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REPORT

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Reinforcement strategies for 3D-concrete-printing

Harald Kloft[1] | Martin Empelmann[2] | Norman Hack[1] | Eric Herrmann[1] | Dirk Lowke[3]

[1]Institute of Structural Design, Technische Universität Braunschweig, Braunschweig, Germany

[2]Division of Concrete Construction, Institute of Building Materials, Concrete Construction and Fire Safety, Technische Universität Braunschweig, Braunschweig, Germany

[3]Division of Building Materials, Institute of Building Materials, Concrete Construction, and Fire Safety, Technische Universität Braunschweig, Braunschweig, Germany

Correspondence
Harald Kloft, Institute of Structural Design, Technische Universität Braunschweig, Pockelsstraße 4, Braunschweig 38106, Germany.
Email: h.kloft@tu-braunschweig.de

Eric Herrmann, TU Braunschweig Institute for Structural Design, Department of Architecture, Pockelsstraße 4, Braunschweig 38106, Germany.
Email: e.herrmann@tu-braunschweig.de

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Abstract

The ingenious bridge, roof, and shell structures of the last century were designed from the understanding of the congenial interaction of the two materials concrete and steel. Nowadays, reinforced concrete is the most widely used material in construction. The use of system formwork and easy-to-install reinforcement support structures that are optimized in terms of labor costs, but often have inefficient use of material. In this context, Stefan Polónyi has repeatedly criticized the engineers' lost understanding of the interaction of concrete and reinforcement. With Additive Manufacturing, an innovative digital manufacturing technology is now available that allows new freedom in concrete design with a resource-efficient use of materials at the same time. With regard to practical application, the integration of reinforcement represents a central challenge in 3D-concrete-printing. The authors see here the future chance of a force-flow controlled reinforcement layout. The paper shows new strategies for the combined Additive Manufacturing of concrete and reinforcement and presents first 3D-printed reinforced concrete elements.

KEYWORDS

3D-concrete-printing, additive manufacturing, digital building fabrication, reinforcement integration, shotcrete 3D printing

1 | INTRODUCTION

Concrete and steel, two materials that have been symbiotically combined to form the composite material reinforced concrete based on an equal coefficient of thermal expansion, have dominated construction work for decades. While the reinforced concrete construction method was originally associated with ingenious shell structures, bold roof structures, and elegant bridge constructions, today reinforced concrete is a material that is used in masses and is closely linked to the high CO_2 emissions caused by construction. This seems to be primarily related to the emission-intensive production of cement, but a closer look reveals that the main contribution to CO_2 emissions is caused by the inefficient use of the materials steel and concrete. Instead of thin-walled shell structures, thick-walled concrete components subjected to flexural stress dominate today's construction activities. The reason for this is the permanent increase in wage costs compared to material costs over the past decades. In concrete construction, this led to the increased use of uniform system formwork, which replaced material-saving construction systems requiring labor-intensive, individualized mold making. Even the reinforcing steel, which is only required in the tensile zone of the cross-section, is nowadays inserted into the formwork systems as full-coverage orthogonal reinforcement, which rather prevents the placing and compaction of concrete than interacting congenially with it (Figure 1). Stefan Polónyi is even convinced that the inefficient use of materials not only wastes resources, but also shapes our engineering thinking: "We engineers only think in terms of plane components and orthogonal patterns. The oversizing resulting from a lack of

Univ.-Prof. em. Dr.-Ing. E.h. mult. Dr. h.c. Stefan Polónyi on his ninetieth birthday.

FIGURE 1 Predominant traditional reinforcement technology using orthogonal reinforcement. *Source:* Institute of Structural Design

understanding not only wastes resources, but can also cause structural damage.[1]"

Today the construction industry has reached an ecological and economical turning point. The adherence to outdated manual building techniques and the one-sided generation of profits by minimizing wage costs is a dead end. While other industrial sectors are pushing the integration of production under the term "Industry 4.0" to the next level of productivity increase, the construction industry—despite the good economic situation of recent years—is lagging far behind in terms of productivity.[2]

Moreover, the traditional manual construction processes also hinder progress in the preliminary planning processes. This happens because the transfer of formwork and reinforcement positioning information from the planning processes to the construction sites still takes place mainly in the form of 2D plans (Figure 2). Whether the 2D plans were drawn with conventional CAD programs or generated from a 3D BIM model is currently irrelevant for the plan-based use of information on the construction sites. A decisive factor for the future of the construction industry is end-to-end digitalization from planning to production. The automation of production processes takes on a central role here. In recent years, there have been repeated attempts to transfer digital production methods from other areas to the construction industry. These attempts have made it possible to realize pioneering innovative architectures. For example, the production of the freely formed concrete components of the Phaeno Science Center

FIGURE 2 Fragmented digitalisation in the construction industry: Digital data generation in planning and analogue handover to the construction site as plans and drawings. *Source:* Institute of Structural Design

in Wolfsburg could not have been realized without CNC-milled formwork inlays. However, the transfer of digital manufacturing technologies from other industrial sectors had not become economically viable, and adaptations to construction processes were limited to their singular use in extravagant architectures.

