Digitally Fabricated Innovative Concrete Structures

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Abstract –

This paper presents the general aim of the research at the Institute of Structural Design (ITE) at Braunschweig University of Technology to bring digital design and digital fabrication together to develop resource efficient construction elements, manufacturing processes and building systems.

Basis of research at ITE is the so-called Digital Building Fabrication Laboratory (DBFL). The paper gives an overview of machine design, the technical parameters and its basic abilities of subtractive and additive processes e.g. milling, printing and scanning.

Based on the combined use of these digital fabrication processes and in cooperation with high-performance materials such as ultra-high performance concrete (UHPC), different research projects are being performed at the ITE. To explain the possibilities of the DBFL, the paper will present the results of two different – additive and subtractive - research projects to develop fabrication techniques for the building industry.

The first project is dealing with the development of "digitally fabricated high precision Non-Waste-Wax-Formwork for innovative UHPC structures" and the second project is investigating "Additive manufacturing of free-form concrete elements using Shotcrete 3D Printing (SC3DP) technology".

Finally, the paper will highlight the possibilities of combining these technologies and transferring them to industry 4.0.

Keywords –

Digital Robotic Fabrication; Construction; Wax; Formwork; Shotcrete 3D Printing; Additive Manufacturing

1 Introduction

Concrete has been continuously developed in recent years into a high-performance material with a variety of different features. Nowadays we have the knowledge and the technology to cast self-compacting concrete, with the compressive strength similar to steel, into complex formwork or to modify the rheology of the concrete to the point where it is keeping its stability after pumping and spraying.

On the other hand, as the digitalization reached the building industry, it provided us with powerful calculation and planning tools, which liberated architects and engineers from restrictions concerning the geometric design of objects. This new freedom is still restricted by the available industrial standard of manufacturing technologies.

For example, the standardized, commercially available formwork systems for concrete components are optimized with regard to simple geometric shapes and joining principles. As a result, concrete structures are still composed of predominantly bending-stressed mass-intensive components. Although there are occasional attempts to realize free form, "non-standard" concrete architectures - such as the "Phaeno" in Wolfsburg by Zaha Hadid Architects - the challenge for the engineers is essentially to translate the architectural shape into reality. Nevertheless, light weighted and highly efficient structures, such as Heinz Isler's shell buildings, are barely to be found anymore [1].

Today, with the help of high-performance building materials, robotic automation and digital tools, we have all the instruments for fundamental developments in building construction. In 2002, Khoshnevis et al. [2] provided a concept how an automated approach to construction could look like, called "Contour Crafting" (CC). CC is extruding concrete and using trowels to create smooth and accurate planar surfaces. Another extrusion based process, called "Concrete Printing" (CP), was developed by Lim et al. [3] in 2011 at the Loughborough University. CP is not using trowels to achieve the surfaces quality needed, but a smaller resolution of deposition. Combining the advantages of all these technological developments, it is possible to build lightweight, efficient and therefore resource-saving structures.

With the research of the Institute of Structural Design (ITE) at TU Braunschweig, we want to develop digital fabrication methods to transfer innovative technology of computational design, automation and materials into building construction industry.

Application processes always depend on the materials used. In order to redefine the traditional manufacturing method, it is often necessary to rethink the entire fabrication process and adapt it to existing technologies and materials. Based on what the process offers the design space is stretched out. Our aim is to enlarge the architectural design space by providing new digitally controlled fabrication processes, see Figure 1.

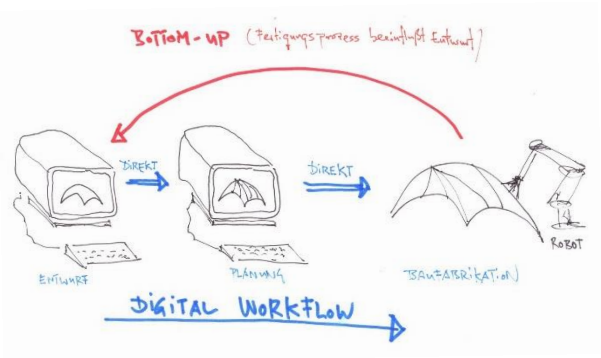

Figure 1. Design process turns into digital bottom-up workflow

2 Digital Building Fabrication Laboratory

The DBFL in its design and capabilities is unique and is the focus point of future research in the field of digital building manufacturing at the ITE. The focus is on combining latest technological developments from car and plane manufacturing with new high performance materials in order to fabricate material efficient structures for the building industry. By combining flexible robotic components with precise and robust machining systems, a huge bandwidth of applications will become available.

