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3D Printed Plastic Formwork for Load-Bearing Concrete Structures

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Abstract

The imperative need for complex geometries in architecture is driving innovation towards an unconstrained fabrication freedom in building components. Fabrication constraints are a critical obstacle when material efficiency through complex, optimized topologies is sought. To address this constraint, this research investigates the use of 3D printed plastic formwork for fibre reinforced concrete at large scale. This novel construction method makes complex topologies and precise details possible for full-scale, load bearing structures. To demonstrate its potential applications, SkelETHon —a functional four-meter-long concrete canoe— was designed, built and raced in a regatta on the Rhine river (Figure 1).

Figure 1: skelETHon, the four-meter-long canoe made entirely out of concrete. (DBT, ETH Zürich, 2017)

Keywords: Concrete; 3D Printing; Formwork; Digital Fabrication; Canoe;

Introduction

With serious concerns regarding the vulnerable state of the environment, material efficiency is becoming a critical design driver in architecture. This is especially relevant for materials that are difficult to recycle, such as concrete.

Concrete is of particular relevance in relation to material efficiency because it is by far the most used construction material in the world, being used twice as much as all the other construction materials combined (Crow, 2008). Moreover, the amount of concrete used annually is predicted to double in the next thirty years.

The reason why concrete is used in such vast amounts is its versatility, which allows it to be used in a wide variety of environments and applications. Concrete is celebrated by architects because it can be cast into any shape and thus it is in theory capable of materializing almost any imaginable geometry. Given this capability, considerable material savings can be achieved by manipulating the geometry of structures and distributing material precisely where it is most needed, without affecting, or sometimes even improving the overall performance and functionality.

Given the significant share that concrete has in the construction industry, the ability to optimize concrete structures for reducing material use can have a global impact in releasing pressure from natural resources and reducing the carbon footprint of buildings and infrastructure.

Designing with material economy as a goal can be achieved through ribbings, porosity gradients, hierarchical articulations, venations and other similar geometric features which are associated with the rise of computational form-finding tools such as volumetric modelling and topology optimization. However, this excellent potential of concrete is limited by the ability to fabricate the necessary formwork.

Formwork

"…although reinforced concrete has been used for over a hundred years and with increasing interest during the last decades, few of its properties and potentialities have been fully exploited so far. Apart from the unconquerable inertia of our own minds, which do not seem to be able to adopt freely any new ideas, the main cause of this delay is a trivial technicality: the need to prepare wooden frames." (Nervi, 1956, p. 56).

This paper describes a method that aims to overcome the limitations of the traditional wooden formwork described by Nervi and unlock the full geometric potential of concrete.

Concrete components with non-standard geometries are investigated in this research for reducing material use in large-scale, functional, load-bearing concrete structures. Formwork free from geometric limitations can open up the possibility of mass customization of concrete components for their specific context, boundary conditions and load cases.

Aside from its key role in defining the shape of concrete structures, formwork is also a critical topic in concrete construction because it is the source of roughly 50% of the overall costs —more than the costs of cementitious materials, aggregates, additives, reinforcement and labour combined (Johnston, 2008). For one-of-a-kind, non-standard shapes, the costs of formwork can be even more significant.

Digital Formwork

Architects designing topologically complex concrete elements with material economy in mind are therefore facing the limitations of the available formwork fabrication methods. A compromise has to be made between material efficiency and formwork fabrication costs.

To aid in this dilemma, digital fabrication of formwork is already being investigated. Production of formwork for non-standard concrete elements can be done by CNC milling of foam blocks (Søndergaard & Dombernowsky, 2011), actuated moulds (Oesterle, Vansteenkiste, & Mirjan, 2012), robotic extrusion (Hack, Lauer, Langenberg, Gramazio, & Kohler, 2013), robotic hot wire cutting (Rust, Jenny, Gramazio, & Kohler, 2016), or robotic welding (Hack & Lauer, 2014). Certain types of lightweight formwork can also be produced with fabric (Veenendaal, West, & Block, 2011). However, all these approaches are resource-intensive as regards the necessary time and labour (robotic cutting and milling tools are slow and wasteful processes, while fabrics require extensive patterning) and have limitations regarding the geometries that can be produced (e.g. no undercuts for milling, provision for collision-free robotic tool-head access paths, only ruled surfaces for wire-cutting 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, Bernhard, Jipa, & Dillenburger, 2017). Binder jetting is particularly interesting because of its precision and great level of geometric flexibility. Still, certain geometric features, such as long tubular voids are difficult to achieve because of the necessary post-processing steps, such as unconsolidated sand removal and surface infiltration for stability. Moreover, due to the frail nature of the 3D prints, very thin free-standing features, such as millimetre-thick shells are also a challenge.

