Visions and Strategies for Reinforcing Additively Manufactured Constructions 2023
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A Dynamic Winding Process of individualized fibre reinforcement structures for Additive Manufacturing in Construction

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Abstract: The integration of load path compliant fibre reinforcement structures into additive manufactured concrete elements opens up new potential in the field of construction. The new design language made possible by 3D concrete printing requires reinforcement structures to be provided in a highly individual shaped manner. Digital and robot-based production processes make it possible to produce on-site, on demand, fully automated and just-in-time. In this paper, a concept for an on-site ready fibre reinforcement production is presented. Based on previous works a Dynamic Winding Machine (DWM) for the on-demand production of individualizable reinforcement strands is developed. The concept and technical functionalities of the machine are presented in detail. The functionality is validated based on the production of single reinforcement bars as well as the production of entire, additively manufactured and reinforced concrete structures. With an industrial robot and adjusted end effectors, freely shaped reinforcement structures can be produced automatically. Different concepts for the use of the DWM with mobile robots are discussed. Due to the flexibility of the process, both filigree reinforcement structures, e.g. for use in particle bed printing, and large structures, e.g. for combination with Shotcrete 3D Printing, can be produced.

Keywords: Additive Manufacturing in Construction; Robot based dynamic fibre winding; Dynamic Winding Machine; Textile-reinforced concrete

1 Introduction and Motivation

The construction industry is responsible for a significant proportion of global CO_2 emissions [1]. The production and use of concrete plays a major role in this. On the way to a sustainable lifestyle, it is therefore essential to rethink the use of concrete in the construction sector and to provide approaches on how it can be used more efficiently and in a more targeted manner.

Additive manufacturing of concrete components can play a key role here. Through the targeted use of concrete, e.g. in load-bearing areas and reductions in non-load-bearing areas, a more efficient use of the material can be achieved. Within the Collaborative Research Centre TRR 277 "Additive Manufacturing in Construction (AMC)",

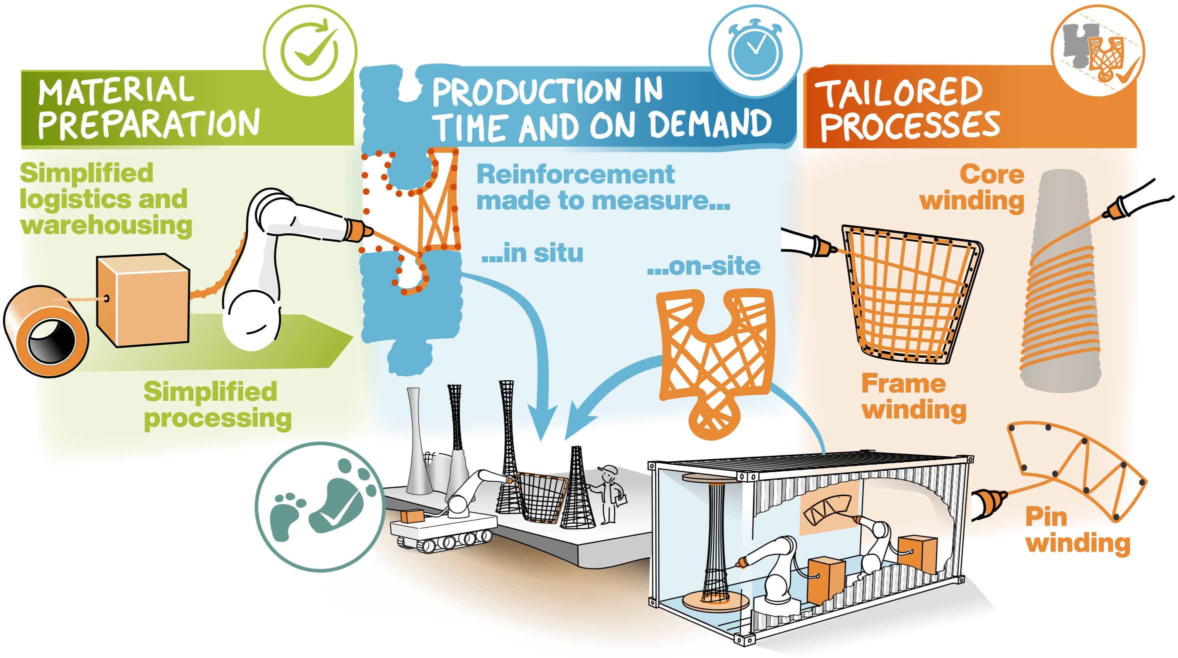


Figure 1. Concept for the on-site and on demand production of individualized additive manufactured and fibre reinforced concrete elements

current 3D concrete printing processes (3DCP) are being further developed and new technologies and their potentials are being investigated [2]. The technologies under investigation include particle bed printing, extrusion and Shotcrete 3D printing (SC3DP). The further development of these methods should enable the production of large building components and engineered structures.

