

IceFormwork for Cast HPFRC Elements

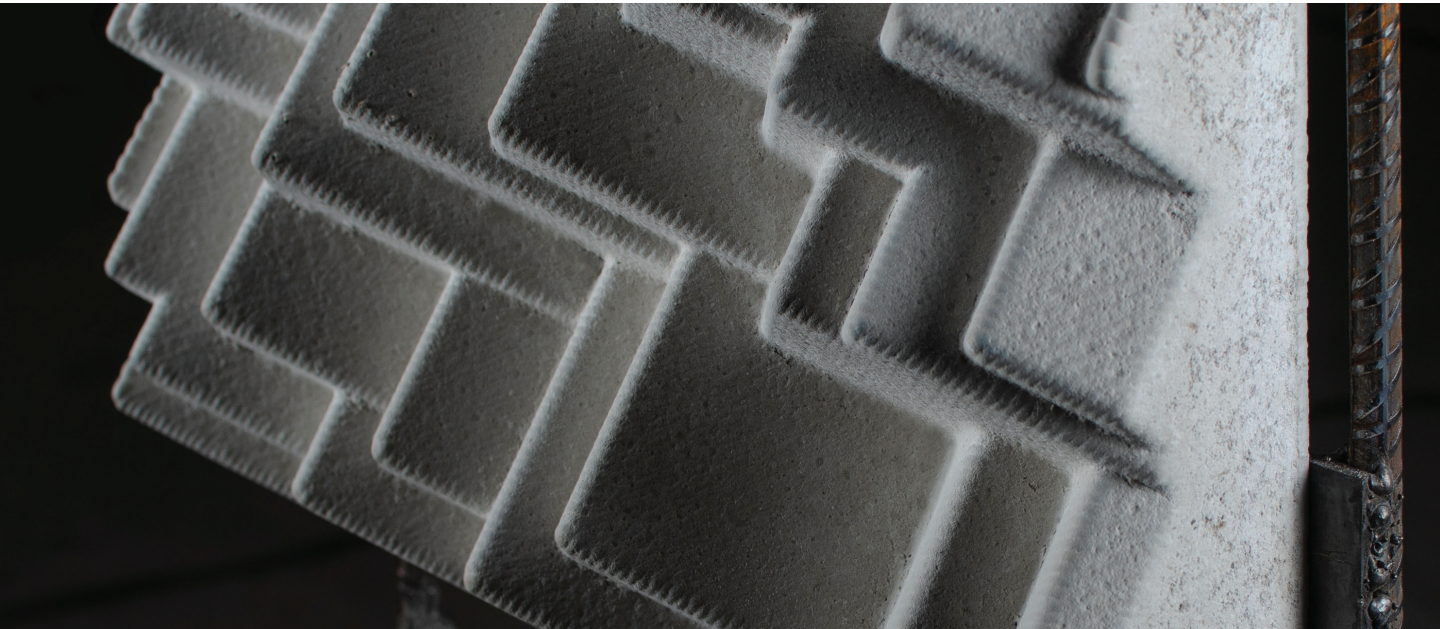
Process-Oriented Design of a Light-Weight High-Performance Fiber-Reinforced Concrete (HPFRC) Rain-Screen Façade

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ABSTRACT

The following paper introduces a design implementation of an innovative fabrication method that aims at enabling an environmental and automated production of geometrically challenging cast concrete elements. The fabrication method is based on the use of ice as the molding material for cast concrete. Empirical testing of ice CNC-processing, and a concrete mix capable of hardening at subzero temperatures was undertaken during previous research stages.

The current paper illustrates a practical application of ice formwork. A façade rain screen has been developed using algorithmic modeling to illustrate a common case in which a non-repetitive geometrical pattern requires individual formwork to be produced for each element. Existing industrial methods capable of delivering such a project for formidable costs are based on CNC-processed expanded polystyrene (EPS), wood-based materials, or industrial wax formwork. These materials have been found to be either difficult to recycle, expensive, insufficiently strong, energy- or labor-intensive to produce. Preliminary evaluation has shown that ice, used in their place, facilitates a much cleaner, economic, and an even more energy-efficient process. Moreover, a very gentle demolding process through ice-thawing eliminates any shock stresses exposed on newly cast concrete and provides optimal curing conditions. As a result, the thickness of façade elements can be reduced while still fulfilling all structural requirements.

