.

(2) In order to overcome the quasi-brittle damage of concrete materials, reinforcement is needed. As described in this paper, manual placement of steel bars

or reinforcement assemblies provides a solution as interlayer or interline reinforcement. Rebar placement can be carried out automatically as part of the 3D concrete printing process or through other automatic equipment. A reasonable ratio of steel to concrete is important in building automation in order to provide sound design guidance for proper anchoring and reduction of reinforcement in 3D printed concrete structures and structural members.

(3) The construction industry and government departments should accept 3D prestressed concrete as a construction technology and there needs to be strict standards in terms of materials, specifications, manufacturing, testing and structural design.

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