PARAMETRIC CUSTOMISATION OF A 3D CONCRETE PRINTED PAVILION

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Abstract. Advances in 3D printing technology have reached architectural scales with 3D concrete printing, a digitally controlled fabrication process in which fibre-reinforced concrete is deposited layer-by-layer to fabricate building elements. In this paper we present a brief overview of key concrete 3D printing related research development efforts, followed by a report on a research project into the parametric online customisation and fabrication of small 3D concrete printed pavilions. The research project is set in, and addresses possibilities and constraints of, the developing local Chinese construction context.

Keywords. 3D concrete printing; parametric design; digital fabrication; online customisation; China.

1. Background

For more than three decades, the Chinese construction boom has resulted in the placement of unheard-of quantities of concrete. Smil (2014, p. 91) illustrates the scale of this transformation with the observation that Chinese construction between 2009 and 2011 consumed 5.5 gigatonnes of cement, while the USA consumed a mere 4.56 gigatonnes of cement in the entire twentieth century. Collateral environmental impacts result, besides other factors, from the import and production of iron ore for reinforcement steel, from the depletion of river sands to be used as aggregate, and from the waste of large quantities of discarded formwork. This developmental push forward is bound to remain in effect for decades to come. At the same time, large-scale urbanisation, the opening of markets, the emergence of a new urban middle class, and the gradual de-regulation of family structures in China give rise to an increasing demand for variety in built form. Despite these
changes, dominant methods and typical forms of concrete construction in China have not changed significantly for decades, and digital automation technologies in particular have remained largely out of reach for China as well as other developing countries. Key reasons for the persistence of concrete construction methods include the lack of skill in labour force as well as challenges of introducing automation at building scale. While low-skilled human labour can be expected to dominate concrete construction in China for the foreseeable future, recent advances in 3D printing based construction automation are now showing promise.

With this paper, we aim to connect recent initial advances to introduce 3D concrete printing technology into the local Chinese construction context with the more advanced possibilities offered by advanced parametric modelling. The research project outlined in the second half of this paper is based on the authors’ collaboration with three undergraduate students of architecture over one summer. The scope of the work comprises primarily the set-up of a parametric model that takes into account local material and construction technology constraints in the fabrication of 3D printed concrete and can be operated through an online user interface.

2. 3D printing at the scale of buildings

In parallel to recent advances in more familiar desktop 3D printing and rapid prototyping technologies, larger-scale 3D concrete printing, currently still in the early stages of its technological development, has progressed significantly over the past few years. Van der Zee et al (2014) distinguish two types of process in in building scale 3D printing: Additive layered depositing, and selective sintering. Among a variety of potential materials, concrete has emerged as one of the most promising materials for automated layered depositing fabrication at the building scale. This approach uses robot arms or, more typically, gantry cranes as large-scale Cartesian robots for the computer-controlled deposition of concrete, and is currently explored at an experimental and early demonstration stage.

The Contour Crafting process, developed by Behrokh Khoshnevis at the University of Southern California (Leach et al, 2012), is an additive layered depositing process. Layers of a concrete mix are extruded and deposited robotically to form building elements, typically walls stabilised by an internally corrugated structure, without the need for traditional formwork. A layered 3D concrete printing process for the manufacturing of building components has also been developed at Loughborough University (Buswell et al, 2007; Lim et al, 2012). This initiative focuses on reinforcement techniques, material science, and the development of robotics for material
placement. The Loughborough group has manufactured prototypes for building elements that are complex in shape and require precise manufacturing, such as doubly-curved cladding panels. In contrast to the previous two approaches, which use a layered depositing approach, the work of Dini of D-Shape Enterprises (Dehue, 2013) employs the selective sintering approach, which requires printed objects to be dug out of a mass of substrate after printing is finished. In collaboration with Kushner Studios, Dini is currently aiming to print a large house in Gardiner, New York (Myall, 2015a).

3. Recent developments in 3D concrete printing in China

While so far most 3D concrete printing research efforts are taking place in academic contexts, with a focus on technology development and small prototypes, the Suzhou, China based company WinSun has made headlines in recent years by producing a series of full-scale 3D printed buildings. WinSun has adopted the recipe for its concrete mix (called “ink” and kept secret by WinSun), along with its layered printing technology and internal wall corrugation construction method (figure 1, left), from those developed by the Contour Crafting group – under controversial circumstances (Sheehan, 2015). Starting from producing ten small pavilion-like structures within 24 hours in 2014, the company has proceeded to unveil two larger record-setting prototypes on their company grounds in early 2015: A large two-floor villa as well as a five-floor building (figure 1, right).