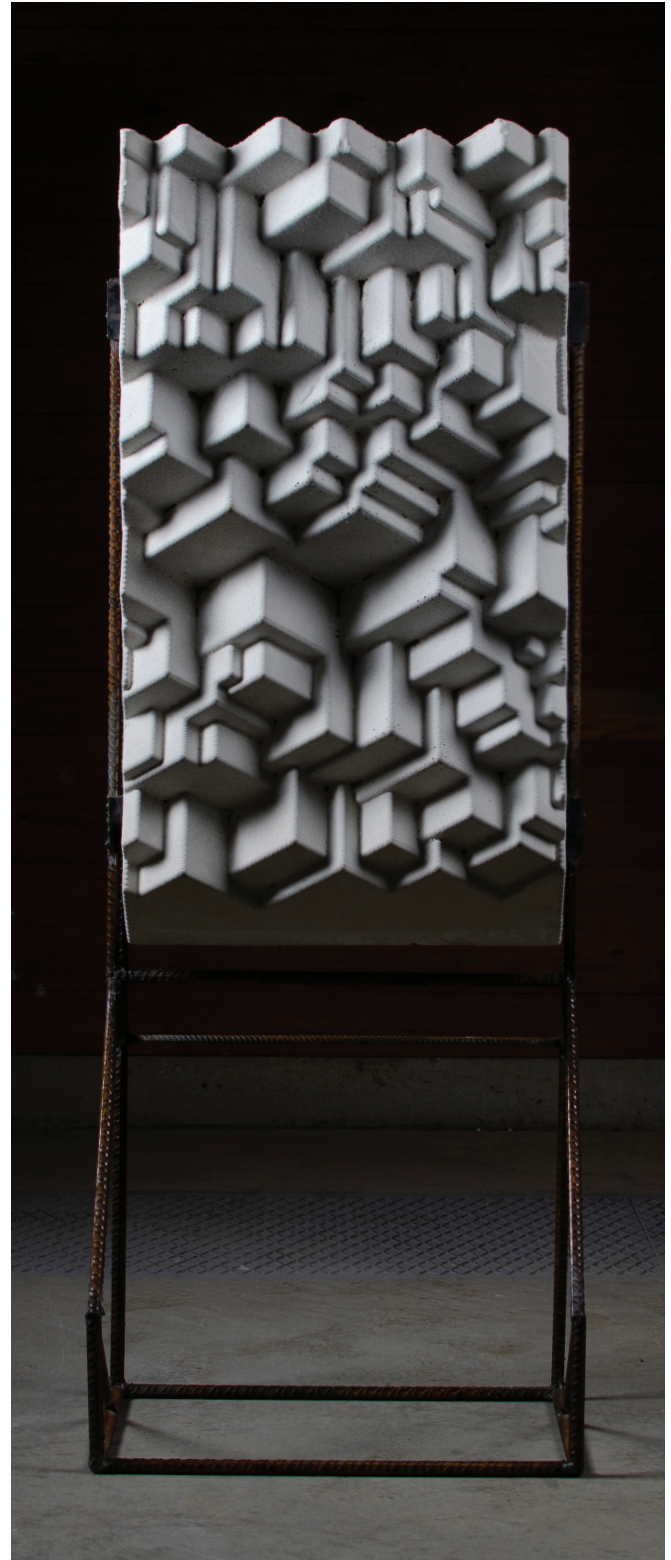
- 1 Front surface detail of the main HPFRC prototype cast in ice formwork

INTRODUCTION

Since the very rapid development of computer-aided-manufacturing, mass customization has come within reach of the construction industry. CAM and CNC tools that enable subtractive and additive processing are becoming part and parcel of industrial manufacturing. In precast concrete, however, computer aided processes haven't progressed too far yet. Although one can find cases of computer-aided manufacturing used in production of full-scale structural panels from as early as 1999 (Kolarevic 2003), the industry has still to find an environmentally acceptable yet economic digital-fabrication process. For instance, conventionally used CNC-milled formwork made of EPS or wood-based materials remains the dominant solution for precise and affordable production of complexly shaped precast concrete. However, there are serious drawbacks in terms of the inevitable and excessive loss of these valuable materials in the process of subtractive processing.

Some precast concrete companies, such as mbX (Bergen op Zoom, Netherlands), are actively involved in research and development for specific construction cases, adjusting the digital fabrication workflow for the demanded design geometry of specific projects in order to achieve a more sparing fabrication process. For example, the award-winning production method for the light-weight fiber-reinforced double-curved concrete rain-screen facade of the Arnhem Central Station has used an in-house developed and unique system of reconfigurable formwork. Similar formwork systems have then been developed by ADAPA (Hoppermann et al. 2015) and Delft University of Technology (Schipper 2015; Eigenraam 2013). The main challenge with this approach is time, as many construction projects run on short and fast-paced programmes. In the UK, for example, a typical programme for concrete clad buildings requires a maximum 12 to 16 weeks lead time from drawings to site, which is based on flat and geometrically repetitive precast elements. In most cases, this time is not sufficient for the development of a reliable industrial fabrication method for a specific design geometry.

Even though the above mentioned reconfigurable formwork system is a resource-saving and a clean method of fabrication, it can facilitate production of a very narrow range of geometrical forms, precisely for surfaces with relatively small and constant curvature. In a way, this formal limitation can be compared to fabric formwork systems. The method has been very elaborated by Mark West and many other scholars (West 2016; Bak 2012; Popescu et al. 2018). Although a smart and efficient way of producing curved concrete shells, fabric formwork provides endless variations of quite scarce number of geometrical effects.



2 Front view of the main HPFRc prototype cast in ice formwork

Therefore both the reconfigurable and fabric formwork methods can perform well only when applied to a very specific type of geometry.