The DBFL operating range is almost 7 meter in width, 15 meter in length and more than 3 meter in height. A 6-axis Stäubli robot connected to a 3-axis portal is the core of the additive manufacturing unit in the DBFL (Figure 2). The robot can carry up to 200 kg and move freely in the entire working area. The end effector can be equipped with various attachments, depending on the examined process. The second portal is carrying a 5-axis CNC milling and sawing machine. It represents the subtractive part of the DBFL and has been designed for low tolerance and high precision milling jobs. It also has the ability to process high-density materials like granite and ultra-high performance concrete (UHPC).

Both units can operate individually or in a synchronized cycle. By combining the additive and subtractive abilities of both portals, complex process chains, in order to fabricate efficient and graduated building elements, can be established without moving the element.

As an example, the DBFL is capable of spraying and printing concrete, milling, scanning objects and connect these features. Its two portals can operate synchronously or simultaneously in order to investigate a majority of different manufacturing processes. Based on these possible digital fabrication processes and available high-performance materials like the ultra-high performance concrete (UHPC), different research projects are being performed at the ITE involving the DBFL.

Figure 2. Digital Building Fabrication Laboratory at ITE TU Braunschweig

3 Digitally subtractive fabricated high precision Non-Waste-Wax-Formwork for innovative UHPC structures

UHPC can generally be cast in any shape, assuming the right additives were used. Depending on the complexity of the required form, the main effort and cost is to build the formwork. The formwork systems, which are mainly used in the building industry today, can only produce geometrically simple basic forms and allow deviations within the range of centimeters.

To produce concrete parts that differ from these common straight and rectangular basic shapes, various 3D free-form formwork principles have been established in the construction industry. Primarily CNC-machined wooden formworks or epoxy resin coated foaming polystyrene (EPS) are used for these geometrically high complex free-form geometries. These CNC-milled formworks have high production costs and the disadvantage of not being recyclable due to the coating. In summary, it can be said that almost all 3D free-form formwork systems currently available on the market are usually expensive custom-made products, which cannot be reused for variable geometries. In addition, the currently permissible tolerance deviations of system formwork for high-precision precast UHPC elements are not acceptable. Precise and free-form shuttering is therefore a decisive factor in the production of UHPC constructions.

Due to this need and inspired by the research of Gramazio & Kohler [2] of ETH Zürich a research approach for free-form concrete formwork by CNC-milling industrial waxes was developed by the ITE.

In contrast, to the research approaches of Gramazio & Kohler, based on an adjustable formwork shell on which liquid wax is cast to preserve the form and the "FreeFAB ™" research approach of the Australian Dr. James B. Gardiner et. al. [4] using hot liquid wax to 3D printed free-form formworks, the ITE approach is based on the use of large cooled down wax blocks that are fast and precisely shaped into form by subtractive CNC-milling to robust Non-Waste-Wax-Formwork with nearly any geometrical shape.

Based on these developed approach, the technical applicability of industrial waxes for the fabrication of free-form formwork elements was investigate at the ITE within the joint research project: “Non-Waste-Wax-Formwork-technology: Innovative precision formwork on basis of CNC milled recyclable industrial waxes for the casting of geometrically complex concrete elements” [5] in the years 2014-2016. In addition to the prevention of waste, the complete recycling of the wax results in low formwork costs, as the material investment can be allocated to the number of applications. The industrial wax used has similar strength properties compared to polyurethanes with the same density, although the material costs per application are significantly lower than those of polyurethanes.