For such applications, the use of reinforcement is essential. However, the integration of reinforcement in additively manufactured components is a major challenge due to their layerwise production [3]. In order to exploit the full potential of load-path-oriented design, it is necessary to adapt the integration of reinforcement to this. New reinforcement concepts have to be developed, implemented and tested. One of these concepts is the winding of individualised reinforcement structures, which is being researched in the project "Integration of Individualized Prefabricated Fibre Reinforcement in Additive Manufacturing with Concrete" as part of AMC [2]. The aim is to establish a holistic process for the production of individualised and robot-assisted fibre reinforcement. This makes it possible to produce structures directly on the construction site, which can be individually adapted to the local conditions. In fig. 1 the overall concept is shown. By using a Dynamic Winding Machine (orange box), whose development and functionality is described in detail in this paper, individualised reinforcement strands can be produced. By means of a following robotic winding process, which can be carried out e.g. by mobile manipulators or within a container directly on the construction site, a wide range of reinforcement structures can be produced. The flexible and not fully cured reinforcement strands can be used for different reinforcement integration strategies, namely Core Winding, Frame Winding and Pin Grid Winding, which are described more in detail by Gantner [4].

To enable mobile and flexible manufacturing, the reinforcement production must be kept as compact and simple as possible. For this purpose the Dynamic Winding Machine (DWM) is developed. It is used to continuously produce reinforcement strands from a primary fibre material with a helical winding of a thin secondary fibre strand.

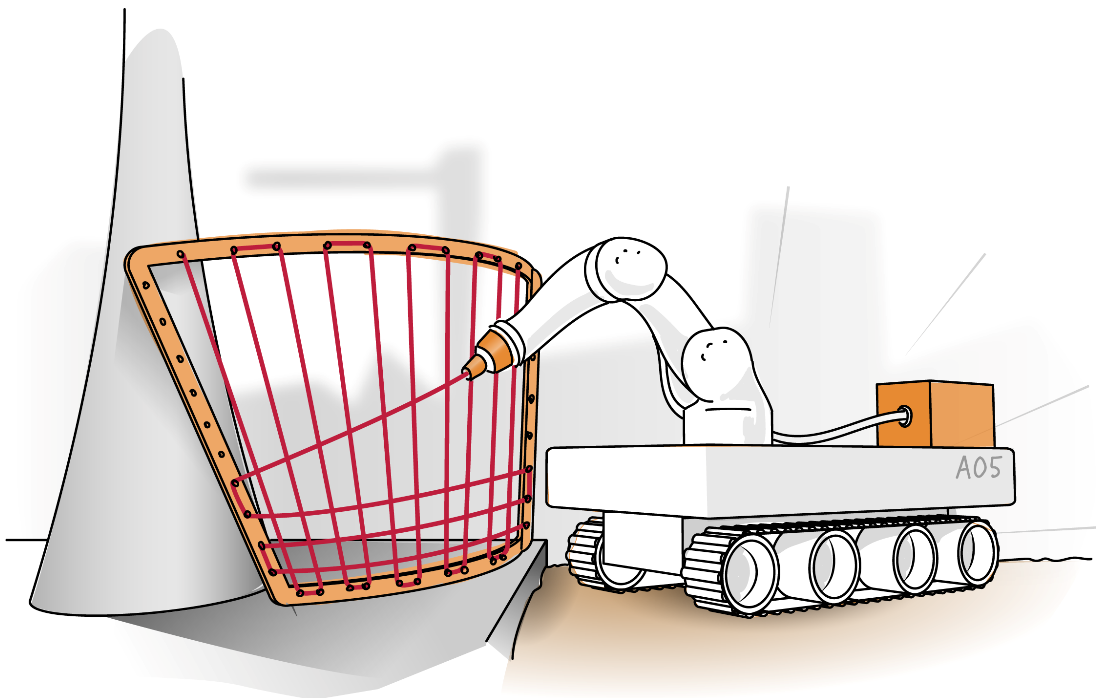


Figure 2. Schematic representation of the production of reinforcement structures by combining a mobile manipulator and the DWM

By using a room-temperature curing epoxy resin, the strands are freely formable after leaving the machine and cure after being processed into reinforcement structures. Due to its compact design, the DWM can be integrated into the production with mobile manipulators, schematically shown in fig. 2.

