DIGITAL DESIGN AND FABRICATION OF A 3D CONCRETE PRINTED PRESTRESSED BRIDGE

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Abstract. In recent years, additive manufacturing and 3D printing technologies have been increasingly used in the field of construction engineering. 3D Concrete printing is a kind of laminated printing method using concrete extrusion technique. Concrete has the advantages of high compressive strength, low deformation, and excellent durability, and has high application value in the construction field. However, as a brittle material, concrete has limited tensile and flexural strength. For beam like components, it is difficult to fully exert the compressive performance of the material relying solely on itself, so it is difficult to apply to the bending member. The experimental case introduced in this paper combined the prestressing system with concrete printing technology. A post-tensioning prestressing system suitable for prefabricated concrete 3D printing components, which combined the excellent tensile properties of steel bars with the compressive performance of the 3D concrete printed part was proposed.

Keywords. 3D concrete printing; Prestressed concrete; robotic fabrication; structural optimization.

1. Introduction

In concrete structures, formwork occupies a large part of the production cost, especially for components with complex shapes, with low formwork reuse rate. Additive manufacturing and 3D printing technologies that have emerged in recent years have been applied in the field of construction engineering, make it possible for the mass-customized production of building components. 3D Concrete printing technology is a template-free and mass customization construction method, which can effectively reduce the production cost of custom-shaped components, improve production efficiency and changes the traditional concrete construction method.

Recently, 3D printed concrete components have been gradually used in large-span structures. However, due to the weak layer bonding, it is difficult to transmit shear and tensile forces, and can only be used for purely compressed structures. Although ultra-high-performance material which shows better tensile performance have been developed for concrete printing (Li et al., 2020), the complex mixing pumping process and much higher material cost still make it difficult for mass production.

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The first all-concrete printing arch bridge with a span of 14.4m was built in Shanghai, China in 2019 by Weiguo Xu from Tsinghua University. The printing material is a fast-hardening sulphoaluminate cement-based mortar with PVA fibre, which has a compressive strength up to 65MPa. The total printing time for the entire bridge is 450 hours. (XU et al. 2020) Post-tensioning is firstly used in concrete printing component by TU Eindhoven in 2018 in a pedestrian bridge. The bridge has a length of 8m and a width of 3.5m, to improve the tensile and post-cracking capability. In the printing process, steel wires were implanted during the printing process. (A. M. Salet et al. 2020)

Figure 1. 3D concrete printed arch bridge by Tsinghua University 2019 (left) 3D concrete printed prestressed bridge by TU Eindhoven 2018 (right).

Post-tensioning technology delays structural cracking and improves load-bearing efficiency in concrete structures. If it is combined with the concrete 3D printing technology, the bearing capacity of the components can be effectively improved, so that the concrete 3D printing components can be used for the beam-like structure.

The experiment described in this paper combines post-tensioning prestressing technology with concrete 3D printing components and uses the cavity of the 3D printing components to place prestressed steel bars. The tensile strength of steel and the compressive properties of concrete was combined to form a lightweight beam-like structure with high load-bearing capacity. As shown in figure.2, the experiment process starts with material research. Several material tests were performed to obtain material performance parameters. Based on the material properties, the model was designed, optimized, and finally, a prestressed beam with a length of 4.7m and a width of 0.6m was printed and built.

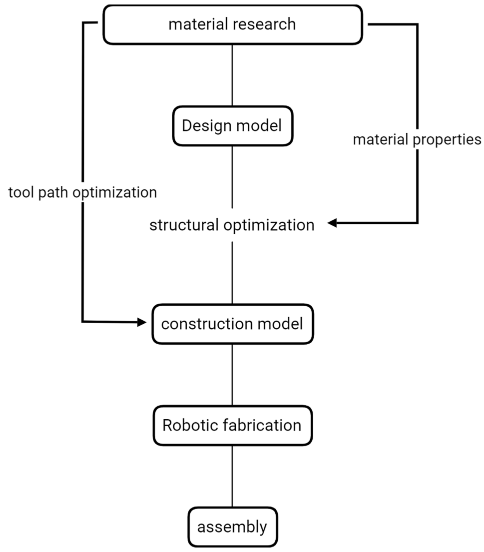


Figure 2. method and design process.

