Conference Paper

Robotically Fabricated Ice Formwork: An Exploration on Casting Morphologically Programmed Complex Concrete Elements with Robotically Milled Ice Formworks

Enrico Pontello[1], Martin Tamke[2], and Vasily Sitnikov[3]

[1]BSc. Arch, M.Arch. MAA Architect
[2]CITA Centre for Information Technology and Architecture, The Royal Danish Academy of Fine Arts Schools of Architecture, Design and Conservation, Copenhagen, Denmark
[3]KTH Royal Institute of Technology, Stockholm, Sweden

Abstract

This document focuses on the exploration of casting complex concrete architectural elements with ice formwork. Replacing conventional concrete formwork with ice formwork, allows to produce architectural elements with complex geometries in a highly controlled offsite production process, with almost complete reuse of the mold material. Using digitally driven fabrication tools such as a robotic arm milling, the goal is to achieve 3d shapes made from one or more ice molds, able to be stacked, assembled and merged together in order to define architectural partitions. One of the main instigators of this research is the sustainability, showcased both through the usage of ice as a mold material that is 100% reusable, and the unique ability of the described process to produce topology optimised shapes in concrete, which reduces the use of this high carbon footprint materal to a bare minimum. Ice formwork allows furthermore, to create bespoke shapes for every single element in an efficient way.

This opens new avenues for architectural design and construction. This project uses a design based research methodology, where each physical iteration is carefully evaluated against the digital model, embracing morphological material programming.

Keywords: topological optimization, 3D scanning, digital fabrication, ice formwork

Corresponding Author:
Enrico Pontello

Received: 15 March 2019
Accepted: 25 May 2019
Published: 20 November 2019

Publishing services provided by Knowledge E

© Enrico Pontello et al. This article is distributed under the terms of the Creative Commons Attribution License, which permits unrestricted use and redistribution provided that the original author and source are credited.

Selection and Peer-review under the responsibility of the Architecture across Boundaries Conference Committee.

OPEN ACCESS

1. Introduction

After coal-powered electricity, cement manufacture is the next biggest emitter of greenhouse gases, accounting for approximately 5% of annual anthropogenic global carbon dioxide emissions.

The environmental impact of the worldwide emission of CO2 is due to cement production, this level of also reflects the unique and universal importance of concrete in the construction industry.[1]

Energy consumption is also another considerable environmental concern with cement and concrete production. Cement production is one of the most energy-intensive of all industrial manufacturing processes. By including direct fuel use for mining and transporting raw materials to the construction site, cement production takes about 1,758 kWh for every ton of cement.

One of the solutions that industry adopted, especially in certain extreme scenarios where the dispendious of energy was incredibly high, has been moving from in situ production to pre-casted concrete elements in a more controlled environment such as side factories.[2]

The perfect control of all steps of producing and casting concrete is characteristic for the industry. It is taken to an extreme in climats, where the conditions strongly influnece the structural and aesthetic characteristics of the intended final outcomes/components. In projects where there can be large temperature differences or warm climates, concrete cooling companies are providing refrigeration solutions (flake ice and conveyor systems), therefore it is immediately clear the importance of an absolute control regarding the concrete mixing and curing process. Situated on the opposite side of the possible range of concrete application are construction sites in sub-freezing temperatures, if the temperature of the concrete is too low during the curing, it can lead to a fragile structure.

In the precast concrete construction method (very commonly adopted in Scandinavia), the construction elements are produced in a production facility with high precision and embedded fixtures for building services (electricity, plumbing, heating, air conditioning etc.).

