Structural behaviours of a concrete façade panel prototype facilitated by 3D printed formwork

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Abstract. Façades are key building components, determining building performance and forming the interface between inhabitants and the general public. Accordingly, façades should integrate high aesthetic value with the capability to bear relevant loads. Contemporary architectural façade design strategies often employ complex shapes, which presents civil engineering challenges in terms of assessing structural performance as well as determining effective fabrication strategies. Using 3D concrete printing for fabrication can achieve freeform shapes but has several limitations including limited structural performance. Instead of directly 3D printing concrete elements, this paper presents an approach to fabricating geometrically complex façade elements in Ultra-High Performance Fibre Reinforced Concrete using 3D printed formwork to achieve greater accuracy and cost efficiency compared to conventional fabrication methods. Following compression test and flexural test to examine the feasibility of using 3D printed formwork for concrete fabrication, a façade prototype with a non-standard shape using 3D printed polymer formwork and UHPFRC is examined for its structural behaviours. Results show that compressive strength and flexural strength are not affected negatively by the exterior 3D printed formwork. Meanwhile, the proposed façade prototype demonstrates good concrete flowability and load test results, promising a new construction method for concrete fabrication.

1. Introduction

Building façades are essential self-load-bearing structural elements in buildings to protect interior structures from deterioration under aggressive environmental conditions. Facades are primarily functional in that they bear relevant mechanical and environmental loads such as wind load and earthquake load [1]. At the same time, building facades are important to how buildings are perceived by both inhabitants and the general public and thus carry a significant aesthetic role. Concrete such as Ultra-High-Performance Concrete (UHPC) is a common building material for facades due to the high strength, workability and ductility [2]. However, there are some limitations for casting concrete façade panels designed with complex and unique geometries due to the requirement of special formworks. Even in conventional building elements, the cost of traditional formworks for concrete casting can be very high, accounting for approximately 50% of the overall costs for a concrete structure [3]. For complex and non-standard concrete elements, this number can be significantly higher and is the reason for few architects and clients to pursue such building facades.

3D Concrete Printing Technology (3DCPT) is a growing field of research, in part motivated by attempts to improve current concrete fabricating methods. Compared with traditional casting technologies, 3DCPT offers several advantages [4]. First, the manufacturing process can be robotized, potentially saving time and human labour. Additionally, it offers greater geometric design flexibility as well as 3D printing-based construction without formwork for increased material economy and sustainability. Already in 2016, the world's first 3D-printed concrete bridge of 12 m length was successfully constructed in Castilla-La Mancha Park in Alcobendas, Madrid [5], where 3DCPT helped to achieve maximum structural performance and optimal material distribution. Gosselin et al. [6] conducted flexural tests on the prismatic samples made of ultra-high-performance printed concrete. Results indicated that the flexural strength of the specimens could vary from 11.7 MPa to 16.9 MPa and the conservatively estimated compressive strength was 120 MPa. Zhu et al. [7] abricated permanent formwork using 3DCPT for concrete column construction and concluded from compression tests that the composite column employing 3D printed formwork had higher bearing capacity and stiffness than a comparable cast-in-place column. Nevertheless, 3DCPT is still in its initial stages and has faced several essential issues and challenges. First, structural failure such as elastic buckling or plastic collapse easily occurs during the 3D concrete printing process because the geometry is instable or the maximum stress reaches yield strength of the material [8]. Moreover, during the layered material deposition process of 3D concrete printing, weak interlaminar bonding may be incurred due to surface moisture evaporation and differing curing rates. This phenomenon impairs the uniformity and integrity of 3D printed concrete, which thus negatively influences the mechanical properties, stiffness, and durability of the concrete elements [9-12]. Additionally, during the printing process, excess deposition of concrete will lead to poor surface quality while insufficient material deposition will result in voids, which can be trapped and weaken the structure [13]. Consequently, utilizing 3DCPT to manufacture complex concrete structures especially in large-scale construction can be difficult.