While their presentation as “3D printed” suggests that these larger structures are completely 3D-concrete printed, they are in fact based on a hybrid construction method in which vertical compression-loaded elements (i.e. walls and columns) are 3D printed, while floor slabs are in-situ cast by conventional means. The ink mix used by WinSun consists, besides recycled construction waste, of cement and a binder that takes 24 hours to dry (Sun, 2015), as well as structural reinforcement in the form of glass or polymer.
The fibre gives the ink some tensile strength within each deposited layer, but little tensile strength between layers where little or no continuity of fibre is present due to the extrusion-based depositing method. This results in weaknesses under tensile stresses, while compressive strength of structures made from ink lie at the lower end of the range of compressive strengths of conventional types of concrete. For these reasons WinSun typically embeds steel reinforcement in larger 3D printed structures, effectively employing the 3D printed concrete elements as lost formwork for an internal conventional reinforced concrete structure. While this strategy supports higher reliability of a new material with not yet well understood structural behaviour, it also renders such building elements heavy and primarily usable as walls and columns. WinSun has recently extended this limited architectural repertoire with large-scale 3D concrete printed structures comprising also horizontal building elements for the Museum of the Future project in Dubai, in collaboration with well-known international architecture and engineering firms Gensler, Thornton Thomassetti and Syska Hennessy (Myall, 2015b).

The 3D concrete printing research initiatives outlined in section 2 above are characterised by different motivations. While Koshnevis expects that future on-site production of buildings will make low-cost but high-quality housing construction possible (Sun, 2015), the Loughborough University team focuses on high precision fabrication of building components for complex geometries. Dini and Kushner, meanwhile, are working towards the automated construction of entire buildings featuring complex shapes (Myall, 2015a). The WinSun company takes a yet different approach in aiming for the prefabrication of simple building elements that cut construction costs by reducing labour cost and construction time. With this aim, WinSun continues to push forward with achieving and announcing new records regarding speed, efficiency and economy, but currently pays less attention to new architectural possibilities, spatial qualities or high quality detail design.

Besides the automation and form giving opportunities they offer, WinSun’s and similar 3D concrete printing technologies show potential with regards to sustainability. Not only does WinSun claim that their ink contains a significant proportion of recycled construction waste, which would reduce the demand for “fresh” aggregate as well as for landfill space; there is also a significant potential to reduce the demand for river sand in concrete construction. A factor that contributes considerably to the demand for river sand is the corrosive effect of salt and chloride contained in other (ocean, desert) sands on rebar steel. Abundantly available and cheap ocean and desert sands are however suitable for 3D printed concrete elements whose glass or polymer fibre contents are sufficient to deal with physical stresses,
and which hence require no steel reinforcement. To deal with tensile stresses in its larger scale structures, WinSun typically embeds rebar in river sand-based concrete added within cavities left in the corrugated interiors of 3D printed extrusions, to ensure cohesion between 3D printed layers. When embedded in this way, rebar steel does not get into contact with corrosive, ocean or desert sand based ink elements. If this construction technique could reduce the demand for river sand even by modest proportions, given the above-mentioned gigantic volume of concrete production in China, the overall environmental and economic effects could be considerable. The economic effect may well offer viable returns on the investments necessary for the development efforts required to bring 3D concrete printing to maturity.

3D concrete printing allows, within some constraints, the production of unique, one-off shapes. It is hence highly suitable for, and easily related to, digital and parametric form giving approaches. The following sections of this paper outline a project in the intersection between parametric form finding and 3D concrete printing. With this project, we aim to explore possibilities for academic and industrial research collaborations, to extend the use of digital parametric modeling, as well as to address a lack of attention towards architectural quality. For a discussion of the general characteristics and possibilities of parametric design have been discussed in other contexts, and will therefore not be reviewed in this paper. Readers interested in this aspect of the background of this study are referred to Jabi (2013), Woodbury (2010) and Herr (2011).

4. Customisation platform and fabrication

The project discussed here was conducted jointly by a team of undergraduate architecture students and faculty members at the Department of Architecture at Xi’an Jiaotong-Liverpool University (XJTLU) within the framework of a novel summer undergraduate research fellowship programme. The research students were invited to explore and evaluate possibilities of customising 3D concrete printed pavilions, and to investigate the potential of 3D printing for online parametric mass customisation (Gilmore and Pine, 1997; Herr and Fischer, 2015) of small concrete buildings to address varying client needs and site contexts. More specifically, the students developed an architectural form language that mediates between the possibilities of simple web-based interfaces and the constraints of 3D concrete printing as currently practiced by WinSun, and implemented a demonstration platform that bridges these technologies. In this manner, the project is related to recent studies exploring
how advanced digital design can be implemented with basic means in projects constructed in developing countries.