The precast concrete elements are then transported to the building site by truck, assembled and connected to each other in a force-fitting manner. The advent of 3D CAD tools, enables the design and specification of geometrical complex concrete shapes with single and double curvature. Large scale CAM provides means to produce molds with high precision. An example of this approach has been The New Zollhof, designed by Frank O. Gehry and completed in 1999, one of the first examples of these technologies implemented in architectural project.[3] The construction technique adopted, was the prefabrication off-site one, which was the key to achieve uniquely shaped concrete elements, first casted and produced in a plant and then transported to the construction site. The novelty at that time was that all the hundreds different elements were casted in unique polystyrene moulds and produced with a CNC milling machine. In comparison with other mould materials, polystyrene (EPS) is cheaper and more precise. Due to this fact, the CNC uses on EPS became a standard, for “fluid” architecture made of concrete and it expanded from precast to even in situ construction.

Another recent example that has been completed is the Kirk Kapital headquarters designed by Olafur Eliasson. In this case, around 4500 cubic meters of formwork were needed, were effectively processed and manufactured in Odico's production facility and then shipped to the construction site in Vejie.[4] One of the main driver for this research topic is the waste of non-degradable EPS left after the construction process, which it is supposed to be packed, transported back and re-processed to the recycling implant.

2. Topology Optimisation for Reduction of Envrionmental Impact of Concrete

Topology Optimization (TO) is a mathematical method that optimizes material layout within a given design space, for a pre-defined set of loads, boundary conditions and constraints with the goal of maximizing the performance of the system. Looking into the research related to Unikabeton prototype, which adopted a series of robotically CNC milled EPS formworks, with the aim of achieving a doubly curved layout for a concrete structure of 12 by 6 by 3.3 meter high. Topology optimization of architectural elements presents itself with structural and sustainable advantages, since it reduces the presence of the material to only structurally necessary locations, producing lighter and more efficient architectural components, however, the complexity of the necessary formworks for casting is usually a limiting factor in the research.[5] In the case of "Unikabeton" project, a loadbearing concrete casted column system has been developed by merging topology optimization with robotic milling of EPS moulds.

Another case-study is a flooring system developed by Block Research Group which consists of a modular and thin concrete construction, made up of a vault, stiffening fins and a system of tension ties at the perimeter.[6] The floor is shaped such that it works in compression only, while externalising any tension to the perimeter, thus avoiding the need for any traditional rebar. However, the prefabrication of this optimised structural geometry is expensive, requiring the making of double-sided moulds and therefore limiting the application to a repeated unit or modular system. To overcome this, additive manufacturing has been studied, however, the printing materials remained weaker than their concrete counterparts, presenting acceptable compressive strength but negligible bending capacity.

The most related contribution to ice formworks for concrete elements is nevertheless given to Vasily Sitnikov, a PhD candidate at KTH Royal Institute of Technology. His 4 years spanning research is dedicated to the development of a sustainable method of fabrication one-off complex shape concrete elements.[7] Combining physical probes and numeric experiments in the methodology of the investigation, the research aspires to establish a novel concrete casting technology, which intrinsic principals would reduce material waste and embodied energy.

His research explores how structural problems can be efficiently solved with much smaller masses of concrete while maintaining the same level of cement consumption, through the use of Ultra High Performance Concrete (UHPC), degradable ice formwork and through active involvement of CNC processing. A survey undertaken in the recent advancements of concrete related technologies has revealed an opportunity to propose a new concept of casting. The new method of fabrication of UHPC elements employs ice as the main material of the temporary formwork construction, involves automation of the fabrication process and solves the problems of waste material and manual labour at the stage of demoulding. This casting method is being developed for cases, where unique and customized concrete elements of complex geometry are needed, e.g. TO structural elements.[8] To minimize machining time, milling is thought to be combined with controllable melting of ice that allows a high-quality surface finish, on a large scale in a very simple way to be achieved. The main hypothesis of the research is, that the control over melting could be possible through digital simulation, that is the melting deformations can be pre-calculated if the parameters of the material system are known.

