Vision and Strategies for Reinforcing Additively Manufactured Concrete Structures

Reinforcing Methods

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Reinforcement Strategies for Additive Manufacturing in Construction based on Dynamic Fibre Winding: Concepts and Initial Case Studies

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Abstract. Whereas entire houses are reported to be built by means of 3D Concrete Printing (3DCP), the automated integration of reinforcement is still a vastly unresolved challenge and - undoubtedly - a crucial requirement for widespread adoption of 3DCP in construction practice. In this paper an automated reinforcement approach using continuous textile fibres is introduced as an alternative to the manual placement of conventional steel reinforcement. Based on a fibre winding technique, in this paper a matrix of methods and applications is presented and substantiated by initial feasibility studies on the 1:1 scale. As such, three case studies for the automated reinforcement integration are presented, addressing particle bed printing (Large Particle 3D Concrete Printing), as well as material jetting (Shotcrete 3D Printing).

Keywords: Additive Manufacturing in Construction (AMC); 3D Concrete Printing; Robotic Fibre Winding; FRP Concrete Reinforcement; Textile-Reinforced Concrete; Shotcrete 3D Printing; Large Particle 3D Concrete Printing

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Introduction

In view of the growing world population and the associated global demands for newly constructed habitats, global construction activity will continue to increase in the coming decades. At the same time, however, the construction industry is one of the world's most resource intensive industries, responsible for the consumption of 50% of all extracted raw materials, 12% of the overall CO_2 emissions and 55% of total waste generation [1]–[3]. New building technologies are needed to reduce this immense consumption of resources. One potential key technology for this is Additive Manufacturing in construction. Within the framework of the collaborative research centre TRR 277 Additive Manufacturing in Construction, 3D printing on construction scale is being fundamentally investigated for a variety of construction materials including concrete, steel and timber [4]. One of the biggest challenges, which is still not sufficiently investigated yet, is the automated integration of reinforcement, without which concrete components would not be able to withstand tensile forces and would therefore only be applicable for construction to a limited extent [5]–[7].

To resolve this pressing issue, and to unlock the full potential of 3D printing with concrete, the TRR 277 research project A05 “Integration of Individualized Prefabricated Fibre Reinforcement in Additive Manufacturing with Concrete” investigates automated fabrication processes for the integration of structural reinforcement for additively fabricated concrete elements. For this the Institute of Structural Design (ITE) and the Institute of Mechanics and Adaptronics (ima) of TU Braunschweig collaborate on a material and process level.

The particular focus of this project is directed towards the use of textile reinforcement as for example alkali resistant (AR) glass, aramid or carbon fibre. The main advantages of using textiles compared to conventional steel reinforcement elements are twofold: Firstly, textile reinforcement is corrosion resistant, which allows reducing the minimum required concrete cover by an order of magnitude [8]. This leads to a significant reduction in the amount of concrete required for structural components and thus to lower energy consumption along the entire value chain, as transport and assembly are also simplified. In addition, fibres as a lightweight and flexible raw material are advantageous for automated individualised manufacturing of complex force-flow-compliant reinforcement structures.

In line with that, this research project aims at developing fabrication methods for integrating textile reinforcement for all concrete related AM processes of the TRR 277, including Particle Bed 3D Printing, Concrete Extrusion, and Shotcrete 3D Printing [9]. For this, the main focus of this project is directed towards fibre winding techniques, for the reason that this fabrication process is fast, the fibres are continuous and the material properties can be varied according to the functional requirements of the building component by combining different fibre types and diameters. The investigated design and fabrication methods are validated through physical experiments, ranging from small scale test samples, middle scale case studies, to large scale demonstrators.

After a short overview of relevant research regarding non-metallic reinforcement in general as well as reinforcement integration in digital fabrication, this paper derives an overarching methodology used as the central development guideline in this project. Three novel fibre reinforcement strategies are derived from that and according feasibility studies are presented.

State of the art

Continuous fibre reinforcement in construction

The potentials of Textile-Reinforced Concrete (TRC) were realized early on by researchers from TU Dresden and RWTH Aachen, who have jointly applied for research funding for the further investigation of this topic. In 1999, the German Research Foundation approved the funding of two major Collaborative Research Centres focusing on fundamental research on textile reinforcement in concrete construction. Whereas the CRC 532 in Aachen “Textile-Reinforced Concrete - Development of a New Technology" focused on the development of novel concrete constructions, the CRC 528 "Textile Reinforcement for Structural Strengthening and Repair" focused on the application of textile reinforcement for deteriorating structures [10].

During the twelve years of funding, researchers of both initiatives developed fundamental material models, basic construction approaches, novel technological applications, new methods of calculation, as well as conducting long term surveys of the properties of TRC. Furthermore, the researchers verified the findings in several large-scale demonstrators, as for example the non-standard bridge structures in Oschatz and Kempten, as well as the research pavilions at the Kahla concrete plant and the Hypar-shell at RWTH Aachen (Figure 1) [11].


(a) (b) (c)

Figure 1: Large-Scale demonstrators from CRC 528 and 532: (a) Rottachsteg, Kempten © Nicolas Janberg, Structurae; (b) Research-Pavilion in Kahla © Ulrich van Stipriaan; (c) Hypar-shells at RWTH Aachen © Alexander Scholzen

For the fabrication of the above structures, mainly two fabrication techniques were developed. Firstly, a hand lamination process, in which pre-cut textile grids were stacked in-between thin layers of fine grain cement (Figure 2); and secondly, a conventional casting technique, where several spaced layers of textile reinforcement were placed in a custom-made formwork.