Methodologically, the project has adopted a research-through-design approach that has also served to explore possibilities for industrial collaboration with WinSun. The research process took the form of alternating cycles of design exploration and synthesis, informed by sketching, model making, experimental coding, data collection and expert feedback focused on material, fabrication, transportation and construction constraints, functional aspects, and structural evaluation. Outcomes and findings include a form language suitable to the material and fabrication process, a parametric customisation approach, a set of structural design and construction constraints, and a range of pavilion designs generated with the system. The research-through-design approach allowed the evaluation of results on a continuous basis, and may lead to the realisation of one pavilion prototype.

The architectural form language developed for this project (figure 2) responds to current possibilities and limitations of 3D concrete printing on the scale of buildings, related material properties and structural performance criteria. It recognises the need to print larger, heavier elements in straight vertical stacks without overhangs that could produce curves in section. To achieve enclosing shapes, the form language hence requires the printing of closed vertical section shapes including floor, walls and ceiling on a flat horizontal surface, and the result to be turned on its side after the concrete mixture has hardened – typically after 24 hours. The form language developed in this project was inspired in part by a precedent project investigating online parametric pavilion customisation (Rüdenauer, 2005). Functional aspects of use, ergonomics as well as fabrication, including the integration of an electrical system, and transportation and assembly constraints were considered.
The online customisation interface (figure 3) offers access to elements of the form language and some of their attributes via an extendable library of segment cross-section profiles, allowing for their recombination and parametric dimensioning. The system is implemented in Python/CGI via an Apache web server driving a parametric Rhino3D model and Grasshopper setup (see figure 4). It permits the exploration of a broad variety of different yet structurally and aesthetically coherent pavilion structures.

Users can select cross section profiles from a cross section library and add them to a stack. The interface offers several functions to sort, edit and process stacks or cross sections. Each cross-section in a stack can be altered parametrically in terms of its depth, concrete pigment colour, and position within the stack. CGI scripts and Grasshopper are interfaced via file system based data exchange, which requires the Grasshopper setup to operate in an error state (indicated by red and orange coloured elements in figure 4) when idle and to enter error-free operation when input data becomes available momentarily.

![Figure 3. Online customisation interface.](image)

![Figure 4. Grasshopper setup.](image)
Of the vast variety of pavilions that can be generated using this platform, the research students chose one (shown in figure 5) for in-depth analysis and implementation.

![Figure 5. Rendering of the pavilion selected for production.]

The structural performance of the pavilion selected for implementation was evaluated in collaboration with XJTLU’s Department of Civil Engineering using Finite Element Method (FEM) in ANSYS (see figure 6).

![Figure 6. FEM-based simulation of deformation (displayed disproportionally) under dead load in ANSYS.]

The structure of the selected pavilion was simulated assuming the structural properties of conventional, non-reinforced concrete, and found to be capable of supporting its own weight within a margin of safety of 150%. However, greater stresses than dead load support must be expected,
especially during handling, transport and assembly of individual segments. In addition, as the structural characteristics of the ink material are not yet fully understood, they were unavailable for simulation purposes. For these reasons it was decided to embed steel reinforcements both within the printing plane (at an interval of ±10 printing layers) and perpendicularly to the printing plane to ensure the connections between printing layers as well as the connections between pavilion segments.

This project allowed extending the scope of previous parametric design related research (Fischer and Herr, 2015) to investigate architectural (functional, aesthetic, structural, economic) aspects of 3D concrete printing within the framework of parametric design. It also extends previous research on integrating advanced digital design methods with local Chinese construction practice (Herr and Fischer, 2013; Herr and Fischer, 2014). The study focuses on a specific building type, a specific fabrication method, a specific material, one form language, and a particular recombinatorial and parametric customisation approach. Alternative approaches and form languages are possible and may be addressed in future research. The FEM analysis could potentially be integrated into the Grasshopper definition in a further development of this research. Findings achieved in this project are expected to inform future 3D concrete printing practice, as well as further research into related materials, technologies, form languages and customisation strategies.

5. Conclusions

With the described proof-of-concept implementation, we have demonstrated how users and clients can be enabled to conduct or to participate in building customisation via an online interface. We have further shown how digitally supported fabrication of such customised buildings through 3D printing can take into account possibilities and constraints of current 3D concrete printing technology and materials locally available in China. This was achieved through the coordinated design of the described online interface, the described form language, and a suitable backend setup. Further development of the presented work will be subject to all involved partners' readiness to engage in collaborative partnership.

Acknowledgements

We gratefully acknowledge our undergraduate research students Hao Wu, Hao Jiang and Yixin Han and the collaboration of Mohammad Hajsadeghi as well as Prof. Pierre Alain Croset at XJTLU. We thank Mr. Ma Yihe and Mr. Cui of WinSun for their generous feedback. We also acknowledge Berokh Koshnevis’ pioneering work on Contour Crafting.
and his providing us with valuable background information. This project was funded under SURF 201501 research grant of XJTLU.

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