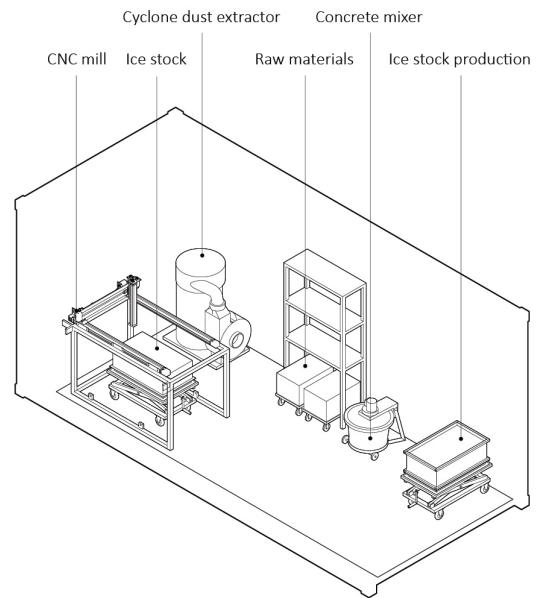
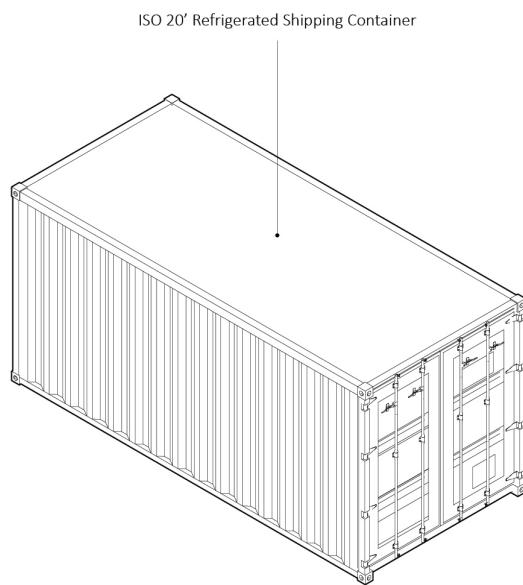
While looking forward an efficient method of fabrication of a broader range of geometrical effects, the fields of additive and subtractive fabrication should be considered. The former refers to the field of concrete 3D printing that can be showcased by the works of X-Tree (Dirrenberger et al. 2016), one of the first commercial concrete 3D printing practices. Though providing an unprecedented efficiency and formal freedom in production of concrete elements, 3D printed concrete is a phenomenological new type of material, precisely because it is an anisotropic material, in contrast to cast concrete that is, to a certain extent, isotropic. For the reason that the interest of the current article spans only the production of cement-based concrete elements, 3D printing resin binders (Rippmann et al. 2018) are left outside the scope of investigation.

Speaking of subtractive methods in manufacturing of concrete elements, one should make a remark that these processes only apply to the production of mold or formwork, while the casting of concrete itself remains to be an additive process. The most popular technique here is CNC-milling of a relatively broad range of materials, such as EPS (Lopez Lopez et al. 2014), MDF (mbX, work in progress), or industrial wax (Oesterle et al. 2012; Mainka et al. 2016). Still, one can also find cases of use of hot-wire cutting or abrasive wire sawing (Søndergaard et al. 2018), which in principle operate a similarly narrow geometrical space as the fabric formwork, however with a higher precision. Therefore, if comparing the environmental and economic efficiency of different types of CNC-milled formwork, the main criteria would be the cost of the material, the possibility of reusing it within the production process, and the precision of the geometry transfer this material is able to facilitate. EPS is definitely the most cost efficient material on the list, and due to its low-density, it is quite convenient to handle in the production process. However, it is very difficult to reuse or recycle, thus excessive EPS waste is either incinerated with emission of carbon dioxide, or dumped in a landfill. Additionally, requirements for smoothness of the surface may require coating, which makes recycling even more difficult. MDF as a formwork material carries similar problems as EPS in terms of recycling. However, while being a more expensive material, there are optimization strategies that allow the production of more concrete elements of varying geometry with much less volume of formwork material. Also, MDF has the advantage of being much stronger and thereby better at resisting hydraulic load. Still, since MDF is hydroscopic it

requires application of a firm coating layer, which is a very labor-intensive operation. Recently, several research groups have started development of formwork systems based on reusable industrial wax (Oesterle et al. 2012; Mainka et al. 2016). It is the first material on the list that can be recycled within the fabrication facility, and thus the use of the formwork material in a subtractive processing can be optimized. However, wax is a relatively expensive petrochemical that degrades slightly after each cycle and as such requires a small but constant supply of new raw material to compensate the loss of quality. Apart from these drawbacks, there are additional practical criteria related to various risks that come with each specific material, such as fragility of EPS foam, hydroscopic deformations of MDF, softening of wax under influence of heat, which have been addressed in a previously published paper (Sitnikov 2019). Therefore, the following research considers that there is a vast opportunity for further improvements and innovation not only for the sake of the economic and ecological performances of concrete production, but also for articulation of the social and ethical values for which contemporary architectural design should stand.

Non-conventional approaches to concrete production that in many cases eliminate material waste are, for example, concrete elements cast locally in sand for Shaikh Ebrahim Center, Bahrain by Anne Holtrop (2019), or prototypes of concrete elements cast against icebergs for a project in Iceland by Olafur Eliasson (2016). This list can be extended infinitely by inclusion of projects such as Bruder Klaus Field Chapel by Peter Zumthor (2007), Atelier Bardill by Valerio Olgiati (2007), or the Truffle House by Ensamble Studio (2010), etc. Even though these examples are far from complying with industrial standards, still they are valuable experiments that explore use of locally found materials and crafts in production of concrete constructions, which were of a great use on the early stages of the conceptual development of the current research.

