buildings

Article

Robot-Assisted Manufacturing Technology for 3D Non-Metallic Reinforcement Structures in the Construction Applications

Danny Friese [1,*], Lars Hahn [1], Hung Le Xuan [1], Johannes Mersch [1], Tobias Neef [2], Viktor Mechtcherine [2] and Chokri Cherif [1]

[1] Institute of Textile Machinery and High-Performance Materials Technology (ITM), 01069 Dresden, Germany; lars.hahn@tu-dresden.de (L.H.); hung.le_xuan@tu-dresden.de (H.L.X.); johannes.mersch@tu-dresden.de (J.M.); chokri.cherif@tu-dresden.de (C.C.)

[2] Institute of Construction Materials, 01187 Dresden, Germany; tobias.neef@tu-dresden.de (T.N.); viktor.mechtcherine@tu-dresden.de (V.M.)

* Correspondence: danny.friese@tu-dresden.de; Tel.: +49-351 463-34869

Abstract: Of all industrial sectors, the construction industry accounts for about 37% of carbon dioxide (CO_2) emissions. This encompasses the complete life cycle of buildings, from the construction phase to service life to component disposal. The main source of emissions of climate-damaging greenhouse gases such as CO_2, with a share of 9% of global emissions, is the production of ordinary cement as the main binder of concrete. The use of innovative approaches such as impregnated carbon yarns as non-corrosive reinforcement embedded in concrete has the potential to dramatically reduce the amount of concrete required in construction, since no excessive concrete cover is needed to protect against corrosion, as is the case with steel reinforcement. At the same time, architectural design options are expanded via this approach. This is achieved above all using novel robotic manufacturing technologies to enable no-cut direct fiber placement. This innovative technological approach to fabricating 2D and 3D biologically inspired textiles, including non-metallic structures for textile-reinforced concrete (TRC) components, will promote an automatable construction method that reduces greenhouse gas emissions. Furthermore, the impregnated yarn which is fabricated enables the production of load-adapted and gradual non-metallic reinforcement components. Novel and improved design strategies with innovative reinforcement patterns allow the full mechanical potential of TRC to be realized. The development of a robotic fabrication technology has gone beyond the state of the art to implement spatially branched, biologically inspired 3D non-metallic reinforcement structures. A combined robotic fabrication technology, based on the developed flexible 3D yarn-guiding and impregnation module and a 3D yarn fixation module, is required to implement this sophisticated approach to fabricate freely formed 3D non-metallic reinforcement structures. This paper presents an overview of the development process of the innovative technological concept.

Keywords: non-metallic reinforcement; robot-assisted yarn deposition; coreless robotic winding; automated path planning; textile-reinforced concrete; carbon fiber heavy tows

check for updates

Citation: Friese, D.; Hahn, L.; Le Xuan, H.; Mersch, J.; Neef, T.; Mechtcherine, V.; Cherif, C. Robot-Assisted Manufacturing Technology for 3D Non-Metallic Reinforcement Structures in the Construction Applications. *Buildings* **2023**, *13*, 2748. https://doi.org/10.3390/buildings13112748

Academic Editors: Ana Luísa Velosa, Alexander Schumann and Frank Schladitz

Received: 25 August 2023
Revised: 26 September 2023
Accepted: 27 October 2023
Published: 31 October 2023

1. Introduction

From cradle to grave, buildings produce almost 37% of global CO_2 emissions [1]. The main driver of emissions in the construction sector in the European Union is the production of ordinary cement [2]. Approximately 9% of global carbon dioxide (CO_2) emissions are attributable to the construction sector during the construction phase of structures alone [3]. As the growing impacts of climate change are experienced around the globe, the evidence that greenhouse gas emissions must fall is clear. The annual Emissions Gap Report of the United Nations Environment Programme concluded in 2022 that an urgent holistic transformation involving all major contributors to greenhouse gas production, such as the electricity supply, transport, and buildings sectors, is imperative for the international community not to fall far short of the goals of the Paris climate agreements [4]. This has resulted in a call to the construction industry for "completely rethought concepts for the design, modeling, construction, manufacture and use of sustainable, resource-efficient building elements made of mineral building materials" [5]. The substitution of conventional steel reinforcement with carbon fiber-based structures, which show superior mechanical performance under tensile stress and are chemically inert, is necessary to address climate change [6]. Concrete consumption can be scaled down because with textile-reinforced concrete components, there is no need for a corrosion-protective concrete overlay having no structurally mechanical benefit. In addition, it can be assumed that the service life of a structural component built with textile or carbon concrete will significantly exceed that of traditional steel-reinforced component [7]. Consequently, the extension of the service life of structural components also contributes to the avoidance of new greenhouse gases, such as CO_2. The reduction in resource consumption and greenhouse gas emissions can be seen in a pedestrian and cyclist bridge built from textile-reinforced concrete (TRC) in Albstadt-Ebingen (Germany) in 2015, where the amount of concrete required was reduced by around 60% and the resulting CO_2-eq. emissions were decreased by 26% compared to functionally identical steel-reinforced constructions [8]. In order to exploit the full performance potential of TRC and thus minimize concrete consumption, the traditional design principles of reinforced concrete construction must be abandoned; in addition, material substitution and intelligent design strategies, such as implementing biologically inspired load transfer principles, must be developed [9]. Robot-assisted manufacturing technology is able to meet this urgent demand for a production technology realizing three-dimensional (3D) reinforcement structures with a complex, hierarchical, and inner-branched textile topology in order to faithfully reproduce load transfer mechanisms from nature, such as in peltate leaves [10,11]. Industrial robots are designed to perform a wide range of tasks in a variety of settings. Some common tasks that industrial robots are used for include material handling, assembly, inspection and quality control, packaging and palletizing, welding and cutting, painting and coating, and machine tending. Figure 1 shows the schematic process flow of the developed technological robotic manufacturing process for spatially branched 3D non-metallic reinforcements imitating biological plant structures.

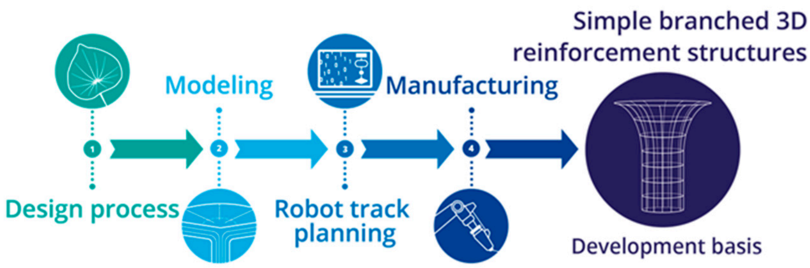

Figure 1. Process flow for robot-assisted manufacturing of non-metallic reinforcement topologies.

New materials combined with novel manufacturing processes can enable new designs and types of construction [12,13]. The ability to produce geometrically sophisticated, branched, and complex topologies attests to the potential of textile-reinforced concrete [5]. In the case of three-dimensional (and inner-branched) non-metallic (textile) reinforcements, conventional textile manufacturing processes cannot offer a flexibly adaptable machine technology in order to produce these textile structures without time-consuming machine and process modifications as well as rework and significant material waste [14,15]. As traditional textile reinforcement manufacturing technologies (e.g., multiaxial warp knitting), which produce grid-like reinforcement mats in a highly productive manner, reach their geometric manufacturing limits, novel machine concepts involving six-axis industrial robots also need to be brought to life for the implementation of novel design principles in the construction industry for component manufacturing (e.g., reinforcement production or concreting) [15]. Currently, different robot-assisted yarn deposition technologies are being developed for the production of textile reinforcement structures for the construction industry or fiber reinforced plastics for the composites market. Six-axis jointed-arm robots have been established in the industrial environment [16]. They have six degrees of freedom, which enables the robot to make translational (X, Y, Z) and rotational (A, B, C) movements. Thus, the robot can work in three dimensions and move its tools to any position within its reach, which allows for the flexible and requirement-based generation of free-form non-metallic (textile) reinforcement structures. Six-axis robots are commonly used in the automotive, electronics, and aerospace industries due to their high precision, productivity, repeatability, quality increase, and reduction of labor costs. However, existing robot-assisted technologies differ in their operating principles. There are robotic manufacturing processes that are oriented toward the requirements of the construction industry (focusing on the reinforcement of concrete components) during the development phase and those that emerged from other industrial sectors (e.g., architecture or automotive engineering).