2 | ADDITIVE MANUFACTURING IN CONSTRUCTION

3D printing (Additive Manufacturing) is a novel digital manufacturing technology with the potential to become a key technology for the digitalization and automation of the construction industry.[2] The great advantage of Additive Manufacturing in construction is that automation and individualization are not contradictory and 3D printing is ideally suited to the high degree of individualization in the construction industry. In this context, the DFG Collaborative Research Centre TRR 277 "Additive Manufacturing in Construction" (AMC), which was recently established at the beginning of 2020, has set itself the goal of fundamentally researching the technology of Additive Manufacturing for the construction industry. In this interdisciplinary, cross-location research project, the two universities Technische Universität Braunschweig and Technical University of Munich are pursuing the goal of investigating novel resource-efficient material-process combinations and using material solely where it fulfills a function. These processes pave the way for a new freedom of design in the building industry while simultaneously using building materials in a design-driven way.

The central topics of the research program are the unity of materials and processes as well as the continuous digitalization in the building industry. For this purpose, the digital interfaces between Additive Manufacturing and the preliminary planning processes as well as the following processes of construction are investigated (Figure 3). The currently most common method of concrete 3D printing is the layer-by-layer deposition of plastically deformable material strands by extrusion. In extrusion 3D printing, the bond between the layers is induced by gravity and mainly by chemical bonding. A representative example of extrusion 3D printing is the contour-crafting technology[3] patented by Khoshnevis in 2004.

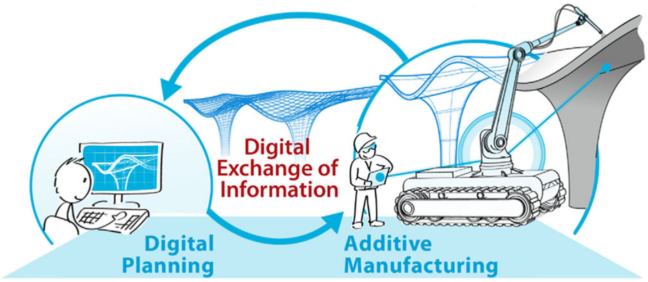

FIGURE 3 Seamless digital processes from planning to construction. *Source:* Institute of Structural Design

Further developments of this process are currently being investigated at TU Dresden,[4,5] TU Eindhoven,[6] and Loughborough University.[7] In contrast to a cast-in-place component, in which the fresh concrete is mechanically compacted in the formwork to achieve the designated hardened concrete properties, this step is not required in Additive Manufacturing. As a result, the area between the layers (interlayer) is very sensitive with regard to homogeneous material properties. The risk of weak interfacial bonding in interlayer zones is known as "cold joints" in this context and is the subject of various current research projects.[5,7–12] Research has also been conducted at the TU Braunschweig for several years on methods for 3D printing of large-scale concrete components. From 2016 to 2018, the Shotcrete 3D Printing Process (SC3DP) was developed in an interdisciplinary joint project, funded by the Ministry of Science and Culture of Lower Saxony, with researchers from the fields of materials technology, mechanical engineering and computer science.[11–14]

The SC3DP technology is a robot-controlled additive manufacturing process that builds up concrete components layer by layer through the controlled addition of compressed air. In the SC3DP process, the rheology and setting behavior and thus the load-bearing capacity of the layers is controlled among other things by adding concrete admixtures to the concrete jet. A benefit of SC3DP is the acceleration of the material caused by the compressed air. The high kinetic energy at impact causes compaction of the concrete as well as a good mechanical bond between two successive layers. As a result, high bulk densities, that is, low porosity, can be achieved with the SC3DP process.[15] This results in good strength and durability properties of the additive manufactured components. Due to the high application rate and the high process speed, the SC3DP process is very well suited for the production of large-scale components. A further advantage of the SC3DP technology is the combination with a robot-supported production unit. The spatial degrees of freedom of robots provide enormous geometric freedom for shaping concrete components. Figure 4 shows a hybrid precast part for a point-supported column, consisting of an 8 cm thick concrete slab (4 m × 4 m) and 12 cm wide, freshly imprinted concrete ribs. Compared with an all-over 25 cm thick flat slab, this results in mass savings of approximately 60%. The ribs were printed in less than 30 minutes.