In light of above, this paper is dedicated to a practical application of a digital fabrication method based on CNC-milled ice formwork that resolves several systemic problems in the production of non-repetitive and complex geometry in cast concrete (Sitnikov 2019). Counterintuitively, several significant advantages of this method have been identified in process of research and development. First, automation of formwork production by means of CNC processing allows rapid fabrication of complex and precise geometry in ice. Second, as the water used to make the ice-mold can be indefinitely reused, the problem of material waste is by far eliminated. Third, as ice naturally melts away once the concrete has hardened, demolding requires no manual



3 Prototype-stage fabrication setup accommodated in a 20' refrigerated shipping container

labor (although it does require time). Fourth, since ice requires a constant sub-zero temperature environment, it is natural for this technique to produce stable and repeatable quality product. In conventional precast process, for example, the appearance of concrete is conditioned by outdoor weather and season. To these process-specific advantages can be added other pluses at a societal and global level. CNC milling in ice is a much healthier process for the workforce and the biosphere than milling in conventional materials—the frozen water dust produced in this process is much safer for humans and other bio-organisms than airborne micro particles of plastics or wood fibers. Finally, a preliminary assessment of the rate of energy consumption shows that the embodied energy of concrete elements produced in a refrigerated environment does not exceed that of elements cast in a mold made of EPS. This is due to the fact that water, the main raw material of this production method, does not require transportation as any petrochemical or wood does, and the production of ice can rely solely on renewable energy, such as solar cells or wind mills (Sitnikov 2019).

The ice formwork system is based on the author's development of a frost-resistant high-performance concrete mix design. Numerous tests have shown that the developed method of casting produces a high quality transfer of geometry from ice to concrete, in absence of any measurable deformations of the design geometry (Figures 1, 2). It has also been found that the total strength of this type of concrete is not affected by the low temperature of casting (Sitnikov 2018).

At the current stage, the research project seeks to illustrate a practical design application developed with consideration of the ice formwork production workflow, and its potentials and limitations. Apart from producing a strong artistic expression, the design development aimed to demonstrate the viability of producing an economic, environmental, and structurally efficient architectural product. In consideration of these aspects, the application was chosen to be a rain screen façade element. The following part describes the design thinking that preceded fabrication, noting the constraints and opportunities the process entails.

METHOD

To test the fabrication method in a practical and geometrically challenging application, a decision was made to design a rain-screen panel for a façade of a non-heated building (e.g. a parking garage). Apart from the fabrication constraints, which were defined during the design process, the resultant geometry was influenced by a list of functions. This work took into consideration the concept of integral façade construction, studied and defined by Tillman Klein (Klein 2013). Based on Klein's systematization of functions, a convenient framework for parametric design has been established.

The primary function of the proposed element design is to provide protection from rain and to control sunlight. The driver of geometrical complexity was aesthetic expression—the intention being to produce an immersive bas-relief that would dynamically interact with daylight whilst maintaining a stone-like material texture. The



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- 4 Back side of the main prototype formed with an ice counter mold
- 5 Cast-in M7 anchoring point located on a 20 mm wide vertical rib
- 6 Elements of the rein screen panel
- 7 Results of FE analysis: Panel deflections under 1kPa uniform load
 - A - 20mm thick UHPFRC crystalline profile with ribs
 - B - 40mm thick UHPFRC crystalline profile without stiffening ribs
 - C - 40mm thick UHPFRC flat profile
- 8 Results of FE analysis: panel stress concentrations:
 - A - 20mm thick UHPFRC crystalline profile with ribs
 - B - 40mm thick UHPFRC crystalline profile without stiffening ribs
 - C - 40mm thick UHPFRC flat profile

element could also bring a modest yet dramatic light to the interior through apertures shown on figure 6.

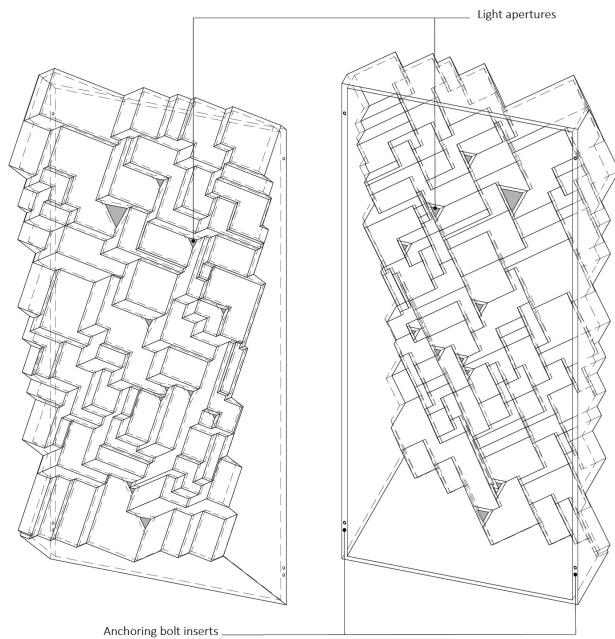
For an external wall element, the structural performance is also important. The element needed to resist its own weight and imposed loads, such as wind, temperature change, handling during construction, and maintenance without reduction in performance or permanent deformation. The element should also transmit safely all loads to the supporting structure via the points of attachment. A key requirement set is to keep the panel weight low aiming to reduce the complexity of the supporting structure but also so as to allow for a quick and safe façade installation process. Reducing the weight is achieved by reducing the panel thickness to a minimum.