Besides new possibilities in the design language the production of more sustainable concrete structures is a main advantage of the investigated processes. By the usage of force-optimized and freely shaped structures, less material is needed and a better material utilization can be achieved [5], [6]. Additionally, the non-corrosive behaviour of FRP reinforcements enables a reduction in the concrete cover height, which additionally reduces the amount of concrete needed [7].

2 State of the Art

The integration of reinforcement into additively manufactured concrete structures is a crucial research aspect of the AMC [2], [3]. However, the combination of reinforcement and additive manufacturing is also being investigated in other research projects. Furthermore, the use of textile reinforcement and new applications resulting from this is a focus of research.

In Dresden and Aachen the SFB/TRR 280 "Design Strategies for Material-Minimised Carbon Reinforced Concrete Structures" is investigating both mentioned aspects. For example, Mechtcherine's research group in Dresden is looking at possibilities for integrating reinforcement for digital production with concrete [8], [9]. A main focus is on the use of textile reinforcement for both classic production processes and additive manufacturing. Especially the usage of a mineral impregnation of the fibre reinforcement is investigated [10]. In addition, possibilities for adapting the bond behaviour of reinforcement by means of complex surface structuring are being investigated [11], [12]. Cherif's research group in Dresden is also investigating possible structures and applications of textile reinforcement [13]. Among other things, coreless truss structures and biologically inspired 3D structures based on textile reinforcement are investigated [14]–[16].

In Aachen, Gries' research group is investigating possible methods of integrating textile reinforcement into a digital fabrication process [17]. Dittel [18] describes a possibility for the usage of vertical textile reinforcement within an extrusion-based printing process. Furthermore, investigations on the Life Cycle Assessment (LCA) of carbon-reinforced concrete are carried out [6].

While the research in Dresden and Aachen focuses on textile reinforcement structures for concrete, new concepts for the production of pure fibre composite structures were developed in Stuttgart, named core-less filament winding [19], [20]. Currently research is bundled within the Cluster of Excellence EXC 2120 ”Integrative Computational Design and Construction for Architecture (IntCDC)”. A main focus is on the development of new winding strategies that are adapted to the limp fibre material and do not require a winding core. For instance, Vasey [21] describes a core-less winding process where the fibre preparation and the winding approach is divided from each other. The winding is happening with adjustable fibre tension. In the described winding process the exit position of the material system is static. Due to this the possible winding pattern is dependant from the position of the pin to be wrapped regarding the filament output of the material system. Mindermann [22] describes another core-less winding strategie by using an end effector for the fibre preparation. This end effector is mounted on a linear moveable robot which is used for core-less filament winding. In contrast to the described process of Vasey the exit position of the material system is dynamic, which influences the trajectory planning and possible winding patterns.

The previously described research has primarily investigated the integration of continuous reinforcement strands. However, the robotic integration of short rebars is practical in certain applications. Hass [23] describes the integration of helical screw-type reinforcements in additively manufactured concrete using an end effector designed for this purpose. Also within the AMC, research is being carried out on the automatic integration of short rebars [24].

The range of research in the field of 3DCP and its reinforcement demonstrates the importance of this area, with a focus on textile reinforcement. The functionality of the reinforcement, regardless of its design and the manufacturing process, depends on its bonding to the cementitious matrix. There are multiple possibilities to influence the bonding behaviour of the reinforcement strand by materiality or surface structuring. Since analytical and numerical calculations can only approximately describe the bond behaviour, it is necessary to carry out pull-out tests. In this way, information about the material properties can be obtained, taking into account special and newly developed application cases.

In addition to the investigation of various reinforcement systems, research is also being carried out in the field of mobile robotics. Among other things, a focus is on the use of mobile robotics for 3D printing [25]–[27]. Besides being used for 3D printing, mobile manipulators can also be used in other functions on the construction site. Interesting research on this exists from Dörfler and Hack [28]. In his research, Melenbrink gives an overview about the actual and future use of autonomous robots on the construction site [29].

