Submillimeter Formwork

3D Printed Plastic Formwork for Concrete Elements

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Abstract

Submillimeter Formwork proposes a novel method for fabricating geometrically complex concrete parts in 3D printed plastic formwork (Figure 1). This research investigates strategies to minimize formwork material and cast concrete in such submillimeter thin formwork. To achieve this, computational methods for optimizing the fabrication speed of formwork with plastic deposition 3D printing are developed. Without any coating and post-processing steps, the plastic formwork is easily removable, recyclable and bio-degradable. The implications of submillimeter formwork are a considerable material reduction, faster off-site fabrication time for the formwork, ease of transportation to site, ease of on-site assembly and unprecedented design opportunities for free form and highly detailed architectural load-bearing components.

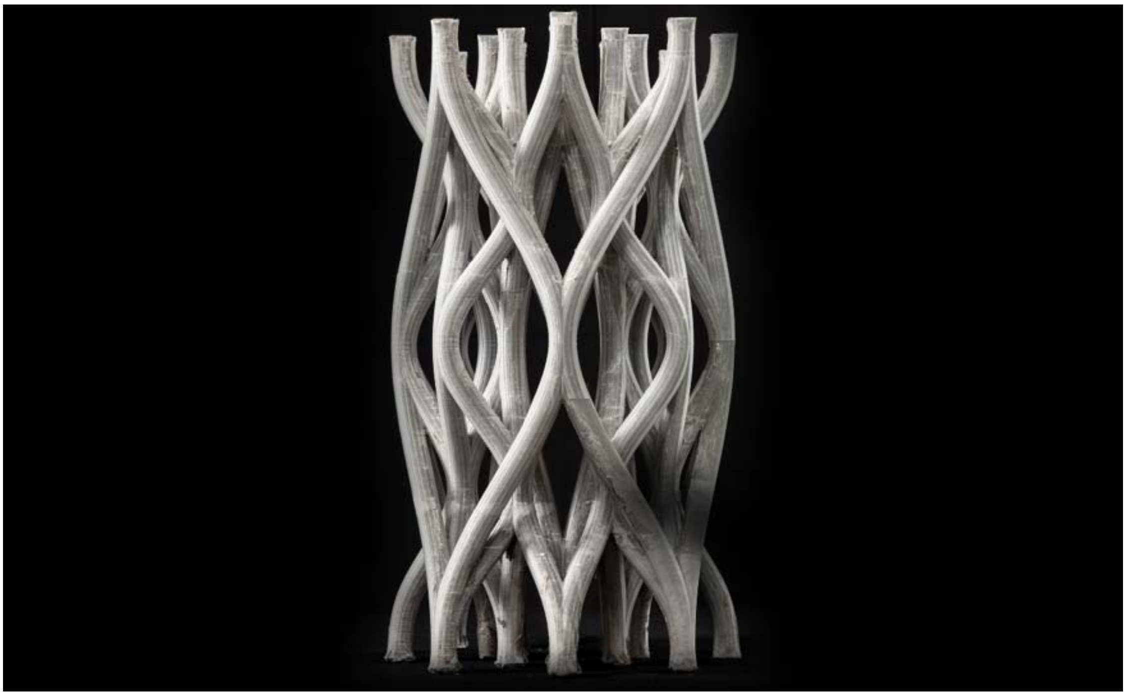

Figure 1. Prototype for an architectural concrete element cast in submillimeter formwork.

1 Introduction

With more than 10 billion tons produced each year, concrete is by far one of the most used materials in the world, second only to water (Meyer 2009). For concrete construction, formwork accounts for a significant amount of resources, both in terms of material costs and labor (Oesterle, Vansteenkiste, and Mirjan 2012). In particular, for free-form, non-standard parts, formwork resources can represent more than 50% of the whole, more than concrete and reinforcement combined (Figure 2).

