



# Shotcrete 3D Printing Technology for the Fabrication of Slender Fully Reinforced Freeform Concrete Elements with High Surface Quality: A Real-Scale Demonstrator

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**Abstract.** This paper presents the recent advances in the development of a novel 3D concrete printing technology called Shotcrete 3D Printing (SC3DP). In order to demonstrate the unique assets of this technique a design and fabrication strategy for fully reinforced, double curved concrete demonstrator featuring high surface quality was developed, and is described in detail in this paper. In particular, two topics were highlighted in this demonstrator, firstly the integration of structural reinforcement in both principal directions and secondly an automated surface finishing process for a high-quality concrete surface. This combination of additive fabrication and formative and subtractive postprocessing was demonstrated at the unique large-scale Digital Building Fabrication Laboratory (DBFL) of Technische Universität Braunschweig. The result of this fabrication experiment, a 2.5 \* 2.3 \* 0.18 m concrete wall element, is finally discussed in relation to the state of the art in 3D concrete printing.

**Keywords:** Shotcrete 3D Printing · Structural reinforcement · Additive manufacturing in construction · Large scale 3D printing

## 1 Motivation and Background

Layer-based extrusion of concrete is the most extensively researched and widely-used 3D printing process for the fabrication of large-scale concrete components today. The most commonly used approaches are based either on the Contour Crafting technique [1] or on the 3D Concrete Printing approach [2]. Particularly the latter is today widely adopted by a large community of researchers and commercial players. While several lighthouse projects of complex and intricate geometry have recently been realized on construction scale, there are still process-inherent challenges that need to be addressed in order for 3D printing with concrete to gain a sustained foothold in the construction industry. In addition to still unanswered economic and regulatory questions, the pending technical challenges include the inter layer bonding, the integration of tensile reinforcement, the creation of pronounced overhangs and lastly, the final surface

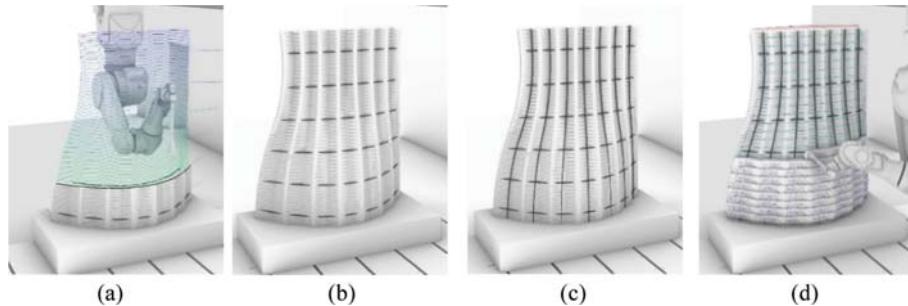
quality of the printed structures [3]. For each of these challenges, solutions are currently being investigated, including layer bonding through gluing [4], post-tensioning [5], hybrid printing of the support material [6] as well as simultaneous troweling of the surface during printing [7]. In this paper the same set of essential research questions is addressed by using an alternative 3D printing method, the so-called Shotcrete 3D Printing (SC3DP) technique [8].

The SC3DP distinguishes itself from conventional 3D printing with concrete through the fact that the material is not extruded in strands, but rather sprayed with pressure in order to create a 3-dimensional structure. Spraying a dispersed stream of concrete promotes several distinct features. Firstly, through the projection of the material a mechanical layer intermixing and hence intense layer bond is created [8]. Secondly, through spraying, the concrete flows around structural reinforcement and embeds it [9]. A third feature made possible by the previous ones is that Shotcrete 3D Printing allows the creation of pronounced overhangs by gradually transitioning from the horizontal to the vertical printing plane [10]. Finally, due to the ability of the shotcrete to adhere to vertical surfaces a second layer of concrete can be sprayed onto vertical surfaces and can subsequently be smoothed automatically. Based on these specific features of the SC3DP technology a distinct printing strategy was developed and demonstrated through the fabrication of a fully reinforced, double-curved concrete element with high surface quality.