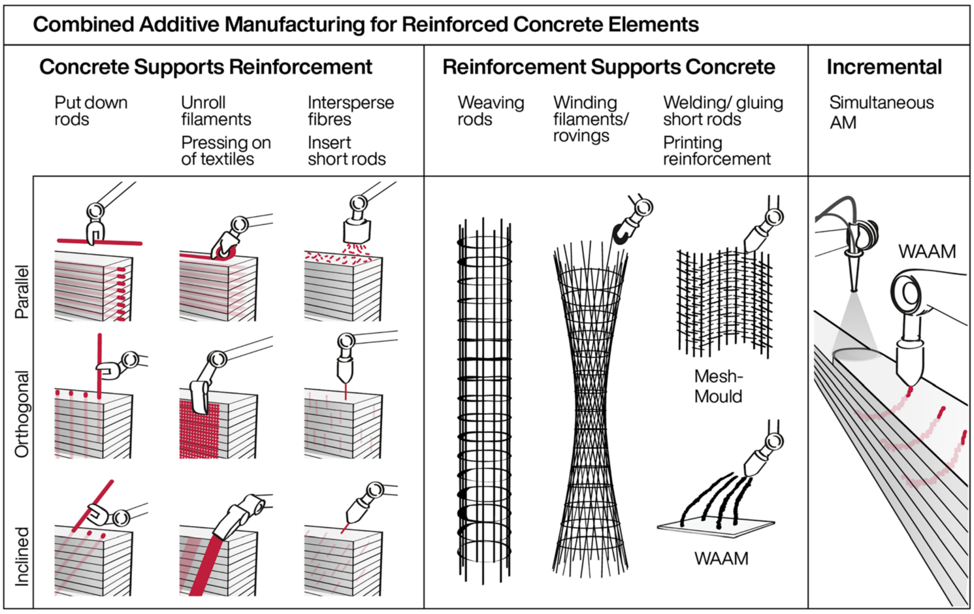


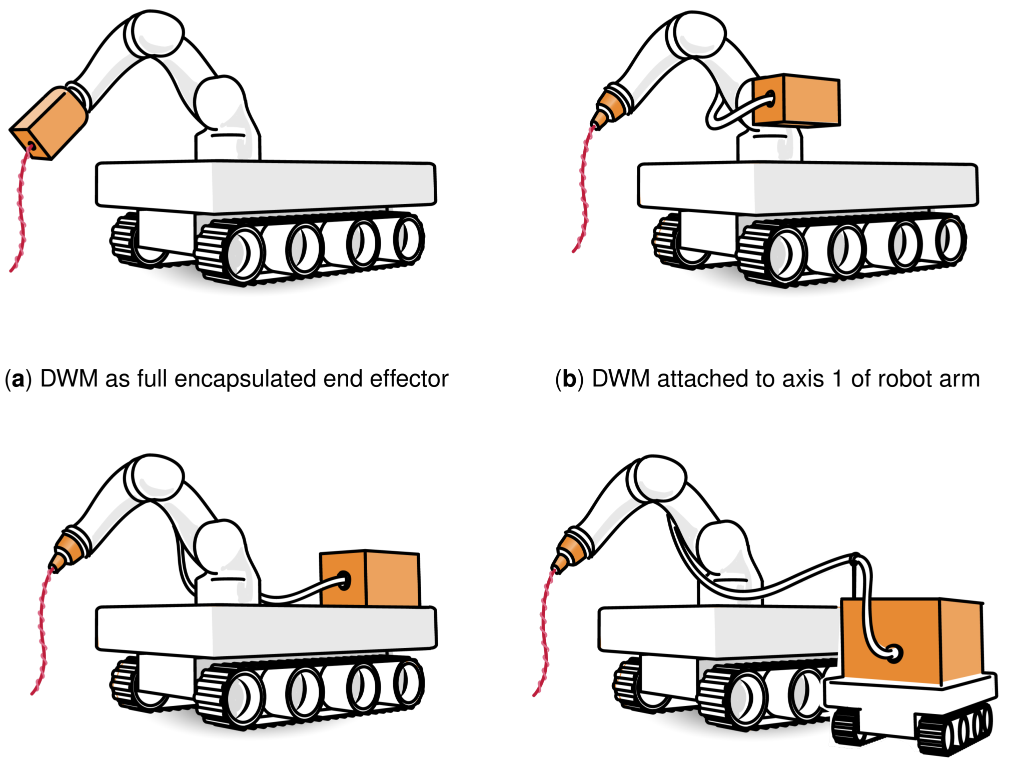
Figure 3. Classification approach for reinforcement in Additive Manufacturing with concrete [3]

3 Concept and idea

In this research project new reinforcing possibilities and strategies for 3DCP are focused. If the reinforcement integration is done prior to the concreting, like it is state of the art in classical production processes, the printing process needs to be adapted and guided based on the already existing reinforcement structure and is therefore limited.