In addition to 3DCPT, utilizing 3D printed polymer formwork for concrete casting has also been explored in recent years as polymer-based 3DPT possesses various advantages such as high precision and customized geometry [14]. Jipa et al. [15] successfully conducted concrete casting in 3D printed PLA formwork with complex tubular geometries. After concrete casting, a favourable enclosure for concrete curing is provided by the exterior PLA formwork, preventing the development of cracks owing to water loss. However, as yet there are no load tests to analyse the structural behaviours of the hybrid material. Katzer and Szatkiewicz [16] studied the properties of concrete beam elements facilitated by 3D printed plastic formwork, featuring ribs with different dimensions at the bottom to substitute steel reinforcement. The results indicated that formwork-matrix specimens without ribs can achieve almost twice the flexural strength of traditional mortar samples and specimens with 3D printed formwork and ribs can achieve four times the flexural strength of the plain mortar element. However, only regular rectangular shapes of formwork were investigated in the study. Han et al. [17] compared 3D printing to two conventional methods such as utilizing wooden formworks for fabricating customized concrete structures. After analysing, they concluded that the method of using 3D printed polymer formwork to fabricate concrete can be more accurate, cost-efficient and time-saving than comparable conventional methods for the mass production of highly complex or customized prefabricated concrete structures. In summary, 3D printed polymer formwork offers promise in the fabrication of geometrically complicated concrete elements as the properties of concrete can be improved and fabrication can be more efficient.

As outlined above, previous studies indicate that 3D printed polymer formwork supports the fabrication of freeform concrete façade panels. In 2018, Herr et al. [18] proposed an architectural design approach to integrate parametric design of sculptural concrete facade elements with the fabrication of 3D printed formwork for complex concrete elements. However, much remains unknown regarding structural properties of complex concrete façade panels cast in 3D printed polymer formworks in the field of civil engineering. No previous study has investigated the suitability of this method in the context of high-performance concrete to fulfil the requirement of both free-form architectural design and excellent mechanical performance for concrete façade panels. In this paper, load tests on specimens with basic geometries made of 3D printed polymer formwork-Ultra-high Performance Fibre Reinforced Concrete (UHPFRC) matrix composite are first conducted to preliminarily analyse the feasibility and mechanical properties of the hybrid material. Then, a prototype of façade panel with a non-standard shape fabricated by 3D printed formwork is employed to investigate its structural behaviours through load testing and Finite Element Analysis (FEA). The presented approach to fabricating the prototype façade panel is the result of a close cross-disciplinary collaboration between civil engineering and architecture and offers an innovative method to design and fabricate concrete façade panels with non-standard geometries that also informs related architectural design approaches.

2. Materials

2.1. 3D-printed formwork

Polyethylene Terephthalate Glycol (PETG) was used as the 3D printed formwork material as it can offer chemical resistance when combined with concrete and higher ductility to improve the flexural strength of concrete compared to other thermoplastics [19]. The mechanical properties of PETG are summarized in Table 1 [20].

A UR10 Robot with a 2mm-diameter extruder was used for formwork 3D printing. As mentioned above, PETG was utilized as the printing material with 230 °C melting temperature. Printing speed (ps) and extrusion speed (es) varied to print different-thickness moulds. 1.5 mm-thickness is achieved by ps14.4 mm/s, es 60 r/min and 2.5 mm-thickness is achieved by ps14.4 mm/s, es 80 r/min. In total, three categories of formwork were prepared for casting including cylinder and cuboid formworks and the mould for one unit façade panel at a small scale (Figure 1). The dimensions of printed formwork elements for different specimens are presented in Table 2, Table 3 and Figure 2.