(a) (b)

Figure 2: Reinforcement of the Rottachsteg in Kempten; a) placing the prefabricated fibre mat; b) Appling the concrete in a lamination process © Dirk Jesse and Harald Michler

Even though the projects demonstrated the high flexibility of the textile formwork, as well as the material efficiency of the construction, it also became apparent that the processes are yet highly labour intensive and hence costly in production. Among others, this lack of methods to automate the integration of reinforcement can be seen as one of the reasons why TRC does not yet find a wide application in the industry.

In order to accelerate the transfer into practice, the follow-up research program "C^3-Carbon Concrete Composite" [8], also initiated by TU Dresden and financed by the German Federal Ministry for Education and Research (BMBF) focused on issues like production optimization, recycling, safety and industrial health.

A notable approach within that research initiative is the robotically aided winding of impregnated fibres around planar rectangular steel frames [12]. Instead of cutting out openings for windows and doors from a standard carbon fibre reinforcement mat, here a winding strategy is chosen to leave the regions of the openings unfilled. After the resin has cured the frame is removed and the reinforcement is placed in a standard formwork for subsequent concrete casting. This method enables the reduction of carbon fibre waste for standardized building components, like for example planar rectangular walls.

Recently a new Collaborative Research Centre, Transregio 280 “Design Strategies for Material-Minimised Carbon Reinforced Concrete Structures” has set out to investigate innovative and material efficient constructions for carbon concrete, that take reference to biomimetic principles in nature [13].

Digitally fabricated fibre reinforcement

In the research field of robotic manufacturing in architecture fibre reinforcement has been used in different material combinations leading to unique processing techniques. The Institute of Computational Design and Construction (ICD) in Stuttgart dispenses with the use of concrete in order to produce large-scale experimental structures in a lightweight design using fibre-reinforced plastic processed by their specially developed "coreless filament winding" method [14]. Further approaches in concrete construction seek to exploit synergetic functionalisation of fibre structures as formwork. By using 3D knitting, [15] was able to create individualized fabric formwork using CNC knitting machines. The resulting webs are held in place by a handcrafted cable net, which itself is stretched over an auxiliary scaffold. Finally, in a multi-step process, sprayed cement is used for stiffening and then concrete is applied in thin layers [16].

However, only few methods are known yet for integrating fibres as reinforcement in digital fabrication with concrete. Among those are, firstly, the “SCRIM” approach [17], where concrete is robotically printed onto a cage composed of regular carbon fibre reinforcement meshes (Figure 3a); secondly, the AeroCrete [18] research of ETH Zürich which uses shotcrete instead of extrusion (Figure 3b), thirdly the manual placement of a pre-cut standard reinforcement mat onto a printed layer of concrete [19]; and fourthly, a similar approach, where individualized 3D textiles are robotically placed and pressed into a fresh layer of printed concrete [20].

(a) (b)

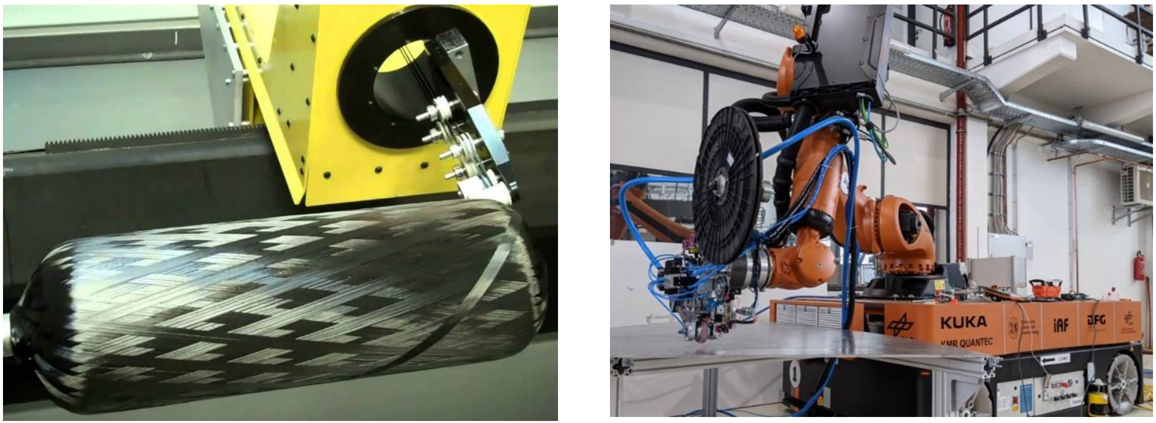
Figure 3: (a) SCRIM - Sparse Concrete Reinforcement in Meshworks[17];
(b) Robotic AeroCrete [18]

Fibre deposit technology in aeronautics and aerospace

In view of the innovation potential, the application of fibre composites is becoming more and more established in many technical products, especially in the aerospace and wind power industries. New automated processing techniques such as Automated Fibre Placement (AFP) or winding processes (Figure 4a) are driving this wider use. The winding and AFP technologies are ideally suited for the production of large-area and/or geometrically complex components. The advantages over manual production are productivity and reproducibility. Especially a combination of AFP and Additive Layer Manufacturing (ALM) with carbon continuous-fibre reinforced plastics (Figure 4b) promises a further quality increase for geometrically complex components [21].

