POTENTIALS AND CHALLENGES IN 3D CONCRETE PRINTING

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ABSTRACT: Reinforced concrete structures have constantly become more safe and durable over the past century and the materials properties have improved tremendously, but the design and construction method have not changed much over time. Concrete structures face a series of challenges like a new degree of freedom for architecture, sustainability, health, increased productivity and a better integration to BIM models. 3D Concrete printing has the potential to meet these demands, although it is not clear yet which type of structures will benefit most from this additive type of manufacturing. However, in order to explore the benefits, the first task of research is to make the print process robust. This is needed since the load bearing capacity of a structure depends on the design and the printing strategy. Besides, the issue of a lack of reinforcing steel must be solved to ensure safe structures, for example by developing new and ductile types of concrete.

Keywords: concrete, 3D printing, contour crafting, zero slump, structural optimization

INTRODUCTION

Concrete is generally considered as the most important construction material, at least from a quantity point of view. World-wide 8 billion m3 of concrete is produced annually, presumably made possible since it consists of simple, common and cheap raw materials (sand, gravel and limestone). This means roughly 1 m3 of concrete is produced per person on earth, per year. The history of concrete as a construction material goes back to the roman period. The Pantheon in Rome (126 AC), with a unique concrete dome spanning 43.2 m, is still an icon and demonstrates the possibilities of plane concrete stressed in compression.

Unlike compression strength, concrete lacks serious tensile strength. Lambot overcame this problem utilising a netted steel reinforcing to take care of the tensile forces in the design of a concrete boat that was exhibited at the world’s fair in Paris in 1855. Monier, a gardener, was not pleased with the materials available at that time to produce flowerpots. He attended the fair, started experiments with concrete reinforced with steel bars and exhibit his invention at the Paris Exposition of 1867. Many initiatives followed, amongst those of Hennebique who granted a patent on reinforced concrete buildings in 1892, designed and constructed as a single monolithic structure. Many buildings have been erected in the years after using this method, like the first Philips building for the productions of light bulbs in Eindhoven. Although codes have been developed to ensure safe structures over time, more attention is being paid to durability today and higher performance types of concrete have been developed, the design and construction of reinforced concrete has not changed all too much over the past 125 years, as shown in Figure 1.

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Figure 1. The first Philips building in Eindhoven, 1909 (left) and present concrete buildings like some colorful housing in Singapore 1977 (right).

CHALLENGES FOR CONCRETE STRUCTURES

General

Reinforced concrete structures probably still exist after so many years due to the capability to realize safe, durable, long span and fire resistant structures. Despite these advantages, reinforced concrete structure do face challenges, to be discussed in the next sections. It is noted that despite the fact that these challenges are general, the weight given to each of them varies over the globe, due to specific regional interests.

Improved design and new architecture

Concrete becomes its beauty by the shape that it has been given during design. Architects like e.g. Nervi designed astonishing buildings in concrete. However, his complex concrete shapes are far too expensive to construct nowadays in order to be competitive with those buildings that follow the rules of concrete casted in simple rectangular formworks. In order to close the gap between desirable and affordable buildings and avoid daily compromising one over the other, new types of construction methods are required. Prefabrication is replacing the traditional in-situ type of manufacturing rapidly over the past decades, but will not solve the issue since concrete still needs to be poured in formworks in the factory. Besides, the prefabrication process requires a large degree of standardization in order to be cost effective and therefore limit the degree of freedom in design again.

Sustainability

The hydraulic binder in concrete is cement. The production of cement is responsible for about 5-7% of the exhaust of carbon dioxide produced by mankind. Major changes in either the concrete composition or concrete consumption are needed to comply with political conventions to stop climate change. Apart from this issue, sustainability can also be improved over lifetime by applying more functions to one and the same element. The thermal mass of concrete can be used as well for heating or cooling of buildings and regulates the temperature in a natural manner. However, the manual implementation of ducts in slabs and walls to allow water to flow through adds another complexity to the manufacturing method.

Healthy construction methods

Despite the increasing amount of lifting tools, construction work is still labor intensive and hard work. Normal concretes needs to be vibrated in order to be well compacted, but vibrating needles are a major cause of the so-called white hand syndrome.

Figure 2. Example of formwork and the complex reinforcement in civil construction work.

Besides, the placement of reinforcement in concrete structures is a major cause of back problems and early retirement.

Increased productivity

Concrete structures commonly are being built twice. The first time out of formwork, comprising about 50% of the overall costs and the second time out of concrete poured in the moulds. This is not cost effective and particularly time consuming, not to forget the manual placing of the reinforcing bars inside the formwork. Taking into account a global shift from green field building activities towards projects in more complex urban environments, the complexity of building construction will only increase over time.

Information management

The supply chain in the building industry is long and there are many suppliers needed to realise a building. Building information models (BIM) are used to be in control of the process and increase productivity from the design phase (early prototyping) up to construction. In order to benefit from these models, concrete structures need to be designed digitally and manufactured digitally.