A. Robot-assisted yarn deposition technologies for non-metallic reinforcement structures in the construction industry

To pave the way for novel resource-saving and cost-efficient textile reinforcement structures, researchers have already developed distinctive robot-based machine technologies. Figure 2 shows the two basic principles of robotic yarn deposition technologies, where a single robot moves either the tool or the workpiece carrier.

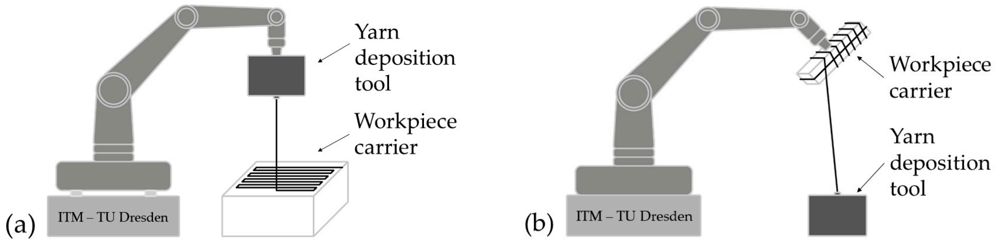

Figure 2. Robot-assisted yarn deposition technologies for non-metallic reinforcement production in the construction industry: (**a**) Principle 1—Robot manipulates fiber placement tool [17] and (**b**) Principle 2—Robot manipulates workpiece carrier [18].

All these robot-based manufacturing technologies comprise several functional modules, namely the manipulating articulated robot, the yarn deposition tool—which performs the functions of yarn storage, guiding, and impregnation—and the workpiece carrier, used to temporarily fix the reinforcement structure. Principle 1 in Figure 2a shows the technological design by von Zuben et al., capable of fabricating planar and grid-like reinforcements using freshly impregnated carbon fiber heavy tows (CFHT) [17]. Hence, yarn impregnation is carried out only immediately before the yarn is deposited. The operation consists of the robot manipulating the yarn deposition tool, while the workpiece carrier is fixed. Von Zuben et al. focus on processing conventional epoxy resin as an impregnating agent [17]. Planar, two-dimensional (2D) structures with cut-free geometries can already be produced based on this manufacturing principle. The robotic manufacturing process of Rittner et al. and Knoch is almost identical in design compared to principle 1 and also includes an articulated robot that places the yarn directly onto a workpiece by means of a yarn deposition tool—as shown in Figure 2a [19,20].

The technological approach, shown in Figure 2b, involves the winding technique by means of a winding core with the workpiece carrier manipulated by an articulated robot and the yarn tool stationary on the ground [18]. The yarn tool can be an impregnation bath with a yarn eye for precise deposition. Alternatively, pre-impregnated CFHTs can be processed, which enables the production of extremely light reinforcement structures with gradual fiber distribution, such as reinforcement cages for a balcony [18]. Michel et al. use mineral impregnation in the carbon fibers, which has a high bond to the concrete due to material homogeneity and can be flexibly processed within a process window of 4 h after impregnation [21].

Another robot-assisted manufacturing technologies for the production of non-metallic reinforcement for the additive manufacturing using shortcrete 3D printing has been developed by Hack et al. [22], whose robot-based manufacturing process for non-metallic concrete reinforcement was developed to increase shape freedom and efficiency in concrete components in construction applications [23].

B. Robot-assisted yarn deposition technologies for fiber-reinforced plastic structures in other economic sectors

Other novel production technologies being developed in parallel are the 3D coreless filament winding technique with two collaborating articulated robots by Minsch et al. (principle 3), shown in Figure 3, and the collaboratively working multi-robot system by Knippers et al. (principle 4), shown in Figure 4. Both enable the production of 3D non-metallic reinforcement topologies [24,25]. The principle 3 technology fabricates truss-like structures in a translative cross-winding process. The yarn impregnation does not take place within the robot process. Since the impregnation tool is positioned stationarily on the floor, and thus the yarn is impregnated outside the robot handling process, the robot simply manipulates the freely fed yarn using a yarn guide tube. This technology was initially derived from the challenge of providing lightweight operating materials in energy-reduced manufacturing processes for the automotive industry.

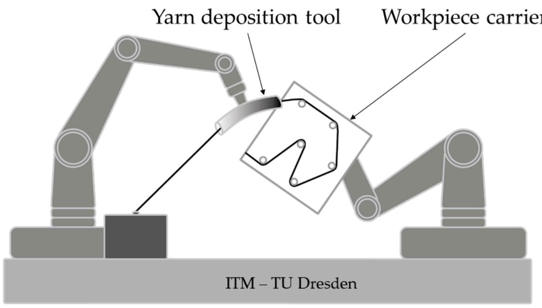

Figure 3. Principle 3—Robot-assisted yarn deposition technology by Minsch et al., initially developed for the production of lightweight operating resources in automotive mass production [24].

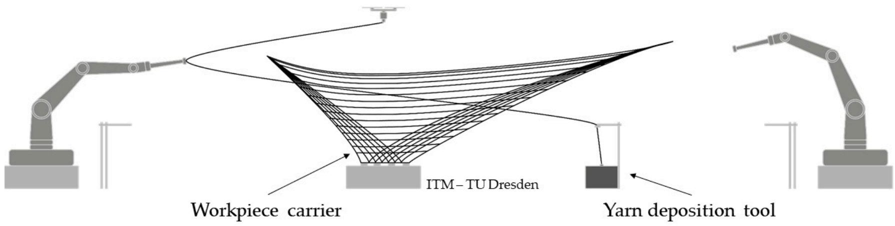

Figure 4. Principle 4—Collaborative robotized production system for large-scale shell elements [25].

The robot system of Knippers et al. in principle 4 uses collaborating robots consisting of articulated robots, drones, and optionally also climbing robots [25,26]. As with principle 1, the workpiece carrier is also fixed, and the individual robots manipulate the pre-impregnated yarn. The yarn impregnation tool is also fixed. In another application, where the textile topology is more complex or the deposition process requires additional degrees of freedom, a rotatable workpiece carrier is used to provide additional uniaxial motion [27,28].

In conclusion, it can be summarized that significant developments already exist in the field of robot-assisted yarn deposition technologies, but that only shell-like or truss-like three-dimensional textile structures can be generated according to the current state of research. In order to establish new construction strategies in the building industry, a robotic manufacturing technology is required which, due to its highly flexible, tool-independent process-technological system concept, will enable the production of hierarchically structured and inner-branched 3D non-metallic reinforcement structures. This paper aims to address these challenges and shows the basic procedure of the development process focusing on hardware modules of the robotic manufacturing technology. In this context, the building requirements as well as the bionic load transfer principles to be implemented (e.g., by Wunnenberg and Sacher et al.) are taken into account [10,11]. Furthermore, the modelling of the target reinforcement structure and the simulation of the yarn deposition process with its travel paths is even necessary for the manufacturing technology. This structure-related generation of the robot's movement paths, in particular the machine control datasets, takes place in advance of the robot-assisted production. The modelling and simulation of the robot motion is a sub-discipline of the overall development process of this manufacturing technology.

Overall, the research work is divided into software and hardware engineering development. The main focus of this paper is to present the development of the hardware components. The software part is only briefly considered below.