In addition, the pultrusion process is one of the oldest processes for the production of endless fibre-reinforced plastic components and at the same time the oldest continuous process. In the classic pultrusion process, reinforcing fibres are impregnated with a matrix-like epoxy resin in a wet process and cured in a shaping tool [22]. An improvement of this process can be achieved by an in situ monitoring of the degree of cure by Resonant Ultrasonic Spectroscopy (RUS) [23]. Due to this, the degree of cure can be adjusted for the desired purpose.

These technologies used in aeronautics and aerospace were taken into account for the development of suitable reinforcement strategies with continuous fibres in construction. The case studies presented in this paper were influenced by the winding process, by AFP as well as by pultrusion. Other aspects like in situ monitoring are interesting for further process optimisation.



(a) (b)

Figure 4: (a) Fibre Winding on mandrel © TCR Composites (b) Integrated robotic end-effector for the combined process of AFP and ALM © Mohammad Bahar

Preliminary work

Mesh Mould

The Mesh Mould technology, developed at ETH Zurich, is a robotically fabricated construction system, which combines reinforcement and formwork into one integrative structural stay-in-place formwork system [24]. In this approach, a robot fabricates a freeform mesh, which is sufficiently dense to hold fresh concrete and is appropriately strong to act as structural reinforcement after the concrete has cured. According to the classification of Kloft et al. [6] this approach can be regarded as “reinforcement supports concrete” and hence acts as a reference to the frame winding reinforcement strategy described later in this paper. Mesh Mould was developed in two consecutive phases. In the first phase an innovative spatial printing process was developed, which allowed printing in mid-air using thermoplastics [25]. A case study demonstrator, of a mesh filled with concrete is shown in Figure 5. In preliminary studies, these meshes were additionally reinforced with continuous carbon fibre strands, that were hot-glued onto the mesh after printing.

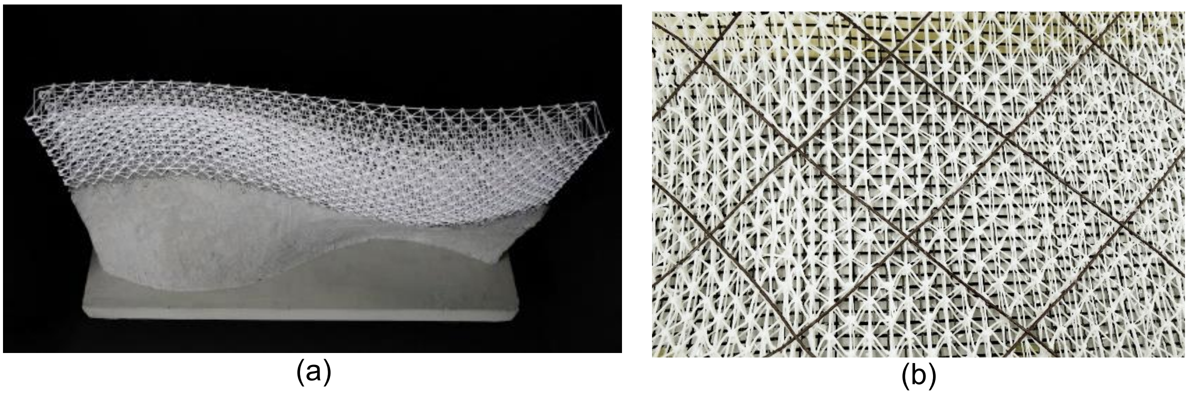

(a) (b)

Figure 5: Mesh Mould: (a) Spatially printed mesh, filled with concrete [25]; (b) Carbon fibre reinforced, spatially printed mesh © Norman Hack

In the second phase of the research project, the material system was changed from printing thermoplastics to bending, cutting and welding of 8 mm steel reinforcement. The geometric freedom and the loadbearing capacity, which are facilitated by this construction system, were recently demonstrated in the DFAB house in Zürich [26]. Here, a mobile construction robot fabricated an undulating, 12 m long steel mesh directly on the building site (Figure 6a).

The subsequent concreting process involved three consecutive steps: firstly, the mesh was filled with a commercially available fine grain concrete by pumping the material laterally into the mesh (Figure 6b); secondly, a concrete cover was applied by using a conventional shotcrete process; and finally, the surface was manually trowelled to create a smooth concrete surface of high visual quality.

