Tor Alva: A 3D Concrete Printed Tower

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TOR ALVA
A 3D CONCRETE PRINTED TOWER

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Advancements in 3D concrete printing

The enthusiasm of the participants captured in the historical video footage of the first 3D-printed wall more than 80 years ago anticipated an innovative trajectory for formwork-free concrete construction (Urschel, 1941). The act of autonomously fabricating a building using a mechanical rotary device to deposit concrete layer by layer, with minimal on-site human intervention, highlights a fascination with this progressive construction method.

Upon the reintroduction of 3D concrete printing (3DCP) with automated tools pioneered by Khoshnevis, a remarkable interest boosted research and industry developments (Khoshnevis, 2004; Wangler *et al.*, 2019). 3DCP is a digital fabrication process based on extruding fresh concrete filament deposited layer by layer to construct a digital design, with on-site printing and prefabrication as possible implementations (Wangler *et al.*, 2019). The former requires building an object vertically, in its final location, while the latter involves 3D printing several components that are subsequently assembled. In a broader context, this raised the question of how this novel fabrication method could change the building culture and what architectural language is best suited to 3DCP.

Today, however, some decades later, even though several 'first' 3D-printed homes are available, and a significant scale-up of the manufacturing process could be achieved, there is a certain disillusionment, and some observations give cause to reflect on past developments (Ma *et al.*, 2022). In fact, while one might find some rounded corners of vertical 3DCP walls, the architecture is typically far from demonstrating the structural potential of concrete, as even already shown more than a century ago in the simple Domino House concept by Le Corbusier or generic concrete-framed structures (Bischof *et al.*, 2022).

The evolution of 3DCP architecture to its present state can be attributed to technical constraints and the strategic selection between divergent development pathways. These decisions refer to opting for on-site 3D printing or prefabrication of components and the preference for low-resolution 3D printing with larger aggregates versus fine resolution with higher cement content. Additionally, determining the most suitable structural system, with options such as compression-only systems, stay-in-place formwork, or the integration of steel reinforcement, is crucial in shaping the architectural vision of 3DCP (Dell'Endice *et al.*, 2023; Anton *et al.*, 2021; Kloft *et al.*, 2020; Asprone *et al.*, 2018; Menna *et al.*, 2020).

Clearly, there is no one-solution-fits-all approach in 3DCP. For example, one can envision an on-site 3DCP system that utilises brick-sized extrusion filaments to produce monolithic masonry-like construction, admitting some compromise in precision and resolution.

The present research showcases a path towards the other end: a controlled high-resolution prefabrication scenario based on discrete assemblies of highly refined load-bearing components. In our interdisciplinary research (architectural design, building materials, and structural design), we refined these concepts through a fruitful collaboration with our client, the Origen Foundation (Origen Foundation, 2005). Our initial collaboration took shape through the creation of the Concrete Choreography installation, which comprised nine bespoke 3DCP columns utilised as stay-in-place formwork (Anton *et al.*, 2020). As the collaboration expanded in scope and vision, it led to the mutual evolution of the fabrication technique and its architectural application. The natural progression of a 3DCP stay-in-place formwork for columns is to directly 3D print load-bearing columns with integrated reinforcement. Moreover, segmentation, modular construction, assembly, and disassembly concepts are proposed for prefabricated 3DCP elements.

These innovative fabrication approaches will be exemplified and discussed within the framework of the Tor Alva project. Tor Alva is a 30m-tall tower located in the remote village of Mulegns, The Grisons, Switzerland, along the Julier mountain pass. This tower, designed for the Origen Foundation, serves as a temporary structure for art performances and installations, infusing vitality into a region experiencing a population decline. In addition to revitalising the area through cultural initiatives, the fabrication and construction of the tower actively involve local industrial partners, thus contributing valuable digital expertise through computational design and robotic fabrication. In this project, for the first time, a multi-floor building is built with load-bearing 3D-printed columns. Investigating principles of circularity and reuse, the tower will undergo a process of on-site assembly and five years of monitoring, followed by disassembly and eventual reassembly in a different location.