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.

This research builds up on the state-of-the-art of 3D printed formwork with the objective of making this possible for a building-scale element. In particular, the research goals are concerning the optimization of the 3D printing process and the stability of the plastic formwork during casting.

Methodology

To pursue the goals above, the methodology follows the design and fabrication process of a four-meter-long functional concrete canoe, dubbed skelETHon. This demonstrates how even for complex load-cases, an optimized geometry can facilitate material reduction and effectively enable a concrete boat to be light enough to float and carry the load of two people.

Why a Concrete Canoe?

At a first glance, a concrete canoe may seem a parody project of sorts, but it is in fact a well-respected international phenomenon, attracting crowds of hundreds of participants at biennial regatta events around the world. While also a sporting event, it mainly draws scientific interest in demonstrating innovations in concrete construction methods. The canoe regattas in Germany have been over the years stepping stones for research projects which have since become valuable contributions to the scientific community, like Mesh Mold (Hack & Lauer, 2014) and Smart Dynamic Casting (Shahab et al., 2013).

Apart from a similar scale to building components, a canoe has complex load-cases, which makes it a representative case study for buildings and infrastructure. The canoe has to be designed for the floating load-case in water (self-weight, live load from two people, hydrostatic pressure) as well as for a transport load-case on land (two support points and self-weight).

When designing a canoe, two aspects have to be considered: structural integrity and waterproofing. Inspired by traditional wood and canvas canoes, these two functions are separated in two different construction layers:

a. The waterproofing of the canoe is ensured by a two-millimetre thick outer "skin" made of concrete coated on cotton reinforcement.
b. The structural integrity is provided by an inner "skeleton" (Figure 2) which is fabricated using a 3D printed formwork, documented in this paper.

Figure 2: The complex concrete "skeleton" which provides the structural integrity for the canoe (DBT, ETH Zürich, 2017)

Design through Topology Optimization

The starting point of the design was a traditional wood and canvas canoe (Miller, 2014). The outer shape of this canoe was used as an input for a topology optimization algorithm aiming to reduce the amount of material used.

Topology optimization is an iterative computational process which can be used to find the most efficient spatial configuration in which material has to be distributed in order to maximize certain performance criteria (Figure 3). The algorithm works within a confined, discretized space, with a set of given loads and supports.

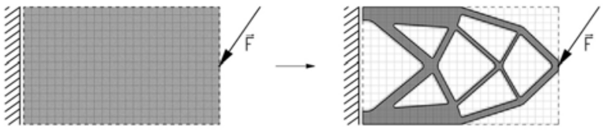

Figure 3: Sample topology optimization of a simple rectangular piece with a single point load (left). After the topology optimization, only 30% of the material is kept and distributed in order to minimize the deflection of the part (right). (DBT, ETH Zürich, 2017)

For SkelETHon, the TOSCA engine of SIMULIA Abaqus was used to perform a simple topology optimization. The design space was discretized into 3x3x3cm^3 cubic nodes. The supports and loads were defined for the two separate load cases as described above. The optimization goals were to reduce material to a 0.15 set fraction of the initial volume while keeping to a minimum the strain energy of each node. The parameters used in the algorithm to describe the behaviour of concrete were a density of 2,400 Kg/m^3, a Young's modulus of 50 GPa and a Poisson ratio of 0.2. The compressive and tensile strengths of concrete can be used in the algorithm to constrain the optimisation to safe results.

Topology optimisation is used as an initial form-finding design tool and the result is interpreted as described by Kim and Baker (Kim & Baker, 2002). It features a typical family of geometric features, with a porosity gradient defined by an interconnected network of ribs and narrow tubes (Figure 4).

The raw result of the topology optimization is refined with the aid of volumetric modelling. Principal topological axes crystalize roughly as dense conglomerates of nodes in the topology optimization. These axes are then extracted as a cage of NURBS curves in order to smoothen the geometry and eliminate discretization artefacts. At this stage, the axes can be adjusted slightly to tailor for any constraints of the fabrication process. For example, in areas with lower density, additional axes are introduced to provide an adequate support for the "skin".