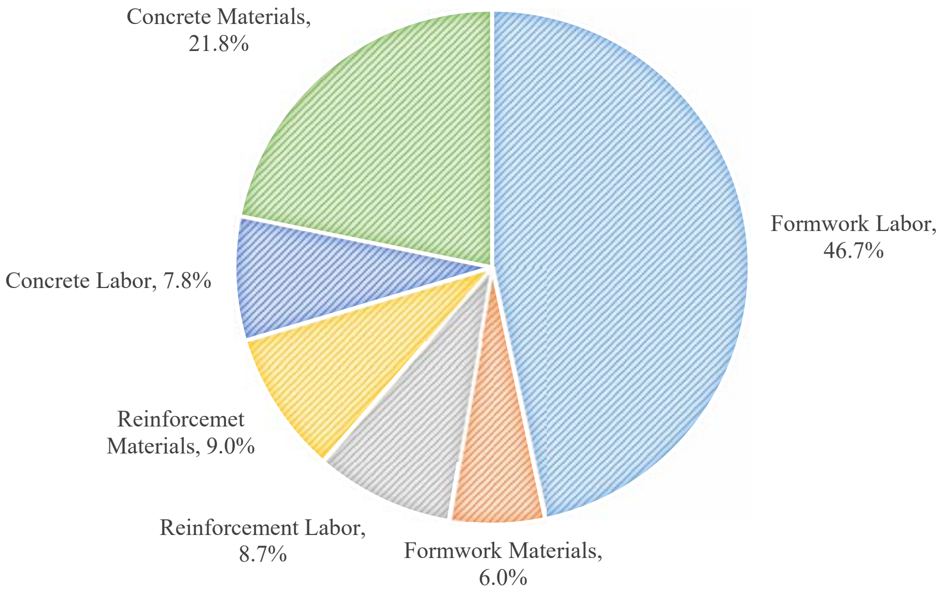

Figure 2. Breakup of costs in concrete production. Formwork accounts for roughly half the resources in terms of both labor and materials.

Given the significant importance of formwork in concrete construction, the aim of this research is to develop an efficient fabrication method for formwork that is feasible for large scale, complex concrete components. The objective is to use 3D printing to minimize the amount of material and labor used for fabricating formwork. This can have further positive effects on the sustainability of formwork, on speeding-up formwork fabrication off-site, reducing the cost of transportation, streamlining assembly on site and facilitating removal and reusability after casting.

Moreover, 3D printed formwork has an indirect benefit for the concrete components by enabling complex topologies to be cast in concrete. The geometric freedom that concrete elements inherit from the 3D printed formwork has significant potential benefits for concrete architectural components:

- Considerable material reduction through computational topology optimization algorithms, which result in complex geometries (Jipa et al. 2017).
- Integration of additional functionality, such as acoustics, thermal activation and services.
- Smart integration of construction and assembly logics that streamline on-site fabrication.
- New design possibilities for free-form geometries and high resolution ornamental surface articulation (Dillenburger and Hansmeyer 2013).

Production of formwork for non-standard concrete elements is generally done by robotic hot wire cutting or CNC milling of foam blocks (Søndergaard, Amir, and Knauss 2013). Lightweight formwork can also be produced with fabric (Veenendaal, West, and Block 2011). However, these approaches are resource-intensive as regards necessary time and labor (milling tools are slow and fabrics require extensive patterning) and have limitations regarding the geometries that can be produced (e.g. no undercuts for milling, and only smooth anticlastic surfaces for fabrics).

To overcome these limitations, different 3D printing technologies have already been proposed for formwork, such as binder jetting of sand (Aghaei-Meibodi et al. 2017). Binder jetting is particularly interesting because of its great level of geometric flexibility. However, certain formwork features, such as long tubular structures and thin walls are difficult to achieve because of the stability of the material and the necessary post-processing steps.

Another 3D printing technology, fused deposition modelling (FDM) has also been proposed for fabricating formwork (Peters 2014). However, there are some inherent characteristics of FDM 3D printing that need to be addressed in order to make it feasible for large scale fabrication. In particular, the stability of the plastic formwork during casting and the optimization of the 3D printing process are investigated in this research.

The research question posed by *Submillimeter Formwork* is if geometrically complex structural concrete parts can be produced with minimal recyclable formwork and how FDM 3D printing can be used to achieve this goal.