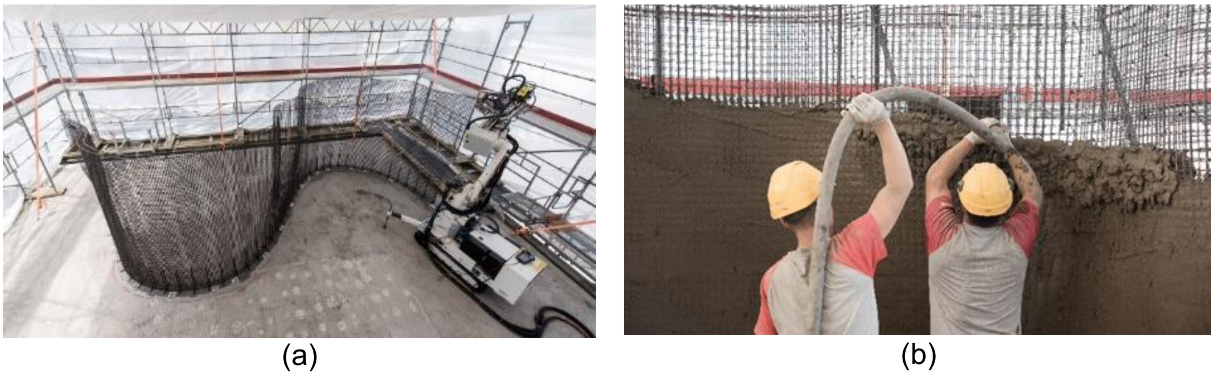
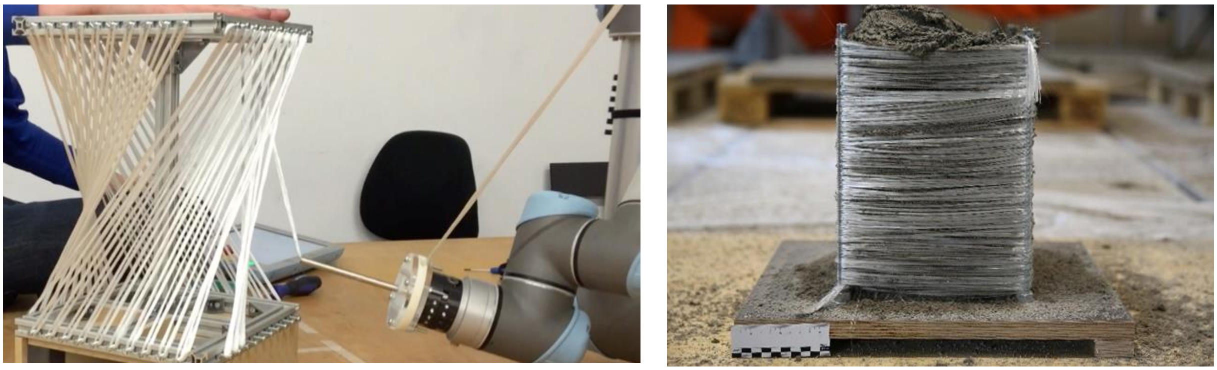

(a) (b)

Figure 6: Mesh Mould: (a) In situ fabrication of a steel mesh that acts as reinforcement and formwork; (b) Filling of the mesh by manually "printing" on and into the mesh. [24]

Fibre winding as concrete reinforcement at ITE

Previously, several methods for robotic filament processing have been developed at ITE. These techniques include for example filament winding (Figure 7a) or 3D knitting and fibre deposition. Besides developing the design algorithms and robotic control routines, additionally different robotic end effectors for an optimal fibre winding and curing process were developed. Here, a successful strategy was to soak the fibre rovings in a resin bath shortly before the filament was wound around a structure. After curing, this fibre impregnation does not only provide more structural stability, but also significantly improves the load transfer and the bonding behaviour of the textile and the concrete matrix. Several of these methods have been tested in combination with automated concrete deposition techniques, as for example Shotcrete 3D Printing (Figure 7b).



(a) (b)

Figure 7: Robotically fabricated textile reinforcement at ITE: (a) Robotic fibre winding at the ITE using custom developed end effectors, 2015; (b) Filling of a robotically wound textile reinforcement cage. © ITE

Methodology

In order to systematically explore the potentials of fibre winding for the above mentioned concrete 3D printing technologies, a matrix was developed that allows to relate part type and geometry, fibre winding technique and AM method to each other (Figure 8). In future, the schematic can be extended by further fibre processing and integration techniques. Currently, the matrix is based on fibre winding technique only, as this constitutive process is fast and provides great flexibility, which becomes evident through the specific strategies described below.