## 2 Experimental Setup

### 2.1 General Fabrication Strategy

To enable the full load-bearing capacity, a complete embedding of the continuous structural reinforcement in both vertical and horizontal direction must be provided. For this, a specific built-up strategy has been developed, comprising five consecutive fabrication steps. The key feature of this strategy is that a slightly undulating version of the intended surface geometry is printed in segments with a predefined height (Fig. 1a). The height of these segments as well as the number and amplitude of the undulations can be adjusted parametrically. After each segment is completed, a pair of pre-bent horizontal rebars is placed close to the perimeter of the structure, resting only on the tips of the undulations. This creates closed loops between the concrete structure and the reinforcement, which, over the entire height of the wall, form vertically aligned channels (Fig. 1b). These are subsequently used for the insertion of the vertical reinforcement from above (Fig. 1c). In a forth step, a second layer is then sprayed vertically onto the reinforced core structure (Fig. 1d). This second layer serves both, to embed the reinforcement structurally and as a foundation for the final surface finishing using an automated troweling process.



**Fig. 1.** Built-up strategy; (a): printing of the undulated core and placement of the horizontal pre-bent reinforcement bars; (b): printed core with horizontal reinforcement at full height; (c) inserted vertical reinforcement; (d): covering the reinforcement with an additional layer of shotcrete.

## 2.2 Fabrication Setup

**Robotic Setup.** For fabrication the unique Digital Building Fabrication Laboratory (DBFL) of the Institute for Structural Design at TU Braunschweig was used. The DBFL is a large-scale robotic fabrication facility which contains two gantries, each with vertical axes attached. One of which is equipped with a 6-axes Stäubli robot, and the other with a 3-axes Omag milling application. The overall cooperative build space encloses  $10.5 * 5.25 * 2.5$  m. The DBFL facilitates the fabrication of large-scale structures, both by subtractive machining, as well as by additive manufacturing processes.

A customized robotic end effector for printing was developed by the Institute for Machine Tools and Production Technology (IWF) based on standard shotcrete printing equipment. This end effector includes a series of custom inlets for the injection of shotcrete accelerator as well as a laser system that measures the distance between the spray nozzle and the printed structure. The latter is used for online process control, regulating the speed of the robot and hence the layer thickness. Additionally, a pneumatic pinch valve was incorporated in order to rapidly stop and start the concrete flow during the spraying process.

**Material.** Regarding the concrete, a pre-packed high strength repair mortar was used. In order to accelerate the concrete, and enable high early strength and high printing rates, 5% of shotcrete accelerator was mixed into the airstream at the spraying nozzle. Whereas, this concrete is suitable for many SC3DP applications, currently also a purpose designed, customizable concrete mix is being developed by the Institute of Building Materials, Concrete Construction and Fire Protection (IBMB) [11].

For reinforcement, standard 10 mm B500B steel rebars were used. The horizontal rebars were pre-bent using a manual rebar bending machine. For ease of placement, additionally 6 cm long pins were welded to the rebars (Fig. 2b).

**Design and Control.** To establish a seamless digital workflow from design to manufacturing, the parametric visual programming interface Grasshopper for Rhino 3D was used. In this particular workflow the 3D surface geometry was generated using parametrically variable input curves. Based on the surface geometry the undulations were generated parametrically and the geometry was structurally analyzed for fabrication feasibility, e.g. regarding the ability to print without collapsing. For this, the Grasshopper plugin Karamba was used and a simplified material model was applied, representing the loadbearing capacity of the freshly printed concrete. These values were measured in previously conducted parameter studies. The structural analysis indicates areas where the stresses in the wall exceed the material's loadbearing capacity. If an excessive load was detected, the geometry was parametrically changed until the stresses remained within the limits of the material capacity. After a stable configuration was found, the printing paths were generated automatically using a custom written python component. Subsequently the machine instructions were generated using the Grasshopper plugin Robots [12].