2 Methods

FDM is a widely available 3D printing technology in which molten material is extruded and hardens immediately after the deposition. The deposition happens in consecutive horizontal layers which are generated as slices through a digital model of the part to be fabricated. Because of the nature of the process –where the build material solidifies and cools down quickly– a limitation of this technology is dimensional accuracy caused by uneven shrinkage during thermal contraction. Shrinkage is a function of the total volume of plastic:

$$dV = \mathbf{V_0}\ \beta\ dt$$

where dV = shrinkage in m^3
V_0 = initial volume of the formwork in m^3
β = volumetric thermal coefficient of PLA in $^oC^{-1}$
dt = temperature variation in ^oC

The overall time necessary for the 3D print is also a function of the volume of formwork:

$$t = \mathbf{V} / Q$$

where t = 3D printing time in s
V = total volume of the formwork in m^3
Q = volumetric flow rate of the 3D print in m^3/s.

By reducing the total volume of formwork material to the thinnest skin possible, both the 3D printing time and thermal shrinkage are reduced to a minimum.

Furthermore, despite these fabrication challenges, among the different 3D printing technologies, FDM is unique for its capability of producing in large scale parts with very thin geometric features, such as walls as thin as 0.4 mm. This section presents how the plastic 3D printing and the concrete casting processes can be optimized to enable the fabrication of submillimeter formwork.

2.1 3D Printing Formwork

FDM is a relatively slow 3D printing process, usually able to produce volumetric flowrates of 15 cm^3/hour and resolve 0.1mm features. With well-tuned machines, flowrates as high as 100 cm^3/hour can be reached, but resolving power increases to 0.2 mm.

A critical factor in achieving such high flowrates is the material used. FDM has access to a wide variety of plastics (biodegradable, water soluble, fiber-reinforced, flexible, conductive, low-shrinkage, bioplastics etc). In order to achieve a balance between fabrication speed, quality and shrinkage, different materials were tested, and translucent polylactic acid (PLA) was selected for its versatility and low shrinkage factor (Figure 3).

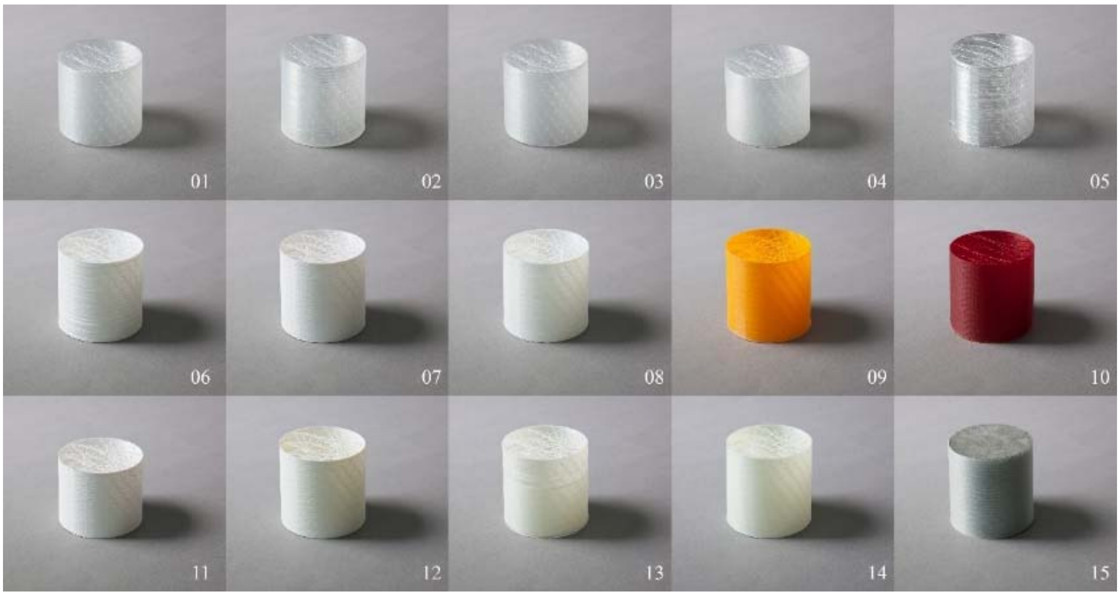

Figure 3. Different thermoplastics tested for finding a balance between printing speed, quality and shrinkage. From the highest printing speeds achieved to the lowest: natural polylactic acid (01); natural polylactic acid/polyhydroxyalkanoate blends (02-04), polyethylene terephthalate glycol-modified (05, 06), polylactic acid with pigments (07-10), polyvinyl alcohol (11), BDP Green-Tec™ (12-15).