The NURBS cage is then converted into a solid mesh geometry with the aid of a custom volumetric modelling tool. This allows the precise control of the node geometry and of the smooth tubes. The tubes have variable diameters, classified into three groups, depending on the amount of stress they undertake: 15, 25 and 35 mm.

Figure 4: The complex concrete "skeleton" displaying an intricate network of narrow tubes. (DBT, ETH Zürich, 2017)

FDM 3D Printing

For the fabrication of the skeleton, FDM 3d printing was used first to produce the formwork. 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.

FDM has access to a wide variety of plastics (biodegradable, water soluble, fibre-reinforced, flexible, conductive, low-shrinkage, bioplastics etc). Translucent polylactic acid (PLA) was selected for its versatility, low shrinkage factor, relatively good mechanical properties and environmentally-friendly pedigree (PLA is compostable, recyclable and based on renewable raw materials). PLA is also not sensitive to environmental factors (humidity and temperature) and it can be 3D printed in a wide domain of parameters, at temperatures between 180 and 240^{O}C, with feed-rates up to 300mm/s.

In particular for skelETHon, FDM was chosen because among the different 3D printing technologies, it is unique for its capability of producing very thin shells with precise geometric features in large scale.

FDM can resolve details with a precision of a tenth of a millimetre. This made possible the integration of a very fine functional surface texture on the formwork, in the range of 0.5 to 2 mm. This texture was introduced to increase the contact area between the skeleton and the waterproofing concrete layer.

Despite all its advantages however, FDM 3D printing also has a number of limitations which are addressed by this research separately:

a. The relatively slow speed of the 3D printing process, usually able to produce volumetric flowrates of 15cm^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 (i.e. less precision).
b. The limited build volume of the 3D printers required a discretization of the whole canoe in smaller parts which have to be assembled prior to casting.
c. The inherent fabrication limitations of FDM 3D printing which limit how much layers can cantilever in relation to each other (Figure 5).

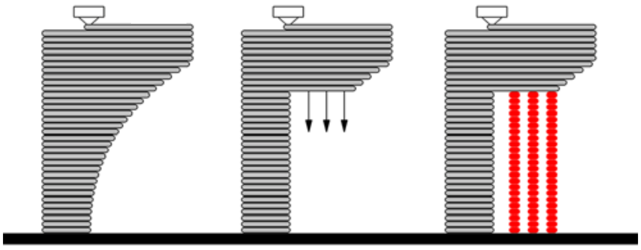

Figure 5: Fabrication limitations of FDM 3D printing. Below a certain threshold, horizontal layers can cantilever freely (left); Beyond this threshold, gravity would cause deformations and artefacts (middle); this can be resolved by introducing auxiliary temporary supports that are removable. (DBT, ETH Zürich, 2017)

Submillimetre Formwork for Concrete

In order to address the slow fabrication speeds, the unique capabilities of the FDM process were exploited to radically reduce the thickness of the formwork shell to submillimetre dimensions. For FDM technology, fabrication time is directly proportional with the volume of the part. Therefore, by producing a 0.8mm thin shell, the overall 3d printing volume was reduced to a minimum and this had a considerable impact on the overall printing time. By comparison, even the thinnest binder-jetted formworks are roughly ten times thicker (Aghaei-Meibodi et al., 2017).

Such an extreme reduction in the thickness of the formwork has further implications:

a. It minimizes tolerances and maximizes dimensional accuracy due to reduced thermal shrinkage, which is also directly dependent on the overall printed volume.
b. Considerable material reduction and lower embedded energy of concrete construction overall, given the significant proportion of resources that the formwork represents.
c. Without any coating and postprocessing steps, the plastic formwork is easily removable.
d. Reduced labor and stream-lined construction process: faster off-site fabrication time for the formwork, reducing the cost of transportation to site, ease of on-site manipulation and assembly.

Formwork Fabrication

Early fabrication tests have shown that in order to prevent 3D printing artefacts such as disconnected layers, over- or under-extrusion and local material deposits, the spatial orientation of the hollow formwork tubes had to be at least 35^{O} as measured from a horizontal plane. This prevented the need to 3D print auxiliary support structures as described in Figure 5, which would have increased printing time unnecessarily.

In order to suit this constraint, a shape optimization step was performed following the topology optimization, in which the angles of the tubes were adjusted to avoid very low inclinations (Figure 6).

