3D Printing of Fire Shelter using Ultra-High Performance Concrete

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Abstract

Building thin, architecturally attractive designs is viable with 3D concrete printing technology but is limited by the strength and stiffness of the concrete. In this regard, the authors recently developed 3D printable ultra-high-performance fiber-reinforced concrete composite. This composite's ultra-high compressive and flexural strengths (>150 MPa and >30 MPa, respectively) and fracture toughness properties facilitate the printing of slender elements, which are lightweight, low-cost and has low-carbon footprint. To demonstrate this, a large-scale shell structure of 2.4 m base diameter and 2.4 m height was designed, and 3D printed using the developed composite in this study. The application of this shell structure is intended to be a fire shelter in a wild fire. The design was made of 400 layers, each had a width of 40 mm and a thickness of 6 mm. To analyze the fire resistance of this shell, thin panels were 3D printed with the same composite and tested under ISO 834 fire conditions for 60 minutes. No explosive spalling was observed in the 3D printed thin panels when polypropylene fibers were added to the developed composite at 0.25% volume percentage. As such, 3D printing enables the rapid construction of lightweight low-cost fire-safe shelters with attractive designs for wildfire prone areas.

Keywords: 3D Printing, Fire Resistance, Fire Shelter, Shell Structure, Slicing, UHPC.

1. Introduction

3D concrete printing (3DCP) is an additive manufacturing technique for construction applications where the concrete is pumped to a 3D printer and extruded via a nozzle to build the desired structure layer upon layer. 3DCP can improve the speed of construction while eliminating the use of conventional formworks, thereby reduces waste, cost and time (Chen et al.). In addition, the freeform construction would enhance architectural expression, where the cost of producing a structural component will be independent of the shape, providing the much-needed freedom from the rectilinear designs (Mechtcherine et al.)

The use of ultra-high performance concrete (UHPC) for 3DCP applications is lucrative as the high compressive strength (>150 MPa) and ductility of UHPC complements the demands of 3DCP in the form of thein architecturally attractive elements (Khayat et al.). However, the conventional UHPC cannot be used for 3DCP as the self-compacting flow behavior of conventional UHPC is not ideal to retain shape in the absence of formworks. Therefore, the authors developed non-proprietary 3D printable UHPC (3DP-UHPC) mixtures with 3D printable rheology while having similar strength profiles (Arunothayan, Nematollahi, Ranade, Bong and Sanjayan; Arunothayan, Nematollahi, Ranade, Bong, Sanjayan, et al.).

In this study, the application of 3DP-UHPC is presented as a fire shelter in a wild fire. The design of the fire shelter was inspired by the shape of conch shells. The shelter was 3D printed in multiple sections, and assembled together on-site. The fire response of long panels made of the same mixture designs were presented.

2. Mixture Design

The development of 3DP-UHPFRC mixtures, selection of local raw materials, and the particle packing model used to evaluate the mix proportions were presented in the previous works of the authors (Arunothayan, Nematollahi, Ranade, Khayat, et al.; Arunothayan, Nematollahi, Ranade, Bong and Sanjayan). Table 1 presents the mixture design of the 3DP-UHPC design. The binder consisted of ordinary Portland cement and silica fume. Three types of sieve graded sands were used to improve the packing density of the mixture. High range water-reducing admixture (HRWRA) was used to enable the flow in UHPC. Viscosity modifying agent (VMA) was added to form a printable rheology. The effects of VMA on the printing rheology and buildability were discussed previously by the authors (Arunothayan, Nematollahi, Khayat, et al.). Short polypropylene fibers (PP), having a length of 6 mm and a diameter of 18 μm were used to ensure fire protection. The effects of PP fibers on 3DP-UHPC were previously discussed (Arunothayan and Sanjayan).

Table 1 Mixture proportions of the printable UHPFRC

Binder		Silica sand			Water	HRWRA	VMA	PP fiber
Cement	Silica fume	Fine	Medium	Coarse				
0.7	0.3	0.4	0.3	0.3	0.16	0.01	0.002	0.5%

Note: All numbers are mass ratios of the binder weight, except the fiber content (volume fraction).