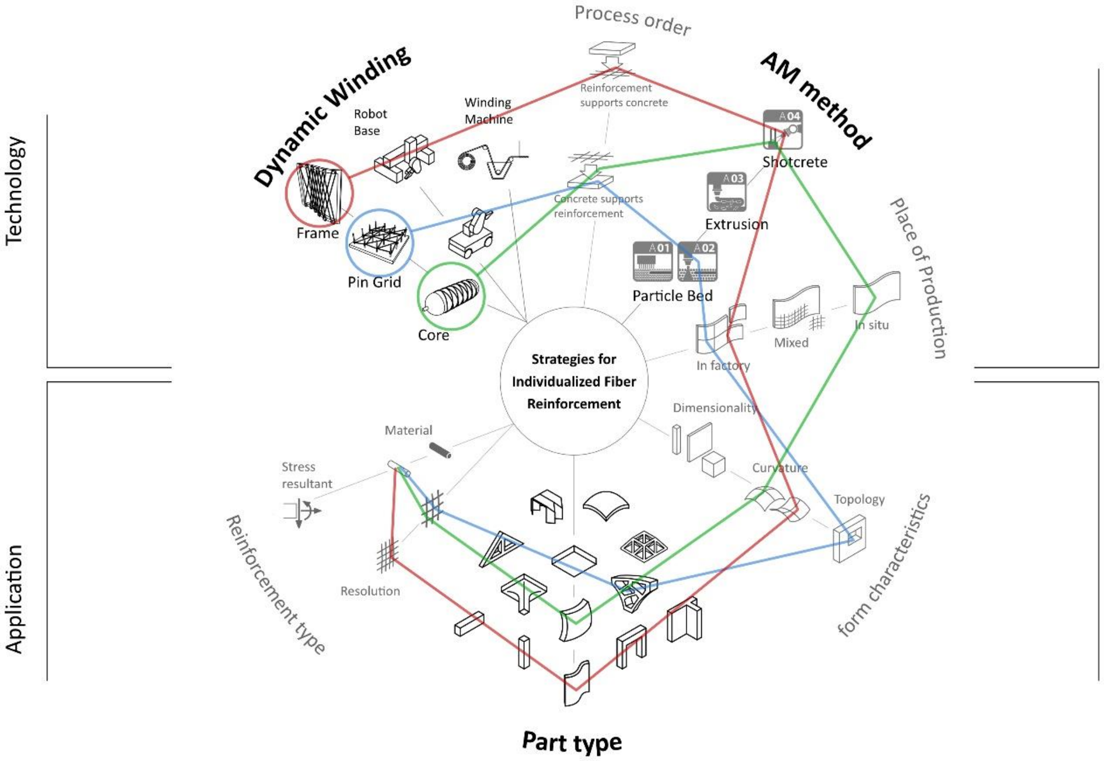


Figure 8: Diagram allowing to trace a path in order to relate part type and geometry, fibre winding technique and AM method.

In the following, three potential parts are exemplified, two for the Shotcrete 3D Printing technology, and one for the Particle Bed 3D Printing technology. The technological boundary conditions and constructive application possibilities for Particle Bed 3D Printing can be traced with the blue path, while those of Shotcrete 3D Printing are marked with a red and a green path. Although variations and other branches are possible, only three paths will be presented and explained in this paper.

The red path shows that with the Shotcrete 3D Printing technique in combination with frame winding, predominantly slender vertical building can be produced. In this process a steel frame with pins is used to wind pre-impregnated fibres to form a surface that is then covered using shotcrete. By removing the frame after curing, a discrete component with precise edges is created, promoting prefabrication. The strength of this method lies in the formation of thin elements with single or ruled curvatures. Using advanced winding techniques, double curvatures are also accessible. For a successful application of concrete, the reinforcement mesh needs to be sufficiently dense to prevent the concrete from passing through the mesh. Due to the straight fibre spans, a curved force flow in structural members cannot be mapped precisely, but the individual winding still allows density and orientation to be varied locally.

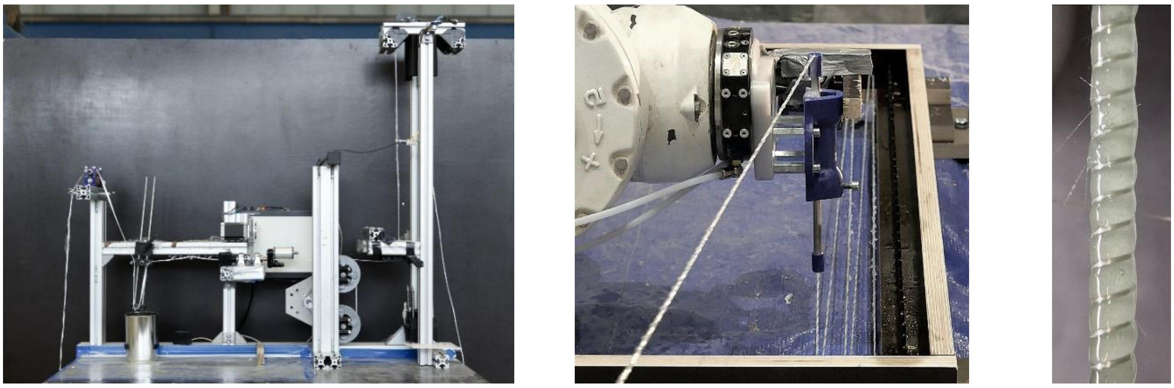
Following the blue path, the diagram shows that Pin Grid Winding is particularly suited for Particle Bed 3D Printing. It originates from the idea of a two-dimensional array of pins, which allows to produce individualized flat fibre structures by robotically winding around selected pins, so that arbitrary outlines and infill patterns can be approximated. Resulting inlays can be placed onto the particle bed in between two consecutive printed layers. Design possibilities are not restricted by the integration of fibre reinforcement, but also not enhanced like in the frame winding example. The placement of inlays seeks to adapt to the printing process with minimal interference according to the principle of “concrete supports reinforcement” [6].

So far, Particle Bed 3D Printing is clearly restricted to off-site production and most suitable for volumetric parts of limited size and high topological complexity, for example shape optimized connecting nodes of space frames. Although the described reinforcement strategy is limited to horizontal orientation, the pin grid allows for approximately arbitrary in-plane orientation and distribution of the fibres. Not only different slice contours, but also force-flow trajectories can be mapped.

Instead of forming the reinforcement in advance, fibres can also be applied after printing the core of an element. This approach, referred to as Core Winding Reinforcement (CWR), is depicted on the green path, and takes advantage of the generative nature of 3D printing by using the 3D printed concrete core as a support to fix fibre strands upon it in any orientation. As CWR fully adapts to the versatility of concrete printing, it is applicable for on-site production and does not impose inherent geometric restrictions. Therefore, this method is especially suited for spatially complex load bearing walls with irregular stress distribution.

Case studies

While in this research project other possible pathways are also being investigated, the above methods have already been studied experimentally. Three exemplary combinations are described below: firstly, Frame Winding and Shotcrete 3D Printing, secondly, Pin Grid Winding and Particle Bed 3D Printing, and thirdly, Shotcrete 3D Printing and CWR. For all tests, a custom designed Dynamic Fibre Winding Machine was used to ensure a reinforcement strand with a good mechanical bond between concrete and fibre. This machine is shown in Figure 9a and described in more detail in [27].

