The use of robots and self-compacting concrete for unique concrete structures

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ABSTRACT: Today's concrete architecture is often dominated by repetitiveness and recognisable geometries like squares and rectangles. Digitally designed and extraordinary concrete architecture involves excessively high construction costs, due to the production methods based on craftsmanship. A way of opening up the prospect of a new and exciting concrete architecture is to find new automated industrial methods for the production of singular concrete structures. The aim of an ongoing Danish project called “Unique Concrete Structures” is to build alternative moulds by using robots and tailor-made self-compacting concrete that will spread in the moulds and thus shape concrete structures according to the architect's instructions. A new High Technology Concrete Laboratory equipped with a robot cell and a fully automatic mixing plant has been established at the Danish Technological Institute.

1 INTRODUCTION

Concrete is the most used construction material in the world. For instance, the production of ready mix concrete in Europe is approximately 500 m³ per year or around 2.5 tons concrete per capita (Ermco).

Many architects see concrete as a fundamental construction material but also as a material, which offers unique opportunities in terms of shaping; however, the nature of conventional concrete production and technology has set up clear limitations to the aesthetic possibilities. The concrete architecture that we know today is often dominated by repetitiveness and recognisable geometries like squares and rectangles. The stereotype appearance of these structures brings negative associations to many people's mind leaving the concrete industry with a serious image problem. Spectacular concrete architecture is rarely seen, and almost only in connection with extraordinary buildings, where the construction costs have been excessively high, despite of concrete being a cheap building material. Examples of such projects are the new apartment building Bispebjerg Bakke in Copenhagen where each separate concrete element is unique (Fig. 1) and The Tenerife Opera House by the Spanish architect Santiago Calatrava.

One of the reasons for the high expenses is to be found in the production of concrete structures. Here the development has not experienced essential innovation since the industrialisation in the first half of the 20th century, which means that the production methods still are based on craftsmanship. To this must be added that the standardized formwork equipment in steel and wood do not have the needed flexibility to adjust into unique geometries. Handmade moulds for unique buildings are both difficult to produce, time consuming and expensive. The costs for preparation of the formwork can amount to 75% of the total costs.

To lower the cost and to utilize the unused potential of concrete for unique structures, innovative development and usage of the construction industry is required. To this must be added implementation of already known technologies and manufacturing process known from other industries. In connection to this, especially the progress on SCC (Self Compacting Concrete) and the expansion within the field of industrial robots for one-off production are of interest e.g. milling, assembling and painting are examples of processes which can be performed by industrial robots.

Figure 1. A new apartment building Bispebjerg Bakke in Copenhagen. The geometry of each concrete element is unique.
(Hanser et al. 2006, Naticchia et al. 2006, and Gassel et al. 2006).

Succeeding in bringing these technologies together will provide an outstanding opportunity for a technological breakthrough in the concrete industry.

1.1 Automatic manufacturing

Rapid manufacturing has developed through the aerospace and automotive sectors, and is now a growing feature of today’s construction industry. One of the most striking developments is the introduction of Digital Fabrication, the application of large scale CAD/CAM (Computer Aided Design/Computer Aided Manufacturing) techniques for the creation of building structural components and facades (Acker 1996, Kolarevic 2005, Buswell et al. 2007). Following is a few examples of projects where the technologies have been used to create unique architecture.

An example of manufacturing of major structural components in concrete by the use of CNC (Computer Numeric Control) milling is the Zoolhof Towers in Dusseldorf, Germany by the American architect Frank Gehry. The double-curved geometry of the load-bearing external wall panels were made of reinforced concrete. The molds were produced using blocks of lightweight polystyrene which was shaped in CATIA and CNC milled to produce 355 different curved moulds that became the forms for the casting of the concrete (Schnabel 2001).

Another project that deals with CNC milled polystyrene moulds is Big Belt House project in Meagher County, Montana by the American architect William Massie. The formwork consisted of approximately 1500 individual pieces of CNC milled polystyrene. This great puzzle was then transported and assembled at the construction site. Concrete was then poured into these forms, creating the walls of the house (Eberhard 2003).

In order to research in digital fabrication processes, the ETH Zurich Department Architecture has developed a fully flexible fabrication installation. Using modified industrial robots, the research involves entirely new approaches to e.g. bricklaying. The installation opens up new possibilities to fabricate brick walls which could not have been conceived or fabricated manually (Gramazio & Kohler 2003 and Jerl 2007). The techniques were used to design and fabricate 400 square meters of brick facade for a functional building of a winery. The single bricks were laid out in a predefined grid and were merely rotated around their centre point by the robot.