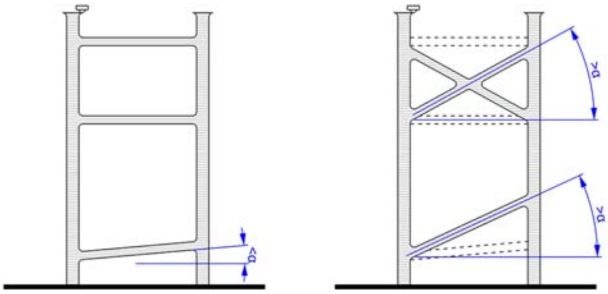

Figure 6: Diagrammatic section through a 3D printed part. In order to avoid auxiliary supports, the tubes are adjusted to achieve a minimal angle of 35º. (DBT, ETH Zürich, 2017)

Another early empirical observation was that for taller parts, the movement of the gantry of the 3D printer caused vibrations which had a negative effect on the quality of tall and thin free-standing tubular parts. In order to prevent this, an auxiliary membrane-like support structure was parametrically introduced. This temporary support interconnects all the tubes in order to increase the stiffness of the part and reduce vibrations while printing (Figure 7).

Figure 7: A 700mm tall sample 3D printed part of the SkelETHon formwork. In order to prevent quality issues for taller parts, a membrane-like auxiliary support structure is introduced. (DBT, ETH Zürich, 2017)

Discretization

In order to address the limited volume of the 3D printers, the whole geometry was discretized into 84 parts fitting the bounding box of the largest available printer: $30x30x60cm^3$ (Figure 8). Due to the two planes of symmetry of the boat, there were only 21 unique parts with their mirrored transformations which had to be printed four times each.

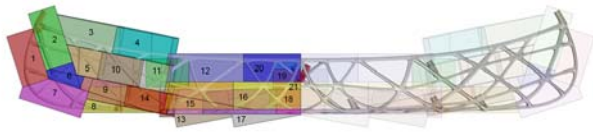

Figure 8: The 21 unique parts of the formwork which had to fit the maximum volume of the 3D printers. (DBT, ETH Zürich, 2017)

Due to the intricate geometry, the size of the parts varied considerably, with bounding box volumes between 3.1l and 25.9l. This opened the opportunity to use smaller 3D printers for the smaller parts in order to distribute the fabrication time. Each part took between 4.5 hours for the smallest and 56 hours for the largest pieces, with an overall printing time of just under 1,000 hours.

Before casting the skeleton, the independent pieces had to be joined together (Figure 9). This was done through chemical welding with dichloromethane, which is a solvent for PLA. A special detail was integrated at each of the connections providing a wider welding area. This detail is visible at the top of the component in Figure 7. The solvent is applied locally with a brush and dissolves the PLA on both sides of the connection. The dichloromethane is highly volatile and it evaporates in a few seconds, leaving a solid connection purely made out of PLA.

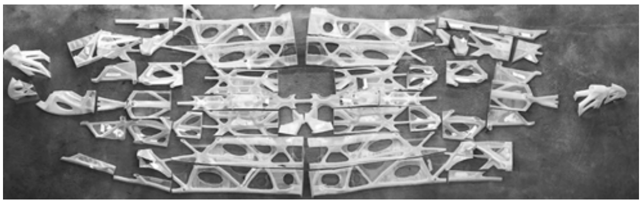

Figure 9: The 84 3D printed pieces before assembly. (Moritz Studer, ETH Zürich, 2017)

Finally, once the skeleton was assembled, a layer of epoxy resin was applied on the surface in order to increase its stability while casting (Figure 10).

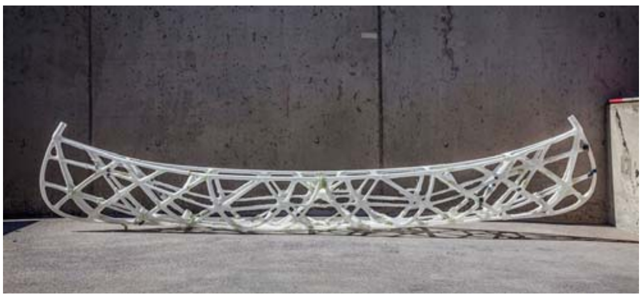

Figure 10: The 84 3D printed pieces assembled and ready for casting. (DBT, ETH Zürich, 2017)

Concrete casting

For the casting process, ultra-high-performance concrete reinforced with ten-millimetre-long steel fibres (UHPFRC) was used (Aghaei-Meibodi et al., 2017). This satisfied the necessary rheological requirements for the concrete to flow through the very thin tubular geometric features of the canoe.