2. Materials and Methods

As part of the process engineering development of robot-assisted yarn placement technology, existing plant technology has been used in addition to conventional consumables such as fiber and impregnation material, which are mentioned individually afterward.

2.1. Materials

Various hardware and software components are required for the development process. Essential hardware components of the production technology are the robot system, consisting of the articulated robot with six axes, the linear unit, the surrounding safety cell, and the control and regulation technology as well as the yarn deposition rack (workpiece carrier) and the yarn impregnation unit handled by the robot (see Figure 5). In addition, different fiber materials and impregnating agents are used in the course of investigations into the influence of materials and processes. Several materials are used in the robotic yarn placement technology and are elucidated below.

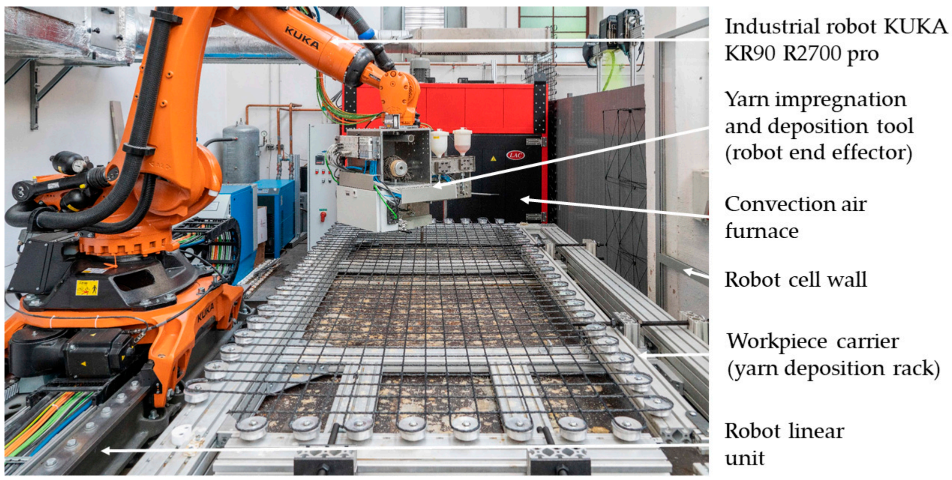

Figure 5. Robot-assisted yarn deposition technology from ITM TU Dresden for the production of two-dimensional textile reinforcement structures, as schematically shown in Figure 2a according to von Zuben et al. [17].

Fiber materials: Different fiber materials have been established for usage as concrete reinforcement, including carbon fibers, glass fibers, and aramid fibers [29]. The class of technical fibers for concrete reinforcement application is characterized by very high stiffness and tensile strength as well as an outstanding degradation resistance when exposed to an alkaline environment. Quasi-endless fibers, known as filaments, are technical fibers with diameters of a few micrometers. CFHTs are bunches with more than 48,000 single fibers (3200 tex). In principle, a wide variety of fiber materials can be processed using this manufacturing method, but not all fiber materials have the potential to reliably reinforce the concrete matrix under tensile stresses over many decades and without exhibiting a decrease in strength in the surrounding alkaline environment. During the development phase, carbon fibers from the company Teijin Limited were used. Table 1 shows the characteristic properties of the fibers.

Table 1. Properties of used technical fiber materials [30].

Fiber Material	Filament Diameter in µm	Density in g/cm^3	Tensile Strength in N/mm^2	Breaking Strain in %	Young's Modulus in $10^3 \times$ N/mm^2
Carbon	7	1.77	4300	1.7	250

Impregnation materials: Another crucial component is the impregnation agent, which has the function of increasing the inner and outer bond, as well as the durability of the reinforcing fiber material, and protecting fiber from external factors during transportation and processing [14]. The technical process of impregnation is defined as a homogeneous soaking of liquid impregnation material into the roving (bundle of parallel continuous fibers) to achieve an optimal load transfer from the outer filaments, which are in contact with the concrete, to the inner filaments [31]. There are two main chemical categories in the field of impregnation materials for textile reinforcement structures for concrete applications: polymer-based and mineral-based agents [29]. In terms of processing properties, the individual impregnating agents differ in their crosslinking or curing times (processing time), viscosities at processing temperature, thixotropic behavior, and type of material mixture (homogeneous/heterogeneous) influencing the processing principle [29]. Various impregnating agents for construction applications are being investigated as part of the manufacturing technology development process, such as a two-component epoxy resin or a one-component aqueous dispersion agent based on acrylate for convenient processing in line with health and safety regulations (see Table 2).

Table 2. Properties of used impregnation materials [21,29,32].

Impregnation Category	Impregnation Subcategory	Impregnation Material	Processing Temperature in °C
Impregnation based on polymers	Thermosetting matrix	Epoxy resin	18–180
	Aqueous dispersion	Based on acrylate Based on polystyrene Based on styrene-butadiene Based on polyurethane	150 150–160 130–160 120
Impregnation based on minerals	Cement-based matrix	Micro-cement and micro-silica suspension	>0
	Geopolymer-based matrix	Metakaolin and potassium silicate solution	60–75

Yarn impregnation tool: The functional module for yarn impregnation and deposition merges fibers and impregnation agent. It is even used to control the yarn tension during the deposition process and to precisely place the yarn on the workpiece carrier. The function of the yarn placement tool, furthermore, consists of storing the individual media such as fiber material and impregnating agent component(s), controlling the yarn tension, and ensuring low-damage fiber processing (see Figure 5).

Workpiece carrier: The workpiece carrier allows for the precise and stable fixation/placement of the impregnated yarn until the textile structure reaches green strength and can be handled without deforming (see Figure 5). The carrier ensures the demoldability of the consolidated non-metallic reinforcement structure (see Figure 5).

Robots: Industrial robots are able to operate with high precision, and their highly flexible movement capability enables them to manipulate yarn-guiding tools to deposit the yarn on a fixation rack or simply in space. In the present research work, a six-axis articulated robot with the model designation KR 90 R2700 pro is combined with the linear unit KL 4000 from the same manufacturer, KUKA AG (Augsburg, Germany) [33,34]. This robot model has a maximum load capacity of 90 kg and a working range of approximately 2700 mm. The linear working axis of the linear unit extends the effective working area by 4000 mm (Figure 5). The robot system shown in Figure 2a served as the basis for the development described.

2.2. Methods

Accompanying analyses of cause–effect relationships are conducted as part of the development process, using systematic procedures to gain insights. Furthermore, algorithm-based methods are used for the automated generation of the robot movement paths, which are further developed and refined during the ongoing development processes. In the context of the ongoing development of the robotic yarn placement technology, the following methods are used.

Control technologies: Point-to-point control is used to control the robot's movements. A pneumatic piston rod cylinder regulates the yarn tension by continuously adjusting around the center position. The control of the target tension value is set via a finely adjustable rotary pressure valve.

Simulation and modeling technologies: These methodologies are used to predict the robot's movements and interactions with the yarn, to optimize the yarn placement process, and for design calculations. Simulation-based predictions with validated models simplify and accelerate the workflow by replacing extensive experimental studies. Structural components (e.g., supporting rods and perforated plate) of the yarn storage rack have been analyzed with regard to deformations and tensions by means of the simulation software Ansys 2021R1 with the software component Mechanical implicit. The generation of the robot paths for the test specimen production was carried out using the software Matlab 2022b (The MathWorks, Inc., Natick, MA, USA).

Methodical approach in the constructive development process: The technological and design development process is based on guideline VDI 2221 of the Association of German Engineers (Verein Deutscher Ingenieure—VDI) [35]. VDI 2221 specifies recognized rules of technology for the development of technical products and systems. The design methodology uses a specific procedure to guide development toward the best possible solution for a design task with respect to the set requirements. The method is divided into the following steps: analysis of the task or problem, creation of the concept, design and constructive elaboration.