While flowrates of PLA can be further increased through mechanical improvements of the hardware, the focus of this research is to speed up the 3D printing process on the software side, by generating an optimal tool-path that controls the movements of the 3D printer tool-head.

2.2 Optimized 3D Printing Tool-paths

Tool-paths are generated from horizontal slices through a CAD model of the part to be 3D printed. A custom slicing tool was developed for optimizing the travel distances between the different contours in each horizontal slice. The contours are sorted with an efficient algorithm that minimizes the distances between consecutive contours (Figure 4). In order to compute this optimization problem, each layer is interpreted as a complete weighted graph, where the graph nodes are contours and the graph weights are distances between contours. The problem is a variant of the classic travelling salesman algorithm where the shortest toolpath (i.e. minimum-weight Hamilton circuit) has to be computed for the given graph (Lin and Kernighan 1973). To compute the shortest toolpath, a heuristic method is used, the nearest neighbor algorithm (NNA).

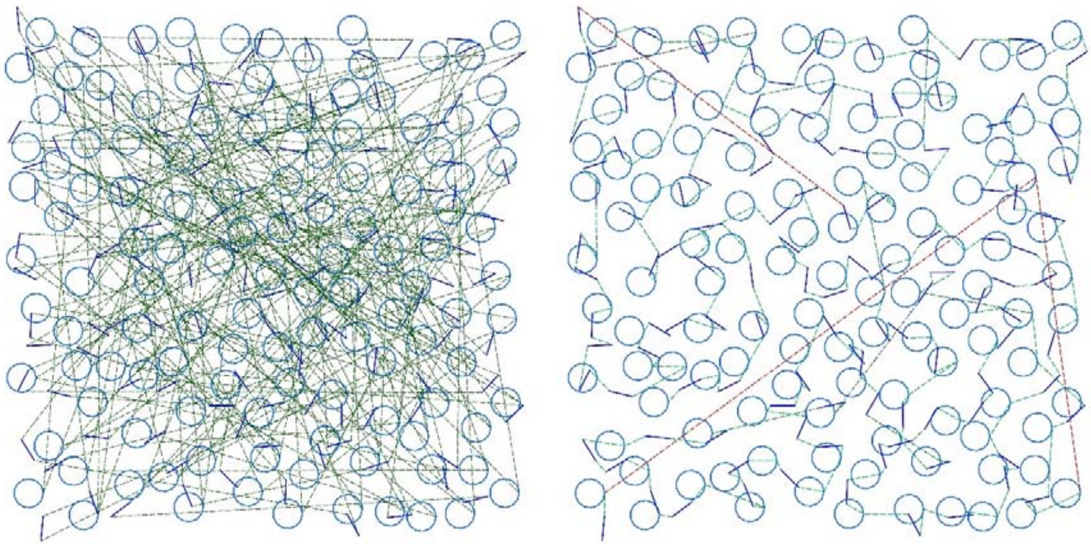

Figure 4. A slice through a CAD model with 100 lines and 100 circles as contours. In a random order, this configuration generates a very long, inefficient tool-path (left). The NNA arranges the 200 contours in an order that minimizes distances between consecutive contours (right).

With NNA, global optimal solutions may be missed because it is a greedy algorithm (it relies on finding the local optimal choice at each step). However, statistically, this deviates from the brute force optimal solution (i.e. optimal found by iterating all possibilities) by an amount that can be ignored, considering that brute force becomes impractical even for graphs with as little as 10 nodes.

Specific features which differentiate this algorithm from a generic NNA include:

- For each graph node that is a closed contour, the seam point can be adjusted in order to find the shortest path at the current step (Figure 5A).
- For each graph node that is an open contour, both ends are compared in order to find the shortest travel distance at the current step and the direction of the contour can be reversed (Figure 5B).
- For each graph weight, a penalization factor is introduced that takes into account the attack angle α between the incoming and outgoing direction of the tool-head:

$$p = 2 \cdot (1 - \alpha / \pi) \cdot (v_{max} - j) / a_{max}$$

where p = penalization factor
α = change in direction in radians
v_{max} = feed-rate of the tool-head in mm/s
a_{max} = maximum acceleration of the tool-head in mm/s^2
j = jerk of the tool-head in mm/s.

This accounts for the fact that the tool head has to slow down more to negotiate tighter direction changes. Deceleration and acceleration times have to be taken into consideration when calculating the total weight of the Hamilton circuit (Figure 5C).