During the design process, the criteria affecting form listed above were assessed in constant juxtaposition to the fabrication process, leading to a process-oriented, aesthetic,

and structural parametric design. The following subsections discuss the design from these four listed evaluation perspectives.

Fabrication Setup

While the final goal of this work is not only to prototype the element, but also to explore the production process as close to full-scale as possible, a general production setup configuration was the first thing to define. Since ice formwork requires a controlled environment, a standard 20' refrigerated shipping container was chosen to accommodate the fabrication process. Due to a very high level of development supported by the global trade industry, this technological unit encapsulates high-end equipment and shows great performance of thermal insulation and energy consumption. On the current stage, the unit accommodates a custom-made 3-axis CNC mill with a workbed of 650mm x 1300mm in the horizontal plane and 300mm of vertical travel. The setup also includes: a



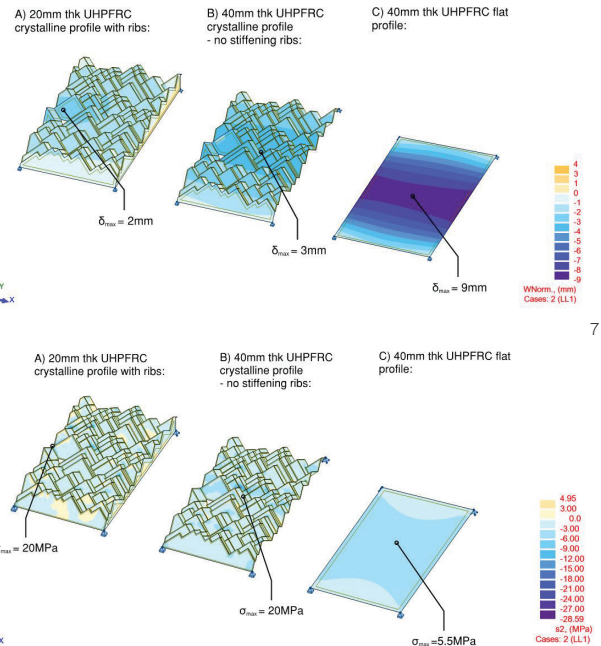
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cyclone extractor to remove the ice dust product of milling, equipment for production of low-defect ice stocks sized 500x900x300mm, storage of concrete raw materials, and a concrete pan-mixer (Figure 3). For the reason of funding, at this stage the setup could not fit a production of a full-size façade panel. Therefore, the experimental setup serves as a proof of concept, and can produce samples of surface finish, scale models, and fragments of full-scale elements. During the research and numerous empirical testing no scale limitations, apart from the internal dimensions of a standard shipping container, were identified.

Another important advantage of a standard shipping container in context of concrete elements production is that the manufacturing plant can be deployed in close proximity to the construction site. This can reduce a lot of expenses and risks associated with the transportation of non-standard concrete elements by public motor roads.

Aesthetic Expression

In challenging the existing praxis for the fabrication of complex non-repetitive shapes in concrete, a continuous yet discrete generative principle was developed. A surface topologically similar to a bas-relief was chosen. The surface was generated using a box rotation in a way that the box's diagonal becomes collinear with the Z axis of the CNC mill. Multiple such boxes are then allocated at knots of a rectangular grid mapped onto an undulating surface following a randomized pattern. The output surface



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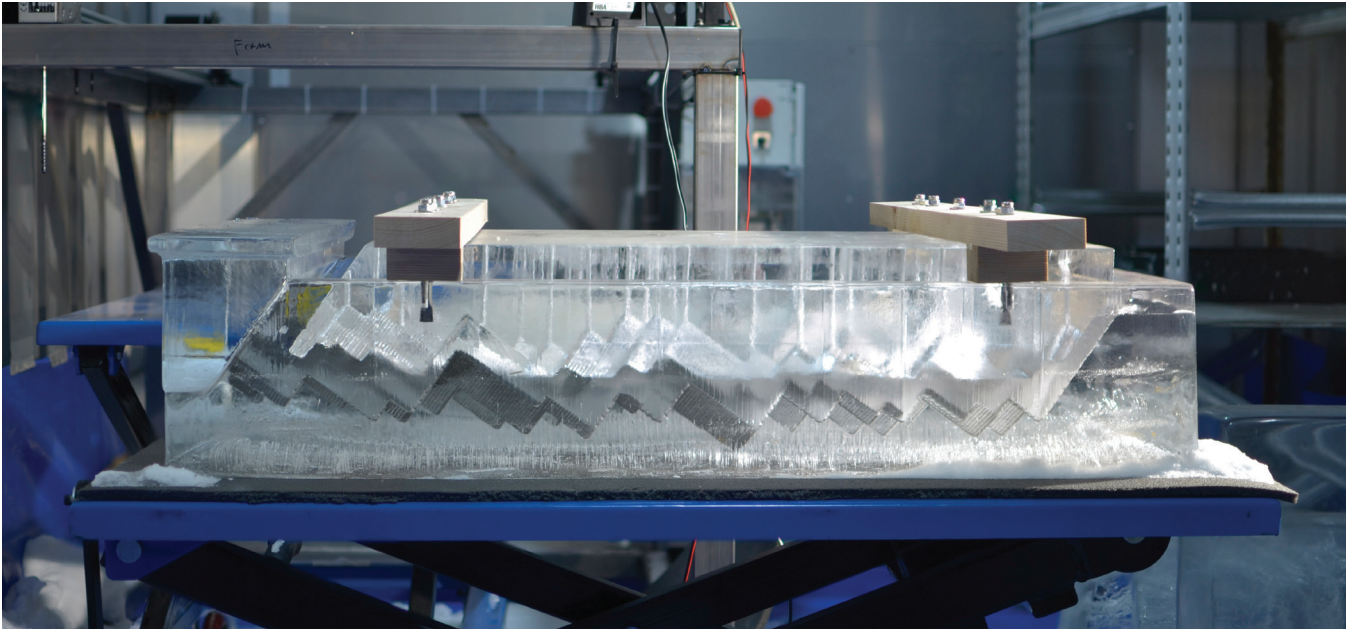
then renders an orthogonal crystalline lattice, while the concrete texture and broken rhythm augments it with natural stone tactile qualities.