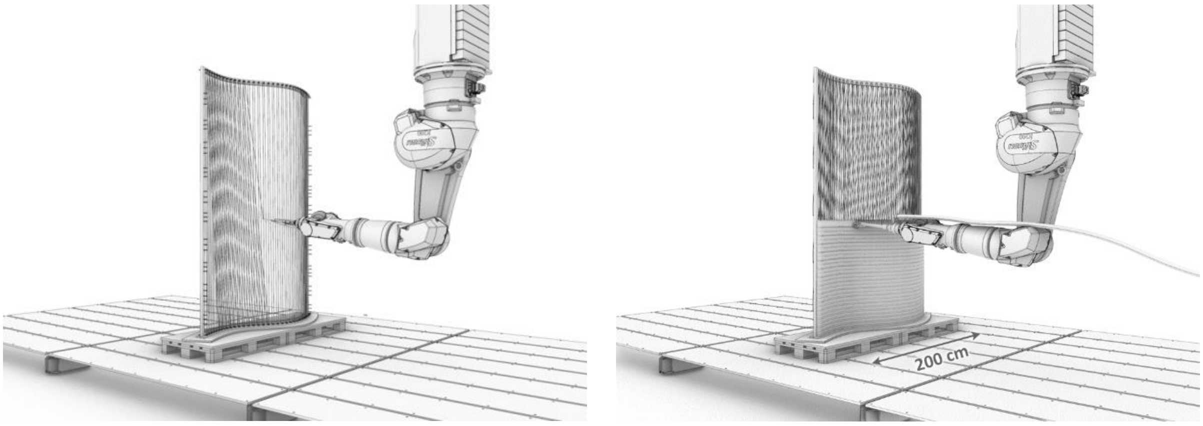


(a) (b) (c)

Figure 9: On demand production of reinforcement from glass fibre roving: (a) Dynamic Winding Machine; (b) Robotic winding end-effector; (c) Resin impregnated roving with helix profile

Frame winding and Shotcrete 3D Printing

Shotcrete 3D Printing is usually carried out by spraying concrete in horizontal layers in order to build up predominantly vertical concrete elements. However, due to the width of the shotcrete jet, elements with a width of at least 15 cm can be created [28]. With the frame winding technique, the realization of thin-walled elements was tested [27]. Here, the reinforcement structure serves as a support for the concreting process and therefore defines the resulting geometry (Figure 10).



(a) (b)

Figure 10: Overall fabrication concept: (a) A robot winds a reinforcement mesh around an individualized frame; (b) concrete is applied to the mesh using the Shotcrete 3D Printing process. [27]

Firstly, rectangular frames of 1 m edge length were used for robotically winding a regular mesh with pre-treated glass fibre roving (Figure 11a). The frames remained in place during shotcreting in order to absorb the weight of the concrete (Figure 11b). In this first attempt, the spraying nozzle was aligned orthogonally to the mesh at a distance of 30 cm. The experiments resulted in a flat reinforced concrete panel shown in Figure 11c, which gave a basic proof of concept [27]. However, unresolved issues like the loss of concrete passing through the mesh without adhesion and uncovered fibres on the rear side (Figure 11c) demand for further improvement of the process. Furthermore, other paths through the schematic of Figure 8 could be tested and compared, for example replacing the concreting method by extrusion.

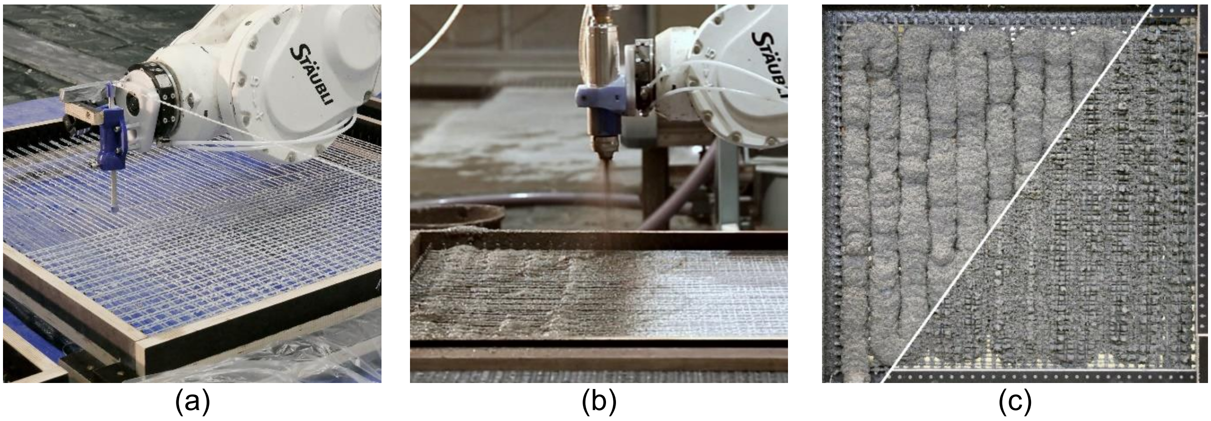

(a) (b) (c)

Figure 11: Automated manufacturing of fibre reinforced concrete element (a) robotic winding process; (b) robotic shotcreting process; (c) first results of robotically shotcreting a winded reinforcement mesh (front and rear). [27]