General complex geometric fabrication issues could be overcome by using ice as formwork to such topologically optimized elements, whether they are a column, floor, wall or even a hybrid structural system as the one explored in two study cases (Figure 1 & 2). Using optimization algorithms, rectilinear milling toolpaths could be obtained, and the melting property of ice could be exploited to create a smooth fluid transition of the optimized element. By knowing the estimated milling time from the software, it would be possible to simulate the melting of the ice. Once the cast concrete is dried and solidified, the ice formwork can be defrosted, and the water collected to be reused for another mould. This technique can create a complex structural architectural element efficiently, in a sustainable way.[7]

3. Methodology

Using ice as a formwork material is a novel methodology that can be adopted into an architectural process to precast concrete elements. The advantages offered by ice, are the possibility to create a sustainable mould employing a 100% recyclable water, while having low limitations in the complexity of the object's geometry. Ice is also a dynamic formwork that changes shape according to temperature and time. This can

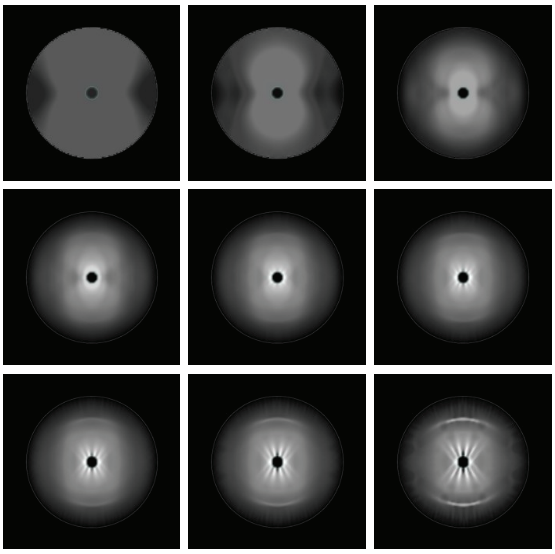

Figure 1: Sequence of nine iterations from a TO analysis using Millipede for Grasshopper. A circular environment with a single support, with the aim to re-create a self-standing capitel.

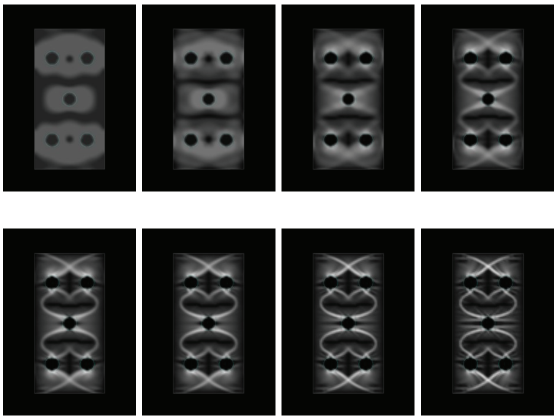

Figure 2: Sequence of eight iterations from a TO analysis using Millipede for Grasshopper. A rectangular boundary supported by five funnel-shape columns.

be used as a mena to further decrease energy consumption in proudction of molds and the amount of necessary milling operation, since it is possible to carve unecessary material and counting on the melting of the ice to smoothen the final object. Moreover, the advantage of ice is that it is not limited by a top-down approach such as milling, but it can as well be strategically molten, using e.g. hot water or dripping salt water on specific areas in order to carve and create cavities in the ice.

Ice formwork could be more efficient production of unique structurally optimized concrete elements, however the milling of ice is still a time consuming process and the question in this research is, which strategies and technologies can be applied to minimise this single use only, it is highly desirable to minimize the time-consuming process of milling as much as possible. For this has been developed a novel approach using a concept of a simulation-based method of hybrid fabrication, where minimal and elementary milling interventions in a volume of a regular ice block can develop into a more complex geometry through the following process of melting.[7] It should be mentioned that the intention to link computer-generated geometry of optimized structures to the natural phenomenon of melting deformations is driven both by the necessity to minimize the effort during fabrication and to provide a natural materialization strategy, that does not solely rely on the transitory machining equipment, but strives to involve new physical processes in the culture of fabrication (Figure 3).