The first step (Phase I) of the individual system development is the clarification of the task, whereby the requirements for the system are defined (see Figure 6). The subsequent development steps, such as the concept (Phase II), design (Phase III) and elaboration (Phase IV) phases, are based on these requirements. In particular, the result in the individual phases would then be:

- Phase I: Requirements list
- Phase II: Functional structures & principle solutions
- Phase III: Modular structures & preliminary designs (variants of possible solution combinations)
- Phase IV: Overall design based on the preferred solution

The underlying material characterization served as a basis for the technology development and is described with it methods in the paper of Friese et al. (2022) [9] and Friese et al. (2023) [36]—for example with regard to the occurring filament damage due to the yarn-guiding process.

The development path presented below follows the design methodology according to VDI 2221 in terms of systematic solution development.

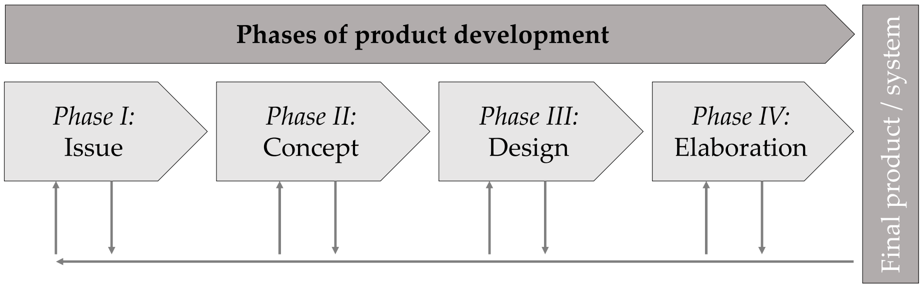

Figure 6. Development methodology in accordance to VDI 2221 [35].

3. Development Process

At the beginning of the development process of the robot-assisted manufacturing technology for complex, hierarchical, and highly branched textile reinforcement structures was the analysis stage. Over the course of this initial development phase, a functional pattern was defined in coordination with the building requirements for the target structures and with the inclusion of biological load transfer mechanisms.

Requirements on the part of the construction industry for the manufacturing process are a continuous, preferably stretched fiber course and demoldability of foreign bodies that are different from the non-metallic reinforcement structure, e.g., deposit base or process-related support elements. The methodology on how to implement the biological load transfer mechanisms is clarified in Friese et al. [9]. Promising investigation results of botanically inspired load transfer principles, such as the petiole–lamina transition, that can be applied to improve the structural performance in technical environment are described by Wunnenberg et al. [11].

Three main target structures for non-metallic reinforcements are instrumental to the development of the technology (Figure 7).

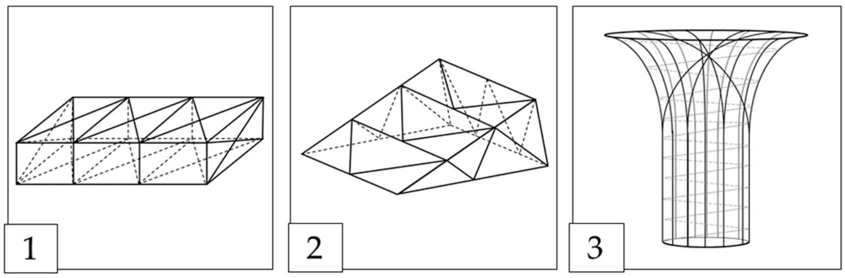

Figure 7. Functional pattern as development basis. (**1**) cuboid reinforcement cage. (**2**) balcony reinforcement cage with diagonal reinforcements. (**3**) Reinforcement cage for column component with load-adapted, internally branched reinforcement.

When selecting the topologies of the structures, as many different geometries and consequently yarn deposition options as possible should be taken into account in order to accommodate the widest possible range of process conditions. Figure 8 depicts one of the target structures as a structurally complex basis for development to provide a guideline for the ongoing development process.

In accordance with the target structures shown in Figure 7, the requirements for the different functional modules needed to be defined in order to gather all necessary qualitative and quantitative information for the constructive development process. In Table 3, the requirements (Phase I) for the yarn fixation module (functional module 1 = FM 1) are listed with the relevant requirement criteria.

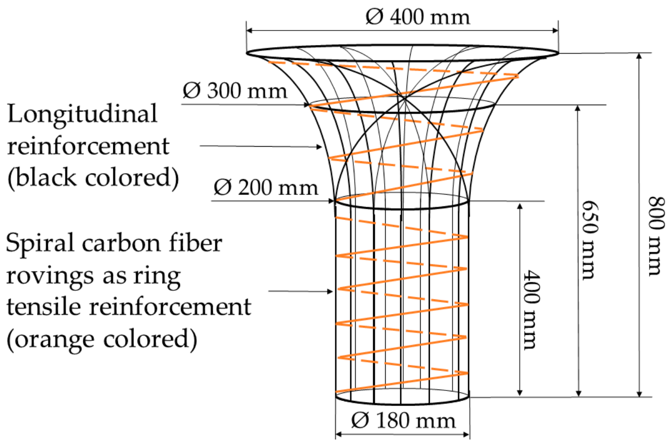

Figure 8. Column-like concrete component with load-path-adapted column-girder transition, inner branchings, and punching shear reinforcement.

Table 3. Requirements for functional module 1: Yarn fixation in space (F—Fixed requirement/M—Minimum requirement/D—Desired requirement).

Feature	Type	Values, Data, Explanation
Geometry	F	Maximum dimensions (width × length × height): 1750 mm × 3250 mm × 1700 mm
Statistics	F	Bending stiffness—maximum displacement tolerance of the support rod under load (bending moment of 25 Nm): 5 mm
Yarn deposition flexibility	D	Granularity of the hole matrix: 50 mm
Position accuracy	F	Predetermined position grid for winding bodies: 50 mm in z-direction; universal winding body topology
Universality	F	Support points are provided according to the textile topology to be deposited
Reusability	D	Complete demoldability of the consolidated FRP structure
Process temperature	M	Up to 200 °C (e.g., hardening of aqueous polymer dispersion)
Mobility	D	Possibility of transferring the deposited, fixed textile structure into the downstream process step (e.g., convection oven)
Yarn storage capacity	M	Minimum 5 carbon fiber heavy tows (area cross-section of 10.2 mm^2)
Geometric winding body specifications	D	Rounded edges; minimum edge radius of 10 mm
Automation and control technologies	F	Individual controllability of the support points (in terms of avoiding collisions and winding feasibility)

According to the overall task of the functional module, a function structure is created that shows the individual sub-functions and places them in an orderly context (Phase II; see Figure 9). Subsequently, solution ideas are collected for the individual sub-functions in a morphological box. The logical linking of the solution ideas as well as the evaluation of the solution combinations leads to preferred conceptual solutions. In consideration of the given functional structure, two concepts were developed for this functional module (Phase III).

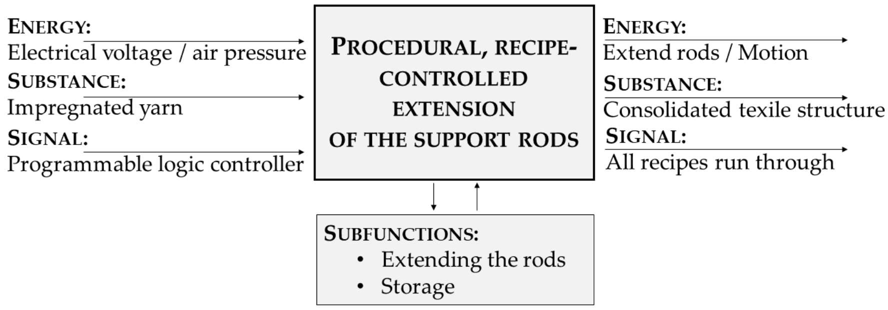

Figure 9. Functional structure of the yarn fixation module.