One of the critical issues related to concrete casting in submillimetre formwork is the build-up of hydrostatic pressure. The hydrostatic pressure is the maximum stress that is exerted uniformly by the concrete on the formwork. Hydrostatic pressure is only dependent on the density of UHPC and the depth of the cast, and it is independent of the diameter of the formwork tubes.

The very thin PLA formwork is unable to withstand the hydrostatic pressure of the dense UHPC used (ρ ~ 2,350 Kg/m^3) for depths larger than ~100 mm. 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, the formwork is submerged gradually in a bed of sand (Figure 11). The sand acts with a counter-pressure on the formwork to cancel out the hydrostatic pressure from the UHPC. Breaks are also neutralized by the sand which consolidates the part locally and prevents further concrete leaks. The inlets for the concrete filling process are located at the bottom of the piece which means that the level of the concrete rises uniformly. The transparent formwork permits a visual inspection of the filling process to prevent air bubbles being trapped at node points. As the concrete level reaches higher points, the sand bed on the outside is gradually filled to provide the necessary counter-pressure.

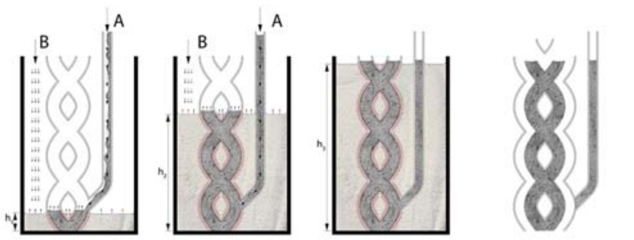

Figure 11: Step-by-step diagram showing the simultaneous infill of concrete through the bottom of the formwork (A) and of counter-pressure material (B). The final step consists of the removal of the formwork and casting inlet. (DBT, ETH Zürich, 2017)

Following the concrete casting, the PLA formwork provides the perfect enclosure for concrete curing, preventing cracking due to water loss. After curing for seven days, a heat-gun is used to supply moderate heat (~200ºC) and the formwork peels off of the concrete on its own (Figure 12).

Figure 12: UHPFRC prototype (left) after the removal of the submillimetre formwork (right). (DBT, ETH Zürich, 2017)

Discussion

The boat took part in the 16th Concrete Canoe Regatta, which took place in June 2017 in Cologne, Germany. Approximately 1,000 participants registered 90 concrete boats and raced them for 200 m on a facility on the Rhine river (Figure 13). The competition is a recognized event, with Lafarge-Holcim and Sika being among the sponsors. skelETHon received the first prize for design innovation.

Figure 13: SkelETHon at the 16th Concrete Canoe Regatta in Cologne, Germany (DBT, ETH Zürich, 2017)

The design and fabrication process of this canoe highlighted the harmonious compatibility which exists between the additive digital fabrication process and the topology optimization used for form-finding purposes.

The key achievement was to keep the thickness of the formwork in the 0.6 to 1 mm range in order to minimise material use and keep fabrication time to a minimum. This was made possible by the unique properties of FDM. The expensive and time-consuming 3D printing process is only used for the very thin shell which defines the shape. This is possible because all the structural stability of the formwork during casting is provided by the sand bed surrounding the formwork.

Freeing the 3D printed shell from the need to provide stability, also allowed an unprecedented geometric freedom to be possible with concrete. Due to the topology optimization algorithm used in the design, concrete was used in a very efficient way, with bones of various thicknesses being optimally distributed to provide maximum stiffness for the frame. The skeleton weighed just under 80 Kg, while the final weight, including the waterproofing layer was 114 Kg. Such an intricate topology, with unique spatial nodes where between three and six linear elements met at custom angles (Figure 14), with various degrees of smoothness, would be otherwise impossible to fabricate with any other production process.

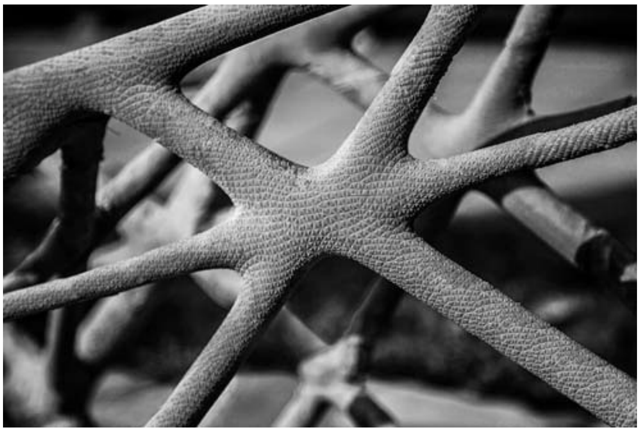

Figure 14: Custom node of the SkelETHon, where six linear elements come together (DBT, ETH Zürich, 2017)

Another key achievement was to transfer faithfully a sub-millimetric surface texture from the 3D printed formwork to the concrete (Figure 15). Extrapolating this capability to architecture, these fine and precise surface treatments could fulfil other roles, such as acoustic diffusion or ornamentation for structural building elements.