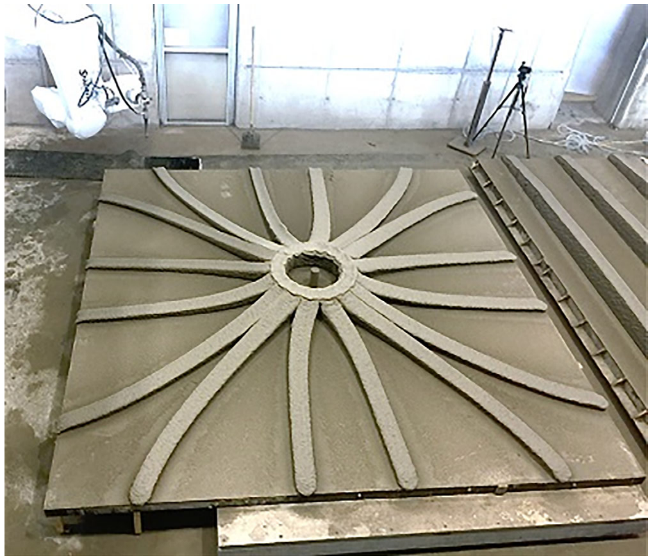

FIGURE 4 Hybrid-manufactured top plate element made of thin concrete plate and imprinted ribs using the SC3DP method. *Source:* Institute of Structural Design

3 | ARRANGEMENT OF REINFORCEMENT IN REINFORCED CONCRETE COMPONENTS

Steel rebars or mesh reinforcement are mainly required in the tensile zone of a flexural component and have so far been arranged in straight lines and often orthogonally in conventional reinforced concrete construction. For the case of structural elements subject to shear forces, shear reinforcement in the form of stirrups is additionally installed. In order to position and fixing the stirrups, additional assembly reinforcement is arranged in the compression zone of the reinforced concrete component. This additional reinforcement, as well as the orthogonal reinforcement arrangement, ensures rapid construction progress and reduces the complexity of the reinforcement layout, but increases material consumption. In this context, Polónyi already pointed out the inefficient reinforcement arrangement of slab reinforcement,[16] Figure 5. If the reinforcement would be arranged according to the principal stress trajectories, no stirrup would be necessary. Fortunately, the principal stress trajectories and subsequently the required tensile reinforcement layout can be nowadays easily determined even for complex loading with the help of a computer. In the field of fiber-reinforced plastics and laminates, the arrangement of reinforcement and its efficiency increase is already a current research topic.[18]

Figure 6 shows the principal stress trajectories for a uniformly loaded single span beam. The arrangement of fibers or reinforcement according to the principal stresses can increase the material utilization.[19] These trajectories were calculated by Karamba3D, a FEM plugin for Rhinoceros 3D Grasshopper. The software calculates the paths of the principal stresses for two-dimensional, continuous, time-independent vector fields, even on irregular FE-meshes, using the method

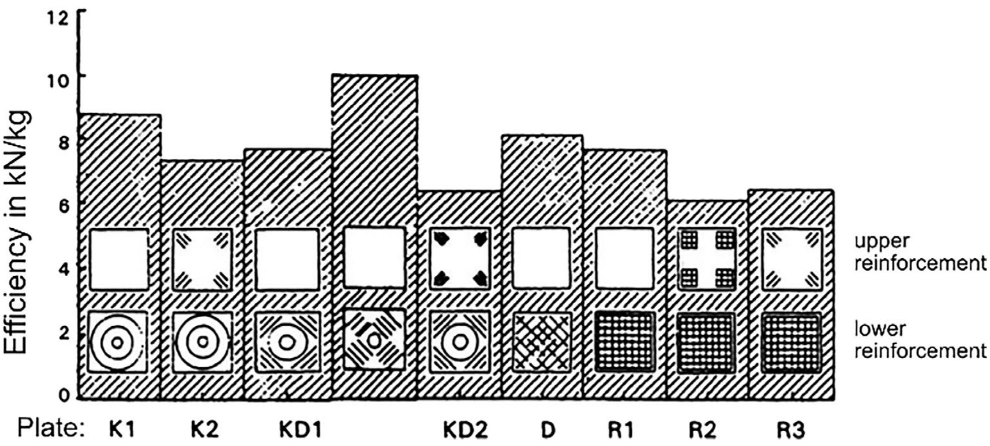

FIGURE 5 Efficiency of different reinforcement patterns of square plates. *Source:* Reference 17

