Concrete Choreography: Prefabrication of 3D-Printed Columns
This paper introduces the cutting-edge 3D Concrete Printing (3DCP) process which stands at the core of the project Concrete Choreography, a family of nine prefabricated concrete columns. By simultaneously overseeing technological development, computational design and robotic fabrication, an interdisciplinary research team was able to reform the challenge of large-scale high-resolution 3DCP.

The prefabricated columns set the stage for the summer season of the Origen Festival of Culture, held annually in the awe-inspiring alpine setting of Riom, Switzerland (Fig. 1). Design and fabrication of the columns was formulated as a studio course brief for the Master of Advanced Studies in Architecture and Digital Fabrication at ETH Zurich (ETHZ). Framing the latest research in 3DCP within the context of the performing arts, the project liberated design thinking from conventional concreting techniques and fostered an holistic approach to the conception and realisation of a novel, multi-layered material system.

Towards an Additive Materiality

Due to their rich formal and cultural history, columns were the perfect archetypical testing ground for computational design tailored to innovative fabrication. The research investigated the characteristics of a new concrete column typology emerging from properties of 3DCP. While previous work in the field of generative design has focused on the procedural articulation of form (Hansmeier and Dillenburger, 2013), Concrete Choreography merged design and fabrication methods. The main research aim of this project was to demonstrate the remarkable architectural qualities achievable through 3DCP, but impossible with any other printing method or conventional casting technique.

A key objective was to deliver fine print resolution as a result of high production speed, process stability and robustness. The specific fast-setting 3DCP process using a low yield stress mortar developed at ETHZ pushes the limits of conventional prefabrication of structural elements. Another objective was to investigate the extrusion layer as a design instrument for high-resolution and multi-scalar material articulation. The column typology fulfilled the geometric criteria to test the fast, vertical build-up rate of the fabrication method, demonstrating the targeted qualities along significant element heights. It also provided the opportunity to assess the robustness of the recently developed 3DCP.
A New Context for Building with Concrete

Aiming to reduce the ecological footprint of concrete (Cra et al., 2015), digital fabrication explores ways to decrease the amount of concrete used and to remove the additional work sequences or unnecessary materials used in temporary scaffolds and formworks. This inherently challenges the rationalisation and serialisation dogmas at the core of the economic motivation to reuse the formwork and not to limit the design space. In this effort, 3DCP provides an opportunity to build less structural elements by placing concrete only where needed (Kleiner et al., 2004). Combining the ecological advantages of no-waste constructions with shape customization and morphological freedom, mouldless shaping of the concrete shifts the focus of concrete research from formwork production to controlling the properties of fresh paste during its transition to cured concrete. Thus, the transition from indirect – formwork-based manufacturing to direct fabrication of 3D printed components triggers a radical paradigm shift in concrete technology.

The challenges in delivering high-quality objects and spaces are motivated by an almost exclusive focus on material and process development rather than on design methods. When it comes to building tall elements quickly, the process can achieve much more than simply inheriting the obvious advantages that can increase the quality of concrete products. The geometric freedom provided by 3D printing enabled the inclusion of imperative features, facilitating a high degree of functional integration, such as space for reinforcement, alignment details, lighting and without process interruptions, a set on-demand is the method on which these processes rely on-demand is the method on which these processes rely on-demand is the method on which these processes rely on-demand is the method on which these processes rely on-demand is the method on which these processes rely on-demand is the method on which these processes rely on-demand is the method on which these processes rely. In support of the freeform concept, a fabrication-driven classification of 3DCP building systems was proposed by Duballet et al., 2016. Succeeding in the development of a substantial body of work, the majority of house prototypes focused on simple, low-resolution elements which materialised in most cases (Reiter et al., 2018). Good formwork production to controlling the properties of fresh mortar paste. Defining a process-specific set of parameters quantitatively describes the geometric affordances of the fabrication technique. Hence, the research asked: what was the set of parameters which define the fabrication space of 3DCP?

Research Focus

Relying on the aesthetics of cast concrete, the majority of realised large-scale 3DCP-constructions contextually the need for design methods more suited for the new fabrication process. Targeting a meaningful materialisation of layered extrusion processes, several research questions sharpened the project focus. 3DCP should successfully balance hardware specifications, print resolution, print speed and strength capacity of fresh mortar paste. Defining a process-specific set of parameters quantitatively describes the geometric affordances of the fabrication technique. Hence, the research asked: what was the set of parameters which define the fabrication space of 3DCP?

Fast production of on-demand, materially-efficient and geographically-complex architectural elements are some of the obvious advantages that can increase the quality of concrete products. The geometric freedom provided by 3D printing enabled the inclusion of imperative features, facilitating a high degree of functional integration, such as space for reinforcement, alignment details, lighting and without process interruptions, a set on-demand is the method on which these processes rely on-demand is the method on which these processes rely on-demand is the method on which these processes rely on-demand is the method on which these processes rely on-demand is the method on which these processes rely on-demand is the method on which these processes rely on-demand is the method on which these processes rely. In support of the freeform concept, a fabrication-driven classification of 3DCP building systems was proposed by Duballet et al., 2016. Succeeding in the development of a substantial body of work, the majority of house prototypes focused on simple, low-resolution elements which materialised in most cases (Reiter et al., 2018). Relying on the aesthetics of cast concrete, the majority of realised large-scale 3DCP-constructions contextually the need for design methods more suited for the new fabrication process. Targeting a meaningful materialisation of layered extrusion processes, several research questions sharpened the project focus. 3DCP should successfully balance hardware specifications, print resolution, print speed and strength capacity of fresh mortar paste. Defining a process-specific set of parameters quantitatively describes the geometric affordances of the fabrication technique. Hence, the research asked: what was the set of parameters which define the fabrication space of 3DCP?
Two procedural computational design engines based on trigonometric functions and mesh subdivision were developed and utilised in the design process (Anton et al., 2020) (Figs 3, 4). Features like macro-porosity, self-inserting print-paths and gradual overhangs exemplify the versatility and significant aesthetic potential of 3DCP when employed in large-scale concrete structures. For instance, features of the column could be distinguished by whether a print-path was self-sealing or self-inserting.