Both rely on a cube-shaped frame with a perforated steel plate and extendable support rods (see Figure 10). Concept A uses three linear actuators combined with an X-Y-Z portal system for the individual expulsion of the supporting rods, wherein the bars are fixed by linear brakes during the steady state. When the rods need to be driven out, the brake is released. Concept B works with several stepper motors for each rod individually.

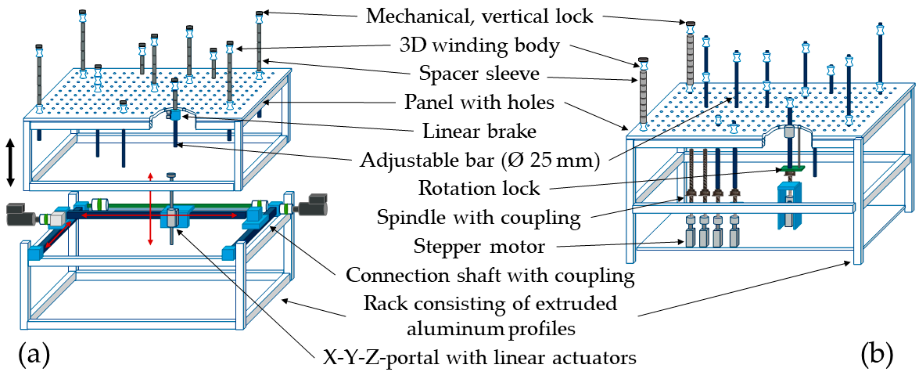

Figure 10. Concepts for yarn fixation modules: (**a**) Concept A with linear actuators; (**b**) concept B with stepper motors.

The procedure for the development of the yarn-guiding and impregnation module (functional module 2 = FM 2) was also based on the design methodology according to VDI 2221, although the individual phases overlapped somewhat with a time delay. This approach was chosen in order to precisely coordinate the requirements for FM 2 with those for FM 1, which were already being developed, to develop the approach in a time-effective manner and to be able to fully coordinate the holistic development process accordingly. Table 4 shows the requirements for FM 2.

The requirements result from the previously mentioned development process, the requirements on the part of the construction industry, and the bionic target structures (Figure 7) to be realized. The resulting functional structure is depicted in Figure 11. Subfunctions of the FM 2 are the yarn guiding and impregnation themselves as well as the regulation of incoming signals, such as the filling level of the impregnation box, the decoiled yarn path, and the air pressure.

For FM 2, solution variants were also created and finally consolidated into a preferred conceptual solution. Finally, both functional modules were combined with the industrial robot to achieve an operational manufacturing system. The schematic draft of this robot-assisted technology is depicted in Figure 12. The yarn impregnation module consists of different sub-modules, which are attached at various points of the robot. The storage of the impregnation material as well as their feed pumps are provided as a kind of backpack solution and fixed on the main axis (axis 1). The yarn spool, the piston rod cylinder for regulating the yarn tension, and the mixing chamber, where two-component polymer systems are homogenized, are mounted on the swing arm of the robot. The yarn fixation module is placed within reach of the robot arm and is controlled and regulated via the higher-level programmable logic controller. The yarn deposition module interacts with the robot controller via an interface so that the recipe sequence is matched to the generated winding paths. The impregnation box hanging on the robot flange (robot end-effector) is designed as a semi-hermetic (almost closed) box including three deflection rollers with diameters of 30 mm and a level sensor to control the impregnation agent supply—see Friese et al. (2023) [36].

Table 4. Requirements for functional module 2: Yarn guiding and impregnation (F—Fixed requirement/M—Minimum requirement/D—Desired requirement).

Feature	Type	Values, Data, Explanation
Geometry	F	Minimum assembly space; closed geometry of the impregnation box
Universality	F	Flexibility in material selection (impregnation agent, fiber material, yarn count)
Reusability	F	Simplicity in cleaning
Yarn compensation capacity	F	Active and passive compensation unit; maximum fiber tensile force: 50 N
Yarn feeding	M	Active and electronically controlled decoiler (controlled by yarn take-off path)
Yarn impregnation process	M	Optimum filament impregnation (validated by grinding patterns and computer tomographic scans)
Impregnation agent mixing	M	Passive mixing via static mixing helix
Impregnation agent return	D	Impregnation circuit (improvement of mixing and avoidance of suspended matter deposition)
Delivery tube	M	Length: 50–150 mm; maximum outer tube diameter: 20 mm; minimum hole diameter: 2.2 mm (depending on yarn)High bending stiffness: displacement of the yarn outfeed center under load less than 1 mm
Process temperature	F	160 °C

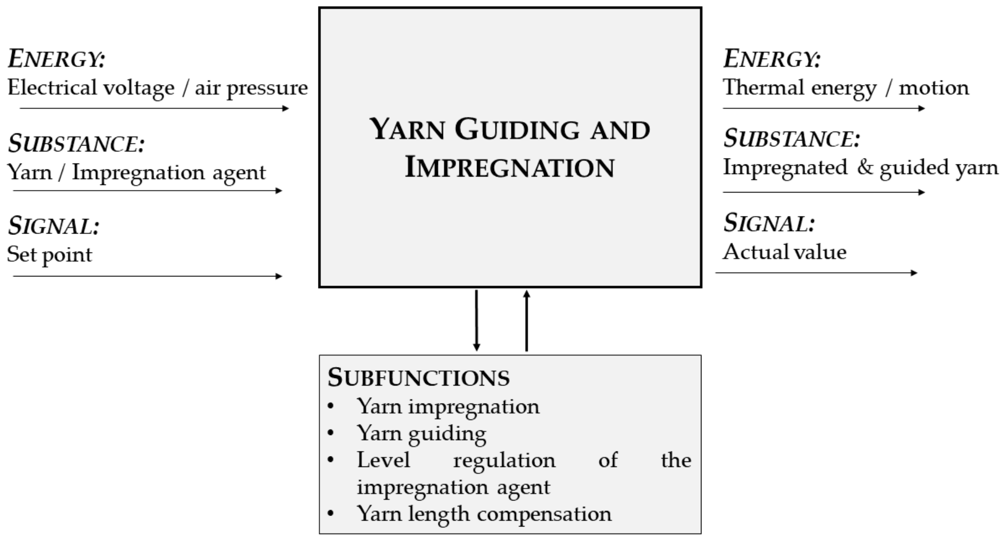

Figure 11. Functional structure of the yarn impregnation module following [36].

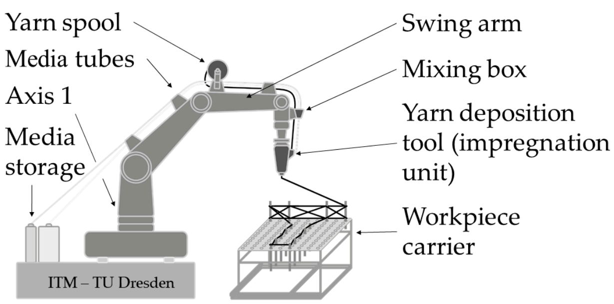

Figure 12. Developed robot-assisted technology (new principle 5) with a yarn impregnation module for convenient yarn impregnation and 3D yarn fixation module.

