DIGITAL DESIGN AND FABRICATION OF A 3D CONCRETE PRINTED FUNICULAR SPATIAL STRUCTURE

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Abstract. In recent years, additive manufacturing (AM) and 3D concrete printing technologies have been increasingly used in the field of construction engineering. Several 3D concrete printing bridges were built with post-tensioning technology. However, the current post-tensioned 3D concrete printing projects are mostly in a single direction of force. There are fewer cases of concrete printing funicular spatial structures, and most funicular spatial structures are currently manufactured by casting-in-place in formwork. This paper presents a case of manufacturing spatial 3D concrete printed structure using post-tensioned technology with multiple force direction. The design of the non-parallel printing path, the joints between single units, and the post-tensioned steel cable system in the design and research process are discussed. A funicular spatial structure is built, and a method of manufacturing 3DCP funicular spatial structure is proposed.

Keywords. 3D concrete printing; Robotic fabrication; Prestressed concrete; Funicular spatial structure; Structural optimization; SDG 9; SDG 11; SDG 13.

1. Introduction

In the last decade, 3D concrete printing has demonstrated its potential to change the traditional construction way by printing concrete walls without conventional formworks (Le et al., 2012), which creates new possibilities in both architectural design and environmental protection. The application strategies for 3D concrete printing in building construction can be generally divided into on-site printing (Scott, 2020) (Mechtcherine, 2019) and prefabricated assembly. For prefabricated assembly 3DCP project, post-tensioned technology is widely applied to make separated printed units become a whole. The past five years have seen the completion of several post-tensioned 3D concrete printing bridge projects (Vantyghem et al., 2020) (Salet et al.,

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2018) (Zhan et al., 2021). However, these projects are tensioned in a single direction, which is why all are beam-like structures, namely bridges.

Typically, elements printed in concrete are achieved by extruding wet paste-material in layers which eventually build up the desired shape, which is first described as Contour Crafting in 2004 (Khoshnevis et al., 2004) and has been popular still now. However, the CC technology is limited to vertical extrusion, hence yielding 2.5D topologies (vertical extension of a planar shape) (Gosselin et al., 2016). Concrete units printed in this way are best stressed in the vertical direction, which is why many 3D printed structures are tensioned in one direction.

From the research of Gosselin, the method of non-parallel printing is described, which makes it possible to realize multi-angle printing (Gosselin et al., 2016). The arched masonry structure from BRG et al. (2021) fully demonstrates the advantages of this printing method in building funicular spatial structure. Separated units are printed in layers orthogonal to the main structural forces and they compress each other to form a compression-only funicular structure. In this arched masonry structure, there are no joints connecting the separate units, yet joint design is important in post-tensioned spatial structures.

The research project described in this paper is committed to exploring how to achieve post-tensioned 3DCP funicular spatial structure. Macroscopically, post-tensioning technology has been applied to achieve the efficiency and rationality of the structure. At the micro-level, non-parallel printing technology is applied to realize the printing of all separated units. A set of steel plate system for positioning and a set of post-tensioned pre-stressed steel bar system were applied. Finally, an experimental funicular spatial structure with a range of about 6m*6m*3m was built. The project discussed the rationality of the structural design of large-scale concrete printing funicular spatial structure and how to use these techniques to achieve the complexity of the printing structure.

2. Research and Prototyping

2.1. PROTOTYING DESIGN

In order to verify the feasibility of prestressed 3D concrete printed spatial structure and to discover potential problems during installation, a simple small-scale experimental prototype was designed, and the printing and installation tests were carried out.

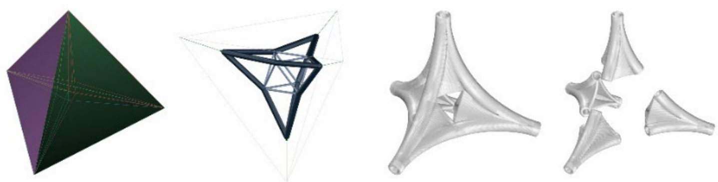

Figure 1. The development of the prototyping design

This simple funicular spatial structure is designed using PolyFrame (Masoud et al. 2019), a Grasshopper plugin based on 3D graphic statics. This plug-in is good at constructing purely compressed space structures. While in this prototype, prestressed steel bars can be used to simulate this compressed state. It is designed into a uniform structure composed of four identical units and four curved steel bars. The four concrete members are compressed tightly together to form a stable structure that presses and restrains each other. Figure 1 shows the development of the prototyping design.