3. Design of Fire Shelter

Since a fire shelter is a requirement based built form, the design concept was developed based on its purpose. The selection of shell structure was reasoned as follows.

- The shells contain a spiral form which restricts the spread of air or fire due to the rotational movement in spaces, so that the effect of the hazard minimalizes.
- The area of a shell structure is less than its rectilinear bounding box, so the disruption to the natural environment is comparatively lower.

Although a shell structure solves the functionality for general applications, its constructability is inconvenient and expensive. However, use of 3D printing can simplify the constructability of the shell structure, since the desired shape is independent of the cost of 3D printing (Carneau et al.). Inspired from Gastropods, Cortie et al. explored a variety of natural shell shapes for construction applications. A conceptual form for the shell structure for the fire habitat was developed with the flat base-on-ground design, as in Figure 1(a) (Alati et al.). However, the closed form of the shell structure restricts the natural light. To address this without losing the aesthetic appeal, a minor design modification was added, as explained below.

The modified shell form followed the golden ratio as architectural proportions. As displayed in Figure 1(b), a proportion grid was applied over the form and the top portion of the shell was chamfered. Then, the void was rotated along a horizontal axis and tilted towards the north for accommodating the highest amount of natural sunlight (note that the structure is located in the Southern Hemisphere). In addition, a slope is introduced to loft the void and create a movement in stabilized symmetric shell form as shown in Figure 1(c). The final design comprises of spiral layers of a shell, a slope for visual movement, and a void for the entry of natural light.

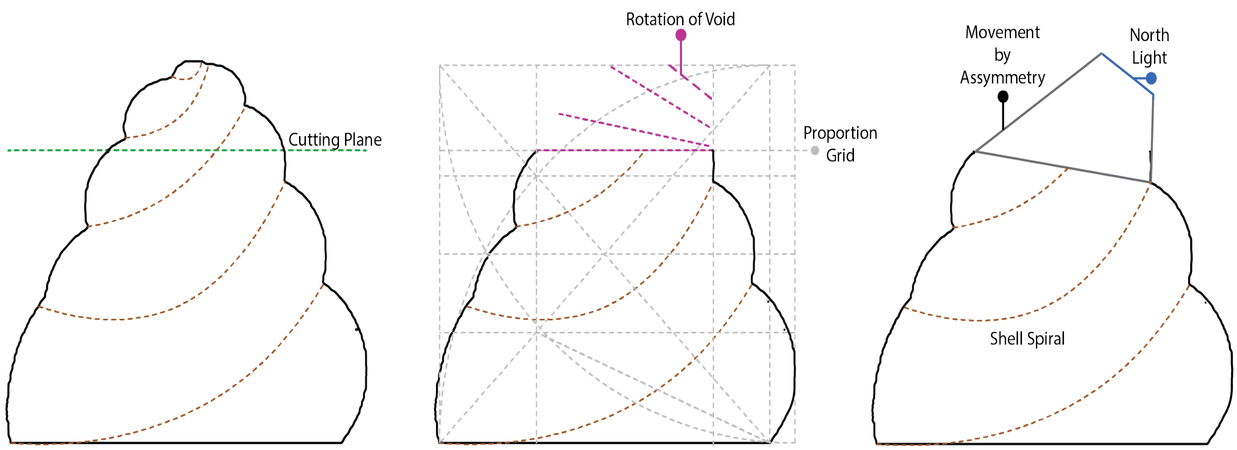

Figure 1 (a) Shell structure with the flat base (Alati et al.) (b) Chamfered using proportion grid (c) Creation of void for natural light

4. Slicing and Code Generation

The shell surface was created in the Rhino 3D modelling software and the model was parametrically created inside Grasshopper from a modified helix and surfaces lofted onto it. Geometric analysis was used to optimize the form to minimize large cantilevers. Then, the model was loaded in the grasshopper plug-in developed in-house as to suit the functionalities of the 3D printer. The plugin slices the parametric surfaces along horizontal planes, each of which represents a layer of the printed geometry. The layers were then divided by interpolating a series of points along them. The grasshopper plug-in acquired the series of points to create the printing path. The planes of these points were used to position the nozzle in perpendicular to the print surface. These points and their corresponding planes were arranged in such a way that the start position of the curve was reversed to follow the end position of the preceding curve, thereby enabling a continuous printing process. The spatial positions of all these points and their planes generated the G-code for the 3D printer. Figure 2 presents the sequence of slicing and code generation using a single layer.