For the control of the kinematic chains (FM 1 and FM 2), the development of a qualified tool that automatically generates the robot paths as well as the timed travel paths of the FM 1 is required. The automatic path planning of robots is a highly challenging problem [37]. Nonetheless, an algorithm for the implementation of flexible axis-variable roving paths was developed as the basis for an automated realization of bionic and geometrically complex reinforcement geometries into the robot control technology as well as for automated path planning. Figure 13 schematically visualizes an innovative algorithm principle for the fully automatic generation of the robot path for yarn deposition processes, with the aim of manufacturing highly complex and biologically inspired fiber-reinforced composite structures. The algorithm processes input data obtained from computer-aided simulations or directly from botanically inspired designs. The outputs in this process step are variables containing geometrical information, such as the number and position of nodes and connections between these nodes in form of node pairs. The robot-assisted production of the desired structure can be abstracted as the solution to the Chinese postman problem, where the result is an optimized and holistic path including all nodes and node connections [38]. The developed pathfinding algorithm, based on Hierholzer's algorithm, utilizes the basis information and further processes it, leading to an optimal node sequence taking into account the structural geometry, such as the path length, orientation, and cross-section of the deposited fibers, as well as deposition constraints, such as fiber angle and slippage, as well as minimal fiber damage and minimizing of wrapping of nodes.

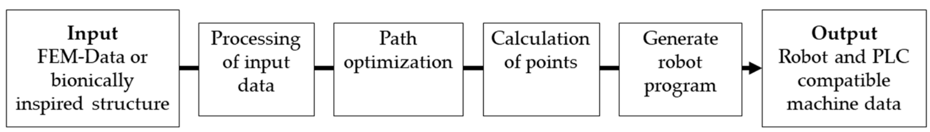

Figure 13. Schematic flow chart of the developed procedure for the automated generation of robot paths and travels paths of FM 1.

In the next step, the coordinates of the deposition points are calculated with respect to the derived node sequence, including collision avoidance of the robot arm with the environment, yarns, and 3D winding bodies. The resulting robot program, generated via the algorithm, provides comprehensive instructions that enable the robotic arm to execute fiber deposition with high accuracy. Moreover, the algorithm successfully produces robot and programmable logic controller (PLC)-compatible machine data, ensuring cooperation between both systems.

4. Results

The developed overall design (Phase IV) of the functional modules is shown in Figure 14 with the final yarn fixation module (workpiece carrier) and in Figure 15 with the comprehensive robot-assisted manufacturing technology, including the yarn impregnation module (yarn deposition tool). The yarn fixation module has a dimension of 3000 mm × 1500 mm × 1000 mm (L × W × H).

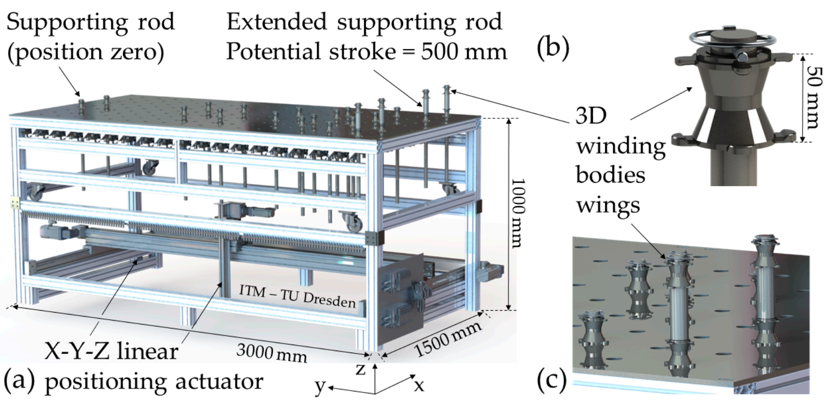

Figure 14. Developed intelligent 3D yarn fixation module with 3D winding bodies—(**a**) yarn placement rack, (**b**) 3D winding body, (**c**) stacked winding bodies with spacers on supporting rod [9].

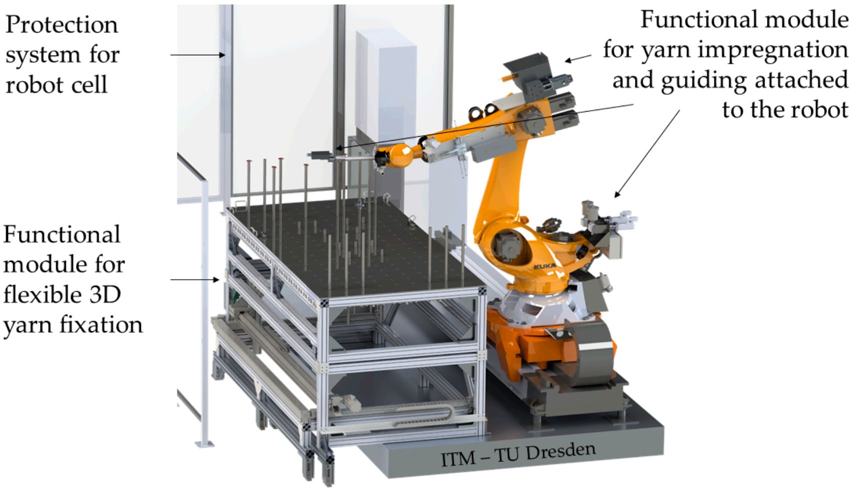

Figure 15. Developed overall design concept of a robot-assisted manufacturing system with the yarn fixation module (FM 1) and the flexibly moveable yarn impregnation tool (FM 2).

Given the requirement to process polymer impregnation agents, which must be hardened in an oven, and the desired requirement for a fixation pattern which features fixation points as close to each other as possible, concept A better meets the initial technological requirements. The electronic stepper motors are not sufficiently temperature-resistant, and rapid disassembly of these components immediately before consolidation in the oven is not feasible.

The 3D yarn fixation module is integrated into a robotic system consisting of a protective robot cell and the industrial robot with the attached yarn impregnation tool. The dimensions of the yarn fixation module were chosen to realize proper textile reinforcement structures for the construction industry, to use the furnace for process-related thermal treatments, and to ensure geometric accessibility to the yarn fixation module on the part of the robot-guided tool without collisions.

The results of the developed algorithms were successfully tested on simple 2D geometries, such as in Figure 16, which depicts the basic structure of the targeted functional pattern 1 in Figure 7. Ongoing efforts are focused on validating the algorithm's performance and enhancing its adaptability to handle more diverse and complex 2D and 3D structures. A particular focus of the software development is the implementation of the developed function module 1 as an additional kinematic chain to be controlled.

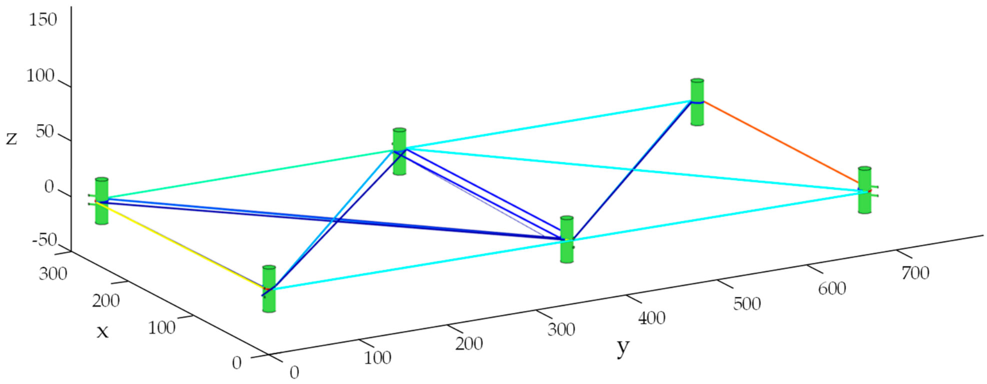

Figure 16. Automatically generated robot path for the yarn deposition of a simple 2D non-metallic reinforcement structure: green pins—winding bodies; strands with different colors according to the already deposit yarn strand counts (turquoise = 2 strands; blue = 3 strands; green = 4 strands; yellow = 5 strands; orange = 6 strands).

5. Discussion

In sum, two elementary functional modules and a winding path generation algorithm have been developed to generate complex 3D, spatially branched, and hierarchically built non-metallic reinforcement structures with coreless robotic winding technology.