2.2. PRINTING AND ASSEMBLY TEST

The segmented units are geometries with multiple direction, which means that they are non-developable curved surface. In Lim et al.'s (2020) work, a method of printing a non-developable curved surface is described (Lim et al., 2020). Compared to traditional method, it required temporary fabric formwork supported by height-adjustable rods. Lim has proposed in his theory within this technology, which is to print with saddle and dome surface on the temporary fabric formwork. The limitation of this kind of method is that a specific height-adjustable system is required, and each piece of printing will consume one piece of fabric. In addition, the temporary fabric formwork has relatively low accuracy and hard to control, which will increase the printing error and may eventually lead to the failure of the entire structure when assembly.

In prototype design, a method of printing the base with concrete material is proposed. As shown in Figure 2, a triangular base was designed according to the shape of the printed segment in this experiment. This base has three inclined surfaces that need to be printed with a specific printing path. After base printing, a piece of plastic flim was in use to separate the unit from the base that it attaches to. With this technique, four identical structural segments are printed.

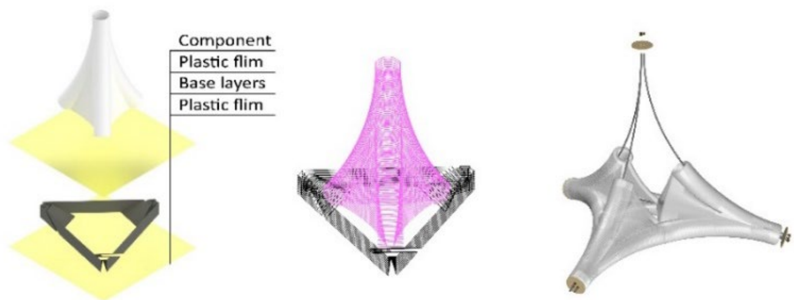

Figure 2. Left: printing process, Mid: toolpath, Right: steel bar system

2.3. PROBLEM

Although the printed base can ensure that the inclinations of the three slope surfaces of each unit are accurate. However, from a micro perspective, as it's shown in Figure 3, the inclined surface of the printed base is stepped. The bottom of the final printed object cannot fit this inclined curved surface completely, which makes the connecting surface of the prints uneven.

Figure 3 shows that because the nozzle has an unchangeable size, the printing height of the first layer needs to be raised to prevent the print head from rubbing against the inclined surface of the base. Therefore, the first layer of the printed component is obviously wider, and the layer height is also different from others.

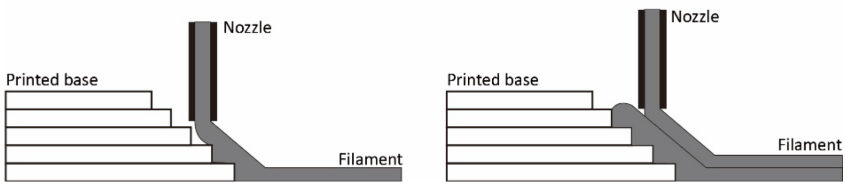

Figure 3. A micro view of the filament

Due to the superposition of the previous two reasons, the stability and accuracy of the entire prototype structure were declined from expectation. When the printed components were assembled, the connecting surface could not be fully attached. This leads to insufficient assembly accuracy of the printed parts and affects structural stability. Figure 4 describes the printing process and the assembly process.

Figure 4. Record of printing and assembly process

3. Computation design

3.1. MULTI-TOOL COLLABORATIVE DESIGN

The design result is attributed to the collaboration of two software, Polyframe, which generates a purely compressed frame, and Ameba (Xie et al. 2016), which calculates the volume through topological optimisation. With the help of PolyFrame, a system of purely compressed funicular spatial structure is created upon the basis of 3D graphical statics. Then optimization based on Ameba was introduced into the design. Some members were set as non-designed regions under the same boundary conditions, and then the Ameba algorithm was used, followed by 90 iterations. Figure 5 shows the development of the design process. As a result, an efficient spatial structural system based on mesh optimization was obtained, which predicts the basic material distribution of the final pavilion shape and improves the feasibility of concrete 3D printing.