Such a high-resolution texture would otherwise be challenging and time-consuming to achieve with subtractive processes like milling or hot wire cutting. While not unlimited, the geometric freedom offered by FDM certainly complements the other digital fabrication processes available for making formwork. A single fabrication process able to produce any geometry in large scale is not available at the moment, but FDM can be a very efficient tool in producing highly specialized geometries, such as networks of tubes and thin shells, impossible to fabricate otherwise.

Figure 15: High resolution texture on the surface of the SkelETHon. This texture maximizes the contact area with the waterproofing concrete skin. (DBT, ETH Zürich, 2017)

Outlook

The canoe also highlighted a number of areas which can be addressed by future research in order to make this method suitable for streamlined large scale production:

a. The speed and reliability of the 3D printing process often caused issues, mostly related to the specific type of hardware used. An FDM machine with multiple hot ends, optimized for sustained printing in large volumes would greatly benefit this research.

b. The stability of the formwork can still be problematic at welding points. This is partly due to the large number of parts in which the formwork had to be discretized as a consequence of the small 3D printers used. 3D printing tolerances accumulate in the welding process and cause weaknesses. These weaknesses can lead to leaks of concrete during the casting process. While the sand bed quickly neutralizes the leaks, the consistency of the formwork fabrication has to be addressed.

c. Partly due to these inconsistencies, the current process is fundamentally suitable for off-site prefabrication of construction elements. The nature of the casting process where the concrete infilling has to be correlated with the sand-bed counter-pressure is only suitable in a controlled environment. This is because the concrete infill does not happen uniformly as initially predicted. Due to the variable friction with the formwork, wider tubes get filled up faster than narrow ones, which causes different concrete levels at different areas of the formwork. In order to overcome this issue, computer fluid dynamics simulations could be used to design an infill strategy as well as adjust the diameters of the formwork tubes in order to ensure a predictable level of concrete throughout the casting process.

d. Another type of simulation that could potentially give valuable insight into this process would be the analysis of the behaviour of the steel fibre reinforcement in such a tubular structure, especially around complex nodes. The consistent orientation of the fibres is critical in ensuring the bending strength of concrete, but the behaviour of fibres in fluids is difficult to anticipate intuitively. Combined with an empirical method such at CT scanning of physical prototypes this could inform the geometry of such skeletons in a meaningful way.

Conclusion

The fabrication process tested with the canoe shows how a cutting-edge digital fabrication technology can be used minimally to fabricate a thin shell formwork which accurately defines the shape, while the stability of the formwork is transferred to a common secondary material, like sand. The gradual sand filling process, combined with the transparency of the formwork allow live feedback on the casting process, which is critical for intricate geometries.

This novel process can be extrapolated and directly adapted for the design and prefabrication of large, load-bearing, concrete architectural components. The size of the canoe, approximately $4x1x1m^3$ is representative for a building component such as a column, a beam or a façade element and the infrastructure necessary for the casting (i.e. containers with sand) is easily available. The key achievements demonstrated with the canoe can make a big difference on the way concrete is used in architecture: almost unconstrained geometric freedom, significant weight reduction, lightweight formwork and high precision for on-site assembly.

The complexity of the formworks possible, combined with the excellent rheological properties of UHPFRC open up an entirely new family of shapes for concrete building elements: microstructures, free form surfaces, highly detailed textures, precise articulations and convoluted topologies.

With 3D printing, each fabricated part can be unique, since the manufacturing process does not involve the use of expensive moulds which need to be re-used to make them cost-effective. 3D printing one-of-a-kind pieces of formwork, for customized concrete elements specifically tailored for their individual purpose is therefore possible, with no cost or time penalties. These are the first steps towards the mass-customization of buildings through non-standard, prefabricated concrete components which integrate structural, functional and aesthetic solutions, as well as additional features such as weight reduction and the assembly logic.

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