POTENTIALS FOR CONCRETE PRINTING

Concrete printing

The idea of printing concrete was first demonstrated by Khoshnevis in the late 90's by means of contour crafting, a layered type of additive manufacturing technique using a zero slump type of concrete (Khoshnevis, 2004 / Khoshnevis et al., 2006). This method has been copied by various researcher workers and start-up companies world-wide ever since and an exponential growth is noticed after 2012. Amongst them is Loughborough University, which further developed the technology using small nozzles to be able printing more complicated and advanced cross sections in a well-controlled manner. The fast growth in attention can be explained by WinSun, a Chinese company, announcing to have built low cost houses first and full apartments soon after, demonstrating the potential of this type of technology. Their method is based on the original idea of Khoshnevis. Large scale elements are printed horizontally, lifted and twisted 90 degrees and finally stacked together at the construction site. It should be mentioned that an alternative type of concrete printing was developed slightly after contour crafting. The method called D-Shape, developed by Dini, injecting a binder in a thin layer of dry material over and over again. The advantage of this method is the true 3D nature, since a supporting layer is always available. An example of recent research on 3D concrete printing using the technology of contour crafting, performed at Eindhoven University of Technology (TU/e), is shown in Figure 3. A disadvantage could be the industry being unfamiliar with the type of concrete printed and the rough finishing of the elements so far.

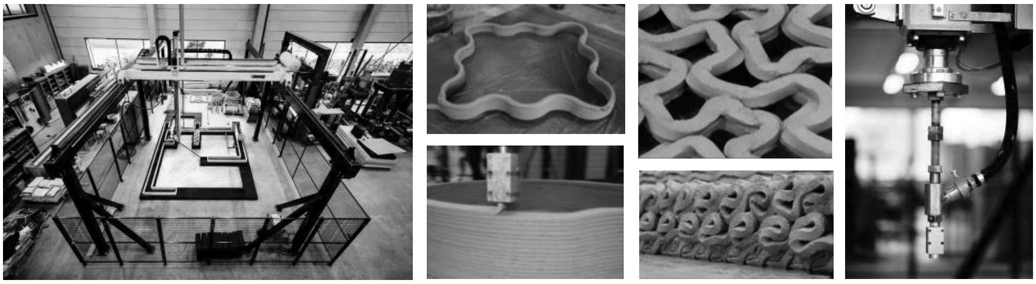

Figure 3. The large scale gantry concrete printer at TU/e and some printed elements.

Contour crafting, potentially, is capable to meet the challenges in concrete structures:

- a new degree of architectural freedom in concrete design is possible since the printer can easily make more complicated shapes, without the limitations of formwork;
- the additive manufacturing method allows to print concrete only at those places needed and therefore save on concrete consumption. Besides, more complex elements can be manufactured, integrating functions and make e.g. use of the thermal mass of concrete;
- robots take over the hard work and vibration of concrete is not required anymore;
- productivity can be increased due to a lack of formwork and robots can work 24/7;
- the digital type of manufacturing comes along with a digital type of design that perfectly matches up with buildings information models.
- Mass customization: repetition is no longer required to make the process (economically) feasible. Elements can be varied over and over without a significant increase in production costs or time.

Potentials

3D printing of concrete definitely shows high potential, but the best way to benefit from it still needs to be explored by the industry. The potentials could be classified at three hierarchic levels of size, if for discussion only. The largest level is in situ 3D printing of entire buildings (see Figure 1). Many visualisations of such an idea struck the eye, mostly showing large gantries printing a whole building on site. However, it can be argued if this is the best way to introduce the new technology. Presently, initiatives in this direction are still limited to low cost housing only. This makes sense since the quality can't compete yet with traditional concrete structures. Besides, safety is also still an issue to be guaranteed. Apart from this, one could also wonder if it makes sense to install large scale printers manufacturing relative smaller objects. However, different initiatives on swarm types of printing are being investigated, using a series of small robots to do the job together. The second level of size could be prefabricated structural elements, either stacked together on site or single printed components in a more traditional building like e.g. façade elements. The technology seems to be dedicated to make smart structures at this level. The smallest level is to make use of the printer in combination with traditional prefabrication and only adjust the prefab elements to make them more mass customized to an extent. Particularly adding those customised parts that can't be poured easily with a formwork, e.g. connections or complex design features.

RESEARCH NEEDS

Printer

Despite the potentials, printing of concrete is far from self-evident due to the nature of the material and particular the cement as a hydraulic binder. Contrary to traditional concrete structures, the materials properties depend on the manufacturing method, as illustrated in Figure 4.

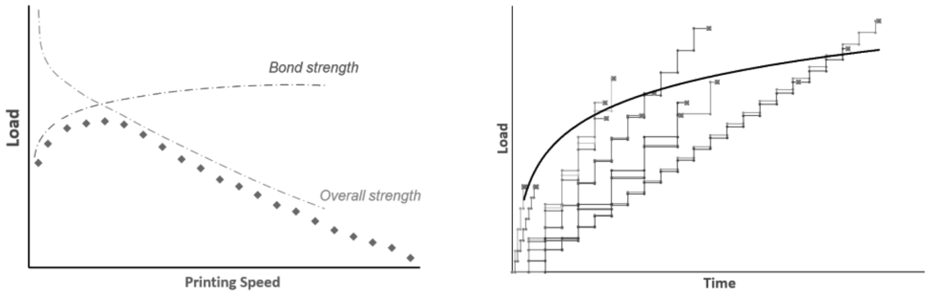

Figure 4. The load bearing capacity of a structure related to the print speed (left). The development of the load bearing capacity of green concrete (right).