**Printing Parameters.** A chosen nozzle diameter of 15 mm, a distance of 20 cm from the nozzle to the printing plane, an air pressure of 2 bar and a robot speed of 0.25 m/s, resulted in a layer width of 12 cm and a layer height of 1 cm. With these settings a volume of approximately 1 m<sup>3</sup>/h can be printed.

### 2.3 Fabrication and Experimental Investigation

**Core Printing and Placement of Horizontal Reinforcement.** According to the printing strategy described above, the core structure was printed incorporating slight undulations. The number and depth were adjusted parametrically to seven undulations with an amplitude of 5 cm. The height of the segments was set to 40 cm, with the first and the last segment being exceptions. After spraying a base of six layers, the pneumatic pinch valve was activated, immediately stopping the flow of concrete. The robot was moved to a pre-programmed position, clearing the way for manual placement of the first pair of horizontal rebars. The rebars were placed merely resting on the tips of the undulations. After placement, the workspace was cleared, and fabrication continued. The entire procedure was repeated for the remaining segments until the full height of the wall was reached.

**Placement of Vertical Reinforcement.** After the wall core was printed, the 10 mm vertical rebars were threaded into the loops that were created between the undulating concrete core and the horizontal rebar. Over the length of 2.5 m, the rebar was sufficiently flexible to be inserted without pre-bending, significantly lowering the amount of labor. In total 7 rebars on the front and 6 rebars on the backside were inserted, within approximately 15 min of time (Fig. 3).



**Fig. 2.** Fabrication process: (a) Shotcrete 3D Printing of the core structure; (b) manually placed, pre-bent reinforcement with additional pins for securing the position.



**Fig. 3.** Vertical reinforcement: (a) Threading in the unbent vertical reinforcement; (b) close-up from seen from the back side.

**Second Layer Printing.** Immediately after inserting the vertical rebars, a second layer of concrete was printed vertically onto the core structure entirely embedding the reinforcement. For this the same concrete as for the core structure was used, however as the concrete of the second layer needs to remain malleable for finishing, no additional accelerator was used. In terms of the printing path, a horizontally oriented printing strategy was chosen (Fig. 4). In order to level out the undulations, the robot speed was programmed in relation to the distance to the surface. More specifically, when approaching a valley of the undulation the robot speed was lowered and more material was applied. In reverse, when approaching the peak of a valley the robot speed was increased, adding less material. The application of a cover layer was repeated twice, until a sufficient cover of 3 cm, measured from the peak of an undulation, was achieved.



**Fig. 4.** Second layer printing: (a) Close-up of the spraying process; (b) slight undulations are still visible after the first pass.

**Surface Finishing.** The surface finishing process was performed with the five-axis milling portal involving three stages of smoothing. Approximately 20 min after the second surface layer was applied, the still malleable concrete was redistributed using a rotating steel disc with a diameter of 20 cm containing three flexible steel blades (Fig. 5a). For this process, the portal speed was set to 10 m/min and the disc was set to 120 rotations per minute.

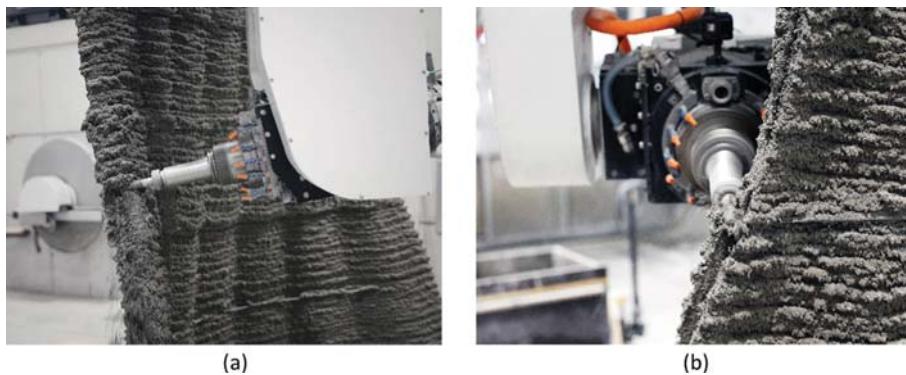


**Fig. 5.** Surface finishing: (a) Vertical finishing using a 20 cm steel disc with blades; (b) horizontal finishing using a 20 cm diameter flat steel disc.