The base diameter and the height of the shell form is 2.4 m each. The structure was divided into 400 layers, each of 45 mm width and 6 mm height. The length of each layer was determined by the shape of the shell form. To avoid early-age buckling failure of the thin layers and the toppling due to the cantilever design, the shell form was printed in multiple sections.

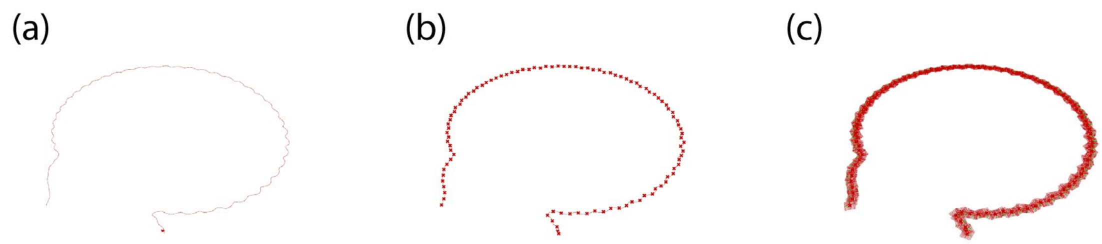

Figure 2 (a) A single layer of the shell (b) Dividing the layer into multiple points (c) The corresponding planes to the points

5. 3D Printing of Fire Shelter

The 3D printer used for large-scale concrete elements is shown in Figure 3(a). The working area of the 3D printer was 8.1 m × 6.5 m × 4.2 m. This 3D printer was based on a gantry robot with a print head moving along beams. The print head was designed to function in 6 degrees of freedom (i.e., 3 axes defined by the linear movement and 3 axes defined by the rotational movement of the print head). The movement of the 3D printer was controlled by a control panel cabinet and a motor control cabinet. The control panel was shown in Figure 3(b). A detachable nozzle, having a circular outlet of 15 mm diameter, was attached to the print head.