Each column was designed as a double shell composition with structural internal bracing. The outer shell dimensions ranged from 250 to 600mm with a highly differentiated ornamental exterior, whereas the inner shell, housing a cavity for traditional reinforced concrete, was kept as rational as possible for increased stability (Fig. 5). Within each layer, these shells were connected by minimal print-paths. Consequently, this internal bracing structurally supported the adjacent shell layers of freshly printed material and increased the achievable overhang for the column geometry, as well as providing a closed core for partial concrete casting.

Trigonometric functions were also used to drive print-path deviations creating material-driven ornamentation. This procedural ornament was calibrated at the limit of material stability from layer to layer. The characteristic dripping behaviour of concrete was a powerful design tool, helping to subvert the horizontal layer aesthetics. This feature was used selectively and to dramatic effect at the base and capital of the columns to emphasise their ornamental purpose and to distinguish them from the shaft (Fig. 6).

A particularity of this mortar is its initial low-yield stress. In geometric terms, the mortar fluidity limits the overhang capacity. The maximum overhang angle was experimentally determined: a central cylinder supported truncated cones that alternate interior and exterior inclinations at angles between 5° and 20°, in 5° angle increments (Fig. 2). Only those cones with an angle too big for the overhang would collapse, thus indicating the expected range of possible overhangs. This experiment essentially contains all elements of the column typology: a vertical cylindrical core that supports the overhanging outer surface.

### Design Space: Qualitative Parameters

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Designing for 3DCP questions if accurate geometric representation is indeed needed for the generation of precise fabrication instructions. As demonstrated by the high accuracy with which surface ornaments emerge solely from print-path manipulation, the fabrication technique affords the creation of complex surfaces previously only achievable with extremely complex moulding or as a result of elaborate craftsmanship. This represents a research turning point from designing the variation in geometry generation to mastering variation in the fabrication process.

### Successful Prefabrication of Nine Columns

The resulting nine, individually designed, 2.7-metre-tall columns were delivered in just ten weeks. Four weeks were dedicated to design and prototyping, followed by five weeks of fabrication and design development. During the final week of the project, concrete cores were cast and the columns were transported to site.

Transportation and site conditions influenced the structural requirements for the prefabricated columns. Situated in an alpine village at an altitude of 1,257m, the columns were subject to significant wind-induced dynamic loads. First, a reinforced concrete foundation – 1.20 x 1.20 x 0.2m – provided a base for the column printed on top. To ensure the robustness of the base to column connection, a vertical rebar cage was inserted through the hollow cavities of the inner shell and base. Next, fresh concrete was cast into the reinforced core making the ensemble monolithic and ready for transportation only 24 hours later. Using a central hook attached to the rebar cage, each column could be lifted into position on site with a crane. Lastly, the timber deck and lighting were executed in-situ by a local carpenter (Figs 7, 8, 9).

Filament cross-section of 0.10mm x 0.10mm and print-speed of 100mm/s were the characteristic fabrication metrics. For a column fabricated to Concrete Choreography project specifications, these translated to an effective print-time of 2.5 hours per column. Each column was considered fully fabricated once the targeted 2.7 metre height was reached, if the rebar cage could be inserted, and if visual inspection revealed no major defects. From a total of twelve columns printed at full height over a period of five weeks, nine became part of the final installation. Thus, the 3DCP process registered a success rate of 75%, calculated for the fabrication period and excluding prototyping. An early evaluation of the 3DCP also led to the conclusion that efficiency and process stability increased with every printing iteration.

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Architectural building elements. The shift in perception is equally relevant in shaping a digital building culture exclusively belongs to the exact sciences; its social impact exposed the general public to new ways of building with plaster or foam. In addition, the performing arts context and experiencing concrete. Digitisation no longer transforms building materials into the final artefact allows for an unprecedented material into the form – through formwork – towards directly organising the overall form, to structural integrity during build-up and high resolution surface textures. Thus, architects may claim responsibility for designing the entire printed element, not only a component’s boundary representation. The fabrication-driven project also showcases an upscaling strategy for 3DCP. Since fabrication data results directly from the design process, intermediate steps like construction drawings are no longer required. The designer/fabricator thus gains valuable time to invest in design development. In less than a day from design completion, the 1:1 concrete column is prefabricated and ready to be manipulated, consequently elevating the form – through processing; (c) seam resulted from self-intersecting print-path; (d) central core insertion; (e) final column.

To conclude, the presented project not only proves transformative from an ecological and economical perspective, but demonstrates that a design-oriented approach to concrete printing research can yield spectacular results that challenge building convention. The designer/fabricator thus gains valuable time to invest in design development. In less than a day from design completion, the 1:1 concrete column is prefabricated and ready to be manipulated, consequently elevating the form – through processing; (c) seam resulted from self-intersecting print-path; (d) central core insertion; (e) final column.


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References