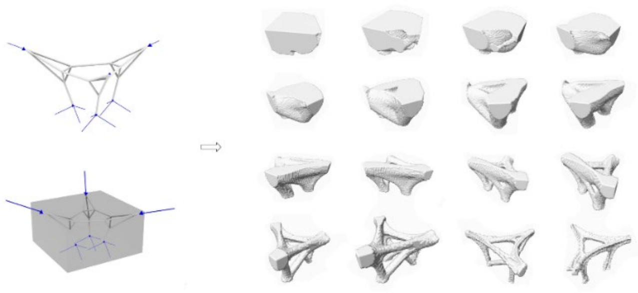

Figure 5. Iterations in Ameba

3.2. SEGAMENTATION

The final structure design needs to be divided into small pieces for printing. The direction of the force, the maximum printing height, and the maximum printable inclination are 3 main factors that need to be considered during the segmentation process. Finally, the whole structure is divided into 18 segments, each of which is less than 1500mm in height. To meet the requirements of reliable printing, every segment has at least one horizontal surface, with a maximum inclination angle no more than 45 degrees. Each column and beam are divided into two and three segments respectively. The remaining three outward heads each become an independent piece. Each segment is attached with one or two steel plates, which are used for positioning in assembly process. The division of the segments, the position and the serial number of steel plates are shown in Figure 6.

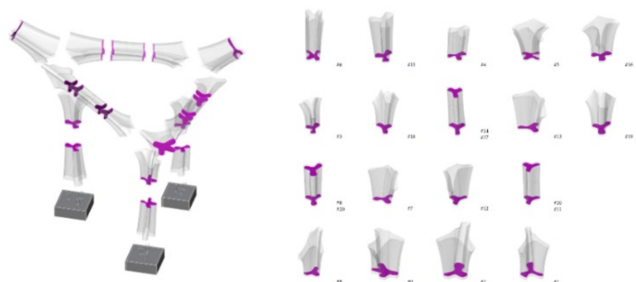

Figure 6. Segmentation

3.3. PRESTRESSED STEEL BAR

To simulate the calculation results of PolyFrame, 9 steel bars were added to this system. Three of them are connected to the column foundation from the overhanging ends and each beam has two steel bars. All steel bars are pre-stressed by post-tensioning.

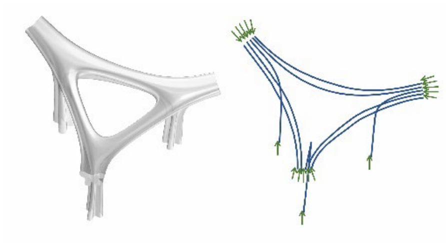

Figure 7. Nine steel bars

3.4. POSITIONING STEEL PLATE

This funicular structure is post-tensioned in multiple force direction, which create another difficulty in accurate positioning. The joints between single units need to be specially designed. 3D printing concrete ink usually has good fluidity during movement and satisfying standing behavior at static state (Zhang et al. 2018). The printing filament is in a wet-state and maintains a certain degree of plasticity for a certain period of time after extrusion. Exploit this property of 3DCP filaments, some scholars have demonstrated the feasibility of implanting micro cable during filaments deposition process (Ma et al. 2019) (Li et al. 2020). In this study, a method of implanting steel plates as positioning joints between the units during the printing process was employed.

Each segment has at least one steel plate, the segment in the middle of the beam has two steel plates. The printing of a single unit is paused during the printing process and the steel plates are then manually placed. After inserting steel plate, the printing process is continued. The concrete and the steel plates will become a whole when concrete gain strength.

The thickness of the steel plate processed by CNC milling machine is 4mm. There are two kinds of holes with diameters of 20mm and 50mm on the steel plate. 20mm holes are used for steel pipe welding during assembly. It plays the role of positioning between segments. The 50mm hole is where the steel bar passes through. The edge of the steel plate is designed to be zigzag, as shown in Figure 8, so that the steel plate and the concrete printing filament can be combined more firmly. The jagged edges make the filaments on both sides have a larger contact area. This is because, through the early printing experiments, it was found that the steel plate with a smooth edge will cause poor connection of the filaments separated by the steel plate. The printing segment brokes easily at where the smooth steel plate was placed.

Figure 8. Steel plates with zigzag edges

4. Robotic fabrication

4.1. TRAJECTORY DESIGN

The final structure is a multi-directional pre-stressed structure. The segmented unit is a multi-directional block, which cannot be printed by the traditional horizontal printing path. As shown in Figure 9, three sets of non-parallel planes are used to cut the printed units and then the intersected curves are connected to form the final path. Filaments are printed in non-uniform and non-parallel layers. The printing layers are orthogonal to the prestressed tensile direction so that the printing filaments within the structural unit can be tightly compressed together.