Like described above, currently a lot of strategies for the parallel extrusion and integration of fibre reinforcement while printing are pursued. Furthermore, concepts for the fabrication and integration of individualized fibre mats as reinforcement are developed [30]. But for most of these strategies the integration perpendicular to the printing level is complex or not possible. A classification of reinforcement strategies for additively manufactured concrete elements is given by Kloft [3] (see fig. 3). The integration methods are mainly splitted into two approaches, "Concrete Supports Reinforcement" and "Reinforcement Supports Concrete". In both strategies, the use of pre-produced reinforcement structures is very challenging in terms of processing and placement. When using reinforcement bars, both steel and fibre composite, handling becomes more and more complicated with increasing rebar length. Especially in curved structures, their integration is challenging due to their stiffness. The use of reinforcement mats is also limited due to their restricted drapability. The usage of flexible and uncured reinforcement strands from fibre reinforced plastic (FRP) opens up new possibilities in forming and integrating reinforcement structures. These strands can be used in a winding process to create a high variety of different reinforcement structures. By the establishment of new reinforcement strategies for 3DCP, a more efficient and more easily production of highly individualized, reinforced concrete elements is possible. One part is the pre-production of the reinforcement strand and the other part is the winding and integration of the strand. A detailed description of different integration methods with freely formable reinforcement strands is given by Gantner [4]. The key element in the implementation of these concepts is the pre-production of the reinforcement strand. For this purpose a DWM has been developed to provide the needed reinforcement strands.

The task of this machine is to provide a finalized reinforcement strand, which is directly useable in a dynamic winding process. Like described in [31] the first concept for



(**a**) DWM as full encapsulated end effector

(**b**) DWM attached to axis 1 of robot arm

(**c**) DWM mounted on mobile manipulator (Backpack approach)

(**d**) DWM positioned next to mobile manipulator (potentially on a mobile platform)

Figure 4. Different arrangements and integration methods of the DWM (orange box) into the robotic winding process with a mobile manipulator

the pre-production of reinforcement strands has been designed as an end effector. Due to challenging mounting on the robotic arm the fundamental question of the positioning of the reinforcement pre-production within the robotic winding process had to be clarified. Different concepts for the positioning have been elaborated and are presented in fig. 4. As described in the introduction, the concept development focuses on the use of mobile manipulators, paving the way for manufacturing directly on the construction site. In addition, the high modularity of the system is intended to enable it to be used in various applications, both mobile and static.

The described positioning as fully encapsulated end effector can be seen in fig. 4 a). In fig. 4 b) the machine is attached to axis 1 of the robot arm following concepts described by Dambrosio [32] and Mindermann [22]. In fig. 4 c) and d) the machine isn't directly attached to the robot arm. In the approach shown in c) the machine is placed on the platform of the mobile manipulator. In d) the machine is placed next to the mobile manipulator and can be placed statically on a defined position or on a mobile platform to follow the movement of the mobile manipulator.

For an evaluation of these concepts and a decision on the most feasible approach a detailed analysis of the requirements for the reinforcement strand and its handling process is needed. First of all, the dynamic winding process for the production of reinforcement structures, like described by Gantner [4], must be taken into account. In general, positioning the reinforcement strand production close to the end effector reduces the distance and complexity of strand routing. Due to this, the first prototype was

