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I. Introduction

As the technology of 3D printing is significantly changing various industries at increasingly higher speeds, China's construction industry also faces a big change. In many countries around the world, technical companies are competitively developing 3D printed buildings and have made rich achievements. The same goes for China. Especially in the recent two years, 3D printed buildings in China have been developed rapidly and vigorously. As early as in 2013, the China 3D Printing Technology Industry Alliance predicted that the size of China's 3D printing market would reach 10 billion yuan by 2016, with a year-on-year growth of 100%. This involves both considerable achievements and problems to be resolved, which are illustrated in the following paragraphs. Before reviewing examples, let's have a look at the principles of 3D printed buildings.

II. Principles of 3D Printed Buildings

3D printing is based on digital model files. 3D printers and common printers have almost the same principles and only differ in printing materials. Common printers have ink and paper as their printing materials, while 3D printers can be loaded with different "printing materials", such as ceramic, plastic, metal, sand, cement, etc., which are, literally, raw materials. After connection with a computer, a 3D printer can break down any three-dimensional model designed by the computer into several layers of flat slices, and by using laser beams or hot-melt nozzles, deposit and bind these materials layer by layer, thus building a whole object ultimately. In the technology of 3D printing, fused deposition modeling (FDM) or patternless casting manufacturing (PCM) is generally used in construction.

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The principle of FDM is described as follows: heat and fuse the thermal-plastic polymer material into wire, squeeze the wire out of a nozzle like squeezing toothpaste, and then deposit on a molding surface for modeling. The equipment covers different application areas from quickly-built conceptual models to slowly-built high-precision models. The principle of PCM is described as follows: convert a computer-aided design (CAD) model to a casting CAD model, obtain the 2D profile information by computer slicing, and then generate the control information based on the slice information. In modeling, the first nozzle sprays a binding agent on each layer of molding sand laid down, and the second nozzle sprays a catalyst along the same path. The two substances have a cross-linking reaction to solidify the molding sand layer by layer for deposition modeling. The features of this process include: short manufacturing time, no wood pattern required, integrated modeling, and manufacturable casting molds with free form surfaces and curves. At present, there have been many successful cases in the attempts for 3D printed buildings in various countries around the world. The development status of China's 3D printed buildings is illustrated in the following paragraphs.

In April 2014, China's Shanghai WinSun Decoration Design Engineering Co., Ltd. printed and built ten houses, as shown in Figure 1, within one day, by using a super 3D printer that is 150 meters long, 10 meters wide and 6 meters deep, as well as a kind of special "ink", i.e., a concrete material reinforced with special fiberglass, whose strength and service life are both much greater than those of common reinforced concrete. The construction cost was only 30,000 yuan a day, and part of construction material was made from recycled waste. The principle is described as follows: print each layer of house framing members first, and then mount them on site manually. The material used for printing framing members was a mix of high-quality cement, recycled construction waste and industrial waste, all of which were reinforced with fiberglass. This material could solidify quickly after being squeezed out, so that the printer might keep working. In the computer software, some space had been reserved for pipelines and windows. These parts were mounted after these houses were fixed in position. The project manager said that the internal structure of 3D printed houses may be optimized in accordance with acoustic, mechanical and other principles according to the requirements while saving materials. For example, their hollow walls can greatly reduce their own weight, be filled with any heat-insulating material, and have freely-designed structures, so that the problems in the bearing structure of walls are resolved once and for all. Hence, the strength and firmness of these buildings, including bridges, simple workshops, theatres, hotels and residential houses, are in accordance with or even higher than national construction standards.