2. Research and Prototyping

2.1. MATERIAL AND MIXTURE DESIGN

A fibre-reinforced high-strength cementitious mortar was chosen as the primary printing material, and an alkali-free accelerator was added to control the set time. The major components of the mortar were list in table 1. P.W. I 52.5 White Portland cement is used as the main binder, which shows good compressive strength with silica fume. Metakaolin is used to make the mixture to reach the required thixotropy for extrusion and buildup (Zhang et al. 2018).

Table 1. Material and Mixture Design.

Material	**Quantity (kg/m^3)**
White Portland Cement (P.W I 52.5)	654
Silver Sand (0-1mm)	785
Silica Fume	65
Metakaolin	65
Water	229
Superplasticizer	0.65
PVA Fiber (13mm)	2.5

2.2. EXTRUSION TECHNIQUE

To simplify the dosing and mixing process. Dry powder of material was preblended and packed into 25kg bag ready mixed mortar according to the formula. And mix with water according to the proportion before printing. A continuous mixer was adopted to automatically add water and mix materials continuously. After the mixing process completed, the material was pumped to the print head for extrusion.

In order to reach the required pressure delivering the material from the ground to the nozzle with minimal pulsation, PCP (progressive cavity pump) was chosen as the pumping machine. However, there is certain inevitable pulsation for high-pressure PCP due to its mechanical properties. First, the material is pump from a high-pressure PCP to the buffer hopper of the print head and then extrude by a relatively low-pressure PCP to dampen the pulsation and reach a constant flow rate. An accelerator is added right before the mixture exit the nozzle. The general extrusion process is shown below.

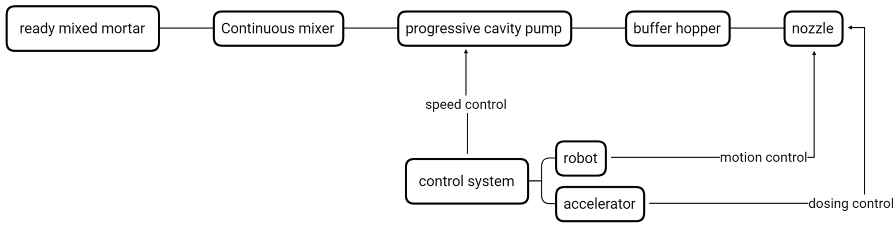


Figure 3. extrusion process.

2.3. MATERIAL PROPERTIES TEST

The shape adaptability and mechanical properties of printing materials are essential parameters that need to be determined before design. The experiments tested the maximum inclination angle of the toolpath, printing speed, and material properties.

2.3.1. Printing parameters test

The maximum overhang test generally bases on the method developed by ETH Zurich (Anton A. et al., 2020). The maximum overhang degree of this mortar was determined by test printing. The rib of the test concrete printed panel was inclined between 15° and 25°. Rib with the incline lower than 20° can buildup successfully, while the one greater than 20° cannot support itself. At the same time, the vertical buildup rate can be up to 1000mm/h to match the required set time of the mixture.

Figure 4. incline angle test 15°(left),20°(middle),25°(right).

The 3D printed component should keep in a full-section compression state by prestressing. So, the compressive strength and elastic modulus are the main design parameters to be determined. The 90° cross pattern was chosen to prevent the transverse split under pressure. After printing, samples were cured for 21 days following the standard curing process and sawed into cubic test block with an edge length of 70.7mm. The test was carried out according to “standard for test method of basic properties of construction mortar (JGJ / T 70-2009)”. The test results are compared in parallel with the casting sample list in table 2. The average compressive strength of the print sample is 45.84MPa, 94% of the result of its casting sample. It shows that there is no significant strength loss caused by the printing process.