Architecture: Design for assembly and disassembly

The tower comprises 41 bespoke prefabricated concrete components interconnected using dry shear-keyed connections. Each component takes the form of a branching column with three distinct segments: column base (Fig. 1) and column capital (Fig. 3), which are precast in 3D-printed formwork, and branching columns that are entirely 3DCP (Fig. 2). Each segment is reinforced following the fabrication method: precast segments are fitted with a reinforcing bar cage, while the 3DCP columns have shear reinforcement placed between the layers during 3D printing (Fig. 4b). A load-bearing 3D-printed column is achieved by inserting longitudinal reinforcing bars into hollow channels that run through the entire component length (Fig. 4c). These channels are subsequently grouted to secure the bond between the longitudinal reinforcement and the printed concrete. Moreover, the components are post-tensioned with unbonded stainless steel rods, which are located in the hollow cores of the columns. The post-tensioning ensures the unity of the three segments as a single component, improves the force transfer through the concrete layers generated by the 3D-printing process, and avoids cracking of the 3D-printed material in the serviceability limit state. Each component interlocks with shear keys to its neighbouring top and bottom components and is connected at multiple points along its edges. The inclined branches of columns significantly improve the structural behaviour of the tower, as they transfer the lateral forces caused by wind or seismic actions via axial forces, which is structurally the most efficient solution. The column types range from having two to four branches (Fig. 3). In the design of the tower, each level has narrower columns than the preceding ones, ensuring a gradation of transparency along the vertical axis.

2

1. 3D concrete printing of the level 1 column of Tor Alva. © Nijat Mahamaliyev, Digital Building Technologies, ETH Zürich.

2. Detail of surface texture: material-driven ornamentation for one branching column.

3. The final design of Tor Alva has 41 components, assembled with dry connections.

4. Diagram of a bracing column component consisting of 1) precast base segment; 2) load-bearing 3DCP column: (a) outer layer for ornamented texture, (b) middle layer for shear reinforcing bar, and (c) inner layer for longitudinal reinforcement; and 3) precast capital segment.

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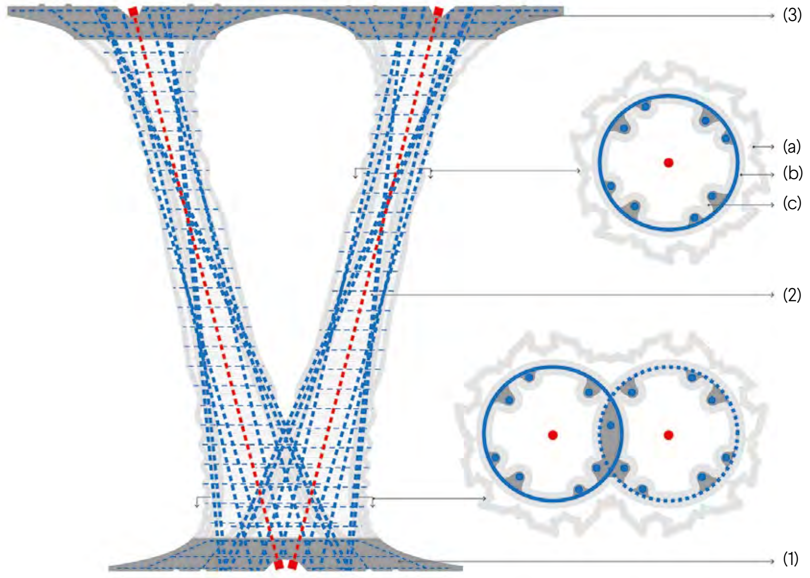

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The project relies on prefabrication arising from the need for precision of components and connection interfaces. This is essential for modular construction and disassembly, a key project feature, which enables faster production speed on site and reuse of the components.