The key elements are the 3D yarn fixation module and the 3D yarn-guiding and impregnation module, forming the basis of the novel robot-assisted yarn placement technology. The fixation module provides support points in space according to the required fixation points without obstructing deposition paths by machine parts. Supporting points and thus even the rods, in turn, can be ignored if they are not needed for yarn fixation. Thus, the production of more complex reinforcement structures with free-form fiber courses is possible, and the natural load transfer principle can be imitated. In addition, the yarn-guiding and impregnation module (FM 2) is impressive, with a geometrically highly flexible manipulation capability and the property of being able to process a wide variety of yarn impregnation agents. At the same time, the rearrangement of individual sub-function modules away from the robot mounting flange to the rocker arm and the robot carousel enables a significantly smaller installation space, which reduces the risk of collision. The design placement of the impregnation box and yarn tube on the robot flange allows for flexible maneuverability and for yarn deposition in confined spaces. The deposition of the yarn between the support points of the FM 1 enables the production of 3D non-metallic structures. The potential scope for the usage of this technology is very promising, as it is intended to enable the automated robotic generation of textile topologies with complex structural designs, such as for the automotive or aerospace industry, but especially for the construction industry. The developed algorithms enable the automated transformation of simple, biologically inspired topologies into complex deposition paths and implementation into plant control by means of machine control datasets. Even though the gold standard in high productive manufacturing of textile reinforcement mats is currently set by warp-knit technology, the production of hierarchically structured and spatially branched textile reinforcement topologies—which are urgently needed—can only be achieved with the unsurpassed flexibility of robot-assisted direct yarn placement technology and an appropriate 3D yarn deposition tool. Thus, the developed functional modules pave the way for novel concrete-based engineering principles with a material-minimizing design ethos within the construction industry.

In the future, the system control of the production line must be finalized. For this purpose, the synchronization between the robot control and the control unit of the yarn fixation module as well as the use of the rotatory tool center point movements must be developed and tested to ensure sufficient process stability for the upcoming investigation work. After successful algorithm development, biologically inspired geometries can be transformed into machine datasets and thus deposition paths. In addition, the reinforcement structures found are to be evaluated in close cooperation between the subprojects in the Collaborative Research Center Transregio 280, and strategies for the generative production of concrete structures with such innovative 3D reinforcement are to be formulated. The focus is on automation, dimensional accuracy, and sustainability in the form of material reductions. In investigations covering the process chains, fundamental requirements for the concreting possibility of 3D textile reinforcement via additive manufacturing are to be determined. Figure 17 shows the technological approach to be used for processing of the reinforcement textiles by means of additive concrete extrusion [39]. In subsequent research work, technological suitability for further processing in generative concrete production is to be evaluated by characterizing dimensional stability and composite behavior with concrete.

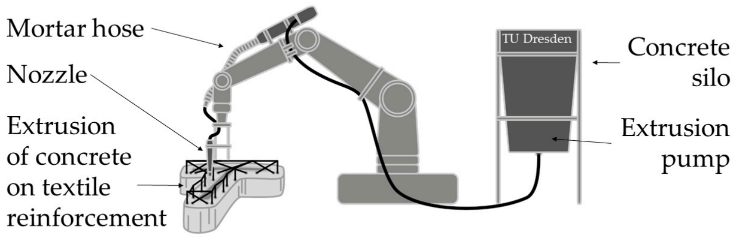

Figure 17. Robot-assisted 3D concrete extrusion (printing) for concreting textile 3D reinforcement structures.

Innovations truly pay off in the long run as from now on there is an intelligent robot-assisted technology capable of producing hierarchical 3D textile reinforcement structures with inner branching. This manufacturing technology is becoming a game changer in the field of the CO_2-reduced construction methods of tomorrow.

Author Contributions: Conceptualization, D.F., L.H., T.N., V.M. and C.C.; methodology, D.F., J.M. and H.L.X.; software, J.M. and H.L.X.; validation, D.F., H.L.X. and J.M.; formal analysis, D.F.; investigation, D.F., H.L.X. and J.M.; resources, D.F.; data curation, D.F., H.L.X. and J.M.; writing—original draft preparation, D.F. and T.N.; writing—review and editing, D.F., L.H., T.N., J.M. and C.C.; visualization, D.F. and H.L.X.; supervision, L.H., V.M. and C.C.; project administration, C.C.; funding acquisition, L.H., V.M. and C.C. All authors have read and agreed to the published version of the manuscript.

Funding: Funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation)—SFB/TRR280, Project-ID 417002380.

Data Availability Statement: The data created in this study are available on request from the corresponding author.

Acknowledgments: In addition, the authors would like to thank Rico Pöschel for the graphical realization of the technological principle sketches and Ziyue Yang for his support during his student research project.

Conflicts of Interest: The authors declare no conflict of interest. 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.

References

1. UN Environment Programme. 2021 Global Status Report For Buildings and Construction. 2021. Available online: https://globalabc.org/resources/publications/2021-global-status-report-buildings-and-construction (accessed on 24 September 2023).
2. Beyond Zero Emissions. *Rethinking Cement: Zero Carbon Industry Plan*; Beyond Zero Emissions Inc: Fitzroy, Victoria, 2017; ISBN 978-0-9923580-2-0.
3. Crippa, M.; Oreggioni, G.; Guizzardi, D.; Muntean, M.; Schaaf, E.; Lo Vullo, E.; Solazzo, E.; Monforti-Ferrario, F.; Olivier, J.; Vignati, E. *Fossil CO_2 and GHG Emissions of All World Countries: 2019 Report*; Publications Office of the European Union: Luxembourg, 2019; ISBN 978-92-76-11100-9.
4. UN Environment Programme. Emissions Gap Report 2022. 2022. Available online: https://www.unep.org/resources/emissions-gap-report-2022 (accessed on 24 September 2023).
5. Beckmann, B.; Bielak, J.; Scheerer, S.; Schmidt, C.; Hegger, J.; Curbach, M. Standortübergreifende Forschung zu Carbonbetonstrukturen im SFB/TRR 280. *Bautechnik* **2021**, *98*, 232–242. [CrossRef]