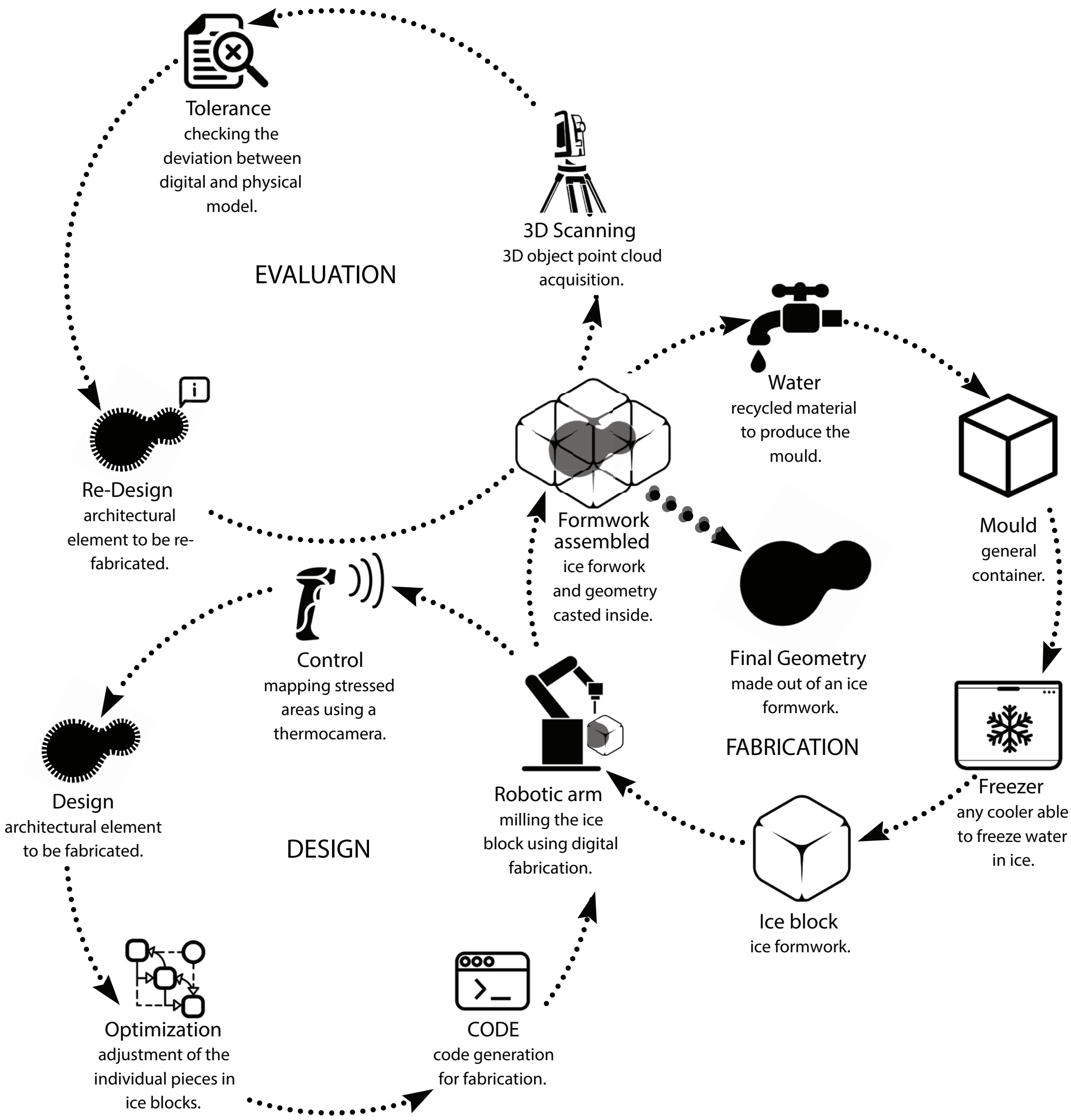

Figure 3: Cyclical workflow on how the design proposal is fabricated and 3D scanned using robotically milled ice formworks.