In a second pass, the surface was smoothed with a flat steel disc of the same diameter. Robot speed and disc rotation remained unchanged. As with the previous tool the process was repeated once following a vertical, and once following a horizontal orientation (Fig. 5b). Finally, a plastic disc with a diameter of 10 cm was used to increase resolution and surface smoothness. In a last pass the wall was smoothed in vertical direction from top to bottom.

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**Edge Milling.** For a precise edge definition, the right and left edges of the wall were trimmed with flank milling process. This process was repeated twice, once before the second layer was applied, and once after. For both passes a flank mill with a length of 20 cm and a diameter of 20 mm was used. The speed was set 7 m/min and 200 rpm. Each edge was cut in one continuous operation (Fig. 6).

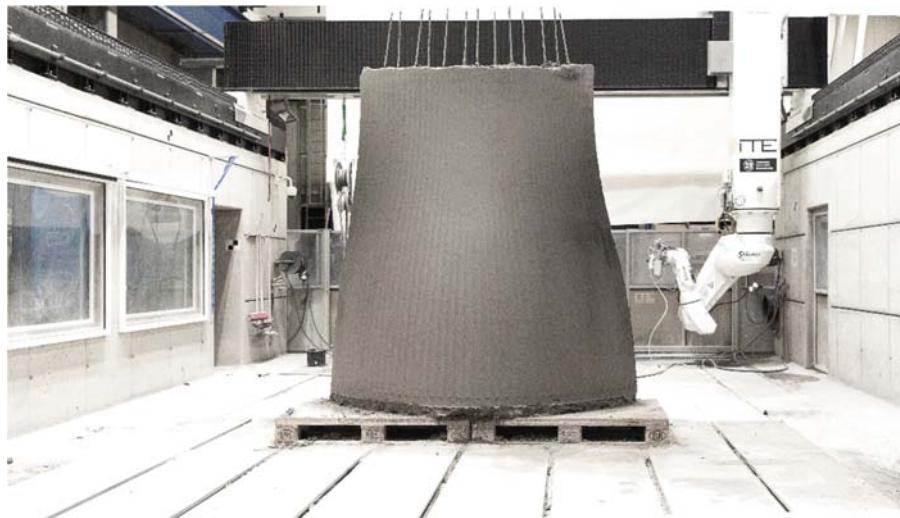


**Fig. 6.** Edge cutting process: (a) flank milling using the five-axis mill; (b) close-up of the milling process.

### 3 Results and Discussion

The total fabrication for the  $2.5 \times 2.3 \times 0.18$  m wall, from printing start to surface finish took 3 h and 45 min of which 45 min were consumed by printing, 35 min for the placement of reinforcement, 30 min for the second layer printing, 45 min for smoothing and 10 min for edge cutting. The remaining time was used for the preparation of the successive steps. Regarding the digital simulation of structural stability during printing, the producibility of the structure was reliably predicted by the Karamba calculation. The placement of horizontal reinforcement was significantly simplified containing the welded pins, as otherwise the pre-bent rebars showed a tendency to slip down from the concrete core. The prefabrication of the horizontal rebars through manual means, proved to be a time intensive and laborious task. Threading in the vertical rebars on the other hand was fast, precise and unproblematic. Due to the length, the vertical rebar showed sufficient flexibility and did not have to be pre-bent. For more demanding load cases, the amount and density of the reinforcement can easily be adjusted, either by changing the number of undulations, or the thickness or the amount

of rebars per loop. A compelling advantage of this system is that the density of the reinforcement can locally be differentiated, according to the specific load case. During the surface treatment, a large amount of material was redistributed during the first troweling operation, which indicates that the horizontal spraying strategy, slowing down in the valleys and accelerating at the peaks, was not sufficiently precise. In contrast to 3D printing of the core, the online measuring method was not used for second layer printing. However, this would allow the speed of the robot to regulate itself according to the distance to the surface. Thus, only the path but not the speed of the robot would have to be programmed. However, after troweling a smooth high-quality surface was achieved, leaving the last vertical troweling pass subtly visible (Fig. 7).