Table 1. Mechanical properties of PETG [20]

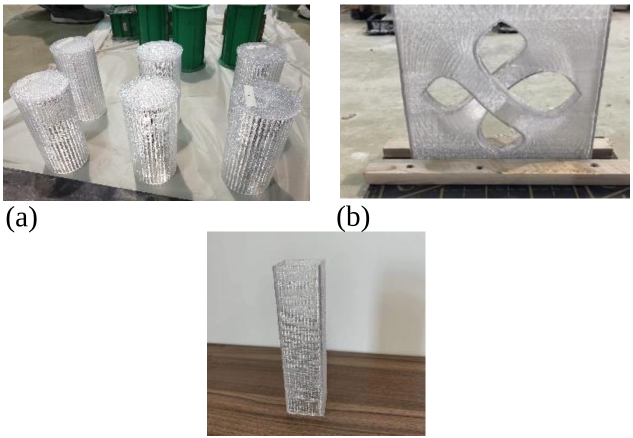
Material	Density (kg/m^3)	Tensile Strength (MPa)	Elongation (%)
PETG	1270	41.7	165.5

Table 2. Dimensions for 3D printed cylinder formworks

Type	Diameter (mm)	Length (mm)	Mould Thickness (mm)	Number
3DP-1.5	100	200	1.5	3
3DP-2.5	100	200	2.5	3

Table 3. Dimensions for 3D printed cuboid formworks

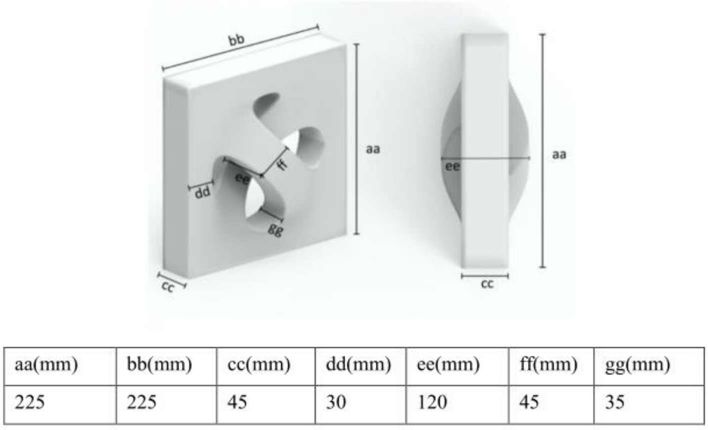
Length (mm)	Width (mm)	Height (mm)	Number
200	50	50	3



(a) (b)

(c)

Figure 1. 3D printed formworks (a) cylinder formwork (b) façade panel formwork (c) cuboid formwork (designed and printed by the third author)



aa(mm)	bb(mm)	cc(mm)	dd(mm)	ee(mm)	ff(mm)	gg(mm)
225	225	45	30	120	45	35

Figure 2. Dimension for 3D printed mould of one unit façade panel (designed and printed by the third author)

2.2. Concrete

UHPFRC was used in the experiment with the mix design listed in Table 4. The density and elastic modulus of UHPFRC are shown in Table 5 [21]. During mixing, fibres were incrementally added and the adding of superplasticizer was postponed to improve the workability of concrete [22]. After mixing, concrete was poured into the 3D printed formworks (Figure 3). Traditional plastic or wooden formwork elements with same dimensions were used to cast conventional concrete using the same method. The experiment demonstrated that the above mix design can satisfy the workability requirement for casting concrete in non-standard façade formwork. For concrete curing, cylinder and cuboid specimens were placed in 60℃ water for 72 hours and façade specimen were put in a steam box at a condition of 60℃ for 72 hours.

Table 4. Mix design of UHPFRC (for 1 m^3)

Component	Quantity
Premix UHPC Powder	2232 kg

Superplasticizer	35 kg
Water	206 kg
PVA Fibre (12 mm length)	26 kg

Table 5. Properties of UHPFRC [21]

Density	2650 kg/m^3
Elastic Modulus	48.8 GPa

(a) (b)

Figure 3. Fabrication of concrete specimens: (a) cylinder samples. (b) façade panel sample.