3.1 Material properties of the selected industrial waxes and production of large wax blocks

Since industrial waxes have not been used as concrete formwork material until now, a suitable wax had to be found. Therefore, a technical wax requirement profile for the application as formwork material regarding the technical properties was specified. Based on this profile different waxes were selected and tested regarding their general machinability (millability) and their different physically mechanical properties for example: compressive, bending and tensile strength, elastic modulus, temperature-dependant strain or volume change, Differential scanning calorimetry (DSC) and thermal conductivity.

As a result of the tests and investigations of the research project, an industrial wax titled “ConFormWax” with a melting point of around 60°C, a (elastic) compressive strength of around 2,5 N/mm² (at 20°C) and an elastic modulus of 1923 N/mm² was selected as most suitable wax for the developed Non-Waste-Wax-Formwork technology [6].

As Dr. Gardiner [7] also mentioned, wax is very difficult to melt and pour into large blocks. Big molten wax blocks contain a considerable amount of latent heat, due to their insulating thermal conductivity they only cool down slowly. Cooling results in thermal shrinkage, which leads to high internal stresses that cause deformations or cracks. If these internal stresses are too high, the wax blocks also deform during CNC milling, which leads to an insufficient dimensional accuracy and precision.

An important part of the investigations within the research project was therefore the development of a process for the production of large-format, low-tension wax blocks for CNC milling. The procedure which turned out to be the most suitable to minimize these effects was to use smaller, tension free, planed cold wax tablets as filler. These wax tablets can be placed in a rectangular shape at regular intervals and can be grouted together with hot liquid wax in almost any dimension of wax blocks, as seen in Figure 3.

Figure 3. Grouting of cold wax tablets with hot wax to wax blocks (left) Cooled off wax block (right)

3.2 Verification of selected wax and developed formwork process

To verify the selected wax, the wax block production and the wax milling process, wax formwork panels, with dimensions of 500 mm x 500 mm x 120 mm where produced. The wax formwork panels were digitally composed of different geometric elements as grousers and grooves, round and pyramidal stubs, uni- and multidirectional curved surfaces. After milling these geometries into the blocks, ultra-high performance concrete were then cast on the resulting wax formwork panels. The aim was to analyse the influence of the aspect ratio and structural refinement as well as the separating properties of the concrete (Figure 4).

Figure 4. Wax formwork panel A after stripping of the UHPC (left); UHPC cast of panel A (right)

Hereafter the wax formwork panels and the UHPC casts were digitalised at GOM (company of industrial and automated 3D coordinate measuring technology) [8] with a standard 3D scanner (type ATOS). The digital 3D-scan data were used to conduct a volumetric form analysis in comparison to the original CAD data.

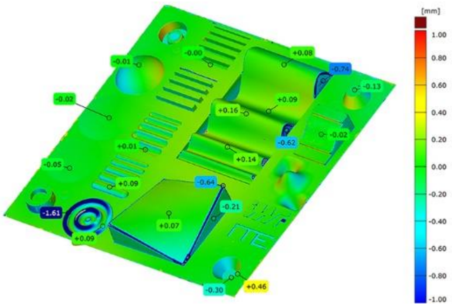

Figure 5. Comparison between the scan data of the UHPC cast (panel A) and the original CAD data

As shown in Figure 5, the UHPC casting of the wax formwork achieves very high precision over the entire area compared to the original CAD data.

The results of the research project have shown that the selected industrial waxes are suitable for the fabrication of precise formwork for complex, free-form concrete, and in particular UHPC, members. The technical properties of the used waxes, as the elastic modulus and compressive strength, are within a favourable range for concrete formwork construction rigid enough to withstand the fresh concrete pressure and soft enough for an efficient milling.

The volume analysis showed that not only the wax formwork, but also the cast concrete components have a high degree of precision for the construction industry. Apart from some production-related deviations, the measured tolerance is only in the tenth of a millimetre range. Due to the possibility of recycling the wax chips and wax formwork elements by re-melting, the Non-Waste-Wax-Formwork technology provides an ecologically and economically viable alternative to modern free-form formwork made of EPS and PU.