4. Fabrication

In order to work with Ice it is necessary to understand its materiality. Here it is important to understand, that there are several categories of ice that correspond to different molecule micro- aggregation form. Therefore, what has been commonly called ice, refers to Ice Ih which is the hexagonal crystal form of ordinary ice, or frozen water. The crystal structure is characterized by the oxygen atoms forming hexagonal symmetry with near tetrahedral bonding angles. Ice Ih is also stable under applied pressures of up to about 210 megapascals where it transitions into Ice III or Ice II. Alike it seems a straightforward manner how to create the ice, the process behind can present some issues, especially if the expectation is to obtain high quality ice.[9] Considering the ice as a very dynamic material, pressure and temperature are two parameters closely correlated and they depend categorically on the status of the substance. Looking at the fabrication of the ice as an initial step, to then subsequently process it through all the phases to achieve a sustainable formwork, few issues might appear during the freezing process. After pouring a few litres of water into a container, some impurities and air bubbles are trapped into the mass. These imperfections do not allow the ice to become not only transparent but a rigid and steady mass as it has the potential to be.

To achieve a clear and transparent block of ice, a method adopted by most of the Ice companies, consist to regulate a series of submersible water pumps into a tub containing the water (Figure 4). This arrangement needs to be adjusted day by day and it allows the water to freeze from the lower layer to the upper one. In the end, vacuuming the exceeded water avoids the crystallization of the water containing the air bubbles and impurities (Figure 5).

These tests show, that a simulation of the behaviour of ice is highly advisable for ice formworks, as it allows to predict the final shape of the mold and hence the concrete element. As the final object supposed to look and perform as been thought and designed, the ice mould might need to acquire a different geometry from the one that is coming from the digital model and consequently exported to the CNC milling machine. To accommodate this configuration, it is essential to predict the closest object shape at the casting time through an analysis of the digital model.[10] As the melting process is going to subtract some of the ice particles, acording to the parameters' values such as temperature and the estimated milling time, the goal is to simulate the surface mold during the melting process. This will allow accomplishing a more accurate result examining a number closer to the maximum erosion factors. (Figure 6).

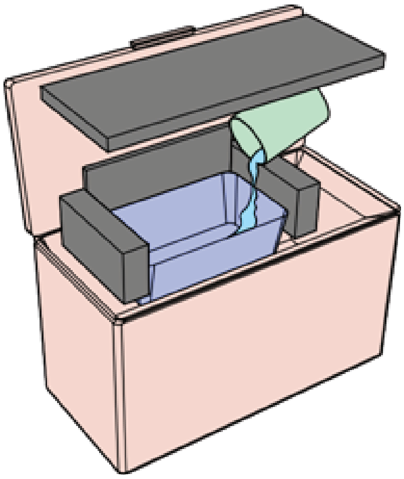

Figure 4: Ice creation setup for methodological experiments with a chest freezer.

Figure 5: Crystal clear ice block ready to be robotically carved.

This prototypical ice simulation, is based on the representation of polygon mesh with marching cubes algorithm. The initial surface condition that separates liquid and solid phase, is used to assign the initial decimal values between 0 and 1, to corners that belong to ice or saline solution correspondingly. These values will be recalculated at every iteration according to the diffusion level of salt particles at a given negative temperature. It is obvious, that the total sum of all the corner's values in this closed system should be constant throughout the simulated period.[11] At every iteration, the polygon mesh that represents the interface will be transformed according to the new distribution of values. Since changes of corner values are affected by changes in the neighbouring corners, in principle it can be computed using cellular automata algorithm.