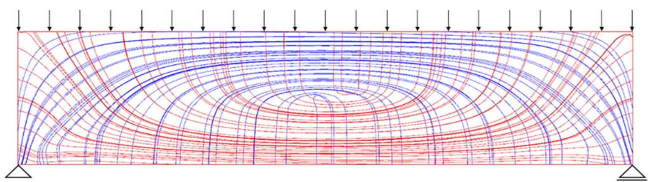

FIGURE 6 Schematic illustration of the main stress trajectories of a single-span beam under uniform load with compression trajectories (blue) and tension trajectories (red), calculated with Karamba3D. *Source:* Institute of Structural Design

of Reference 20. For the integration of reinforcement in 3D-printed concrete components, mainly the tensile stress trajectories are essential. Depending on the size of the mesh, the number of calculated tension trajectories and their exact visualization varies. Choosing the tension trajectories from the multitude of possible curves according to the highest tensions will result in the position of the reinforcement layers.

The arrangement of the reinforcement along the tension trajectories is nowadays not economically feasible with conventional construction techniques and manual interlacing methods, especially since the reinforcement has to be positioned in the formwork in advance, which means that, in addition to the time required, appropriate additional installation reinforcement is necessary. Since no formwork is required for 3D-concrete-printing, new possibilities arise for integrating the reinforcement into the automated layer-by-layer building process and for realizing simple as well as complex reinforcement designs without additional assembly reinforcement. The advantages are expressed in a reduction of material, energy and personnel costs.

4 | STRATEGIES FOR COMBINED ADDITIVE MANUFACTURING OF REINFORCED CONCRETE COMPONENTS

Based on concrete, numerous processes for the Additive Manufacturing of nonreinforced concrete components have been developed in recent years.[3,21–27] The fabrication of reinforced concrete components represents the next step in the development of 3D-concrete-printing. In this context, the integration of materials with high tensile strength is essential as reinforcement to enable the transfer of the released tensile stresses upon concrete cracking and to ensure ductile failure of the structural concrete components. When integrating reinforcing elements, it is crucial to maintain the flexibility and efficiency of Additive Manufacturing methods while ensuring the effective utilization of the reinforcement from a material technology point of view. The aim should be to develop combined Additive Manufacturing methods for concrete and reinforcement, which maintain the freedom of form given in the manufacturing process and at the same time create a good bond with the surrounding material.

The combined Additive Manufacturing enables reinforcement to be guided in line with the load path and also eliminates the need for assembly reinforcement, thus reducing the amount of material that is not statically and constructively required. Not least because of this, more complex and more efficient structural components can be developed compared to the status quo. Here, ensuring the bond between concrete and reinforcement is a major challenge. A specific increase in the bond can be achieved, for example, by controlling the consistency of the printed concrete,[28] by using an additionally applied bonding mortar between concrete and reinforcement[29] or by using mineral-bound carbon fiber reinforcements.[30,31] There is also a need for research into the cooperative coordination and combination of the individual combined Additive Manufacturing process steps. Thereby it is necessary to integrate the insertion of reinforcement elements into the 3D-printing-processes of concrete components. The potential of Additive Manufacturing of reinforced concrete components lies in the wide combinatorial variety of innovative Additive Manufacturing techniques for different reinforcement materials with various 3D-concrete-printing methods.

Figure 7 shows a new approach to systematize the combined Additive Manufacturing of reinforced concrete components. In contrast to formwork-based concrete construction, where the reinforcement must be fully positioned and fixed in the formwork before concrete placing, 3D concrete printing offers the possibility of using the layered material structure as a supporting structure for the installation of the reinforcement (concrete supports reinforcement). And vice versa, prebraided reinforcing elements can be subsequently provided with an additive manufactured concrete application (reinforcement supports concrete).