When developing the tectonic system, we explored various detailing principles for 3DCP components. The design of this system took account of factors such as the scale of the production facility and transportation logistics. Achieving a concrete structure assembled with dry connections presents notable challenges for the 3DCP process, as it typically requires large tolerances. The approach proposed in this case draws inspiration from the match-casting technique commonly employed in precast segmental concrete bridges. A series of fabrication strategies for dry and permanent connections were tested in this context. To achieve sub-millimetre matching between dry-connected components, the parts are printed directly onto precast concrete components, milled timber formwork, or 3D-printed substrates (Fig. 5).

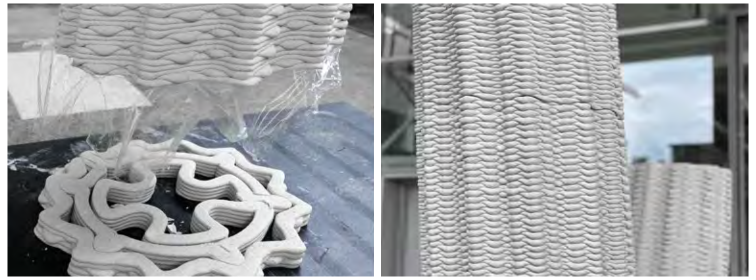
A comparable strategy was employed to produce the segmentation connections along the length of the 3DCP columns. This involved reprinting the last five layers of the previous segment as a substrate for the subsequent component. To facilitate easy removal, the 3DCP substrate was covered with a thin layer of plastic upon which the new segment was 3D printed (Fig. 6). The uninterrupted visual connection between the distinct 3DCP elements is achieved via material-driven ornamentation. The print path has purposefully integrated points along its length, resulting in an overhang of the concrete filament over the previous layer. As the material drips, it solidifies to form a non-planar feature (Fig. 6). In this approach, the connecting layer extends slightly onto the substrate, effectively concealing the gap between the elements. As a result, the assembly interface seamlessly aligns with the layered texture of the column, blending into the overall surface finish (Fig. 6).

Material: 3D-printing setup and material system

The 3D-printing process relies on a prefabrication setup, which involves dry-mixing material preparation and multi-component 3DCP (Fig. 7). The dry mix is stored in a silo with the supply flange connected to a M-Tec D10 continuous mixer. Material preparation in the mixer is triggered by a sensor that monitors the concrete level inside the pump. The pumping system includes three continuous cavity pumps: one PFT Swing L concrete pump and two ViscoTec ViscoPro C, one for accelerator and the other for thickener. The role of the extruder is to

5

5. Branching column with shear-keyed connections. © Ana Anton, Digital Building Technologies, ETH Zürich.



6

6. Assembly detail of a segmented 3DCP column: removing one segment from the substrate and assembling it to the adjacent component. © Ana Anton, Digital Building Technologies, ETH Zürich.

blend the three components and dispense the filament along the print path. The extruder is mounted on the sixth axis of an ABB IRB 6700 industrial robot. The pumps and extruder are numerically controlled by the robot interface and monitored via pressure and temperature sensors. Throughout 3D printing, process data is recorded in an open-loop system with feedback, implemented through COMPAS FAB (Rust *et al.*, 2018) and COMPAS RRC (Fleischmann and Casas, 2020).

The dry mix is composed of a white Portland cement (CEM I 42.5R) at a proportion of $525 kg/m^3$ combined with limestone (<125µm) and three grades of quartz sand (<0.1mm, 0.1-0.6mm, and 0.6-1.25mm). A superplasticiser and a viscosity modifier are also added in dry form, dosed to the cement content. The dry mix material is then directly mixed with water at a proportion that gives a water-to-cement ratio of 0.5. The accelerator is a slurry of white calcium aluminate cement and calcium sulphate anhydrite (1:2.1 ratio) at a water-to-powder ratio of 0.35. The thickener is based on a sodium metasilicate solution and a starch ether-based viscosity modifier. The accelerator and thickener are dosed at the printhead at standard ratios of 0.05 and 0.01 by mass of the concrete flow rate, respectively. The three components can be adjusted throughout the process depending on room conditions, with the accelerator dominating strength buildup behaviour and the thickener dominating initial yield stress, which governs the filament shape.