Pin Grid Winding with Large Particle 3D Concrete Printing

In the novel approach of Large Particle 3D Concrete Printing (LP3DCP) the integration of fibre reinforcement inlays has been tested [29]. LP3DCP is based on the concept of Selective Paste Intrusion (SPI) [30], but instead of using aggregates below 5 mm of size, here large aggregates with up to 32 mm are used. The large aggregates, that consist of recycled construction waste, are selectively bound using the Shotcrete 3D Printing method (see Figure 12a). The use of coarse recycled aggregates does not only reduce the CO_2 footprint, but can also increase the compressive strength compared to shotcrete only. [29]


(a) (b)

Figure 12: Large Particle 3D Concrete Printing LP3DCP: (a) Process schematic with indicated reinforcement inlay; (b) final demonstrator of one cubic meter of size. [29]

In order to improve tensile load bearing capacities, two layers of prefabricated fibre-winded reinforcement were integrated at structurally relevant positions – namely in layer 12 and 26, where all contour branches meet in the sections centre (compare Figure 12a). The above-mentioned Pin Grid Winding approach was applied in a simplified manner. From the respective slice contours a planar truss layout was derived, whose node positions were used to robotically drill holes in a wooden base plate. With the help of pins an individualized grid for fibre winding was generated.

The Dynamic Winding Machine, equipped with a 2400 tex glass roving and L-285 epoxy resin for impregnation, was used to provide a helix surface profile and prepare the fibres for subsequent winding onto the grid (Figure 13a). After curing and removing the pins, the reinforcement inlays were positioned and placed manually onto the fresh concrete after printing the respective layers (Figure 13b). By printing the next layer, the reinforcement was embedded into the structure. The manual placement of pre-fabricated fibre inlays is rapid and does not cause significant delay in the fabrication process, as it would be the case when winding the inlays in situ. Even with manual placement, a satisfactory alignment between shotcrete contour and the fibre inlay could be achieved, as both processes are based on digital fabrication.

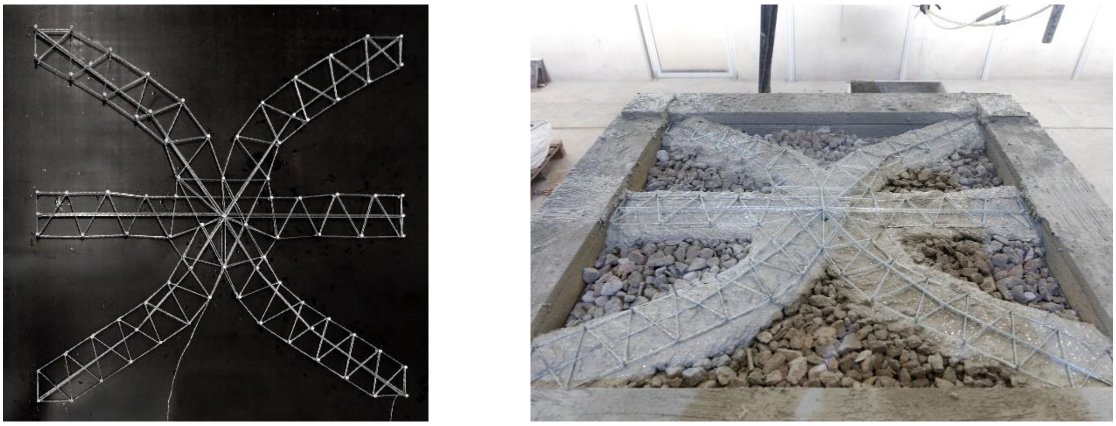

(a) (b)

Figure 13: Integration of fibre reinforcement in LP3DCP: (a) prefabricated fibre inlay on pin grid [29]; (b) placement of inlay within the printing process.

Shotcrete 3D Printing and Core Winding Reinforcement (CWR)

For CWR, the third reinforcement strategy described here, a robotic end-effector was developed (Figure 14a), which extends the fibre deposition tool by a modified stapling device, so that the reinforcement strand can be fixed to a freshly printed concrete surface at an arbitrary location and orientation. A moderately double-curved wall of 120 cm height was structurally analysed for an exemplary load case in order to retrieve a two-dimensional stress distribution (Figure 14b). Based on this, a polyline pathway along the wall's faces was derived for reinforcement deposition. The same digital model was used to define concrete printing paths, which allowed for the synchronisation of all process steps.

