Visions and Strategies for Reinforcing Additively Manufactured Constructions 2025

Contribution to the symposium

https://doi.org/10.52825/ocp.v7i.2764

Published: 19 Jan. 2026

Reinforcement Concepts for 3D Concrete Printing and Modular Construction in Tor Alva

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Abstract. Tor Alva is a 30-meter-high tower and, at this point, the tallest structure in the world constructed using Reinforced 3D Concrete Printing (R3DCP). The building system is modular and prefabricated, using branching columns that are stacked and connected with bolts and grout. It is designed for easy disassembly and reuse. Each structural component follows a common typology: a precast base, a 3D-printed segmented column with varying numbers of branches, and a precast capital. Within the 3D-printed section, a combination of reinforcement strategies is employed—including inter-layer stainless steel reinforcement, vertically embedded conventional steel bars bonded via grout, and unbonded post-tensioning rods. These possible reinforcement strategies are applied in different components of the tower, depending on structural design and construction requirements. This paper presents the steps taken from stay-in-place 3D-printed formwork to fully R3DCP. It also discusses how each reinforcement strategy was constructed by focusing on the implications of each technique on the fabrication workflow. The findings show how hybrid reinforcement methods in R3DCP can support broader architectural and structural uses, making concrete 3D printing suitable for load-bearing applications.

Keywords: Reinforced 3D Concrete Printing, Branching Columns, Modular Construction

1. Introduction

3D Concrete Printing (3DCP), meaning automated layered deposition of extruded fresh concrete filaments, is a growing technology in construction. Despite considerable advancements in the last decade, 3DCP is frequently criticised for a lack of aesthetic qualities, structural performance, and sustainability. Restraint in aesthetics acceptance by the general public arise from the limited geometric complexity achievable with the process, reduced overhangs, and the characteristic stepped texture of the extruded layers [1]. Structural limitations are largely due to anisotropies that coincide with the layers' orientations and to difficulties in integrating reinforcement in two directions during the printing process [2], [3]. In terms of sustainability, the extrusion mixes typically have a large embedded footprint as they contain smaller aggregates and higher cement volumes than conventional concrete mixes [4]. These major challenges still need development as the 3DCP technology matures - and they are central topics to be addressed in this symposium.

One example that directly engages with these issues is Tor Alva [5], a 30-meter-tall tower and the tallest, to date, structure in the world constructed using fully-loadbearing Reinforced 3D Concrete Printing (R3DCP) [6]. This paper defines R3DCP as a fabrication process based on the layered deposition of concrete, in which construction steel reinforcement is placed between the layers at a given interval. This process enables the automated placement of reinforcement to occur simultaneously with the 3D printing process, thus ensuring a satisfying bond between the fresh extruded filament and the steel. Realizing R3DCP at the building scale required a series of technological and workflow developments based on interdisciplinary investigations.

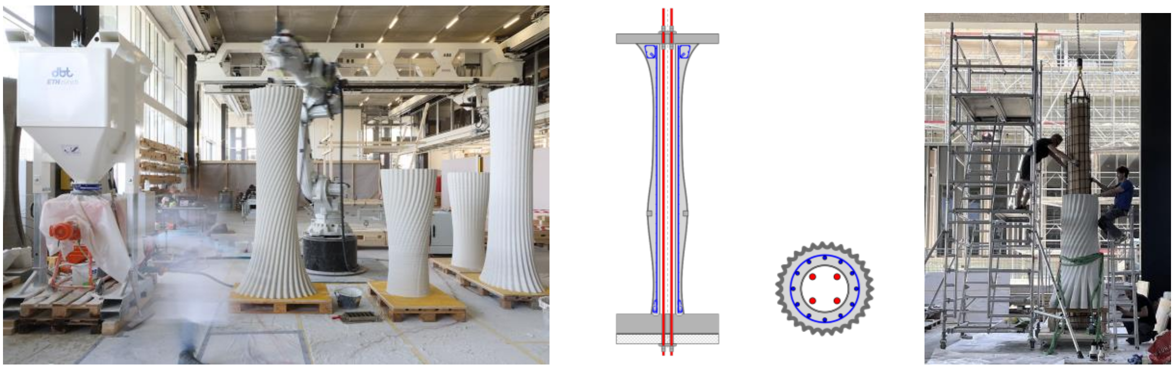
Tor Alva shows that despite significant advancements in reinforcement integration, 3DCP alone cannot replace established construction methods in concrete. In addition, Tor Alva reveals that 3DCP demands not only technical expertise but also design intelligence - attention to detail, elegance of form, and control over material behaviour.