Another important aesthetic aspect is the property of concrete surface finish and consistency of color. In conventional industry, consistency is very difficult to achieve—the temperature in an industrial production space always fluctuates depending on weather, so that concrete cast during winter usually looks different than that cast during summer. Because the ice formwork fabrication approach is based on a highly controlled environment and timing of the automated technological process, as well as high quality and precise batching of raw materials, the consistency of concrete appearance can be guaranteed (Figure 2).

Structural Design of the Element

The main goal of this work chapter is to reduce the weight of the rain screen element down to 90kg/m², which is considered a light-weight cladding system if compared to a typical glazed aluminum curtain wall system which weighs between 70 to 90kg/m². For comparison, a typical steel rebar-reinforced precast system weighs between 320 to 360kg/m².

Considering the density of used concrete is 2100 kg/m³, the average thickness should not exceed 40mm, which corresponds to a limit of 84kg/m². However, for structural



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reasons, the element should be given a type of waffle-grid on the back side; therefore, the thickness of the shell should be reduced to allocate the material in the ribs.

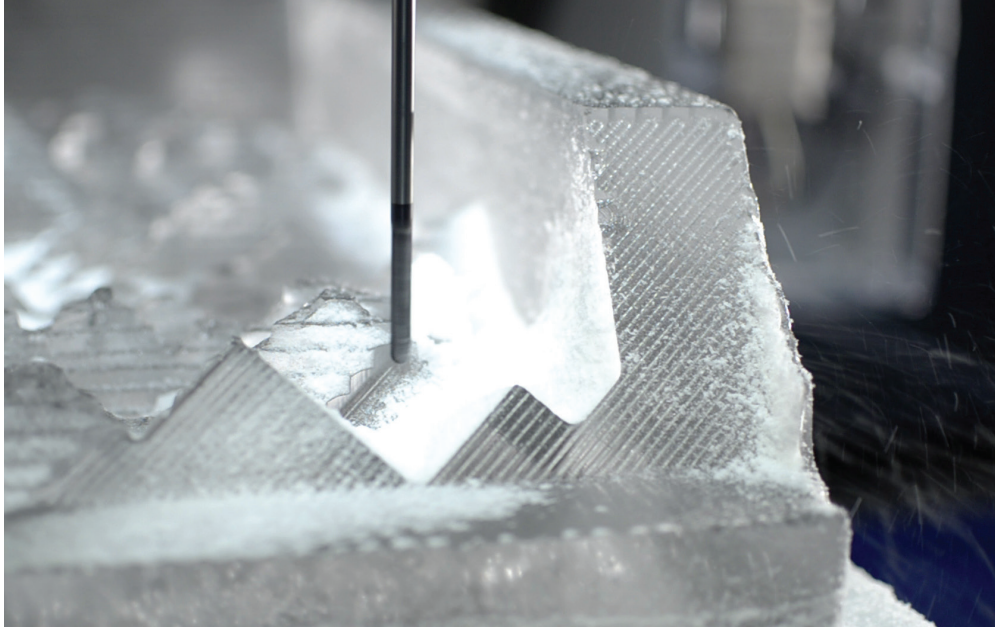
When using a traditional formwork, a shell is usually given additional thickness to account for the risks of braking the element during demolding and to prevent cracking and deformations due to shrinking. This additional material is considered a dead load, as it is not required for structural performance, and it merely helps to demold earlier when concrete has gained only 20-30% of its final material strength. Since ice formwork provides a completely new approach of a gradual demolding through ice thawing, the thickness can be kept at the structural minimum.

Some initial FE analysis shows how well the structure responds to the geometry of the crystalline-like profile, as well as the addition of backing ribs. Figure 7 shows the deflections observed for: (A) a 20mm thick UHPFRC panel with crystalline profile and backing ribs; (B) a 40mm thick profiled panel, but without backing ribs; and (C) a 40mm thick flat planar panel, as control. Hand calculations show that the 9mm deflections experienced by the control sample (C) matches well with expectations. Profiling the surface (B) increases the structural depth and so reduces deflections,

while adding back ribs (A) reduces deflections still further, even when using half the material thickness.