The technical foundations of the developed Non-Waste-Wax-Formwork therefore provide a technology and an industrial wax that enables the production of concrete and especially ultra-high performance concrete (UHPC) elements. The wax can be cast with adjustable surface qualities, with an accuracy in the tenth of a millimetre range and in almost any geometric form with sharp edges and very small curvature radii. A further advantage is the achieved sustainable closed loop recycling process, since the recycling (melting) of the wax chips and the disused wax formwork elements does not produce any waste in the process. This not only makes the wax formwork technology ecologically interesting, but also offers an economical alternative to modern free-form formwork made of epoxy resin-coated foam polystyrene (EPS) and polyurethane (PU). By reusing wax, material costs per application can be reduced to a comparable EPS level, while at the same time achieving better material properties - comparable to those of medium-density PU [5].

3.3 Transferring the Non-Waste-Wax-Formwork technology to the industry

Based on these good results and the industry's need for sustainable free-form formworks, the Non-Waste-Wax-Formwork technology was awarded with the German Innovation Prize of the Supplier Industry for Structural Concrete Products 2017 and is now being converted into industrial applications. The challenge of transferring the technology into an industrial process lies in the fulfilment of the respective user-specific requirements and the associated adaptation and optimization of the individual process steps, such as the production of the wax blocks.

To do so, two actual research projects are currently being carried out at the ITE together with industrial partners following different requirements and approaches.

The first project entitled "Development of a modular and fully automatic production process for free-form concrete formwork in building construction based on technical wax" is funded by the German Federal Ministry of Economics and Technology (BMWi). The focus of this research is the fast and fully automated production of modular expandable wax formwork, with a low demand on the achievable precision (Figure 6). The concept is to replace the disposable CNC milled eps formwork used today. In this project, the strategy of producing wax blocks by pressing cold wax chips into form is tracked. These pressed wax blocks have a four times lower compressive strength than cast blocks of wax (Figure 7) but their production is significantly faster and does not require any melting energy.

The second project entitled "Innovative Non-Waste-Wax-Formwork for the Fabrication of High-Precision Machine Frames made by UHPC", funded by the German

Research Foundation (DFG), focuses on the development of a precise and robust wax formwork (replacement of PU / Steel / timber "multiple formwork"). Therefore, wax blocks are made by casting filler-added wax. These wax blocks have shown a higher compressive strength (Figure 7) than compressed or cast wax blocks without filler. Their production is also less complicated, since the thermal shrinkage and the high melting energy are reduced.

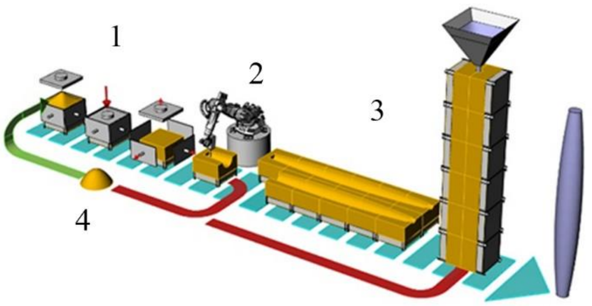

Figure 6. Principle of automated modular wax formwork: (1) compression of chips to blocks, (2) CNC-milling, (3) assembly of modular formwork, (4) closed loop recycling

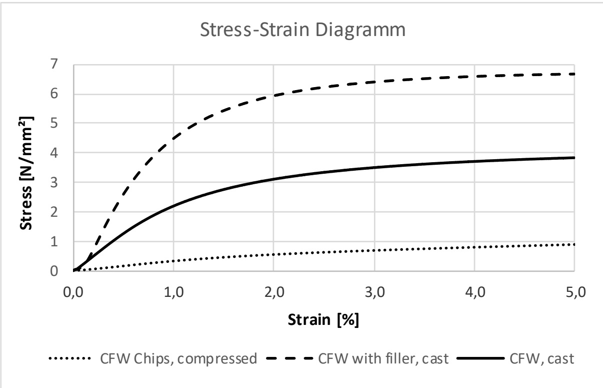

Figure 7. Stress-Strain Diagram of ConFormWax (CFW) samples produced by: cast (a), cast with 20% filler content (c) and compressed chips (b)

The aim of both projects is to make wax accessible for a variety of industrial applications. The fields, which both projects cover, makes it possible to use the wax, for example in precast factories, which then are able to react flexibly to requested free-forms.