From a research standpoint, the construction of the tower was enabled through sustained, incremental advancements that connected the novel 3DCP technology with conventional casting methods in concrete. This hybrid approach ensured full compliance with Swiss building codes. The development included five key steps: (1) developing the 3DCP process as a dry-mix production line suitable for large material volumes [7], [8]; (2) investigating the possible reinforcement strategies compatible with the 3DCP process, ranging from having the printed concrete as stay-in-place formwork to integrating it as part of the load-bearing system; (3) implementing a design-to-fabrication workflow that enables modular construction and mass-customization; (4) automating the placement of reinforcement during 3DCP; and (5) process integration of architectural design, fabrication constraints, and structural requirements.

This paper outlines the reinforcement strategies that were considered during the development phase of the tower and explains the rationale behind the selected solutions of the final execution.

2. Methods

2.1 Hollow-core vertical columns with 3DCP stay-in-place formwork



(a) (b) (c) (d)

Figure 1. *Fabrication steps for hollow-core vertical columns using a 3DCP stay-in-place formwork: (a) 3DCP fabrication setup, image: Rami Masllam ; (b) vertical section showing the elements of the structural column; (c) horizontal section; (d) assembly and casting process, image: Ana Anton.*

The first method considered for the fabrication of Tor Alva utilised a colonnade of vertical columns connected by monolithic precast slabs with shear-keyed dry connections and post-tensioning rods. Each column was to be fabricated using stay-in-place 3DCP formwork with a layer width of 25 mm and one filament (Fig. 1.a-c). This formwork was segmented into two parts, 2.5 m and 1.5 m, respectively, to fit into the printer's reach. The connection detail between the two parts was resolved using a precast recessed profile in gray concrete, measuring 60 mm in height.

Once the formwork was fabricated, column assembly began by positioning one segment on a timber plate, gluing it to the base, and securing it with straps to prevent leakage during casting. The timber plate was milled to incorporate six truncated hollow pyramids, serving as formwork for positive shear keys. A PVC pipe with an inner diameter of 300 mm was inserted to form the hollow-core, followed by the insertion of the rebar cage in the space between the 3DCP formwork and the PVC pipe. A self-compacting structural concrete was cast in stages of maximum 500 mm height, to prevent the hydrostatic pressure from damaging the 3DCP formwork (Fig. 1.b-c).

Upon the completion of the first segment, the precast connection detail was glued on top, and the second segment was bonded in position. For gluing, the commercial product SikaFlex was utilized, which did not provide a structural bond between components, but rather a solution for sealing the individual formwork components. The upper segment was then filled in a similar staged casting sequence. Assembly procedures for multiple columns were executed in parallel, with the total production per column averaging two days.

2.2 Evaluation of the Tor Alva demonstrator

The Tor Alva demonstrator consisted of ten prefabricated columns, which were transported on site by truck in a horizontal position. The columns were handled with lifting straps and tilted on the transport deck of the truck, where they were laid on EPS foam boards to support them at the two ends and in the middle. The assembly of the ten columns and two slabs was completed (Fig. 2.a), which allowed the architects and engineers to evaluate the results and update the design as follows.