6. Scheerer, S. Was ist Textilbeton? Eine kurze Einführung in das Thema. *Beton und Stahlbetonbau* **2015**, *110*, 4–7. [CrossRef]
7. Spelter, A.; Bergmann, S.; Bielak, J.; Hegger, J. Long-Term Durability of Carbon-Reinforced Concrete: An Overview and Experimental Investigations. *Appl. Sci.* **2019**, *9*, 1651. [CrossRef]
8. Seifert, W.; Lieboldt, M. Ressourcenverbrauch im globalen Stahlbetonbau und Potenziale der Carbonbetonbauweise. *Beton-Stahlbetonbau* **2020**, *115*, 469–478. [CrossRef]
9. Friese, D.; Hahn, L.; Cherif, C. Biologically Inspiried Load Adapted 3D Textile Reinforcement Structures. *MSF* **2022**, *1063*, 101–110. [CrossRef]
10. Sacher, M.; Lautenschläger, T.; Kempe, A.; Neinhuis, C. Umbrella leaves-Biomechanics of transition zone from lamina to petiole of peltate leaves. *Bioinspir. Biomim.* **2019**, *14*, 46011. [CrossRef]
11. Wunnenberg, J.; Rjosk, A.; Neinhuis, C.; Lautenschläger, T. Strengthening Structures in the Petiole-Lamina Junction of Peltate Leaves. *Biomimetics* **2021**, *6*, 25. [CrossRef]
12. Otto, J.; Kortmann, J.; Krause, M. Wirtschaftliche Perspektiven von Beton-3D-Druckverfahren. *Beton Und Stahlbetonbau* **2020**, *115*, 586–597. [CrossRef]
13. Goldmann, M. Betondruck: Deutschlands Erstes Wohnhaus Aus Dem 3D-Drucker. Available online: https://www.dabonline.de/2020/11/26/haus-3d-drucker-betondruck-deutschlands-erstes-wohnhaus-gedruckt-beckum-beton-peri/ (accessed on 24 September 2023).
14. Cherif, C. (Ed.) *Textile Materials for Lightweight Constructions*; Springer: Berlin, Heidelberg, 2016; ISBN 978-3-662-46340-6.
15. Hahn, L.; Zierold, K.; Golla, A.; Friese, D.; Rittner, S. 3D Textiles Based on Warp Knitted Fabrics: A Review. *Materials* **2023**, *16*, 3680. [CrossRef]
16. Ji, W.; Wang, L. Industrial robotic machining: A review. *Int. J. Adv. Manuf. Technol.* **2019**, *103*, 1239–1255. [CrossRef]
17. Von Zuben, M.; Cherif, C. Robot based Technology for the Production novel Resource-Saving and Cost-Efficient Textile Reinforcement Structures for Direct further Proceedings into Prefabricated Parts. In Proceedings of the 19th World Textile Conference on Textiles at the Crossroads, AUTEX2019, Ghent, Belgium, 11–15 June 2019.
18. Mechtcherine, V.; Michel, A.; Liebscher, M.; Schneider, K.; Großmann, C. Neue Carbonfaserbewehrung für digitalen automatisierten Betonbau. *Beton und Stahlbetonbau* **2019**, *114*, 947–955. [CrossRef]
19. Rittner, S.; Grauer, O.; Kahnt, A.; Holschemacher, K. Entwicklung und Fertigung nichtmetallischer Bewehrungen im automatisierten Prozess. In *Betonbauteile 2023: Hintergründe, Auslegungen, Neue Tendenzen im Betonbau*; Holschemacher, K., Ed.; Beuth Verlag GmbH: Berlin, Germany; Wien, Austria; Zürich, Switzerland, 2023; ISBN 978-3-410-31562-9.
20. Knoch, E. Entwicklung einer Hochgeschwindigkeits-Garnablage zur Fertigung von Textilbewehrungen. In Proceedings of the 15. Carbon- und Textilbetontage, Dresden, Germany, 19–20 September 2023.
21. Schneider, K.; Michel, A.; Liebscher, M.; Terreri, L.; Hempel, S.; Mechtcherine, V. Mineral-impregnated carbon fibre reinforcement for high temperature resistance of thin-walled concrete structures. *Cem. Concr. Compos.* **2019**, *97*, 68–77. [CrossRef]
22. Hack, N.; Bahar, M.; Hühne, C.; Lopez, W.; Gantner, S.; Khader, N.; Rothe, T. Development of a Robot-Based Multi-Directional Dynamic Fiber Winding Process for Additive Manufacturing Using Shotcrete 3D Printing. *Fibers* **2021**, *9*, 39. [CrossRef]
23. Rothe, T.; Pösch, J.; Gantner, S.; Hack, N.; Hühne, C. (Eds.) *Optimization of Tensile Properties and Bond Behaviour to Concrete of Fibre Reinforcement Strands Produced Within a Dynamic Fibre Winding Process*; Zenodo: Geneva, Switzerland, 2023.
24. Minsch, N.; Müller, M.; Gereke, T.; Nocke, A.; Cherif, C. Novel fully automated 3D coreless filament winding technology. *J. Compos. Mater.* **2018**, *52*, 3001–3013. [CrossRef]
25. Knippers, J.; Koslowski, V.; Solly, J.; Fildhuth, T. Modular coreless filament winding for lightweight systems in architecture. In Proceedings of the CICE 2016 8th International Conference on Fibre-Reinforced Polymer (FRP) Composites in Civil Engineering, Hong Kong, China, 14–16 December 2016.
26. Solly, J.; Frueh, N.; Saffarian, S.; Prado, M. ICD/ITKE Research Pavilion 2016/2017: Integrative Design of a Composite Lattice Cantilever. In Proceedings of the IASS 2018 Creativity in Structural Design, Boston, MA, USA, 16–18 July 2018.
27. Gil Pérez, M.; Guo, Y.; Knippers, J. Integrative material and structural design methods for natural fibres filament-wound composite structures: The LivMatS pavilion. *Mater. Des.* **2022**, *217*, 110624. [CrossRef]
28. Mindermann, P.; Gil Pérez, M.; Knippers, J.; Gresser, G.T. Investigation of the Fabrication Suitability, Structural Performance, and Sustainability of Natural Fibers in Coreless Filament Winding. *Materials* **2022**, *15*, 3260. [CrossRef] [PubMed]
29. Friese, D.; Scheurer, M.; Hahn, L.; Gries, T.; Cherif, C. Textile reinforcement structures for concrete construction applications—-a review. *J. Compos. Mater.* **2022**, *56*, 4041–4064. [CrossRef]
30. Teijin Limited. Tenax Filament Yarn: Technical Datasheet. Available online: https://www.teijincarbon.com/fileadmin/PDF/Datenblätter_en/Product_Data_Sheet_TSG01en__EU_Filament_.pdf (accessed on 24 September 2023).
31. Giessmann. *Substrat Und Textilbeschichtung*; Springer: Berlin/Heidelberg, Germany, 2019; ISBN 978-3-662-58493-4.
32. Zhao, J.; Liebscher, M.; Schneider, K.; Junger, D.; Mechtcherine, V. Influence of Processing Conditions on the Mechanical Behavior of Mineral-Impregnated Carbon-Fiber (MCF) Made with Geopolymer. In Proceedings of the 10th International Conference on FRP Composites in Civil Engineering, Istanbul, Turkey, 8–10 December 2021; Ilki, A., Ispir, M., Inci, P., Eds.; Springer International Publishing: Cham, Switzerland, 2022; pp. 1173–1182, ISBN 978-3-030-88165-8.
33. KUKA Deutschland GmbH. KUKA KR 90 R2700 Pro: Technical Data Sheet. Available online: https://www.kuka.com (accessed on 24 September 2023).

34. KUKA Deutschland GmbH. KUKA Lineareinheit KL 4000: Technical Data Sheet. Available online: https://www.kuka.com (accessed on 24 September 2023).
35. VDI Verein Deutscher Ingenieure, e.V. Design of Technical Products and Systems-Model of Product Design; Düsseldorf. 2019. Available online: https://www.vdi.de/richtlinien/details/vdi-2221-blatt-1-entwicklung-technischer-produkte-und-systeme-modell-der-produktentwicklung (accessed on 24 September 2023).
36. Friese, D.; Mersch, J.; Hahn, L.; Cherif, C. Development of a Yarn Guiding and Impregnation Technology for Robot-Assisted Fiber Manufacturing of 3D Textile Reinforcement Structures. In Proceedings of the 11th International Conference on Fiber-Reinforced Polymer (FRP) Composites in Civil Engineering (CICE 2023), Rio de Janeiro, Brazil, 23–26 July 2023.
37. Karur, K.; Sharma, N.; Dharmatti, C.; Siegel, J.E. A Survey of Path Planning Algorithms for Mobile Robots. *Vehicles* **2021**, *3*, 448–468. [CrossRef]
38. Dreifus, G.; Goodrick, K.; Giles, S.; Patel, M.; Foster, R.M.; Williams, C.; Lindahl, J.; Post, B.; Roschli, A.; Love, L.; et al. Path Optimization Along Lattices in Additive Manufacturing Using the Chinese Postman Problem. *3D Print. Addit. Manuf.* **2017**, *4*, 98–104. [CrossRef]
39. Neef, T.; Müller, S.; Mechtcherine, V. 3D-Druck mit Carbonbeton: Technologie und die ersten Untersuchungsergebnisse. *Beton und Stahlbetonbau* **2020**, *115*, 943–951. [CrossRef]