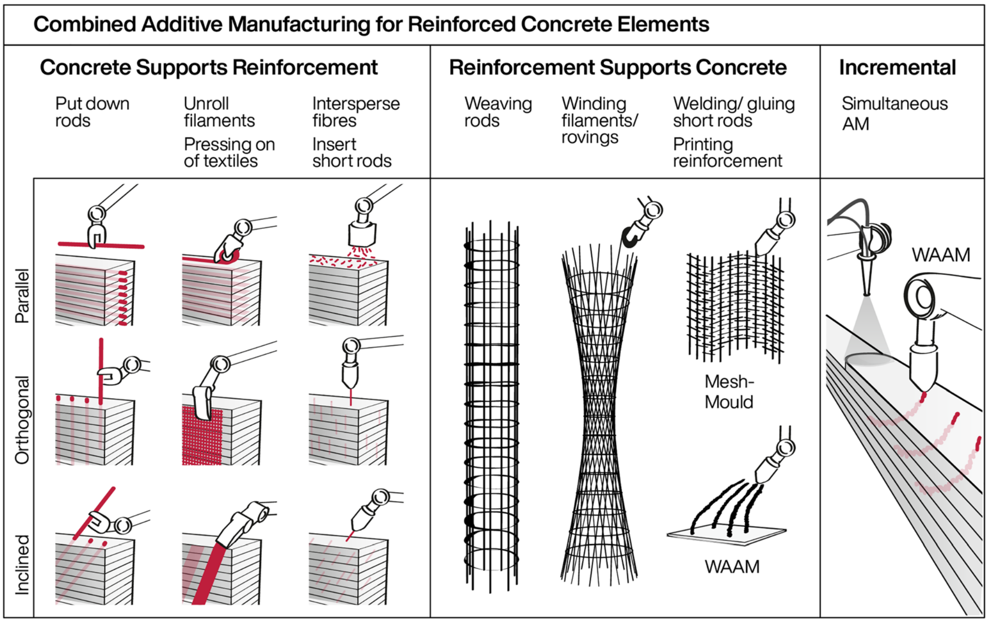

FIGURE 7 Systematization of combined additive fabrication of reinforced concrete components. *Source:* Institute of Structural Design

In Figure 7 both tracks are presented: (a) preliminary concrete printing processes which, while not hardened yet, offer the possibility of inserting reinforcement (bars, mats, filaments, textiles, fibers) by putting down, unrolling, intersperse or inserting (concrete supports reinforcement) or (b) preliminary reinforcement processes which can be formative for the additive concrete printing processes (reinforcement supports concrete). In the following, first prototypical combined Additive Manufacturing processes for reinforced concrete components are presented. Also shown in Figure 7 is the simultaneous additive manufacturing of concrete and reinforcement. After the concrete layer is printed, the rebars can be welded using the wire arc additive manufacturing (WAAM) process. This allows free movement of the printing robot, as no rods are in the way. In addition, the rods are directly incorporated which leads to a more flexible design.

5 | FIRST PROTOTYPICAL COMBINED ADDITIVE MANUFACTURING OF REINFORCED CONCRETE COMPONENTS

5.1 | Freeform reinforced concrete wall elements (concrete supports reinforcement)

The prototypes presented show that for standard components such as walls, ceilings, and columns, Additive Manufacturing opens up new possibilities for shaping and efficient use of materials. The reinforced concrete components were produced in the Digital Building Fabrication Laboratory (DBFL) of the TU Braunschweig[13] by using Shotcrete 3D Printing (SC3DP). An innovative reinforcement strategy has been developed for printing freeform walls, which allows the components to be reinforced in both horizontal and vertical directions. This reinforcement strategy comprises five successive production steps, which are shown schematically in Figure 8.

For an outer wall geometry previously created in a CAD program, a slightly undulating inner "core geometry" is parametrically generated. This undulating geometry is then vertically segmented so that prebent horizontal reinforcement elements can be inserted at defined points (Figure 8A). The prebent reinforcement is inserted manually while the robot is paused. The bending shape of the reinforcement elements and the undulating core geometry of the concrete body are matched to each. Thereby, loops are formed over the entire height of the wall through which the vertical reinforcement can be threaded (Figures 8B,C). Due to the length of the rebars, even 12 mm thick rebars remain sufficiently flexible so that the vertical reinforcement does not have to be prebent for large radii of curvature. The reinforcement is then structurally embedded by printing a 4 cm thick top layer, the so-called "second layer printing" (Figure 8D).

In a final process step, the freshly printed top layer is smoothed. This step of the process is taken over by the second portal of the DBFL. An end effector in the form of a rotating steel disc was developed for the smoothing process and integrated into the spindle of the five-axis milling unit (Figure 8E). As the number of segments, as well as the amplitude of the waveform of the concrete core, can be controlled parametrically, it is possible to adapt the degree of reinforcement to the specific load applied to the structural element. Figure 9 shows sections of the production of the large reinforced concrete component in the DBFL. Figure 9A shows the covering of the reinforcement using second layer printing, and Figure 9B shows the finished smoothed component.