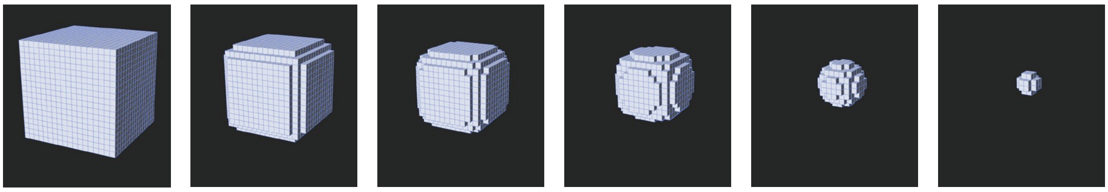

Figure 6: sequence of six iterations simulaing an 18 voxels-based ice cube using a looping Python algorithm, in Grasshopper environment.

For the initial prototypes, gypsum has been used in a mix with water to create a very compact mixture, ideal for quick casting and giving shape to small specimens. The speed of the process using the gypsum is certainly one of the pros for this type of experimentation, however, the properties that this material brings on the ice formwork might work against the already dynamic mould. As a matter of fact, gypsum and cement when mixed with water, heat up and they consequently speed up the melting process. Operating outside a sub-frozen temperature wasn't producing satisfying results in terms of model accuracy, however, a robotic setup where the milling process was taking in place in a cold environment the tolerance appeared within an acceptable range for a prototyping phase (Figure 7 & 8). According to Sitnikov's experimentation, the concrete can also be used with an attentive choice of the temperature on both materials, e.g. the concrete at the casting moment should not exceed the temperature of 0 degrees. After the mould has been defrosted, the shutterings can be removed which allows the ice to melt and the water be reused for the next mould.

5. Evaluation

The methods chosen to evaluate the prototype geometry are the 3D scanning and thermo- analysis technique. These procedures grants the ability to analyse the deviation due to the ice melting behaviour, to evaluate the prototype shape with the initial design intent and to re-adjust the machining toolpath using the developed algorithm. This approach, based on empirical error study, can also be put into practice using a thermal-camera monitoring the areas most affected by the thermal conduction and intervene in the defined range. Pre-calculating the tolerance spectrum could also concede a natural smoothing touch to the shape edges that a fluid design might demand without implementing this extra detail in the milling procedure (Figure 9).

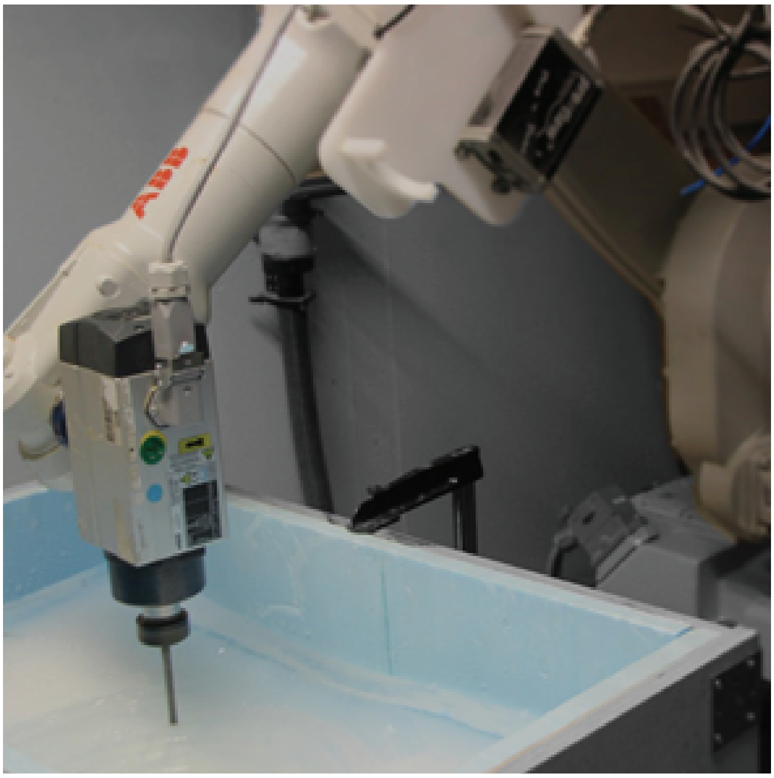

Figure 7: Initial robotic setup using an xps polistirene isolating container.

