Final Report:
Practical Applications of Concrete Elements Produced by Ice Formwork Fabrication

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Project number: 6:2019

Summery

The project has successfully conducted research, design development, fabrication and dissemination of a practical application of innovative digital concrete fabrication method studied by the main applicant as a PhD thesis at KTH School of Architecture. The method is based on the use of ordinary ice as the molding material in production of precast concrete element. The result of the project is a prototype fabrication of a façade element – a lightweight complex geometry concrete rain-screen panel. The design has been developed in dialogue with a progressive Dutch precast manufacturer (mbX) and UK structural engineers (Buro Happold).

Results

The financial support provided by ARQ foundation allowed to conduct in-depth study and physical testing of a innovative method of sustainable production of complex architectural elements of high-performance concrete.

In the period from May through November 2019 a functional prototype of an ice-based digital concrete fabrication plant has been set up on the KTH campus (fig. 1). The industrial hall has been kindly provided by Akademiska Hus for the purpose of research. An industrial refrigerated container equipped with a girder-based CNC-mill has been installed on site (fig. 2,3). Numerous design and fabrication tests have been performed on the first stage before moving on to the final façade element fabrication, which took place in September 2019.

The design logic, economy and environmental performance of such a façade element are captured in the peer-review conference paper presented on ACADIA conference, 26th October 2019, Austin, TX. (see *Dissemination 1*).

Additionally, a video documentation of the prototype fabrication has been produced and published online, first presented on the same conference (see *Dissemination 2*).

Finally, an full-year exhibition has opened at Swedish Concrete and Cement Institute (RISE), Stockholm on December 19th 2019 (see *Dissemination 3*).

Fig. 1 - View of the experimental ice-based digital concrete fabrication plant at KTH

Fig. 2 – CNC-control desk and the refrigerated 20’ container

Fig. 3 – CNC machine and ice stock generator installed in the refrigerated container

Fig. 4 – First prototypes fabricated during the summer months 2019

Fig. 5 – Final façade element prototype

Dissemination 1. Conference paper and presentation

The design development and fabrication of the façade element has been published in a peer-reviewed conference paper. The presentation took place on 25th October 2019, Austin, TX, USA.

http://2019.acadia.org/

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 façade 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 18 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.

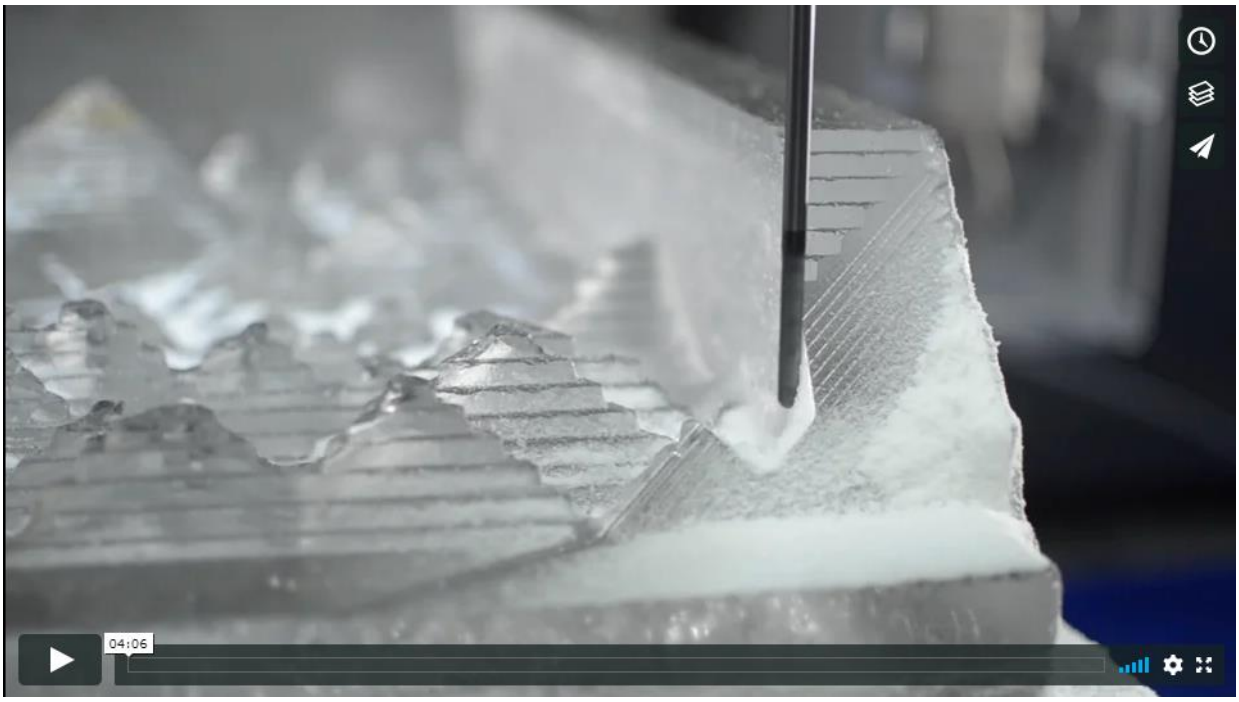
2 Front view of the main HPFRC prototype cast in ice formwork

Presentation at the ACADIA conference 2019

Dissemination 2. Video documentation

A video documentation capturing the fabrication process of the final prototype has been produced and presented first on the ACADIA conference 2019. It is also available online:

https://vimeo.com/367759187



Dissemination 3. Exhibition

We've been invited to exhibit a selection of prototypes in the Swedish Concrete and Cement institute (RISE), Stockholm. The exhibition has opened on December 19th and will be open through January 2021.

In January 2020 there will be a lecture at CBI dedicated to Ice Formwork research and application.

Prototypes 1 and 2 - (Left) Light-Weight Rain-Screen Facade Element
(Right) Packed-Fused Ice Aggregate Formwork

Prototype 3 - Geodesic Terrain Model

Prototype 4 - Media Facade Panel