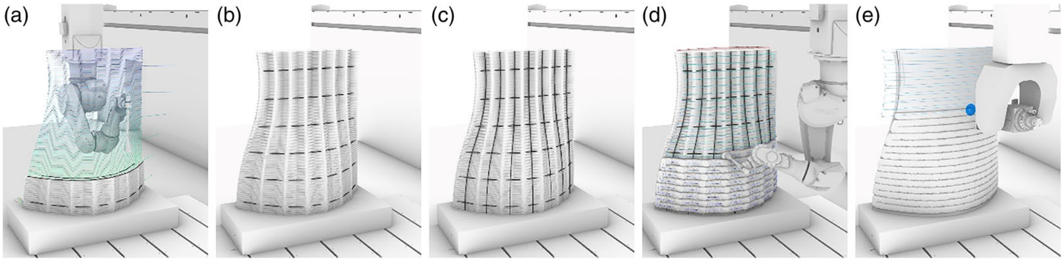

FIGURE 8 Manufacturing strategy: A, printing the undulating core and inserting the prebent horizontal reinforcment bars; B, printed core with horizontal reinforcement; C, inserted vertical reinforcement; D, covering the reinforcement with an additional layer of shotcrete; E, smoothing the surface with a rotating steel disc. *Source:* Institute of Structural Design

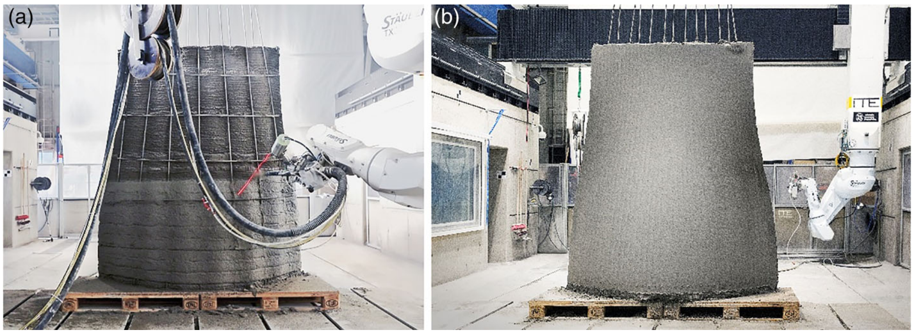

FIGURE 9 Manufacturing process in the Digital Building Fabrication Laboratory (DBFL): A, horizontal printing of the top layer; B, finished component after smoothing with the rotating steel disc. *Source:* Institute of Structural Design

5.2 | Concrete floor slabs with add-on-printed reinforced ribs (concrete supports reinforcement)

Figure 10 shows a hybrid manufactured concrete floor slab with add-on-printed ribs, which was fabricated according to the principle "concrete supports reinforcement." The slab is conventionally reinforced with mats and was not printed but cast-in-place. Printing the slab would have been technically possible, but inefficient, as the production of simple slab elements by casting concrete is fast and practical.

The ribs were printed onto the freshly concreted slab using the SC3DP process. Reinforcing bars were routed up from the slab near the supports to achieve a better bond with the ribs. Each rib consists of several sprayed layers printed on top of each other. The height of the ribs is about 10 cm at the supports and 20 cm in the middle. The printing speed has been adjusted in such a way that the robot moves faster toward the supports. Therefore, less material is applied at the end of the ribs than in the middle of the ribs. With the same concrete volume flow, faster execution of the printing path results in a slimmer concrete strand. In other words, the height of the concrete layer is indirectly proportional to the printing speed.[14] For this reason, the layer heights vary from about 1 cm at the supports to 1.8 cm in the middle of the beam. Since the reinforcing bars have the same cross-section over the entire length, but the bending moment and thus the flexural tensile forces decrease toward the supports, the static height can decrease toward the supports without reducing the bending resistance of the component. The four longitudinal reinforcement bars of the ribs were installed manually. The 20 vertical reinforcement bars, which were guided up from the slab at the supports, and the robotically printed concrete layer served here as an installation aid (Figure 11).

In this way, the horizontal position and the distance between the bars on the printed concrete strands could be convoyed. The vertical positioning of the reinforcement was controlled by the varying height of the robotic printed concrete ribs. After inserting the reinforcement, another four layers of concrete were applied, which corresponds to a concrete cover of about 4 to 6 cm. The experiment illustrates the principle of "concrete supports reinforcement" and shows an example of adapting reinforcement layout to the force flow with minimized material use.

5.3 | Reinforced concrete columns, manufactured using the SC3DP method (reinforcement supports concrete)

The first additively-made reinforced concrete column shown in Figure 12 was manufactured according to the principle of "reinforcement supports concrete."[32] The required reinforcement was determined according to the current EC2 standards and prefabricated as a conventional reinforcement cage (Figure 13, left). The reinforcement cage defines the core geometry for the final column shape.