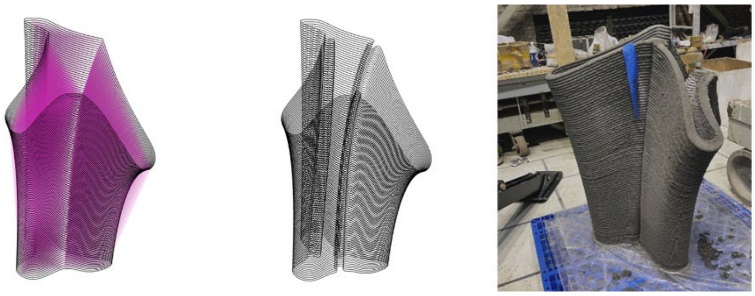

Figure 9. Toolpath generation

4.2. PRINTING PROCESS

In the prototype experiment, the bottom of the printing segments was uneven which will cause poor integrity when assembly. The accuracy of the connecting faces is not only an important factor but also an essential guarantee for the structure stability.

To achieve good connectivity, the contact surface of each unit must be flat. Thus, the printing strategy with the multi-directional side down in the experiment is abandoned. Every unit is printed with one-direction side down to obtain a rational flat surface connected with the base. This contact surface allows the unit to be stressed evenly during the printing process to ensure stability of the final structure.

The printing process is described in Figure 10:

- Place the tray (for the convenience of subsequent transportation)
- Lay the plastic film
- Print the base and pause for a horizontal surface)
- Lay the plastic film (for the subsequent separation of the base and the unit)
- Print the first 4 layers of the unit and pause
- Manually place the steel plate
- Print the remaining part
- Manually place the 2nd steel plate (for units in the middle of the beam)
- Print the remaining part (for units in the middle of the beam)

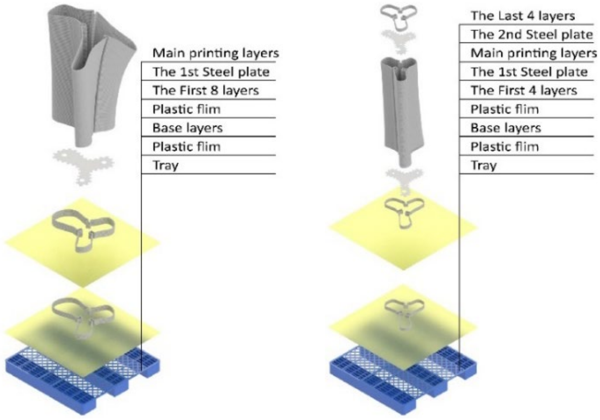

Figure 10. Printing process

4.3. ASSEMBLY

After all the printing work is completed, each unit has been cured for at least 14 days to ensure that it has obtained sufficient early yield strength. The installation process is as follows:

- What installed first is three pillars. The steel bars inside the three pillars are welded to the foundation. Inside the three pillar legs, 300mm-thick mortar is poured to connect the pillars with the embedded steel components.
- Install the second section of the column.
- The three beams are assembled on the ground respectively, and then the three beams are hoisted up.
- The three overhanging units are put on last.

The connections between the units are installed with anti-collision strips with a width of 30mm. The steel pipes are welded to the steel plate in the 20mm hole, and then assembled with the other segment whose steel plate they go through to achieve

Figure 11. Record of the assembly process and final outcome

precise positioning between the units. Pre-stressed steel bars with a diameter of 15mm pass through the 50mm hole in the steel plate and reach three overhang ends respectively. At the end of each overhang end, 9 steel bars are tightened with nuts to realize the post-tension of the entire structure.

5. Result and discussion

The final structure presents a relatively good surface quality. Although there are some discordant seams in some connections, but the overall quality is within the acceptable range of the architectural scale. The reasons for this may be:

- The error of non-parallel 3D printing is larger than that of traditional 3D printing.
- The deviation of the position of the pillars.

The method of placing the steel plate during the printing process needs to be optimized. It is found that the filament where holds the steel plate will sightly bulge, which declare that the method of embedding the steel plate in the concrete need further investigation. Methods such as optimizing the zigzag design, reducing the size or thickness of the steel plate deserve further exploration.

At present, the mainstream concrete 3d printing construction is divided into two categories: on-site printing and prefabricated assembly. The on-site printing technology is relatively mature and there is no segmentation problem. When it comes to prefabricated assembly, however, there are more issues to be settled.

In general, the concrete printing segments are relatively heavy and fragile, which leads to lots of difficulties in assembly period. In this project and the arched masonry structure from BRG et al. (2021), although each unit was manufactured using template-free 3D printing technology, a large amount of supports were used for positioning, including wood scaffold, during the assembly process, which led to a significant increase in both construction and environmental costs. Recent years, non-parallel concrete printing becomes popular and further eliminates the limitations of complex shapes. It is foreseeable that more large-scale 3DCP funicular spatial structures will emerge in the near future, which will also mean more complex scaffolds are needed. In this context, perhaps 3DCP technology needs to be re-evaluated, because the best option for these complex scaffolds is wooden waffle scaffold.

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