3. Methods

3.1. Compression test

Before the test, the bottom surfaces of cylinder specimens with 3D printed formwork were ground to be smooth and even. Compression tests were conducted on the cylinder specimens at a speed of 10 kN/s as shown in Figure 4.

Figure 4. Compression test on cylinder specimens

3.2. Flexural test

Flexural tests were performed using two supports and two loading points as shown in Figure 5. The span between the two supports is 150 mm. The distance between loading points is 50 mm. The tests were performed at a displacement rate of 5mm/min. The sampling frequency is 10 Hz.

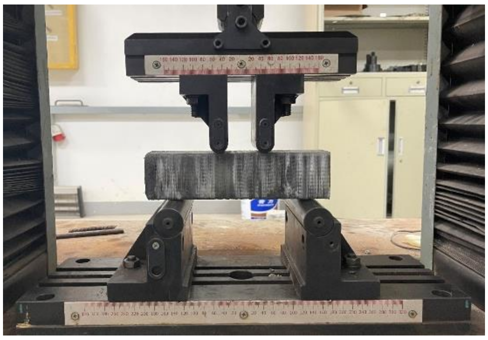


Figure 5. Flexural test on concrete specimens

3.3. Load test on the façade specimen

The 3D printed formwork was dismantled before load testing. Rhino model was rendered to demonstrate the support condition for the concrete panel clearly as shown in Figure 6. The concrete façade panel was supported by four steel supports, whose dimensions are all 30×30×60 mm. One point load was added on the middle part of the façade sample as shown in Figure 7. The specimen was sprayed with white colour in advance in order to better observe the crack patterns. The load was applied at a speed of 0.5 mm/min.

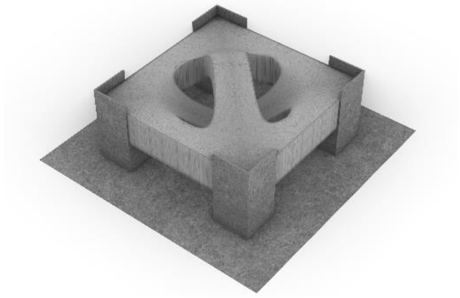


Figure 6. Support demonstration in the Rhino model

Figure 7. Load testing on the façade specimen

3.4. Finite element analysis

ABAQUS software was used to perform Finite Element Analysis. Concrete Damage Plasticity model is used for simulation. The elastic properties used for FEA are presented in Table 5. After importing the model from Rhino software into Abaqus, several parameters in Abaqus were adjusted in order to properly mesh the complex geometry and analyse the generated mesh. First, the model was meshed by using Tet elements. Meanwhile, it was found that if the number of elements is too large, the mesh could not be analysed successfully. The number can be reduced by increasing the size of interior elements through adjusting parameters such as non-standard interior element growth rate. After decreasing the element number to approximately 30000, the mesh could be analysed successfully. The final mesh of the model is shown in Figure 8.

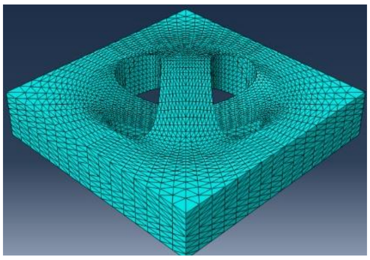


Figure 8. Mesh of the façade panel in Abaqus

4. Results and discussion

4.1. Compression test results

Table 6 shows the results of compressive test. For each type, three specimens were tested. For 3DP-1.5 (concrete specimen with 3D printed mould of 1.5 mm thickness), the compressive strength is 69 MPa, which increases to 89 MPa for 3DP-2.5 (concrete specimen with 3D printed mould of 2.5 mm thickness). The compressive strength of the concrete sample cast in traditional moulds is 82.8 MPa. The results indicate that the compressive strength will not be influenced negatively to a large extent and can be even improved by the exterior 3D printed formwork.