For the additive concrete application it is basically possible to let the robot move the full 360° around the column, but without countermeasures, the hoses can twist and block each other. For this reason, a turntable was developed and the reinforcement cage was fixed on it

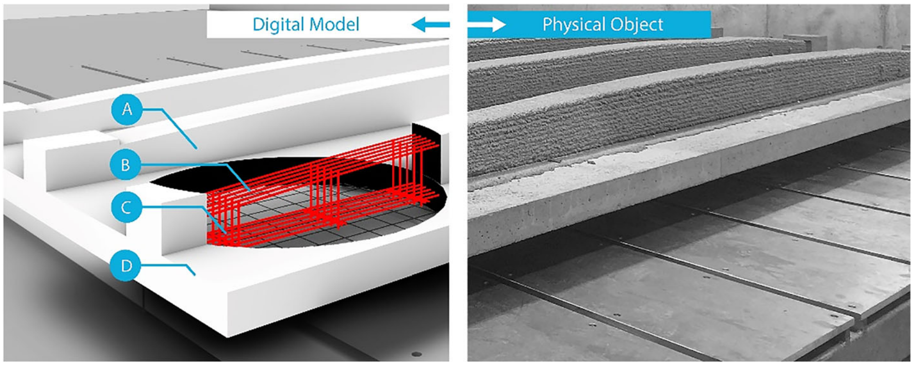

FIGURE 10 Reinforced plate beam printed with the SC3DP method with a plate measuring 500 cm × 210 cm × 10 cm: Digital model (left), printed beam (right); A, ribs; B, tensile reinforcement inserted into the ribs; C, ribs reinforcement with raised bars; D, cast concrete ribs. *Source:* Institute of Structural Design

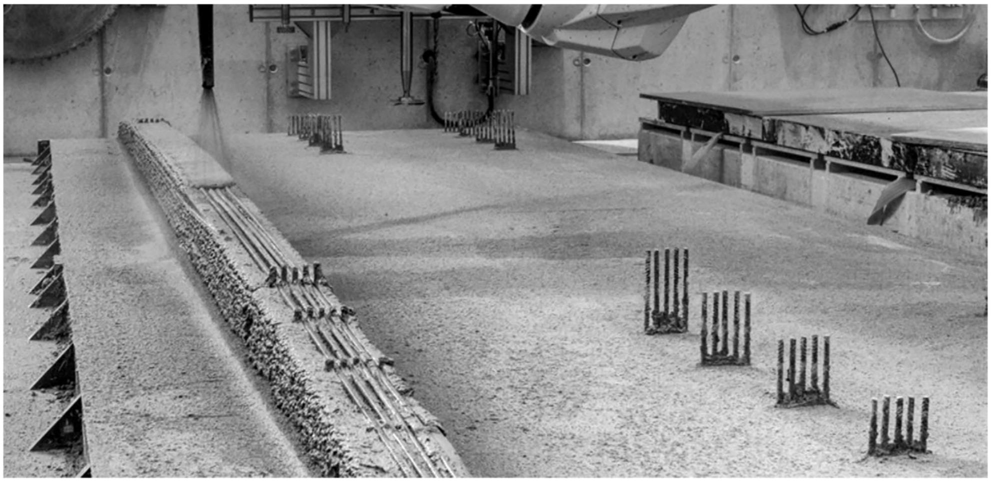

FIGURE 11 Printing the concrete cover of the tensile reinforcement. *Source:* Institute of Structural Design

for the 3D printing process. In the concrete printing process, the spray nozzle was tilted by 60° against the horizontal and moved upward along the Z-axis by the robot (Figure 12). The decisive factor is that the speed of the vertical spray application is matched to the rotation of the reinforcement cage.

The experiments have shown that little material is lost due to the inclined nozzle guide and that the formation of spray shadows behind the reinforcement can be managed in this way. In Figure 13, on the right, it can be seen that the reinforcement is completely enclosed, which opens the way to use the SC3DP process for reinforced concrete components.

6 | OUTLOOK

In the context of the current research of the TRR 277 Additive Manufacturing in Construction, one goal is to integrate the demonstrated methods of reinforcement placement into the automated 3D concrete printing process.

In particular, the tension trajectories shall be automatically integrated into the path planning and enable new combined application strategies of concrete and reinforcement (Figure 14). In order for the concrete to support the reinforcement even with curved reinforcement, the concrete layers must also be printed parallel to the reinforcement layer. Since the compression trajectories are always orthogonal to the tension trajectories, this arrangement of the concrete layers means that the compression forces always act perpendicular to the bond zone between the layers. As depicted in Reference 11, this load direction allows higher compressive strength values.