The system operates at a flow rate of 1.5 l/min with a print speed of 125mm/s, resulting in a filament 25mm wide and 8mm high (Fig. 8), where the latter dimension corresponds to the 8mm diameter inter-layer reinforcing bars. At present, the interlayer reinforcing bar is manually inserted during the 3D-printing process. The automation of this reinforcing bar insertion is currently in development and will not be addressed in this paper. Furthermore, the bases and the capitals are cast with conventional commercial concrete (C30/37), and the hollow channels are grouted with a commercial product.

One-to-one demonstrators served as tests for structural and fabrication concepts. The process started with stay-in-place formwork and gradually progressed towards load-bearing 3D-printed concrete columns.

The first demonstrator (Fig. 11) has ten segmental hollow-core columns connected between two continuous precast slabs through post-tensioning rods. Each column is prefabricated with a 3DCP outer shell one layer thick, within which a reinforcing bar cage and a hollow PVC tube are inserted before casting (Fig. 9). The PVC tube ensures enough space for the post-tensioning rods. The 3DCP formwork comprises two segments connected via a precast interface. The columns, cast with self-compacting concrete, have shear keys at the bottom. After curing, they are transported to the site horizontally. On site, they are connected to the precast slabs to test the tectonic and structural systems.

The creation of the demonstrator revealed several essential insights. One significant obstacle during the construction process, when using non-load-bearing, unreinforced 3DCP as a lost formwork, is for the formwork to withstand the hydrostatic pressures generated during concrete casting. Hydrostatic pressure is significantly higher in self-compacting concrete than in normal concrete. Initially, an attempt was made to mitigate the hydrostatic pressures generated by the fresh concrete by incorporating sand within an external formwork. Unfortunately, this approach did not prevent the failure of one of the columns. The final strategy consisted of pouring the concrete in stages, limiting each filling stage to a maximum height of 80cm. While this method effectively managed hydrostatic pressures, it significantly reduced the overall production speed.

From a structural point of view, the potential for optimisation of columns lies in using 3DCP as load-bearing elements (integration of reinforcement is necessary) and reducing the required post-tensioning by exploiting the maximum capacity of stainless steel (investigation of prestressing losses is required). This aligns with the sustainability perspective, since using a high-performance material such as 3DCP as stay-in-place formwork is wasteful unless the 3D-printed material is activated to transfer loads. However, compared with lost formwork, utilising load-bearing 3D-printed columns requires structural testing to ensure a safe design. Furthermore, the design of the columns was found to be overly conservative, requiring too many vertical columns to achieve the desired architectural vision of an enclosed and protected space. The connection details between 3DCP segments, the grey precast concrete stripes located at one-third along the height of the 3DCP columns (Fig. 11), were refined to align with the space's aesthetic requirements (Fig. 3).

The findings from this demonstrator confirm the viability of the building sequence and structural approach. However, after the project's evaluation, innovative load-bearing 3D-printed columns, together with remarkable architectural, tectonic, and structural redesigns, will be introduced in the final tower project.

7

7. Fabrication setup for the building-scale demonstrator. © Rami Masallam, Digital Building Technologies, ETH Zürich.

8

8. 3DCP of the branching column prototype. © Ana Anton, Digital Building Technologies, ETH Zürich.

A more ambitious approach to 3DCP was embraced in the broader project development. This shift involved designing columns with geometries that could not be readily produced through conventional fabrication methods. Transitioning from vertical to branching columns ensured a more efficient and stiffer structural system, and hence a reduced number of columns and a smaller number of inner post-tensioning rods.