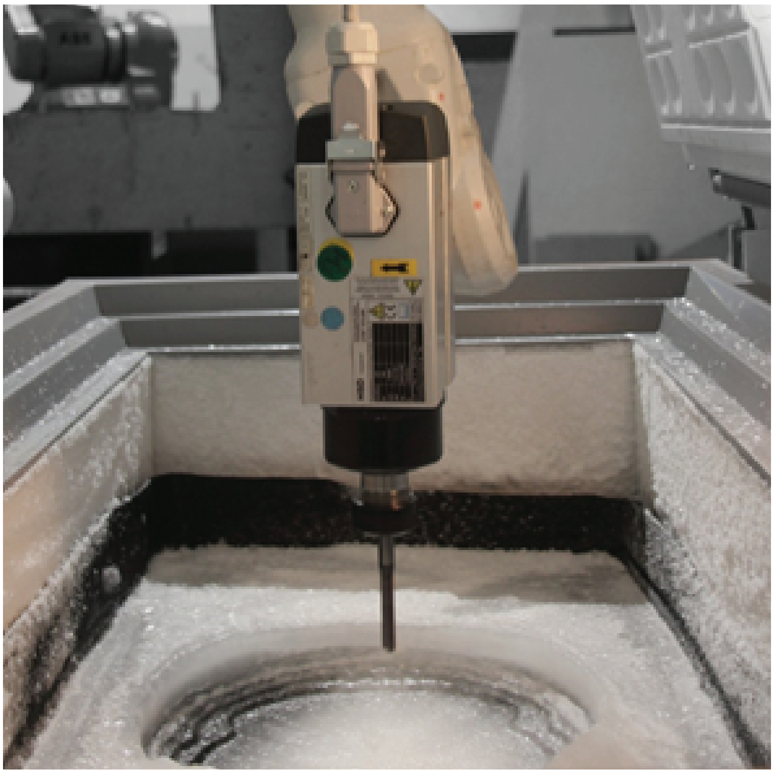

Figure 8: Further developed robotic setup, adopting a chest freezer adjusted next to a robotic arm in order to decrease the ice block's temperature exposure.