Figure 5. 90° cross pattern of test sample.

Table 2. compressive strength of print and cast samples.

Item	No.	1	2	3
	Length, mm	72.84	72.35	73.81
	Width, mm	71.46	70.77	71.95
Print samples	Compressive Strength, MPa	43.78	47.12	46.63
	Average, MPa		45.84	
	No.	**1**	**2**	**3**
	Length, mm	72.92	71.42	71.66
Cast samples	Width, mm	70.82	71.13	70.87
	Compressive Strength, MPa	47.64	50.59	47.53
	Average, MPa		48.58	

3. Computational design

The bridge body adopts a beam structure, two bundles of prestressed steel bars are placed at the lower part of the bridge body so that the printed components of the bridge body always maintain full section compression.

3.1. TOOLPATH OPTIMIZATION

The toolpath of the section was optimized according to the stress distribution. More material was distributed in the compressive part, which reduces the weight of the unit while ensuring the maximum section efficiency. Due to the pumping and extrusion methods, the printing process cannot start and stop in real-time. So the path of each layer is optimized to ensure each unit was printed in one continuous stroke.

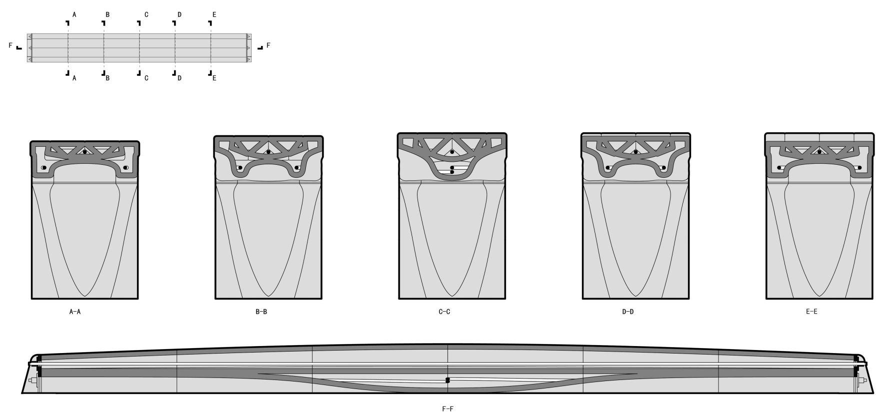


Figure 6. section drawings.

3.2. FEM ANALYSIS

Finite element analysis and simulation of the bridge were carried out to verify the design strategies and get the correct amount of prestressing. The structure diagram is as follow:

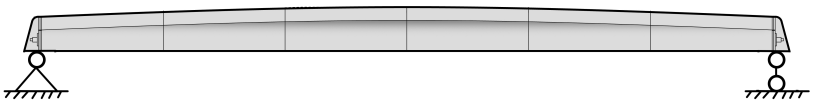


Figure 7. structure diagram.

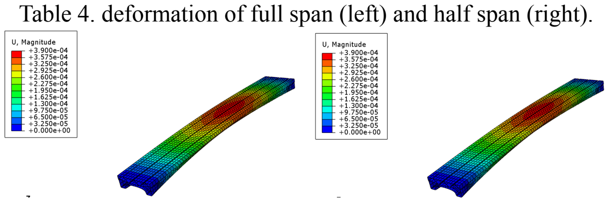
Supports at both ends of the bridge are hinged. According to related regulation and the test result above, the material properties of the prestressed steel bars and the printed parts were listed as follows:

Table 3. material properties.

Material	strength	Young's modulus
Φ15 PSB 830 finish rolled rebar	830MPa (tensile strength)	200GPa
3D printed part	40MPa (Compressive strength)	20GPa

The steel bars were made of finished rolled rebar without longitudinal ribs, connected by rebar nuts on both sides, manually tightened by a torque wrench, and the amount of the tension is controlled by the wrenching torque. The live load of the bridge deck was set as 4.5kPa and calculate with the full span and half span load case.