1.2 Self-compacting concrete

Self-compacting concrete (SCC) emerged on the building scene in the 1980s in Japan together with new types of high performance water reducing admixtures. SCC is simply defined as concrete that is able to compact and flow under its own weight into its final position, while filling the formwork completely and embedding the reinforcement (Ouchi 1999). The concrete should not be subject to vibration and only manual handling is allowed by means of hand tools such as rake and shovel. Therefore, the fresh properties of SCC are significantly different from traditional concrete. The original idea of SCC was to improve the concrete quality by eliminating the effect of vibration that could harm the inner structure of the concrete and to simplify the execution of concrete casting in order to avoid the need for a highly skilled labour force. For heavily reinforced structures with a complicated geometry it is difficult to perform vibration properly and therefore, SCC has obvious advantages.

The extension of the art museum Ordrupgaard in Copenhagen by the Iraqi/British architect Zaha Hadid (Fig. 2) is an example of an SCC application. SCC was chosen due to a complex form work geometry and reinforcement configuration.

To benefit from the full potential of Self-Compacting Concrete (SCC) tools for prediction of the form filling of SCC are needed (Roussel et al. 2007, Thrane 2005). It is essential to have tools predicting the flow and the subsequent hardening process for mould design and process planning. Trial and error may be applied to optimize the casting process when a large number of small samples are produced. However, when casting concrete, especially in-situ, trial and error is rarely an option and full control of the casting process is particularly important. The structural size and in-situ production often leaves only one attempt to obtain a satisfactory form filling and thereby the required structural quality. Indeed, just as numerical simulations of the loading of concrete structures allow a civil engineer to identify a minimum needed mechanical strength, numerical simulation of the casting process could allow the same engineer to specify

Figure 2. Example of SCC application. The extension of the art museum Ordrupgaard in Copenhagen.
a minimum workability of the fresh concrete and a casting technique that can ensure a proper filling of a given formwork. It has been shown that flow patterns, filling time and final position and geometry of free surfaces can be predicted with reasonable accuracy based on information on rheological properties and form geometry as well as filling technique (Thrane 2007, Roussel 2007).

Though promising, pioneering work has been carried out, the approach is far from standard in the concrete industry and clearly the approach does not yet hold all the answers to relevant questions. Further development is needed in order to bring computational modelling of SCC into practical applications such as planning the execution of unique concrete structures.

2 A NEW RESEARCH PROJECT

The Danish project “Unique Concrete Structures” started its activities in 2007 and runs for three years. The aim of this project is to find solutions for mass customisation of concrete constructions. This requires new ways to build unique moulds by the use of robots, and development of tailor-made concrete with special, engineered properties in the fresh state, that will spread in the formwork and around even complicated reinforcement arrangements by its own weight.

The project gathers leading Danish expertise within architecture, concrete technology, and robot technology. The challenge is to create opportunities for a more interesting and distinctive architecture within a reasonable cost frame. The participants in the project are Danish Technological Institute (concrete technology, robot technology, mould materials), University of Southern Denmark (robot technology), School of architecture in Aarhus (architecture), Spæncom A/S (pre-cast concrete structures), Unicon A/S (ready-mix concrete), Giben Scandinavia A/S (robot technology), Paschal Danmark a/s (formwork systems) and MT Højgaard A/S (contractor). The project is financially supported by The Danish National Advanced Technology Foundation.

2.1 Innovation of the project

Figure 3. The eight subprojects.
Architecture plays an important role in our culture. Through history, architecture has always reflected the technological possibilities of an epoch. Think of the bridges in the early 20th century with long spans due to the invention of reinforced concrete and the big structuralised housing projects in the middle of the 20th century due to the industrialisation of pre-cast concrete elements. The latter example could just as well have been the description of today's situation, despite the almost unlimited possibilities with ICT (Information and Communications Technology).

New digital tools for 3D shaping and form optimization have set a new agenda for the future architecture. The computer allows the architect to design a digital architecture that is beyond imagination. The research in this subtask involves describing and visualising hypothesis of the needs and demands to the future concrete architecture and thereby a new architectonic idiom, characterised by the parametric design tools used.

The architectonic statement was finished in the first half of 2007. Through a mapping of the history of concrete architecture from the Romans to today and a near future, the statement gives some answers, in which direction the concrete architecture will move. It concludes that the future will introduce a new amorphous digitally created architecture only possible to build with new industrial production methods. This means that new industrialised technology in the production chain will update the architectonic design possibilities and thereby be able to match today's technological possibilities with ICT.

2.2 Flexible formwork systems

Traditional formwork systems are typically a unit, where the actual formwork material is an integrated part of the formwork system. This project distinguishes the system from the material because of their different functions and properties. This means, that the formwork system in this project is the bearing structure of the formwork, which both can carry the load from the wet concrete and the hydrostatic pressure.