Table 6. Compressive strength [a]

Type	Compressive Strength
3DP-1.5	69.0 MPa
3DP-2.5	89.0 MPa
Cast-1	82.8 MPa

[a] Average compressive strength is presented in the above table

4.2. Flexural test results

Three specimens were tested for flexural strength. For concrete specimens with 3D printed formwork, the flexural strength is 13 MPa, which is approximately equal to the strength for samples cast in conventional formwork. The results indicate that the flexural strength will not be influenced negatively by the exterior 3D printed formwork.

4.3. Façade panel test results

Figure 9 illustrates the load-deflection curve of the façade panel sample. The ultimate load is approximately 6.5 kN. According to Figure. 10, an elastic response is first observed. After the elastic phase, load drop related with onset of cracks was observed in the curve followed by load increase due to fibre reinforcement. After reaching the load capacity, no sudden drop of the load was observed, which indicated good ductility of the material. Cracks associated with the drop of load-deflection relationship on the side and arch part of the sample were observed during the testing (The cracks are highlighted by red dotted circles in Figure 10).

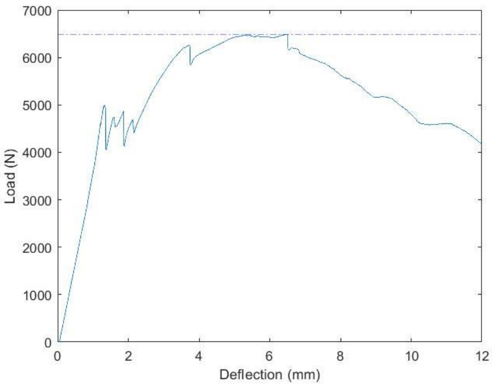


Figure 9. Load-Deflection curve for the façade panel

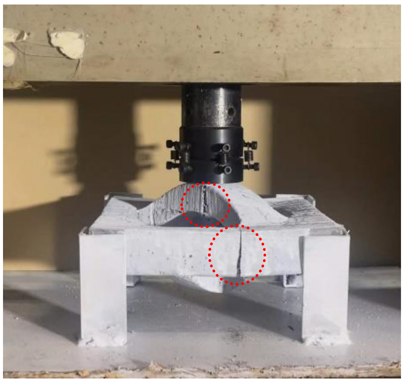


Figure 10. Crack development during the load testing

4.4. Façade panel simulation results

The deformation and stress distribution of the model under point load are shown in Figure 11. Stress concentrates on the part where load is added. The preliminary analyses within the elastic stage shows that the model is acceptable for further analyses considering the material nonlinearity.

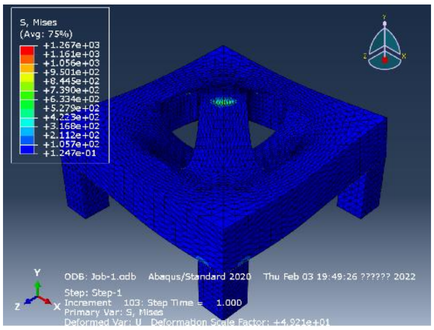


Figure 11. Deformation and stresses

5. Conclusions

This study employed innovative 3D printed formwork instead of conventional moulds in combination with UHPFRC to fabricate a concrete façade panel prototype with complex geometry. This paper outlines in detail initial tests on the prototype's structural behaviour. Experimental results indicate that the exterior 3D printed formwork presents no obvious negative influences on the flexural strength and compressive strength of the UHPFRC elements. Compressive strength can be even improved lightly by including the 3D printed formwork. A prototype for a UHPFRC façade panel using 3D printed formwork is proposed in the paper, offering a novel construction method for fabricating non-standard concrete façade elements as satisfying workability of concrete and test results are observed in the experiments. Future research in this project will include the testing of prototype façade panels at 1:1 scale to examine the feasibility of the construction method at larger scales. Meanwhile, façade panels with other shapes will be casted and tested in the future.

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