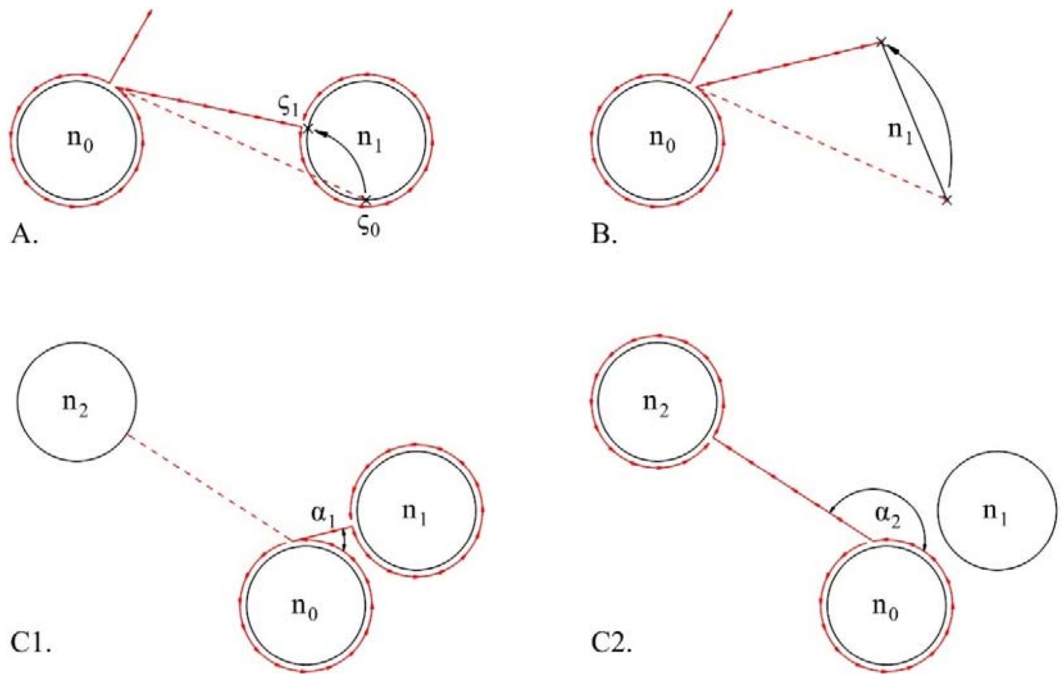

Figure 5. Aditional features of NNA. The tool-head first prints contour n_0. When traveling to n_1, the algorithm can: A. adjust the starting point ς of closed contours; B. flip open contours; and C. calculate the loss in speed due to direction changes. Angles α_1 for contour n_1 and α_2 for n_2 are used to calculate a penalization factor.

2.3 Concrete Casting in Submillimeter Formwork

Ultra-high performance concrete (UHPC) reinforced with 10 mm long steel fibers was used (Aghaei-Meibodi et al. 2017). This satisfied the necessary rheological requirements to flow through tubular geometric features as thin as 10 mm in diameter used in a series of prototypes (Figure 6).