Figure 1 : Houses built by Shanghai WinSun Decoration Design Engineering Co., Ltd. within one day by using the technology of 3D printing(Photos:Liangfeng)

In 2014 World 3D Printing Technology Industry Conference and Exhibition, Qingdao Unique Technology Co., Ltd. rolled out the largest 3D printer in the world, as shown in Figure 2. The length, width and height of the printer independently developed by Qingdao Unique are all 12 meters. On June 19 when the conference opened, the printer started printing a classic Chinese architecture, i.e., a 7×7 square building with the Temple of Heaven as its prototype. As estimated, the printing job will be finished in half a year. Qingdao Unique's 3D building printer has both a one-step modeling process and a shorter printing cycle. Most importantly, this large printer, looking cumbersome though, has very sophisticated techniques. By using the technology of FDM, it may deposit and stack the half-melt printing material, layer by layer, on a base ground, and construct the prototype directly from the software data. With a millimeter-level printing precision, it is a qualitative leap for the traditional construction industry, which has a centimeter-level calculation precision. For this time, the new material developed by Qingdao Unique in combination with the 3D building printer is a kind of glass reinforced plastic, which is a light, solid, anti-corrosion, anti-aging, waterproof and insulating composite material. More importantly, it may greatly reduce energy consumption and pollutant emission during the production and application process. There are also many other examples, but due to the limitation of length, this article doesn't mention them.

Figure 2 : The largest 3D printer in the world, independently developed by Qingdao Unique Technology Co., Ltd. (Photo:Liangfeng)

III. The Key of 3D Printed Buildings – Changes in Materials of Commercial Concrete

3D printing is a technology of additive manufacturing. Printing of any object is possible only if the problem of materials is resolved. Based on the same technology, 3D printed houses only have larger equipment and different materials. Hence, the "ink" for printing is the key of 3D printed buildings. Although there are many types of "ink" available for printing of 3D buildings, commercial concrete is still the relatively stable and most frequently used material for 3D printed buildings. In order to match this new technology, however, it must be adapted. Since commercial concrete still dominates the market, our discussion focuses on how it should be upgraded in the application of 3D printing.

Firstly, based on the two current forms of 3D printed buildings mentioned above, i.e., "one-step modeling" and "assembling", we suppose the commercial concrete available for 3D printed buildings may be developed in two different ways. Similar with the current method, "one-step modeled" buildings will be built in the following way: the concrete used for 3D printing is produced in a blender, transported to the construction site and then sprayed out from many printing heads of a large 3D printer. After printing layer by layer, a building will "grow up" like a large plant. Just like a prefabrication factory at present, "assembled" buildings are built in the following way: a designed house model is broken down into several modules, and different types of modules are produced by a large 3D printer and transported to the construction site for quick assembly. Quicker than the traditional prefabrication process, this process will help realize modularized construction of buildings, which is far more complicated than the current way for prefabrication of parts.

Secondly, the raw materials, the mix-proportion design concept and the production & supply mode of commercial concrete used in 3D printed buildings all have changed.

The raw materials of commercial concrete will become more extensive. For example, the cementing material may be made from special cement, resin or magnesia cement; the coarse/fine aggregate has to comply with higher requirements for quality to meet the demands of 3D printing, for which a new crushing technique may be used to produce a new material different from traditional ones; the additive may be changed in essence, and its function and mechanism in the concrete system will also be wholly different from those at present. In order to meet the demands of 3D printing, the concrete must have better rheological behavior and be capable of solidifying quickly in the air. Meanwhile, the maximal diameter of aggregate grains will become smaller to ensure these grains have nearly round shapes. In addition, the problem of how to perfectly bind all layers together should be resolved, for which a new additive is to be used.

In terms of mix-proportion design, a new theory may be used to serve as the supporting basis. Since the concrete used for 3D printing is different from the traditional concrete, there are significant changes in its functions. This cannot be achieved by simply changing the water-cement ratio or the sand ratio. Instead, its hardenability and contractibility have to be changed in essence. The current theories for concrete strength, durability, hydration and other aspects are no longer applicable to the demands. In order to achieve higher strength, longer durability, better blending capacity, quicker hardening speed and higher hardenability, it is necessary to discover new theories and mix-proportion design methods from a new perspective and to build new calculation models, hardening models and service life prediction models.