As may be expected, stress concentrations collect around the stiffest elements, in this case the ribs (Figure 8). Previous research has shown that a flexural strength of 20MPa is achievable with minimum amount of fiber reinforcement, meaning that the point of highest tension in the elastic stress distribution must remain under 20MPa. If using suitably deep ribs, or optimizing the geometry, it is clear that the 20mm profiled panel can be made to meet the allowable tensile resistance. While adding considerable complexity in terms of its need for additional formwork, the ribs and profiled finish of such a casting allows a significant reduction in material thickness.

As in typical precast concrete panel construction, the panel must use two support points at the base to carry the dead weight and two restraints at the head which resist the horizontal loads (Figures 4 - 6). The support and restraint points are formed of brackets that fix into the concrete panel through sockets precast in its body. The brackets, in turn, are bolted into cast-in-channels embedded into the primary structure (Figure 12).



- 9 Assembly of the CNC-milled mould and counter-mould of ice
- 10 Finishing path on the ice mould using 6mm ball endmill.

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These various fittings and degrees of separation between primary structure and the UHPFRC panels allows onsite adjustment to account for fabrication and installation tolerances. As an example, industry guidance allows $\pm 25\text{mm}$ tolerance for the difference in slab line. The various bolt connections allows the contractor to fix misalignments by adjusting the bolt from the nominal position by the required amount.

By industry convention, when looking at the exterior of the panel, the bottom left billet is modelled as a pin support (restraint in X, Y and Z directions), while the bottom right billet is modelled as a roller support (X and Z), and the top two billets are only restrained out-of-plane (X). The required restraint conditions are manifested by using oversized slotted holes to allow freedom in the required direction. The purpose of these restraint conditions is to permit freedom to expand and contract when exposed to temperature fluctuations, or if long term effects such as creep or shrinkage are to be expected, as is the case in conventional concrete panels. By comparison, if all four supports are modelled as pins, the panel would be subjected to internal stresses, either pulling or pushing against the billets.

Formwork Design and Fabrication of the Prototype

The design and research work resulted in an ice-based formwork system for sustainable and economic production of customized façade geometry. The system consists of a mold and a counter-mold produced out of ice through CNC milling. The counter-mold is to be placed on top of the base mold, resting on several points of predesigned apertures. According to the industry standard, all straight and sharp corners in the concrete element need to be filleted with minimum radius of 3mm. This requirement can be met through use of a 6mm ball end mill on the final processing stage (Figure 10).

The assembly of CNC-milled ice parts can use other materials too, such as reusable shuttering made of a durable material. This specific design used two wooden beams bolted to ice with M6 screws to center the counter-mold over the main mould. The second function of these beams was placement of cast-in anchoring sockets in a precise and consistent manner, meeting the industrial standard of 1mm tolerance.

At the current stage the material tests have been carried out and a sample of the concrete surface cast in a



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rough-cut ice formwork has been produced. Three ice parts of the formwork were CNC-processed using low-defect ice stocks. The third part was required since one wall of the external volume is inclined inwards the formwork, and therefore, cannot be produced on a 3-axis mill. To assemble the formwork, this part was fused with the base mould by injecting water in their interface.

RESULTS

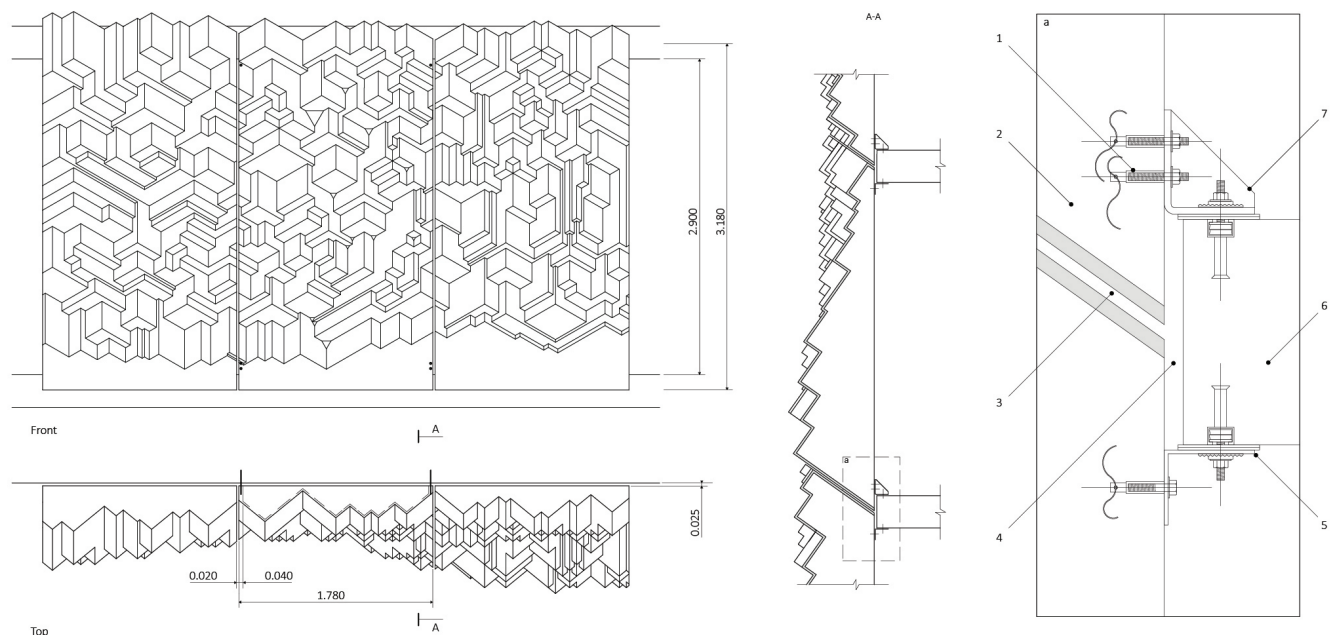
The design work conducted with consideration of the specifics of ice formwork method of fabrication has led to a light-weight concrete rain screen façade element of reduced mass, 93kg/m². Results of this ongoing work contribute greatly to the development of innovative sustainable concrete design, produced through an automated and environmentally- and socially-sustainable method. Moreover, the proposed geometrical design provides an example of aesthetic yet structurally functional pattern which allows the reduction of the thickness of the element. It avoids conventional steel reinforcement or excessive number of ribs on the back of the element, allows to develop rich decorative functions from the exterior as well as from the interior.