4 Additive manufacturing of free-form concrete elements using Shotcrete 3D Printing (SC3DP)

For over 100 years, shotcrete has been used to spray reinforcement and produce lightweight and efficient structures. This technology is supposed to be transferred with the help of a robot into a digital, formwork-free and automated fabrication process. To achieve this goal a major collaborative research project of the Universities of Braunschweig, Hannover and Clausthal is carried out. Under the direction of the ITE, researchers from the fields of material science, mechanical engineering and computer science are developing a "robot-assisted shotcrete technology for generative manufacturing of complex concrete structures without formwork". The developed robot-controlled process is called "Shotcrete 3D printing" (SC3DP) see Figure 8. In addition to the development of a process technology, it is also necessary to develop a suitable shotcrete whose properties can be adapted to the respective components and the production process [9].

Figure 8. Application process of the new developed Shotcrete 3D Printing technology

Within the conventional Additive Manufacturing methods, the production of concrete elements is limited due to the layered application. Since no formwork is used for the 3D Printing process, the production process relies on self-supporting of the material. The material has to be applied on top of already printed material and overhangs as well as thin-walled elements are hard to realize. The use of the SCP3D method in additive manufacturing makes it possible to vary the application angle in contrast to the extrusion process. This opens up new possibilities in terms of geometric freedom. The material no longer simply has to be "deposited", but can be applied spatially to an already sprayed layer. In addition to a better surface bond, the resulting degrees of freedom can lead to a new surface quality and offer approaches for the integration of reinforcement in 3D printing with concrete. While the composite zone, according to Le T. T, et al [10], in extruded concrete components, from a mechanical point of view, is to be regarded as a weak point, this problem could not be observed using the shotcrete method [9]. In order to demonstrate the possibilities of robotic, generative manufacturing, it is planned to produce a single curved and a double curved wall without the use of formwork at the end of the project. In particular, curvature in two axes cannot be realized with current standard formwork systems.

4.1 Application parameters

One of the biggest disadvantages of the shotcrete process is also one of the biggest advantages. For example, the SCP3D process and the sprayed geometry depends on a many parameters, such as air pressure, concrete volume flow rate, robot speed and the distance of the nozzle to the target (see Figure 9). All these parameters must be controllable by the program in order to realize the desired application. Furthermore, the computer has to get real-time information about all parameters and the resulting geometry in order to control the shotcrete 3D printing. However, if you manage to regulate the parameters and adapt them to the application strategy, there are many possibilities for the shotcrete process.

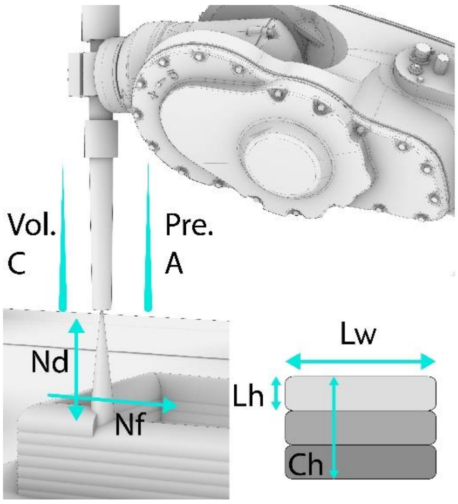

Figure 9. Overview of important parameters: Nd=Nozzle distance, Nf= Nozzle feedrate, Vol.C=Volume flow concrete, Pre.A=Pressure air, Lw=Layer width, Lh=Layer height, Ch=Concrete hardening

As the ITE has already been able to show, the control of these parameters is currently possible [11]. However, research is still in progress on the measurement technology for this complicated process. Currently, the focus of the integration is on a laser and a camera for in situ measurement of the sprayed geometry. This enables measurement of the width and height of the layer as well as the distance between the nozzle and the surface. This information is used to readjust the robots speed to either increase or decrease the thickness of the applied material.