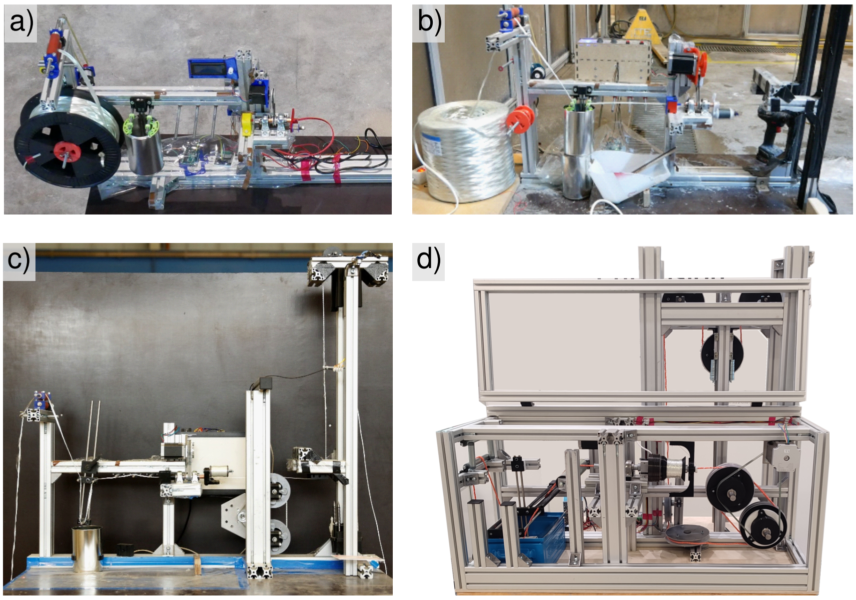


Figure 5. Different versions of the machinery for the pre-production of reinforcement strands: a) Version 1: Prototypical end effector; b) Version 2: Transformation of the prototypical end effector into a stand-alone DWM c) Version 3: Additional active extrusion and tensioning and storgae unit; d) Version 4: Newly constructed current version of the DWM with several improvements

planned and built as fully encapsulated end effector like shown in fig. 4 a). However, the mechanical properties of robotic arms limit the size and weight of an end effector. From a perspective of robotic movement, it is desireable to have a low end effector mass for faster acceleration and increased accuracy [33]. In a limited form, the mentioned restrictions of approach a) also apply to approach b). Further reasons against an end effector design are the more difficult process monitoring and the manageability of the resin impregnation. Therefore a DWM as stand alone machine with the possibility for an integration into the robotic winding process like shown in fig. 4 c) or d) is developed. This results in the necessity of developing an independent end effector for winding and integrating the reinforcement strands. However, in contrast to approach a), this offers opportunities for new end effector and integration concepts, as the work of Gantner [34] examplifies.

4 Pre-production of reinforcement strands for a dynamic winding process

As described above, a first iteration loop considering the required process properties resulted in the development of a stand alone DWM for the pre-production of reinforcement strands. In its first mention [31], the machine is in the second stage of development (fig. 5 b). It represents an adapted version of the first prototypical approach of an end effector (version 1), which was mountable to a robotic arm, shown in fig. 5 a). With version 2 of the machine first production tests have been carried out and a rough validation of the production process and production strategy has been described. In fig. 5 c) a further improved version 3 of the same machine is shown and has been used for the experiments described by Gantner [34].

In this paper a detailed description of the DWM is presented. The pre-production of the reinforcement strand has been broken down into individual modules. Neces-