(a)

(b)

Figure 2. *Demonstrator assembly with dry connections: (a) ten columns and two precast slabs are post-tensioned with steel rods; (b) detail of the assembly connection with the precast elements, images: Hansmeyer/Dillenburger.*

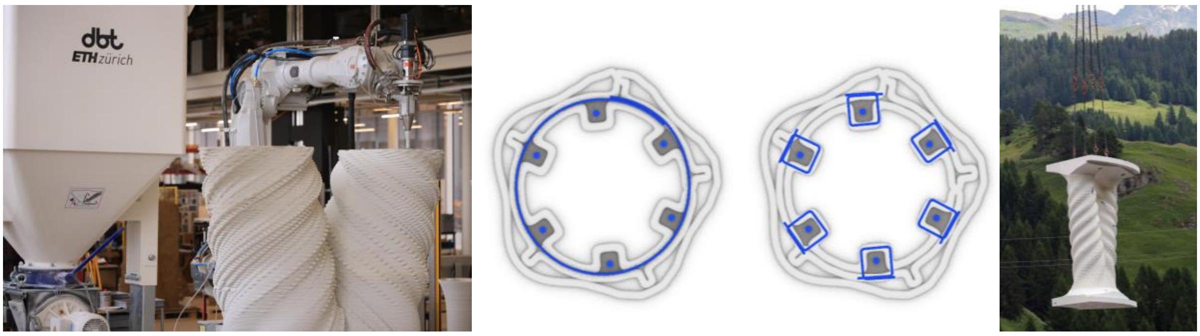
The overall structural system, consisting only of vertical columns and slabs, without shear members, required a large number of columns to resist lateral loads from wind and zone 2 earthquake, moderate seismicity according to SIA-261 [9]. Each column was connected to the slab using four post-tensioning rods. This technical solution was considered too material-intensive, while a similar load resistance could potentially be achieved with structural elements of different geometry. Moreover, the 3DCP was utilized primarily for its ornamental potential rather than for enabling a novel structural system. These findings suggested adapting the design to incorporate branching columns; however, such geometries would require another design-to-fabrication strategy, as the existing formwork approach was incompatible with inserting a branching reinforcement cage.

From an architectural design perspective, the connection detail between the 3DCP segments was considered too prominent and aesthetically disruptive (Fig. 2). Functionally, it also introduced unnecessary complexity in the assembly process. The team concluded that developing a connection detail entirely relying on 3DCP could reduce assembly steps and the reliance on secondary fabrication methods.

To free the site for the construction of the actual tower, the columns of the demonstrator were dismantled, post-processed, and reassembled into a bus stop structure, marking the entrance to the Tor Alva site (Fig. 5.b). This relocation demonstrated the potential of modular construction to enable the reuse of structural elements with minimal material waste and extended functional life.

In parallel to the 3DCP of the column segments, the precast concrete bases and capitals were manufactured. The precast segments were designed to include all features that require precision for assembly, including the shear keys, holes for connecting screws between components, channels for the vertical reinforcement, and alignment details for the post-tensioning anchor plates. They also incorporated provisions for building services, such as ducts for electrical wiring and spaces for light fixtures. The tolerances included in the project were 10 mm between each precast component and 10 mm for the height of each column. During construction, these tolerances were compensated using a levelling mortar.

Following fabrication of 3DCP and precast, assembly began by gluing the precast concrete base to the 3DCP segments and to the precast capital using a two-component epoxy resin for structural bonding, the Sikadur commercial product. Next, the vertical reinforcement fitted with anchor plates was inserted through the pre-formed channels, and the structure was grouted with SikaGrout 800 in its entirety to achieve the final load-bearing configuration (Fig. 3.d). If needed, at this point, the columns would be post-tensioned. The structural part of the column is defined in cross-section by the two inner 3DCP filaments and the grouted channels (Fig. 3.c).