The figure shows the relationship between the load bearing capacity of a simple structure, related to the speed of the printer. An optimum in print speed is achieved due to a combination of an increasing bond strength between the layers in time and a decreasing strength of the overall structure with increasing print speed due to the development of concrete properties over time by means of a simulated annealing algorithm (Wolfs & Salet, 2015). The load bearing capacity also depends on both the height of each layer and the concrete temperature, which in turn is again related to the type of pump and length of the hose between mixing unit and nozzle. Finally, the materials properties of the full structure will be orthotropic due to the layered type of manufacturing. In order to avoid trial and error in the industry, research at TU/e is being performed to make the print process robust and define the optimal printing strategy related to both the materials properties and the design to be printed in a reversed engineering manner.

Concrete

Obviously a zero slump type of concrete is needed. However, it still needs to be fluid enough to pump the concrete from the mixing device to the nozzle of the printer. Research on this apparent contradiction has been performed and well performing materials are based on thixotropic behaviour (Hoornahad, 2014). Research at TU/e is being performed in order to get familiarized with the properties of printed concrete, both in the dormant period and in the hardening phase. A state parameters type of approach is applied in order to relate the materials properties to influences of e.g. time and temperature. Besides, the relationship between the concrete properties and the properties of the layered concrete are studied due to the nature of the print process and improved if needed. In order to improve the materials properties, FEM based numerical tools have been developed, using the concept of Numerical Concrete (Roelfstra, 1989). This has been illustrated in Figure 5 by means of two examples. The figure shows a test on the tensile strength on concrete composed with a light weight type of aggregates and a pull out test on large scale fibres.

It is noticed that one of the possible show stoppers of this new technology might be the lack of structural reinforcement. A simple way to solve this matter is to print a concrete formwork, place reinforcement and finally pour concrete in site, if only at special parts of the structure. However, in this case still a traditional type of reinforcement is needed. Research is performed at ETH Zurich to print a non-metal type of reinforcement and pour concrete in the reinforcement cage or bend steel reinforcement with a robot. TU/e focussed on the improvement of the ductility of concrete loaded in tension, in combination with high strength concrete in order to be able to print safe concrete structures without the need to use traditional reinforcement.

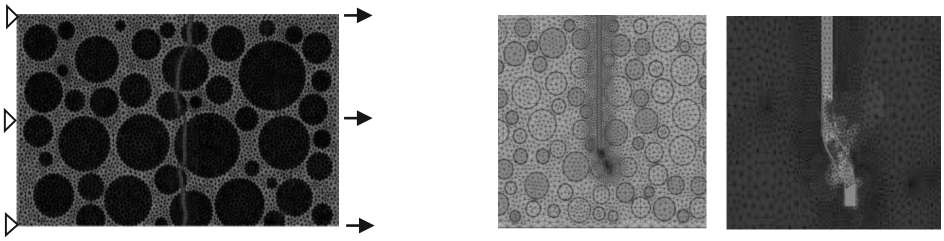

Figure 5. Numerical Concrete models developed at TU/e.

Structural design

The additive type of manufacturing challenges to design effective types of elements using a minimum of material needed from a structural point of view. The structures can be designed by using structural optimization tools, as shown in figure 6. The figure shows a part of a bridge designed and manufactured by means of structural optimization. Both concrete properties and limitations of the manufacturing method need to be taken into account in the optimization process in order to design valuable and realistic shapes.

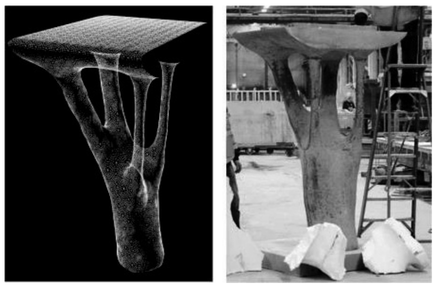

Figure 6. Example of structural optimization of concrete structures at TU/e.

REFERENCES

Hoornahad, H. (2014). “Towards development of self-compacting no-slump concrete mixtures”, *thesis Delft University of Technology.*

Khoshnevis, B. (2004), “Automated construction by contour crafting-related robotics and information technologies”, *Automation in Construction*, 13(1), 5–19.

Khoshnevis, B., Hwang, D., Yao, K. & Yeh, Z. (2006), “Mega-scale fabrication by contour crafting”, *International journal of Industrial and System Engineering*, 1(3), 301–320.

Roelfstra, P.E. (1989). “A numerical approach to investigate the properties of concrete-Numerical Concrete”, *Thesis no.788 EPFL Lausanne*.

Wolfs, R. & Salet, T. (2015). “An optimization strategy for CAD/CAM oriented design”, *proceedings of the 22th EG –ICE workshop 2015, Eindhoven*.