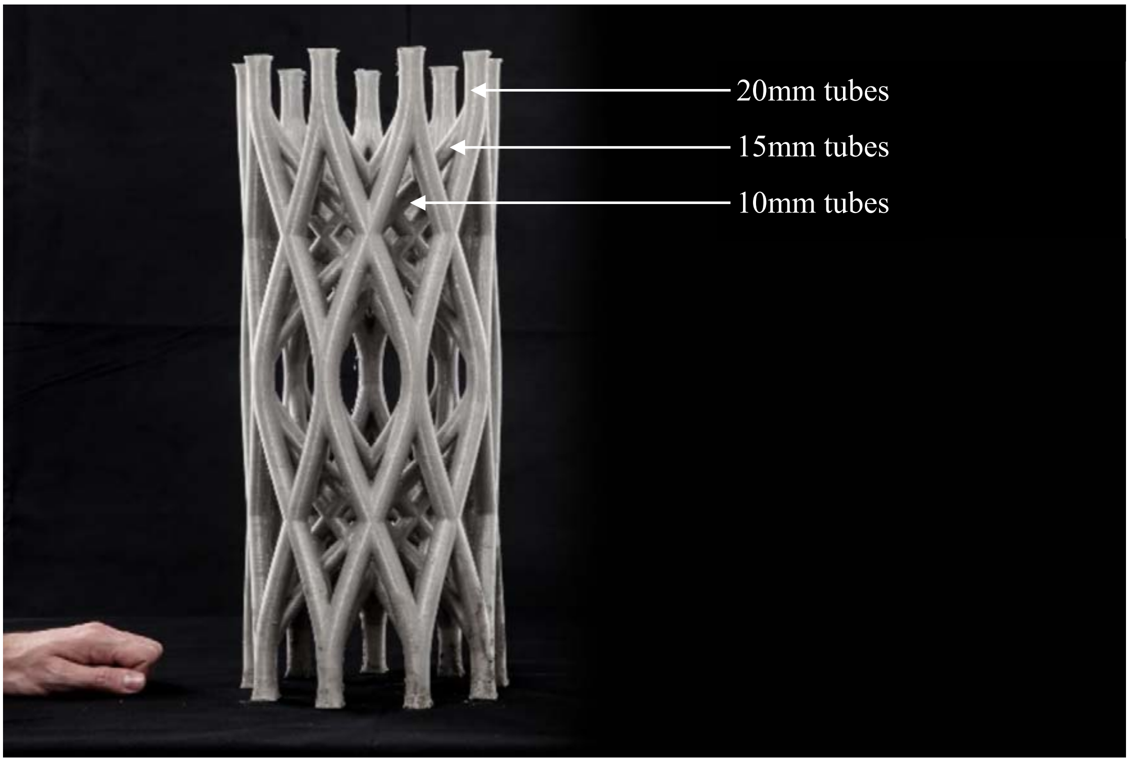

Figure 6. Concrete prototype using 3D printed formwork displaying microtubular structures as small as 10mm in diameter.

The early prototypes revealed that one of the critical issues related to concrete casting is the build-up of hydrostatic pressure. The hydrostatic pressure is the maximum stress that is exerted by the concrete uniformly on the thin formwork. Hydrostatic pressure is only dependent on the density of UHPC and the depth of the cast:

$$p = \rho \cdot g \cdot h$$

where p = hydrostatic pressure in N/m^2
g = gravitational acceleration in m/s^2
h = depth of the cast UHPC column in m.

The very thin PLA formwork is unable to withstand the hydrostatic pressure of the dense UHPC ($\rho \sim 2{,}350\ Kg/m^3$) for depths larger than ~100mm. The breaks in the formwork generally happen along the contact surface between consecutive 3D printed layers, where there is a weak interface and lower tensile strength. In order to overcome this, several strategies have successfully been tested:

- Submerging the formwork in a bed of sand. The sand acts with a counter-pressure on the formwork which cancels out the hydrostatic pressure from the UHPC. Breaks are also neutralized by the sand which consolidates the part locally and prevents further concrete leaks.

- Submerging the formwork progressively in water. This method also provides a counter-pressure on the outside of the form, but has the advantage of keeping the casting process visible throughout. In combination with the transparent PLA, this is an important tool for monitoring the casting process for very challenging thin geometric features (Figure 7).
- Coating the formwork with organic resins to increase its strength. Clear epoxy or polyester resins have been used to make the formwork waterproof in addition to the two methods illustrated above.

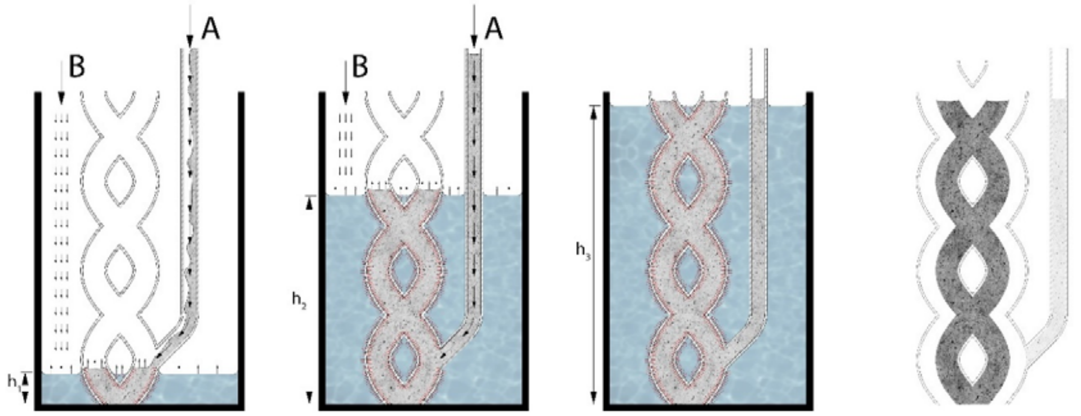

Figure 7. Step by step diagram showing the simultaneous infill of concrete through the bottom of the formwork (A) and of counter-pressure material (B - sand or water). The final step consists of the removal of the formwork and casting inlet.