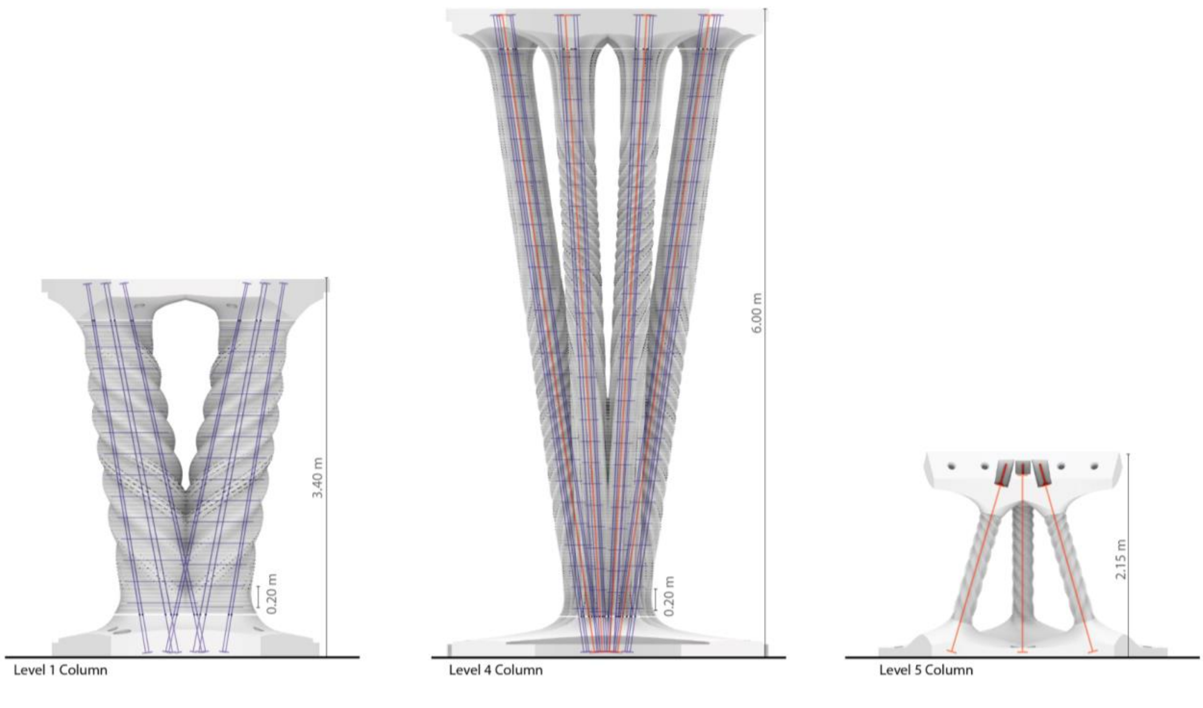
(a) (b) (c) (d)

Figure 3. *Fabrication of R3DCP columns: (a) 3D Printing process in the Robotic Fabrication Lab of ETH Zurich, image Nijat . Mahamalyiev; (b) characteristic cross-section through one branch of the Tor Alva column showing stirrup rebar rings; (c) and stirrup rebar loops; (d) Assembly of components by crane, image: Hansmeyer/Dillenburger.*

It is worth noting that the quality of the assembly and the precision of the joints between individual elements were ensured through a fabrication process inspired by match casting in conventional concrete construction. Specifically, the final five layers of each sub-component were printed again and covered with a thin plastic film, after which the subsequent component was printed directly on top. This approach relies on the high repeatability of the 3D printing process to achieve precise geometric matching. The assembly of the elements was carried out by experienced construction workers in a prefabrication hall, following unique identifiers assigned to each component, alignment details, and assembly instructions provided by the research team.

2.3 Hollow-core branching columns with R3DCP

As the conclusions from the demonstrator were drawn, the design of Tor Alva refocused on branching columns. Instead of only one outer filament, the second fabrication method employed a three-filament printing strategy that integrated stirrup reinforcement into the design-to-fabrication sequence. The column design comprised three distinct co-planar filament extrusions arranged from the exterior to the interior, each fulfilling a specific role. In the given design, it was not possible to use a layer larger than 25 mm because the required geometric features were too complex for the cross-section of the column. The outermost layer, referred to as the ornamented filament, defined the outer geometry and aesthetic qualities of the column. It incorporates macro- and micro-scale patterns that make each column unique. Inside this, the intermediate filament, which forms the structural core, provides placement surfaces for inter-layer reinforcement and offers additional infill support to extend the printability limits of the ornamented layer, particularly for overhanging features. The intermediate filament integrates co-planarly bent rebar rings of varying diameters with a splice length of 200 mm (Fig. 3.b). Each stirrup ring is inserted every 25th layer, at 200 mm distance along the height of each branch, following testing campaigns and the spacing guidelines of the SIA 262 for structural compression members [10]. Finally, the innermost filament creates continuous 60x60 mm2 vertical voids to allow for the insertion of the main reinforcement bars and subsequent grouting. This filament also supports inter-layer rebar loops arranged around each channel at 400 mm intervals (Fig. 3.c). The combination of inter-layer reinforcement and grouted main vertical reinforcement forms the passive reinforcement system, which exhibited ductile behaviour in structural tests, as published in [11]. The spacing of the inter-layer rebar was experimentally investigated, and the results were published in [6]. Post-tensioning rods can also be installed along the axis of each branch to provide additional strength.