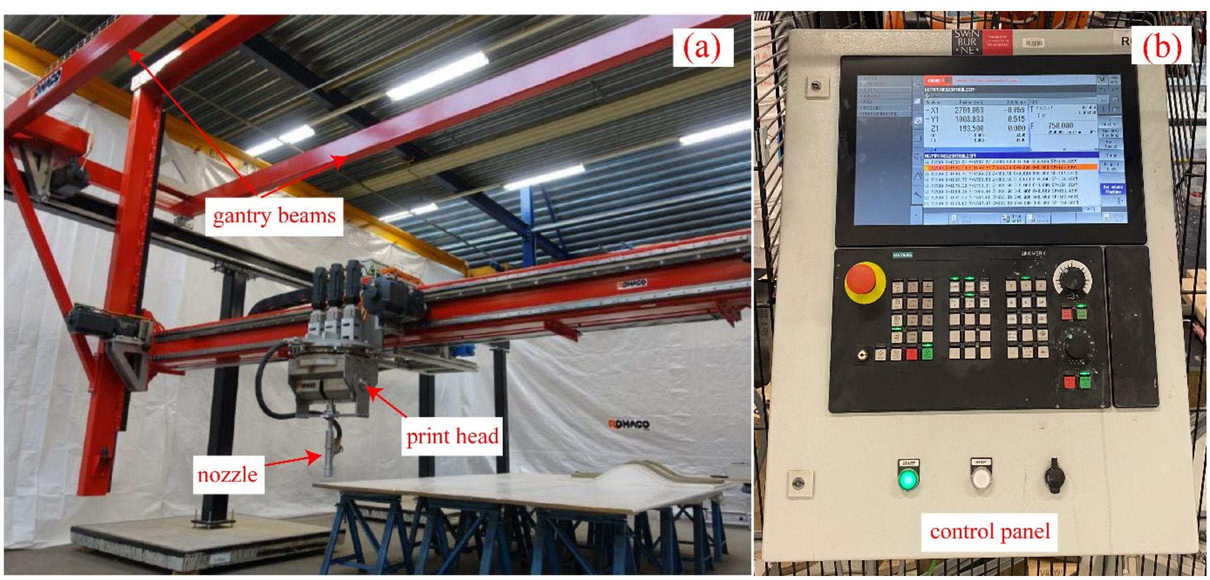

Figure 3 (a) Large-scale 3D printer (b) Control panel of the 3D printer

A twin pumping system was designed for the transfer of concrete from the mixing location to the printer. The first pump was located away from the printing area/platform and connected to the second pump via a hose. The second pump was connected to the actuator of the 3D printer and was connected to the print head via another hose. In this manner, the extrusion of the concrete was controlled at two locations simultaneously. Having multiple controls over the extrusion enables the continuous layer deposition and reduces the incidences of tearing, blockages or segregation in the concrete mixtures.

Figure 4(a) shows some of the 3D printed sections. A constant printing speed of 1.5 m/min was maintained for all printing. Soon after the completion of the printing, the sections were sprayed with a curing compound to eliminate water loss due to evaporation. The use of curing compound also avoids the restrained shrinkage in the printed sections. Figure 4(b) shows the partial assembly of the shell structure on-site.

Figure 4 (a) Some of the separately 3D printed sections of the fire shelter (b) Partly assembled fire shelter on-site

6. Fire Performance of the Shelter Panels

The 3DP-UHPC mixture design was tested for fire to ensure no spalling. Panel sections with a length of 1000 mm and a height of 230 mm were 3D printed. Each panel section is made of a single filament, having a width of 40 mm and a height of 10 mm (i.e., each panel consisted of 23 layers). At the end of 3D printing, the specimens were covered with plastic sheets to reduce excessive evaporation. The specimens were then cured for 28 days in room temperature before the fire tests. Following the curing, the panels were attached to a furnace as such that one side is exposed to the furnace heat while the other side was exposed to room temperature. The furnace temperature was set to follow the standard fire curve according to ISO 834 (ISO834-1). The experiment was conducted for 30 minutes. At the end of the tests, the specimens were allowed to cool down to room temperature without disturbance for 24 hours.

UHPC is generally susceptible to spalling due to its dense microstructure (Kodur and Banerji). Additionally, the interlayer delamination failure can be predominant in 3D printed specimens due to their weak interlayer bond strength (Cicione et al.). When the PP fibers were used at 0.5%, neither spalling nor interlayer delamination was observed in the panels, as in Figure 5. Additionally, no surface cracks were seen in the panels. Therefore, it was concluded that the panels offer sufficient resistant to standard fire tests. More analysis on the fire protection of these panels can be found here (Arunothayan and Sanjayan).

Figure 5 Exposed surface of the 3DP-UHPC specimen following the ISO 834 standard fire test

7. Conclusions

This study presents the design and production of a shell-shaped fire shelter formed by 3D printing using ultra-high performance concrete. The following conclusions can be drawn from this study.

- 3D printing a thin and architecturally attractive large-scale structure with locally developed ultra-high performance concrete was established.
- The printing of curved shell structure was controlled by the local cantilever of the printed structure. Printing the structure in multiple sections (up to a limited cantilever) and assembling them on-site can be a solution.
- The developed mixture had sufficient fire protection (i.e., neither spalling nor interlayer delamination) for up to 30 minutes.