The use of ice formwork has a list of practical benefits yielded by the potential weight savings in the cast units. Beside the fact that lighter elements have smaller carbon dioxide footprint and embodied energy, they facilitate simpler transport and lifting of panels into place and reduce the forces acting on the primary structure.

As for the forces experienced on the primary structure, when using precast concrete façades, the structural engineer will need to take account of likely forces and torsions on the main structure at an early stage, as this can create high deflections at the slab edge. In addition to the vertical loads that the bottom brackets exert on the structure, there is also a lateral force component, resulting from the push-pull of an eccentric vertical force. This means that the top bracket is trying to pull out from the concrete slab and the bottom one push in. By reducing the weight, the bracketry can be designed with much smaller dimensions.

CONCLUSION

Based on the results of work conducted so far, ice formwork appears a promising technology enabling fabrication of a complex design elements, providing structural performance in a radically clean and sustainable way. Further



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- 11 Detail of the assembled mould featuring predrilled air escape canals
- 12 Drawing of the facade assembly and detail drawing of the fixing
(1 - cast-in sockets; 2 - precast concrete panel; 3 - panel joint (10-30mm);
4 - slab edge clearance (min. 25mm); 5 - lateral restraint bracket; 6 -
primary structure; 7 - dead load bracket)

research is needed to understand the overall synthetic potential of such systems. The fabrication limitations entailed by the refrigerated space demand a very thorough logistical planning, as well as limiting the size and certain kinds of complexity of the produced element. The production pace can also be a drawback since the cold regime of casting slows down the hardening of concrete.

Recycling of ice that is re-freezing melt water has certain factors too. For instance, in contact with cement water pH level rises a lot, usually to 12. This means that recycling requires recovering the neutral pH level, and the environmental effects of this operation is yet to be analyzed.

Finally, refrigeration requires large amounts of energy. The rates of energy consumption now need to be carefully examined. The fabrication setup described in the subchapter 2.1 is consived not only to serve as a proof of feasibility, but also as epistemic tool to produce statistical data of temperature, energy and time requirements. This data will be collected and analyzed in the next phase.

Speaking of the element's design, a façade has to fulfil many roles: alongside the aesthetic component, it has to

create a weatherproof screen against rain and moisture ingress, avoid internal mould and dirt build-up, provide a thermal insulation and acoustic barrier, avoid becoming a fire conduit, as well as to meet the structural demands placed on it. The current project rig does not test all these aspects. However, there are clearly potentialities in the ice formwork system for engaging with the complex synthetic demands of architectural façade design. These might include its potential for flexible adaptation, such as by allowing small recesses for gaskets or cavity barriers, or by optimizing the facade profile and section depth for tailored structural requirements.

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IMAGE CREDITS

All drawings and images by the authors.

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Peter Eigenraam is a production and structural engineer, focusing on design and production of complex geometry structures. At the company mbX (part of Concrete Valley, The Netherlands, www.mbx.nl), he is responsible for parametric engineering of prefabricated double curved concrete elements. Eigenraam is a teacher and researcher in the field of Structural Design and Mechanics at the Faculty of Architecture and the Built Environment of the Delft University of Technology.

Panagiotis Papanastasis joined the Façade Engineering group in BuroHappold in 2012 and is currently based in London as an Associate. Having a dual degree in Architecture and Engineering, Panos' background has enabled him to effectively apply his architectural and engineering knowledge to a variety of façade solutions for both new developments and refurbished works. Panos' particular interests lie in freeform facades, parametric analysis and design of specialist façade systems. Since joining BuroHappold Panos has worked with architects and contractors on projects within a wide range of sectors including: sports, aviation, education, commerce and residential, both internationally and in the UK.

Stephan Wassermann-Fry studied Civil Engineering at the RWTH Aachen and Architecture at Bath University. In 2015, he joined BuroHappold Engineering as a Structural Engineer, where he worked on projects including the new Tottenham Hotspurs stadium, the conversion of the Battersea Power Station, and a range of cultural, sculptural and concept schemes. As of 2018, he has been seconded to the Facades team, and counts detailing, structural calculations and computational modelling as his core strengths. Alongside his engineering roles, he works as associate lecturer and technical tutor at the University of Arts London.