The use of steel for reinforcing concrete elements has many distinct advantages. Among these are, for example, that concrete and steel establish a good mechanical bond, have a similar coefficient of thermal expansion and, in addition, have already been tested in practice for decades. Concerning reinforcement corrosion, textile reinforcement concepts such as glass or carbon fiber reinforcement also offer promising alternatives to steel. In the scope of TRR 277, reinforcement concepts are also being developed for this purpose and examined for their potential in connection with Additive Manufacturing.

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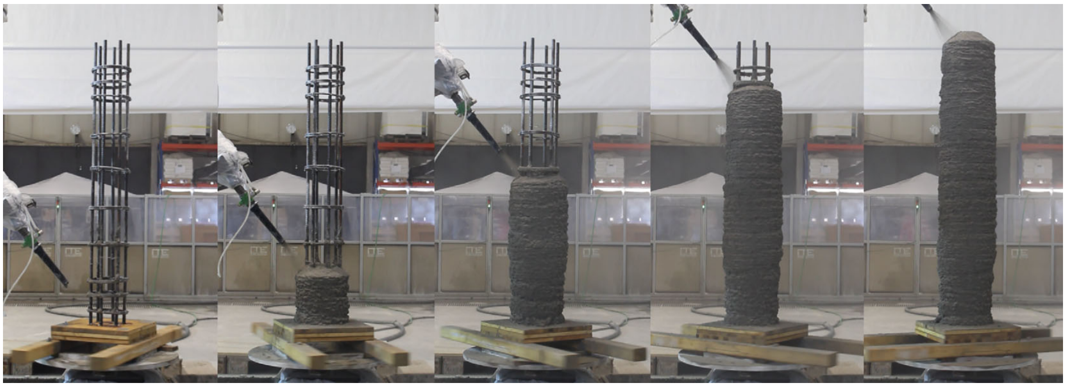

FIGURE 12 Reinforced column produced with SC3DP method on a rotating table. *Source:* Institute of Building Materials, Concrete Construction and Fire Safety, Division of Concrete Construction

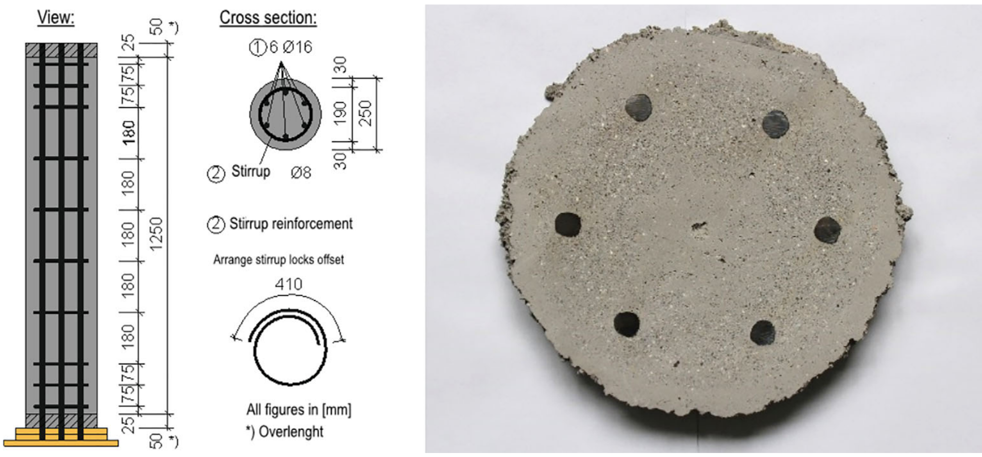

FIGURE 13 Bending schedule of the column (left) and crosssection with full surface coating of the reinforcement (right). *Source:* Institute of Building Materials, Concrete Construction and Fire Safety

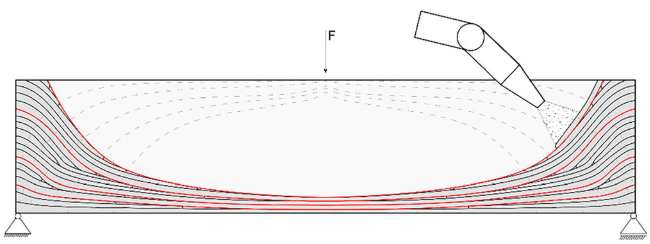

FIGURE 14 Exemplary path planning strategy for the force flow controlled combined additive manufacturing of a single-span beam consisting of prerunning supporting concrete layers (gray) and following running in place reinforcement (red). *Source:* Institute of Structural Design

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