Following the concrete casting, the PLA formwork provides the perfect enclosure for concrete curing, preventing cracking due to water loss. A heat-gun is used to supply moderate heat (~200ºC) and the formwork peels off of the concrete on its own (Figure 8). After the removal, PLA can be combusted, composted or recycled.

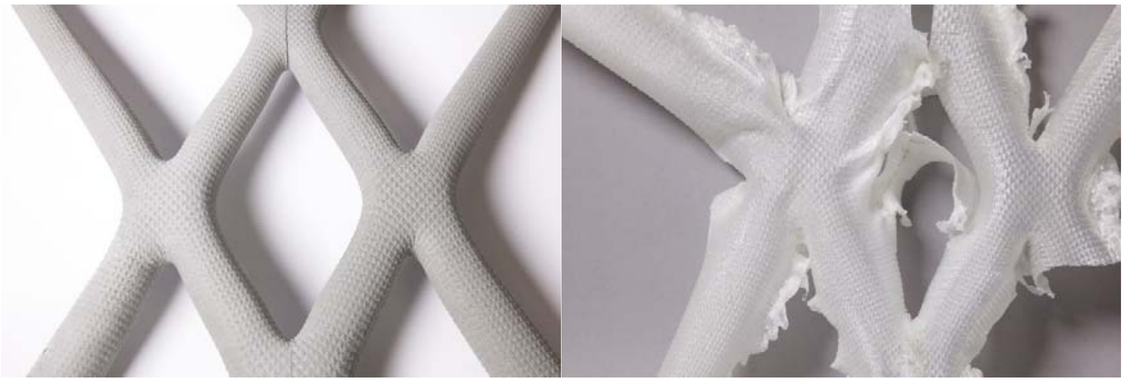

Figure 8. Concrete component displaying high resolution texture (left) after the submillimeter plastic formwork has been removed (right).

Ongoing research is investigating alternative methods for the formwork removal, such as using polyvinyl alcohol as a 3D printing material. This can be removed easily because it is water-soluble, but the interaction with the hydration process of concrete needs to be tested further.

3 Results

The method presented above optimizes fabrication times through a custom tool-path generation algorithm for 3D printing. Several commercial slicer tools do exist, but they produce tool-paths that take at least twice as long to be 3D printed (Figure 9).