The research will focus on analysing and optimising existing formwork systems and if needed also the development of completely new systems. Whether the final formwork system is an existing, new or a combination of the two is not important. The essential property of the system is that it has the needed flexibility in order to comply with the demands for total design freedom. To this must be added that the formwork system both can be used in a pre-cast concrete production and on the construction site.

2.3 Formwork materials

Opposite the formwork system, which is mainly focusing on static aspects, the formwork material is focusing on design. The formwork material shapes the concrete both in overall geometries and down to surface textures.

The research will focus on analysing both traditional and new formwork materials. These are analyzed in relation to aspects like environment, economy, strength, flexibility and architectonic possibilities.

The project divides the formwork materials into two categories: A basic material and a coating/paste. The basic material is manufactured into the requested geometry. It could be wood, polystyrene, moulding sand, paraffin etc. This manufactured formwork material can be used in the formwork system as it is or a coating can be applied. A coating is typically a release agent like form oil but in this project it is also materials which can give new surface properties to the basic formwork material. It could be silicone, latex, epoxy, that will be sprayed or pasted on to the surface. The coating opens up new possibilities to achieve different surface textures.

An extensive analysis of potential formwork materials has ended with a detailed list, which is the starting point for the test activities in laboratory. The list of potential formwork materials includes plywood, polystyrene, PU-foam, paraffin, latex, acryl, mould sand, clay and many more. Coating materials is represented by epoxy, bio resin, silicone, EVA-foam and many more.

The first material tested was polystyrene. The material was tested for compressive strength in order to make mathematical models for strain due to the hydrostatic pressure and uplift from the wet concrete. Afterwards different milling tools were tested at different milling speeds in order to determine the optimized speed and tools in relation to the requested surface of the milled polystyrene.

After the initial testing a block was milled by the robot and afterwards filled with SCC. This test not only showed possibilities with the geometry but also the potential to integrate graphic milled into the mould and pictured on the concrete as a depression or elevation (Fig. 6). When casting in polystyrene moulds the surface of the concrete becomes rough. Tests with different coatings in order to achieve smoother surfaces of the concrete were made and with promising results (Fig. 7). The test was carried out with an open mould, which results in a plane backside on the final
concrete element. The next step is to make closed moulds with more complex geometries of which an example is shown in Figure 8.

2.4 Processing techniques

The main tool for manufacturing the formwork materials is a 6-axis robot. The potential of the robot regarding automation of i.e. the cutting, milling, melting and lifting processes will be exploited in the project. Based on the different tasks the robot can change its tool with the automatic tool changer. This gives the robot the needed flexibility in order to develop and verify the full process in fabrication of unique concrete structures. The formwork materials are decisive for the choice of tools and processing techniques applied. Research will involve mathematical modelling in order to carry out the required processing operations.

2.5 Software

To be able to translate the architects CAD drawing into a work plan for the robot, CAM software is needed. In this project Delcam PowerMILL is used to perform this translation. Initially, PowerMill is used for planning of milling strategies. Later on, the possibilities of other processing techniques will be exploited.

The toolpaths from PowerMill are translated into joint angles of the robot. However, as there may exist more than one solution for the same robot position it is important to develop software to ensure and verify that the robot positioning is actually physical possible.

The research will focus on robots for single production, where the robot control unit automatically calculates the movement of the robot based on input from a 3D CAD production drawing. Based on mathematical models known from spray coating it is pursued to develop accurate mathematical models for formwork processing and formwork coating.
Developed mathematical models can lead to a system of automated generation of robot paths.

2.6 Form filling

New and complex geometries give new challenges to the SCC in order to fill the form properly. The main research in this subproject is to simulate the form filling using CFD (Computational Fluid Dynamics) in order to tailor the rheological properties of the SCC. Based on the results of these investigations, the concrete composition and the casting techniques will be optimised. The model strategy proposed by Thrane 2007 will be improved with focus being on form filling of formwork with complex geometries.

2.7 Laboratory and full-scale

Formwork materials, processing techniques and form filling are tested in The High-Technology Concrete Laboratory at Danish Technology Institute.

Full-scale tests are then carried out aiming at realising the new unique geometries put forth in the Architectonic Statement

3 CONCLUSION

Different projects show the potential of integrating automated industrialised production methods and self-compacting concrete into construction. By transferring the technologies and bringing them together into construction and concrete production could create a breakthrough in the concrete industry. One of the challenges will be to prepare and implement the technologies in the production of concrete structures.

But to fully utilize the unused potential of concrete, not only the shaping of concrete, but also the surface texture has to be explored. This involves research in many different formwork materials and coatings to achieve different surface qualities and also different processing techniques in order to achieve graphics on the surface. The project “Unique Concrete Structures” deal with these issues and if succeeded the project can show directions for the concrete industry how to meet the demands for a new digitally created concrete architecture in the future.

REFERENCES