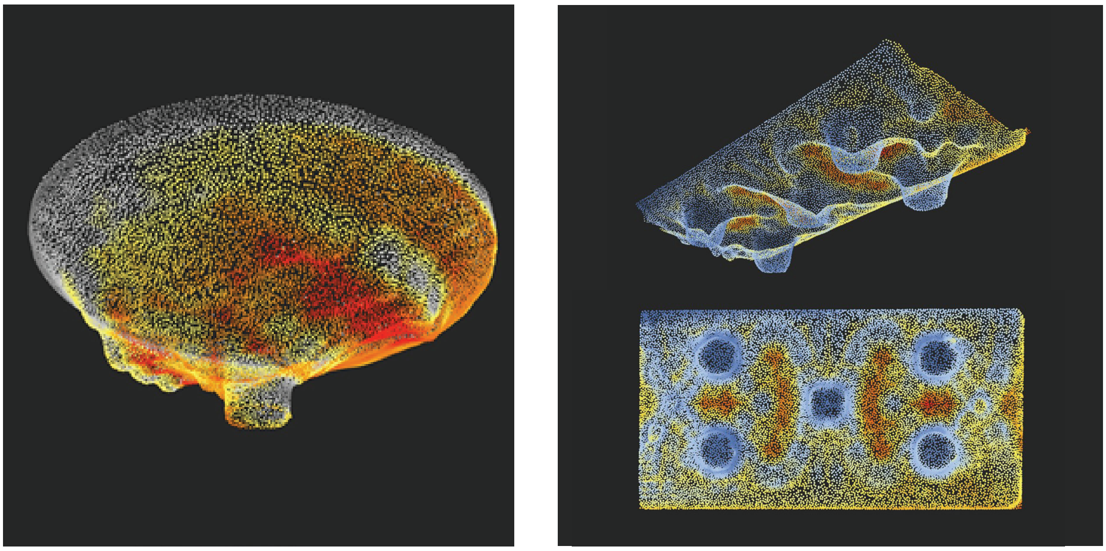

Figure 9: 3D Point cloud comparison between digital and physical model, using a 3D-scanning method based on photogrammetry.

6. Conclusion

This research has presented a series of both digital and physical experimentation on casting complex geometries using ice formwork (Figure 10). In the current state of the project, the final sample does not meet the desired precision in order to be used in a building context. The search for the perfect ice creation technique is still ongoing, and it is crucial to obtain casted elements with a sufficient quality to be subjected to physical compression tests and compare the actual performance to the digitally simulated one. Moreover, further developments on the ice melting simulation should be made to tune the correct milling parameters to obtain more consistent and performative TO complex geometries.

Acknowledgements

This paper presented the research developments of Enrico Pontello's MAA dissertation, supervised by Prof. Martin Tamke within the CITAstudio: Computation in Architecture Master Program at the Royal Danish Academy of Fine Arts, Copenhagen. The author would like to thank Vasily Sitnikov to keep developing ice formwork techniques and maintaining an open conversation on the research topic. The author is also thankful to all the reviewers who gave their valuable inputs to the manuscript and helped in completing the research paper.

Figure 10: Topologically optimized fibre-reinforced casted concrete element using an ice formwork.

References

[1] Babor, D., Plian, D. Buletinul Institutului Politehnic Din Iaşi. Publicat de Universitatea Tehnică, Gheorghe Asachi" din Iaşi Tomul LV (LIX), Fasc. 4, Secția CONSTRUCȚII. ĂRHITECTURĂ. *Environmental Impact Of Concrete.* (2009).

[2] Andrew, R. M. Global CO2 emissions from cement production. CICERO Center for International Climate Research, Oslo 0349, Norway. (2018).

[3] Peck, M. (2014). Modern Concrete Construction Manual. *Structural Design, Material properties, Sustainability.* Edition Detail: pp. 110-111.

[4] Søndergaard, A., Feringa, J., (2017). Scaling Architectural Robotics: Construction Of The Kirk Kapital Headquarters. Fabricate 2017. UCL Press: pp. 264-271.

[5] Dombernowsky, P., Søndergaard, A.: Three-dimensional topology optimisation in architectural and structural design of concrete structures (2009).

[6] Block, P., Rippmann, M., Van Mele, T.,: Compressive Assemblies - Bottom-Up Performance for a New Form of Construction. In: Armadillo Vault, 'Beyond Bending', Venice Architecture Biennale, (2016).

[7] Sitnikov, V., (2017) Ice Formwork for Ultra-High Performance Concrete: Simulation of Ice Melting Deformations, in: Humanizing Digital Reality, Springer, Paris: pp. 395–406.

[8] Sitnikov, V., (2019) Ice Formwork for High-Performance Concrete: A Model of Lean Production for Prefabricated Concrete Industry, Structures.

[9] McFarlan, L.: The Structure of Ice III. In: The Journal of Chemical Physics 4, 253 (1936).

[10] Iwasaki, K., Uchida, H., Dobashi, Y., Nishita, Y.: Fast particle-based visual simulation of ice melting. J. Compil. Pac. Graph. 29(7), 2215–2223 (2010)

[11] Wojtan, C., Carlson, M., Mucha, P.J., Turk G.: Animating corrosion and erosion. In: Ebert, D., Mérillou, S. (eds.) Eurographics Workshop on Natural Phenomena 2017, Prague (2007)