(a) (b) (c)

Figure 4. *Fabrication of R3DCP columns: (a) 3D Printing process in the Robotic Fabrication Lab of ETH Zurich, image Nijat . Mahamalyiev; (b) characteristic cross-section through one branch of the Tor Alva column showing stirrup rebar rings; (c) and stirrup rebar loops; (d) Assembly of components by crane, image: Hansmeyer/Dillenburger.*

For ease of fabrication and assembly, the columns were segmented into two parts: the intersecting base, which consistently comprised the first 2.0m of the column, and the individual branching elements (Fig. 4.a-b). These branches were further divided into segments ranging from 0.6 to 1.3 m in length, determined by the position of their centre of mass to ensure stability during handling and assembly.

Two geometric strategies were investigated for the design of the structural core to accommodate the main vertical reinforcement. In a first approach, a hyperbolic structural core was considered, where the reinforcement channels followed the ruling curves of a one-sheeted hyperboloid [5], [8]. Twelve square channels, each measuring 80 mm in width, were positioned based on two sets of tangent lines to the hyperboloid surface. This configuration allowed the placement of two intersecting reinforcement bars with diameters of 10 mm. The second approach, the cylindrical structural core, positioned the vertical reinforcement channels evenly along a cylindrical surface corresponding to the minimum radius of the column. In this case, four to eight square channels, each 60 mm wide, were created to accommodate reinforcement bars with diameters of 20 mm fitted with end-hooks of 45 mm diameter. While the hyperbolic solution could have provided better structural stability due to its shape and the bidirectional reinforcement arrangement, it was discarded. The complex network of intersecting hollow channels of the hyperbolic core would have been impossible to fully grout without large entrapped air pockets. As a result, the second solution was utilized in the final project.

In parallel to the 3DCP of the column segments, the precast concrete bases and capitals were manufactured. The precast segments were designed to include all features that require precision for assembly, including the shear keys, holes for connecting screws between components, channels for the vertical reinforcement, and alignment details for the post-tensioning anchor plates. They also incorporated provisions for building services, such as ducts for electrical wiring and spaces for light fixtures. The tolerances included in the project were 10 mm between each precast component and 10 mm for the height of each column. During construction, these tolerances were compensated using a leveling mortar.

Following fabrication of 3DCP and precast, assembly began by gluing the precast concrete base to the 3DCP segments and to the precast capital using a two-component epoxy resin for structural bonding, the Sikadur commercial product. Next, the vertical reinforcement fitted with anchor plates was inserted through the pre-formed channels and the structure was grouted with SikaGrout 800 in its entirety to achieve the final load-bearing configuration (Fig. 3.d). If needed, at this point the columns would be post-tensioned. The structural part of the column is defined in cross-section by the two inner 3DCP filaments and the grouted channels (Fig. 3.c).

(a) *(b)*

Figure 5. *Completion of Tor Alva: (a) View from the village of Mulegns; image: Birdviewpicture; (b) Night view from the Bus stop; image: Benjamin Hofer.*

It is worth noting that the quality of the assembly and the precision of the joints between individual elements were ensured through a fabrication process inspired by match casting in conventional concrete construction. Specifically, the final five layers of each sub-component were printed again and covered with a thin plastic film, after which the subsequent component was printed directly on top. This approach relies on the high repeatability of the 3D printing process to achieve precise geometric matching. The assembly of the elements was carried out by experienced construction workers in a prefabrication hall, following unique identifiers assigned to each component, alignment details, and assembly instructions provided by the research team.