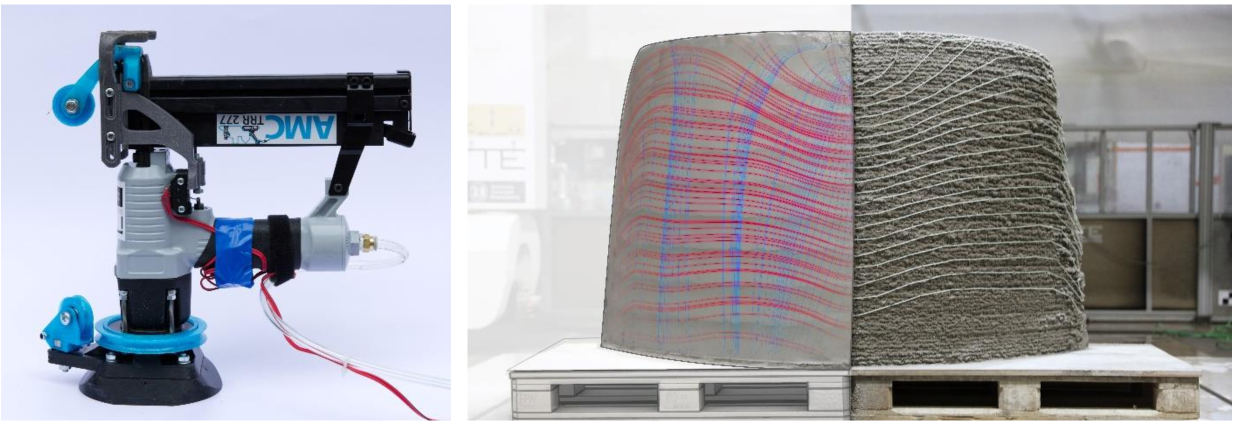

(a) (b)

Figure 14: (a) Robotic fibre deposition end-effector with incorporated staple device; (b) demonstrator wall with reinforcement layout (right) derived from structural analysis (left)

After printing a 12 cm thick core by means of SC3DP (Figure 15a), the robotic end-effector was changed to the CWR-tool and equipped with 40 mm long staples and the pre-treated 9600 tex glass fibre roving coming from the Dynamic Winding Machine. As proof of concept, the automated fibre deposition was only performed on one side of the wall (Figure 15b). In order to establish a proper compound, half of the front was covered by a layer of concrete in a second vertical shotcreting process (Figure 15c). Lastly, the wall was trowelled robotically to achieve final surface quality (Figure 15d).

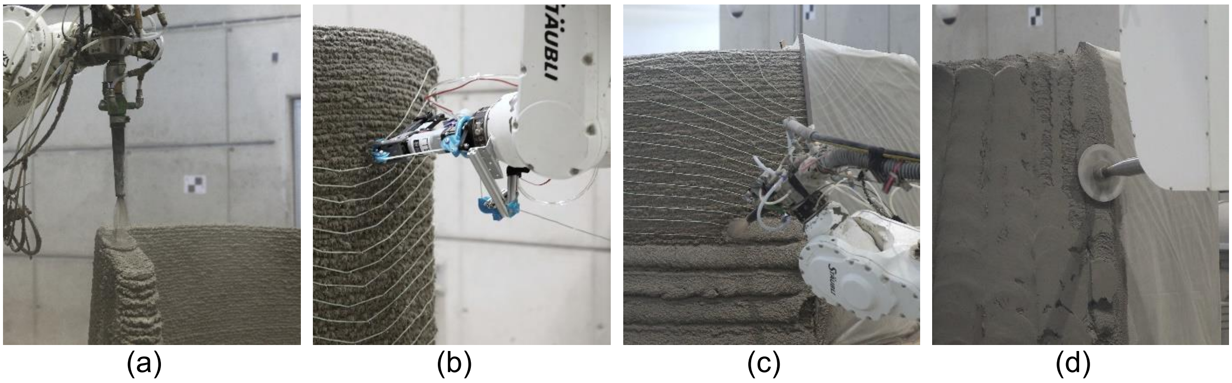

(a) (b) (c) (d)

Figure 15: Fabrication steps: (a) shotcrete printing; (b) fibre application; (c) cover printing; (d) surface finish

Despite its early development stage all process steps of this technique were performed successfully in a fully automated manner. Thus, it is worthwhile to investigate the performance of CWR more in detail regarding for example the grip of staples in fresh concrete and the compound quality between fibres and concrete.

Conclusion und outlook

In this paper, the importance of integrating reinforcement into digital fabrication with concrete was described. In particular, continuous fibres have been identified as a promising alternative to conventional steel reinforcement - mostly due to their corrosion resistance and their flexibility in processing. A methodology which helps to detect yet overlooked process combinations and which allows to compare and assess them from varied perspectives was developed. Three approaches were described in particular, providing reinforcement strategies for Large Particle 3D Concrete Printing and for Shotcrete 3D Printing. Finally, their feasibility has been proven by case studies.

These initial investigations lead to differentiated findings: due to the different functions, most importantly the compression resistance of the concrete and the tensile strength of the fibres, each building component requires a unique reinforcement layout. Moreover, it affects the form of the part itself and thus the manufacturing process. Choosing an appropriate reinforcement strategy is not a deterministic downstream process, but the most effectiveness can be achieved by involving even the design of the respective parts and their physical environment. However, by considering only the application and the ideal representation, one ends up with unproducible designs. Both the technical possibilities and the practical requirements need to be considered in a holistic manner when developing a manufacturing framework for additively concreted fibre reinforced elements. In accordance with this, the scheme in Figure 8 can be utilized as a tool to classify and assess different possible approaches.

The presented case studies are still at their early stages. In the future they will be investigated upon their geometric potential, but also upon their structural performance. Moreover, several other possible paths leading through the diagram will be investigated.

Data availability statement

There is no relevant additional data to this article beyond the presented content.

Author contributions

Stefan Gantner: Conceptualization, Investigation, Methodology, Software, Visualization, Writing – original draft, review & editing. Tom-Niklas Rothe: Conceptualization, Writing – review & editing. Christian Hühne: Conceptualization, Funding acquisition, Supervision, Writing – review & editing. Phillipp Rennen: Investigation; Norman Hack: Conceptualization, Funding acquisition, Methodology, Supervision, Visualization, Writing – original draft, review & editing.

Competing interests

The authors declare no competing interests. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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