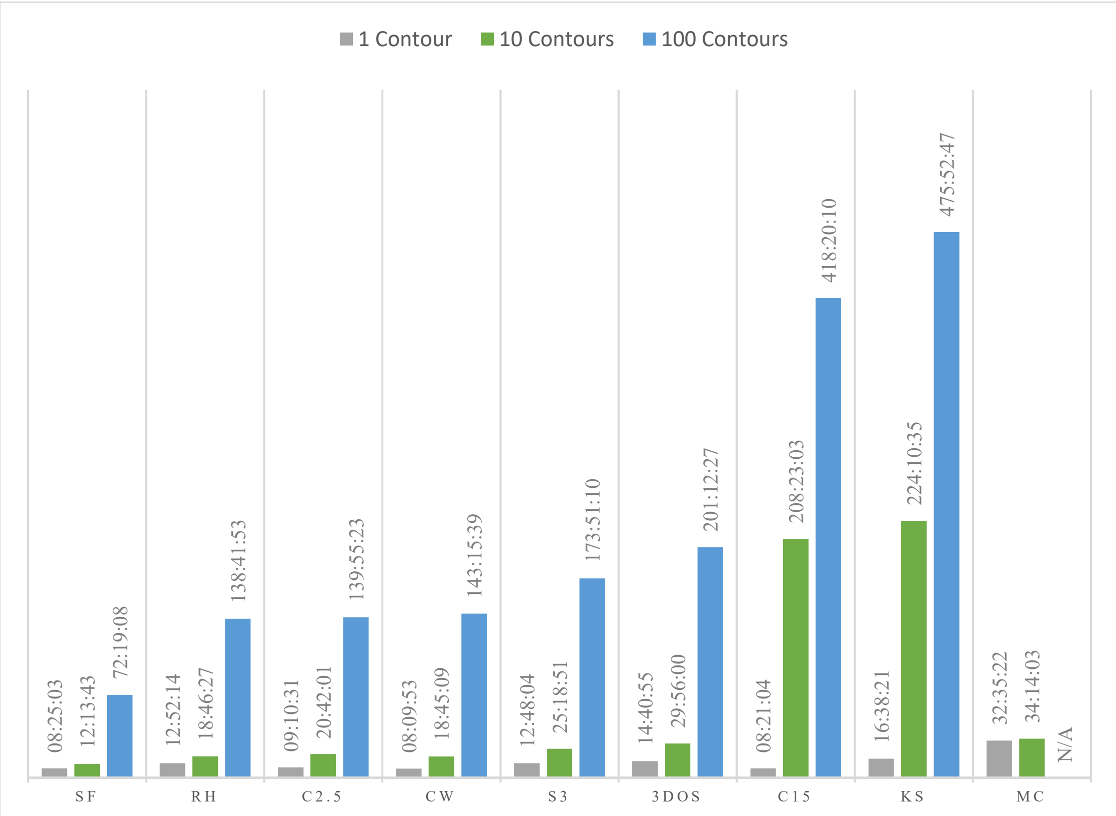

Figure 9. Comparison of printing times (in hours:minutes:seconds) of tool-paths generated with different commercial slicers. Three different digital models with 1, 10 and 100 contours each were used for benchmarking. The printing time improvement for the custom slicer developed for Submillimeter Formwork (SF) is significant, especially for the model with 100 contours where the fabrication is at least 50% more economical compared to Repetier Host 2.0.1 (RH), Cura 2.5x64 (C2.5), Craftware 1.14 (CW), Slic3r 1.2.9 (S3), 3DPrinterOS.com (3DOS), Cura 15.04 (C15), KissSlicer 1.5x64 (KS) and MatterControl 1.4 (MC).

Using such a thin shell as concrete formwork presents a number of challenges. Apart from the thermal shrinkage and the fabrication speed, the research so far has identified challenges where further investigation is needed:

- The focus so far has been on parts which fit the size of a 3D printer. In order to fabricate larger parts, strategies for segmentation and connection need to be considered.
- Geometric limitations of the concrete casting and FDM processes have been identified empirically. An optimization process could address the limitations of the two processes and integrate geometric adjustments that make fabrication possible.
- The structural performance of the components needs to be tested. Of particular interest is the orientation of the steel fibers in the intricate narrow tubes. A computational fluid dynamics simulation could give some insight in this regard.

4 Conclusion

This paper presented a method for producing complex, free-form and non-standard concrete elements with minimal, submillimeter formwork (Figure 10). The novelty is twofold: on the one hand an optimized 3D printing process for the formwork and on the other hand a casting process that is suitable for such fragile formwork. This method promises a more sustainable construction process, with no waste material, an easier on-site assembly with lightweight formwork, as well as a greater design freedom for concrete elements. The method relies on reducing the precious 3D printed formwork to a minimal skin that provides the complex shape, while the stability of the cast is provided by an ordinary material such as sand or water, which does not need digital fabrication.

Figure 10. Prototype for an architectural concrete element cast in submillimeter formwork.

The next step in the research is to address the challenge of scaling this process up. In order to test this, a four-meter-long, full-size, functional canoe has been designed and will be fabricated with the proposed method. The canoe has a complex load-case (water hydrostatic pressure, concentrated loads from the two paddlers, as well as a separate load-case for transportation on land) which make it a relevant study for scaling the method up to architectural applications. In such architectural settings, this method opens new design possibilities for building elements with functional inner porosity, intricate surface qualities for functional or ornamental purposes and integrated assembly logic.

5 Acknowledgements

The authors would like to thank a number of partners and collaborators whose dedication helped us fulfill the research described in this paper. Should this paper be selected for the conference, an extensive list will be included for the final submission.

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