4.2 Integrate reinforcement into the printing process

The manually spraying of steel and textile reinforcement was approved in different construction projects over the last years with great success.

The first studies at the DBFL to integrate reinforcement into the automated shotcrete process were performed in early 2018. It has been shown that it is possible to integrate textile and steel reinforcement without major problems. Although the reinforcement was still inserted manually, it can be assumed that a robot arm could perform this work even more precisely. Figure 11 shows a curved wall produced with the "Shotcrete 3D Printing" method. The wall is about 1.0 meters high and was reinforced at the backside with a textile (Figure 10, left). The smooth surface also on the backside was post processed manually by a trowel, based on Khoshnevis et al. [2]. Because the concrete hardens from the inside to the outside, it is already stable in the middle, but the outside is still soft enough to be processed. Therefore, the processing of the concrete with a trowel succeeds well. In preliminary tests with small robots [12], it could be shown that different surface qualities can be achieved in an automated process using trowels, rammers and scoops. However, the next experiments are intended to show that subsequent processing of the surface can also be carried out in real scale by a bigger robot.

On the frontside, a steel-reinforced console was added (Figure 10, right). To show the position of the reinforcement in the console, two reinforcement bars were not sprayed, as shown in Figure 11, left. The reinforcement is placed in the middle of the console and not in the upper part where it would statically belong, due to an easier integration process of the bars.

Figure 10. Wall produced with Shotcrete 3D Printing; backside smoothed and with implemented textile reinforcement (left); frontside with steel reinforced sprayed console (right)

Figure 11. Wall produced with Shotcrete 3D Printing; Detail of the console, with 2 reinforcement bars left blank (left); top view of the wall (right)

5 Summary and Outlook

In order to build concrete structures and elements more efficiently to save resources by making them lighter, alternative construction techniques to today's standard techniques are needed. With the development of the Non-Waste-Wax-Formwork technology, it is possible to realize a multitude of individual free-form concrete forms. Thereby the wax can be reused, which is not only ecologically but also economically reasonable. Further, the achieved surface quality can be utilized for high-precision components, which opens up new ways of use. But also low surface qualities and the associated rapid production of wax blocks is yet being applied in industry.

The next steps on the way to industrial use are the improvement of the wax by using fillers and the wax block production. This would reduce the energy absorption to melt the wax and increase its strength. Improving the material will always improve the process itself, which in return could reveal new fields of application.

In contrast, the Shotcrete 3D Printing requires no formwork at all, by assembling layers to bigger elements. This saves the intermediate step of producing a formwork and the time and cost associated with it. In this way, a complex curved shape could be produced without formwork. As the first tests showed, it is also possible to integrate reinforcement (textile or steel) without any major effort and to apply concrete horizontal up to a thickness of about 16 cm. As Hack and Lauer [12] stated it is possible to print a mesh-mould by a robot. This mesh could be sprayed with concrete, which would fully automate the building process. Upcoming experiments using meshes and more complex reinforcement structures will investigate the opportunities of the SC3DP to produce viable real scale structures.

Going along with these experiments, the integration of a closed control loop is prepared. This will push the method ahead by getting more control of the spraying process and the sprayed structures.

Strongly connected to the process is the used material. Just as with other additive manufacturing strategies, a high-performance concrete material, which meets the requirements, must be developed for this process. This is currently carried out at the Inst. of Building Materials, Concrete Construction and Fire protection (IBMB) of the TU Braunschweig in cooperation with the ITE. The objective is to create an adjustable concrete that can be adapted to the printing process in terms of rheology, mechanical properties and hardening [9].

In the future, the possibility of combining these two methods, described in this paper, will also be explored. This means that the concrete can be sprayed onto a single-face wax formwork and thus be graduated over its thickness. It would be possible to integrate reinforcement, other components or to leave out areas and have a precise and free-from single-side surface.

To produce load-bearing components for the use on construction sites it is necessary to implement reinforcement on an affordable level. This will be one of the next challenges for the 3D printing techniques. Using the DBFL, the ITE has the opportunity to address these challenges and enhance digital fabrication.

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