**Fig. 7.** Finished wall after smoothing and edge trimming

The extent of these visible traces depends on the size of the smoothing disc and how it is mounted on the milling portal. Flexible mounting would allow the disc to adapt more closely to the curvature of the wall. To achieve an entirely smoothed surface, a felt disc or sponge could be used in a final pass. The edge cutting delivered satisfactory results, which could be further improved by grinding the surface at a time when the concrete has further cured. A separate strategy must be developed for the upper edge, considering the protruding reinforcement bars. For geometric quality control, the surface was digitally measured twice using 3D scanning. Once after the reinforcement was installed, and once after surface finishing. Despite the use of the online laser measuring system, a comparison of printed core (without reinforcement) showed geometric deviations of up to 10 mm. Here it is probable that the structure has subsequently sagged slightly under its own weight, which cannot be detected globally by the online measuring system during printing. However, these small inaccuracies

were geometrically levelled out by applying the second layer and finishing the structure with the smoothing discs. In this particular demonstrator the backside was left untreated, showcasing the printing and reinforcing strategy.

#### 4 Conclusion

This final demonstrator showcased the advances made during the interdisciplinary research project “generative manufacturing with concrete”, which involved specialists from the field of architecture, civil engineering, mechanical engineering and material science. Interdisciplinary and experimental research made it possible to fabricate a fully reinforced, double-curved concrete wall with high surface quality using Shotcrete 3D Printing, an alternative approach to extrusion-based 3D concrete printing processes. The demonstrator was specifically designed to showcase the unique capabilities of the Shotcrete 3D Printing method.

In addition to the good layer bonding properties, inherent in the Shotcrete 3D printing process and the extended geometrical freedom, two other main features of the process are the capacity to integrate reinforcement, and the automated surface finishing. Regarding the reinforcement, in this demonstrator the steel bars are continuous in both principal directions following exactly the geometry of the double-curved wall. This was enabled, through a unique reinforcement strategy, where the concrete supports the horizontal reinforcement in its spatial position, creating loops for the vertical reinforcement to be threaded through. Without pre-bending, the vertical reinforcement can follow geometrically complex, i.e. non-orthogonal, trajectories.

Moreover, the reinforcement is structurally fully embedded by means of the second layer printing routine. Hence, the second layer printing routine is not only contributing to the aesthetic qualities, but is rather an essential part for fostering the structural integrity of the system. In future research the automatization of the reinforcement will be addressed. For this also other material processes, as for example the use of robotically placed, continuous fiber placement will be addressed. Regarding the second layer printing and troweling process, the digital capacities for surface finishing go well beyond smooth surfaces. Here a variety of other digitally controlled surface structures, for example by means of formative, subtractive and additive processes, will be investigated.

In summary, the demonstrator showcased that Shotcrete 3D Printing is a viable addition to the more widely studied extrusion-based 3D printing approaches with concrete, especially for the fabrication of structural elements where high geometric resolution only plays a subordinate role.

**Acknowledgements.** This final demonstrator is the result of a four years collaboration between Technische Universität Braunschweig (Institute of Structural Design (ITE), Institute of Building Materials, Concrete Construction and Fire Protection (IBMB), Institute of Machine Tools and Production Technology (IWF)), Leibniz Universität Hannover (Institute of Assembly Technology (Match)) and Technische Universität Clausthal (Institute of Non-Metallic Materials). The research Project was funded by the lower Soaxony Ministry of Science and Culture and the Lower Saxony Technical Universities (NTH). The Digital Building Fabrication Laboratory was

funded through the German Research Foundation (DFG). The Junior Professorship for Digital Building Fabrication is funded by the Gerhard and Karin Matthäi Stiftung. The concrete was supplied by MC Bauchemie. Furthermore, the authors would like to thank Hendrik Lindemann, Niklas Nolte and Roman Gerbers for their contributions during the project period.

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