Moreover, part of the 3DCP material is now structurally activated following a three-layer approach: the outer layer creates the ornamented and visible texture of the column, the middle layer accommodates the shear reinforcement, and the inner layer creates hollow channels for inserting the vertical reinforcement (Fig. 4). This approach to reinforcement breaks down the traditional reinforcement cage into separate vertical and horizontal steel elements that are positioned in space concurrently with the 3DCP process (Anton *et al.*, 2022). Unlike entirely hollow columns, the trunk of the Y-shape preserves the logic of branching by intersecting the paths of the individual branches, thus ensuring the uninterrupted flow of forces within the structure. While the layer print path in the trunk area of the column becomes relatively complex, the shear reinforcement maintains a circular shape. It is placed at an offset height to avoid collisions with neighbouring branches.

Sustainability, impact, and vision for 3D concrete printing

Initially, 3DCP was introduced as a means to boost productivity and minimise material consumption in concrete construction. Intensive research on this fabrication method reveals unique opportunities and clear constraints. The transformation of 3DCP into a genuinely effective tool for reducing resources (considering workforce, formwork, and concrete) in construction demands a multi-disciplinary approach that fuses architecture, material, and structure into a comprehensive fabrication method.

9

10

There are clear advantages to using 3DCP in construction, including creating customised structures, eliminating the need for formwork, and introducing automation. However, there are also many challenges associated with this fabrication method. These include issues related to 3D-printing speed, material formulation, aggregate size, cement content, reinforcing bar integration, accuracy, structural performance, and durability, among others. Selecting the appropriate options among the many possibilities enabled by 3DCP is a critical question towards paving the way for sustainable concrete construction.

The research behind the Tor Alva project moved away from the homogenisation of fabrication, as experienced in the industrial age, to a heterogeneous, rich architecture that celebrates diversity, individuality, and adaptivity to the local context.

3DCP enables a significant shift in the level of resolution achievable in both computational design and digital fabrication. The Tor Alva project serves as an example of how columns can be intricately designed with a resolution as fine as 8mm, matching the layer height of the 3DCP process. This layer height not only determines the material-driven ornamentation on the visible concrete surface but also influences factors such as the placement and diameter of shear reinforcement and the design of the assembly interface between 3DCP components. This fusion between structural system and ornament in 3DCP elements brings this technology closer to digital craftsmanship.

The exploration of reinforcement strategies for 3DCP highlighted several promising avenues for the future of concrete construction. Designing concrete reinforced elements starting from the reinforcement layout enables the creation of hollow structural elements with slender sections. Building on these advancements, our vision extends to developing digital composite materials in which both reinforcement and concrete are strategically placed for optimised lean shapes.

Beyond the focus on material efficiency, the architectural objective is to create designs that can actively engage with and contribute to the social and cultural aspects of society. Tor Alva demonstrates that 3DCP can help construction to move from volume to value by consequently building with thin-shell, hollow concrete elements. Moreover, the chosen structure, the tower typology, is a scalable system particularly suited for denser construction. In the Tor Alva project, these aspects are integrated through developing a novel formal language for 3DCP, integrating circular construction, assembly and disassembly strategies, and customisation. Through these initiatives, the project paves the way for an enhanced sustainable construction practice that is scalable and quickly disseminated throughout the building industry.

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9. Assembly of reinforcing bar cages and casting process for the demonstrator. © Ana Anton, Digital Building Technologies, ETH Zürich.

10. Assembly of the building-scale demonstrator. © Eleni Skevaki, Digital Building Technologies, ETH Zürich.

11. Building-scale demonstrator consisting of ten columns assembled with dry connections. © Michael Hansmeyer, Digital Building Technologies, ETH Zürich.

12. Assembly of a segmented branching column. © Ana Anton, Digital Building Technologies, ETH Zürich.

11

12

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