There are also big changes in concrete production and supply. Since 3D printers work without interruption, the production of concrete will continue in the whole process of 3D printing. All tasks will run continuously and be finished once and for all within a cycle, and even the blending system may be changed. Alternatively, the blending task may be done in the blending and transportation vehicle. Since the production system has higher requirements for measurement accuracy and uniformity of concrete blending, the conditions for entry into the industry of commercial concrete are stricter. To produce qualified products, many technicians who have undergone long-term, professional training are required.

IV. Advantages of 3D Printed Buildings

Based on the description and analysis above, we know that 3D printed buildings, compared to traditional buildings, have very obvious advantages, which mainly include:

1. High speed – 10+ times quicker than the traditional construction technology.
2. Low cost – Patternless and not so many construction workers required. Moreover, the structure may be optimized to save materials, thus greatly reducing cement demands, significantly decreasing the energy consumption in construction and improving the production efficiency.
3. Low carbon, green and environment friendly – Printing materials may be collected from local sources, and the construction waste, industrial waste and gangue may be recycled for use. After technical treatment, processing and separation, they may be converted into the raw materials of 3D printed buildings, so as to reuse the construction waste in buildings and to greatly reduce the waste.
4. It is very easy to print the high-cost curved buildings that are hard to build in other ways. Thus, architects may have an open mind and make breakthroughs in the design process. Meanwhile, this helps realize the integration of architecture and arts.
5. Concrete buildings will have higher strength, lower weight and better earthquake resistance.
6. At present, the technology of 3D printing cannot be used to build larger buildings, to a wide extent. The widely-seen high-rise buildings cannot be printed. Instead, they can only be assembled with printed parts. Hence, 3D printed buildings may change the development trend of the construction industry, and more assembled buildings will emerge.

V. Problems to be Settled for 3D Printed Buildings

3D printing has many advantages that traditional construction methods don't have, but based on the current conditions, the physical buildings built by 3D printing still have the following problems to be settled.

Firstly, 3D printing brings a revolution in architectural design. Traditionally, buildings are designed to meet the requirements for functions and construction processes. However, the design of 3D printing is totally different. Most of 3D printed buildings are made of special concrete, instead of reinforcing steel or stone. Thus, the features of materials should be taken into consideration in the design process. Since nozzles, three-dimensional nozzles in particular, are used to transfer materials in 3D printing construction, the design should comply with the features of pressure and mechanical modeling. Besides, such problems as comfort, safety and compliance with relevant construction standards should also be taken care of. Hence, existing architectural design systems cannot be used directly, and a system of architectural design principles that comply with the requirements of 3D printing must be rebuilt.

Secondly, the technology of 3D printing forms a trend of integration of such industries as engineering construction, infrastructure and manufacturing, in terms of construction equipment. Constructing a building is just like producing a product in a manufacturing enterprise. A 3D printer is similar with the existing "robot", which integrates automatic machines and construction machines for printing of buildings. Hence, precision and automation have to be ensured, which is a big challenge for China's manufacturing industry, especially for the manufacturing industry of large machine tools.

Lastly, 3D printing also has high requirements for construction materials. Since 3D printing has a high speed, the materials have to solidify very quickly. Traditional construction materials fail to meet this need, and a special R&D job is required to be done.

The technology of 3D printing for buildings has a bright future. The paragraphs above only give some assumptions. In order to make real breakthroughs in the key technology, to realize large-scale production in practice, and to change the traditional construction industry and the industry of commercial concrete in essence, the technology of 3D printing still has a long way to go. There is no doubt that 3D printed buildings will be new landmarks in the future world. In April 2014, Wang Shi, founder of Vanke Group, the leader in China's real-estate sector, said that Vanke Group would roll out 3D printed houses in three years. Up to the present, modern buildings and concrete materials have been developed only for over 100 years, but significant changes have been made in the world. Nowadays, skyscrapers, cross-sea bridges, tunnels and underground railways can be seen everywhere. We have a reason to believe that the upcoming era of 3D buildings will inevitably bring more unexpected changes to the world.

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