3. Results and discussion

The final construction of Tor Alva consists of 32 load-bearing components and the cupola, which is segmented into an additional 16 components with 3DCP columns. These elements use different reinforcement strategies, as shown in Figure 4: Level 1-3 employ passive reinforcement (blue), Level 4 combines passive reinforcement (blue) and post-tensioning rods (red), and cupola components use only post-tension (red).

Most columns are transported on site in the same orientation as in the final structure (Fig. 4.a). The combination of regular steel reinforcement and post-tension in Level 4 columns was primarily dictated by transportation requirements. Having 6 m in length, these columns were transported horizontally on site, thus requiring an additional structural safety margin (Fig. 4.b). In the cupola, the columns are part of a compression-dominant structure, so post-tensioning alone was considered sufficient (Fig. 4.c). In the case of Tor Alva, the entire structure will be temporarily covered by a membrane facade in winter. However, for columns exposed to harsh environmental conditions and repeated freeze-thaw cycles, the inclusion of passive reinforcement could offer a better long-term durability.

In addition, rainwater management should be considered for the design of hollow concrete columns. It is well known that 3DCP material exhibits a higher porosity at the layer interface [12]. In this case, stainless steel reinforcement was used between the layers to mitigate premature rebar corrosion (Fig. 3.c). Furthermore, water noses are needed to divert rainwater from accumulating inside the 3DCP elements and drainage holes for the evacuation of any rainwater that could accumulate within the inner cavities of the columns.

On-site assembly was completed at a rate of one floor per day and required the use of a construction crane. The only exception was Level 4, which, although assembled within a single day, required two cranes to rotate the columns into a vertical position.

4. Conclusion

From its initial demonstrator phase to its final realization, *Tor Alva* illustrates the progressive development of structural concepts for 3DCP, starting from stay-in-place formwork systems to loaded reinforced 3D-printed concrete (Fig. 5). All reinforcement systems were realized at the building scale. The primary achievement of this research is the integration of R3DCP into the tower's main load-bearing system. This achievement was made possible through a comprehensive design-to-fabrication workflow and a robust data-management strategy that brings together multiple disciplines. Structural requirements derived from calculations and laboratory testing were used as input for a parametric system able to accommodate multiple interdependencies—from precise reinforcement placement to the assembly of printed components into larger structural systems.

The findings show that hybrid reinforcement methods in R3DCP can broaden architectural expression and structural performance, making 3DCP viable for load-bearing applications.

However, the current implementation still depends on precast components for precise connections and skilled labour for assembly, underscoring the next challenges in achieving fully automated, modular R3DCP systems.

At the same time, Tor Alva illustrates how the future of 3DCP may lie in complementing established concrete construction methods, thus serving as a specialized, high-value process integrated within conventional structural systems rather than replacing them outright.

Author contributions

Ana Aton: Conceptualization, Investigation, Methodology, Visualization, Writing – original draft.

CheWei Lin: Conceptualization, Investigation, Methodology, Writing – review & editing.

Benjamin Dillenburger: Conceptualization, Methodology, Funding acquisition, Supervision, Writing – review & editing.

Competing interests

The authors declare that they have no competing interests.

Funding

This work was funded by the Swiss National Science Foundation, within the National Centre for Competence in Research in Digital Fabrication (project number 51NF40-141853) and by Innosuisse - Schweizerische Agentur f r Innovationsförderung (project number #102.414.1 IP-ENG).

Acknowledgement

Architecture: Benjamin Dillenburger (ETHZ DBT) Michael Hansmeyer

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Supporting Structure: Walter Kaufmann (ETHZ CSBD) Alexandro Giraldo Soto, Lukas Gebhard; Lucia Licciardello

Building Materials: Robert Flatt (ETHZ PCBM) Timothy Wrangler, Lex Reiter

Geodesy: Andreas Wieser (ETHZ CSEG)

Robotic Fabrication Laboratory: Mike Lyrenmann, Philippe Fleischmann, Tobias Hartman, Lucas Petrus, Jonathan Leu

Client: Nova Fundaziun Origen, Giovanni Netzer

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