8. Acknowledgements (Optional)

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9. References

- Alati, M., Curcio, L., Di Martino, R., Gerosa, L., Tresoldi, C., "From Natural Forms to Models." *Nexus Network Journal,* Vol. 7, 2005, pp. 18-41. https://doi.org/10.1007/s00004-005-0003-5
- Arunothayan, A.R, Nematollahi, B., Khayat, K.H., Ramesh, A., Sanjayan, J.G., "Rheological Characterization of Ultra-High Performance Concrete for 3D Printing." *Cement and Concrete Composites,* Vol 136, 2023, pp. 104854. https://doi.org/10.1016/j.cemconcomp.2022.104854
- Arunothayan, A.R, Nematollahi, B., Ranade, R., Bong, S.H. and Sanjayan, J "Development of 3D-Printable Ultra-High Performance Fiber-Reinforced Concrete for Digital Construction." *Construction and Building Materials* 257, 2020, pp. 119546. https://doi.org/10.1016/j.conbuildmat.2020.119546

- Arunothayan, A.R, Nematollahi, B., Ranade, R., Bong, S.H., Sanjayan, J.G. and Khayat, K.H., "Fiber Orientation Effects on Ultra-High Performance Concrete Formed by 3d Printing." Vol 143, 2021, pp. 106384. https://doi.org/10.1016/j.cemconres.2021.106384
- Arunothayan, A.R., Nematollahi, B., Ranade, R., Khayat, K.H. and Sanjayan, J.G. "Digital Fabrication of Eco-Friendly Ultra-High Performance Fiber-Reinforced Concrete." *Cement and Concrete Composites,* Vol. 125, 2022, pp.104281. https://doi.org/10.1016/j.cemconcomp.2021.104281
- Arunothayan, A.R, Sanjayan. J.G., "Elevated Temperature Effects on 3d Printed Ultra-High Performance Concrete." *Construction and Building Materials,* Vol 367, 2023, pp. 130241. https://doi.org/10.1016/j.conbuildmat.2022.130241
- Carneau, P., Mesnil, R., Roussel, N. and Baverel, O., "Additive Manufacturing of Cantilever-from Masonry to Concrete 3D Printing." *Automation in Construction* Vol 116, 2020, pp. 103184. https://doi.org/10.1016/j.autcon.2020.103184
- Chen, Y., He, S., Gan, Y., Çopuroğlu, O., Veer, F. and Schlangen, E., "A Review of Printing Strategies, Sustainable Cementitious Materials and Characterization Methods in the Context of Extrusion-Based 3D Concrete Printing." *Journal of Building Engineering,* Vol 45, 2022, pp. 103599. https://doi.org/10.1016/j.jobe.2021.103599
- Cicione, A., Kruger, J., Walls, R.S. and Van Zijl, G. "An Experimental Study of the Behavior of 3d Printed Concrete at Elevated Temperatures." Vol. 120, 2021, pp. 103075. https://doi.org/10.1016/j.firesaf.2020.103075
- Cortie, M., Hargittai, I., and Pickover C.A., "The Form, Function, and Synthesis of the Molluscan Shell." *Spiral Symmetry, World Scientific*, 1992 pp. 369-87.
- ISO834-1. "Fire-Resistance Tests Elements of Building Construction Part 1: General Requirements." International Organization for Standardization, 1999.
- Khayat, K.H., Meng, W., Vallurupalli, K. and Teng, L. "Rheological Properties of Ultra-High-Performance Concrete—an Overview." *Cement and Concrete Research,* Vol 124, 2019, pp. 105828. https://doi.org/10.1016/j.cemconres.2019.105828
- Kodur, V., and Banerji. S., "Modeling the Fire-Induced Spalling in Concrete Structures Incorporating Hydro-Thermo-Mechanical Stresses." *Cement and Concrete Composites* Vol. 117, 2021, pp. 103902. https://doi.org/10.1016/j.cemconcomp.2020.103902
- Mechtcherine, V., Bos, F.P., Perrot, A., da Silva, W.L., Nerella, V.N., Fataei, S., Wolfs, R.J., Sonebi, M. and Roussel, N., "Extrusion-based additive manufacturing with cement-based materials–production steps, processes, and their underlying physics: a review." *Cement and Concrete Research*, Vol 132, 2020, pp.106037. https://doi.org/10.1016/j.cemconres.2020.106037