Table 4. deformation of full span (left) and half span (right).



4. Robotic Fabrication

In order to reduce the difficulty of transportation and printing, the bridge section is divided into six equal-length units for printing. After 21 days of curing, the test block is assembled on a simple bracket constructed by bricks. Finally, the bridge body is stretched and hoisted to the steel support.

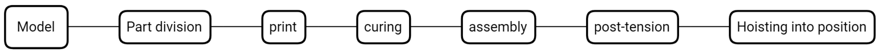


Figure 8. workflow.

Due to the fast printing speed, the print head moving speed is up to 200mm/s. The traditional 3-axis printing platform has a heavy motion mechanism and a long acceleration and deceleration process, which is prone to jitter at the turning point. The print head discharge speed is difficult to achieve real-time adjustment. Thus effects the corner printing quality. The six-axis mechanical arm movement mechanism is light in weight and flexible in movement, which is more suitable for high-speed printing. The printing control system is based on rhino and grasshopper platforms. Based on the FuRobot system (Lu et al. 2020), computers can communicate with the robot in real-time and transmit the real-time position of the robot arm. The printing path is generated in real-time according to 3D model so that the printing path length is not limited by the file size. The robot's movement speed can be controlled in real-time based on external feedback.

Figure 9. printing process.

Due to the relatively lightweight of the components, six printing units, each weighing around 80-90kg, can be directly transported and assembled manually. The joints between components are filled with mortars to ensure the force transmission at the joints.

Figure 10. assembly.

Figure 11. final result.

5. Result and discussion

This bridge combines concrete 3D printing, post-tensioning, and robot fabrication technology. The printing process of the components only takes three days, and the assembly process only takes 2 hours. Fast and formless fabrication of customized components was achieved. At the same time, the total weight of the bridge is about 600kg. Compared with the solid beam structure, the printed components can optimize the material distribution in the section more freely, and make the structure lighter and more efficient.

Table 5. time comsumption.

	Time consumption of Fabrication	**Labor**
Printing	3 days	2
Curing	21 days	0
On site assembly	2 hours	3

References

Anton, A.n.a., Bedarf, P., Yoo, A., Reiter, L.e.x., Wangler, T., Flatt, R. and Dillenburger, B.: 2020, Concrete Choreography: Prefabrication of 3D-Printed Columns, *Fabricate 2020: Making Resilient Architecture*, 286-293.

Li, V.C., Bos, F.P., Yu, K., McGee, W.e.s., Ng, T.Y., Figueiredo, S.C., Nefs, K., Mechtcherine, V., Nerella, V.N., Pan, J., van Zijl, G.P. and Kruger, P.: 2020, On the emergence of 3D printable Engineered, Strain Hardening Cementitious Composites (ECC/SHCC), *Cement and Concrete Research*, **132**, 106038.

Ming, L.u. and Yuan, P.F.: 2020, A NEW ALGORITHM TO GET OPTIMIZED TARGET PLANE ON 6-AXIS ROBOT FOR FABRICATION, *Proceedings of CAADRIA 2020*, 393-402.

A. M. Salet, T., Y. Ahmeda, Z., P. Bos, F. and L. M. Laaglandb, H.: 2018, Design of a 3D printed concrete bridge by testing, *Virtual and Physical Prototyping*, **13**(3), 222-236.

Xu, W.: 2020, Fabrication and Application of 3D-Printed Concrete Structural Components in the Baoshan Pedestrain Bridge Project, *Fabricate 2020: Making Resilient Architecture*, 140-147.

Zhang, Y.u., Zhang, Y., Liu, G., Yang, Y., Wu, M. and Pang, B.o.: 2018, Fresh properties of a novel 3D printing concrete ink, *Construction and Building Materials*, **174**, 263-271.