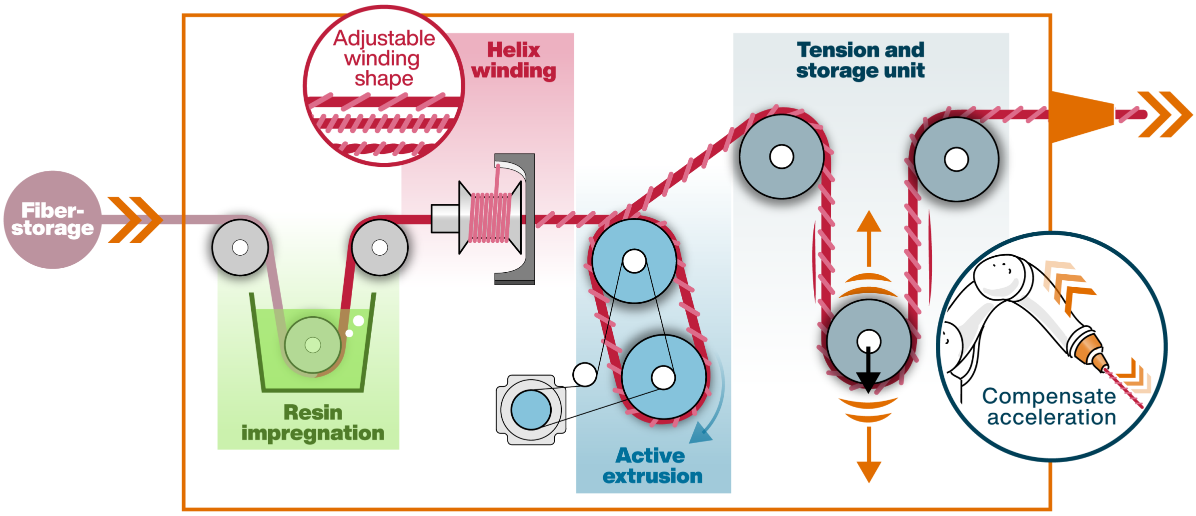


Figure 6. Schematic description of production of fibre reinforcement strands within the DWM [35]

Figure 7. Dip-type resin impregnation bath integrated into the DWM

sary modules are identified and implementation options are evaluated. Based on this, a new, revised version 4 of the DWM is developed and implemented (s. fig. 5 d). This machine is designed to fulfil the requirements resulting from the described overall concept in chapter 3. Furthermore, it should overcome limitations of the previous versions especially regarding producible reinforcement diameter and production speed. A reinforcement strand diameter up to 8 mm is desired.

Based on the first prototype of the DWM, an analysis and modularisation of the different components of it lead to the schematic concept shown in fig. 6. The individual modules are arranged according to their sequence within the reinforcement strand prefabrication from left to right. The first module is the fibre storage. Rovings, which form the main strand of the reinforcement strand, are stored in this module. For a usage of the DWM in rough conditions an enclosure for up to 12 spools of rovings has been designed.

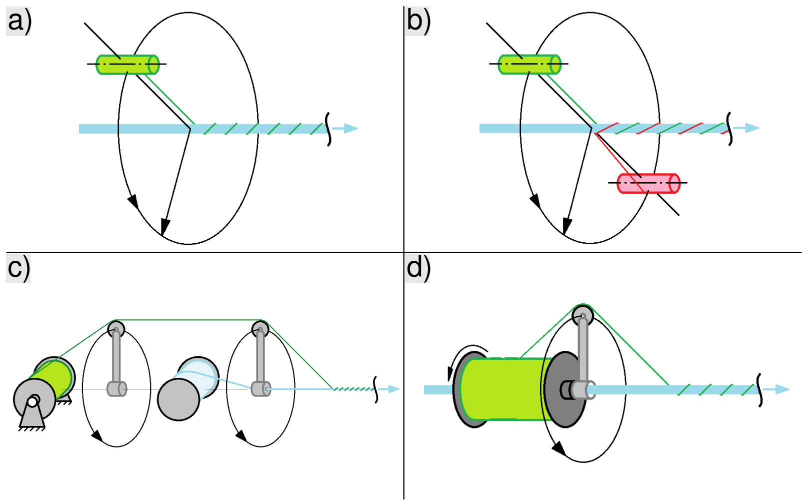


Figure 8. Possible options for the winding of a secondary fibre strand as surface structuring

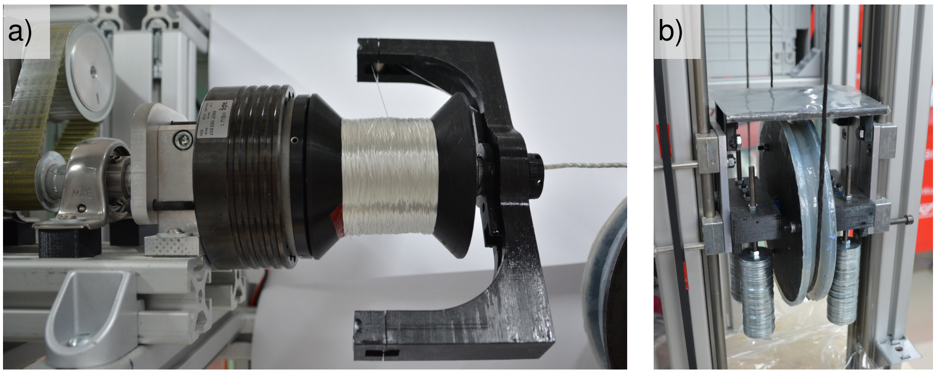


Figure 9. Different modules of the DWM: a) Secondary fibre winding module; b) Dancer of the fibre tensioning and storage module

The second module is the resin impregnation. Therefore, a dip-type impregnation bath is used (s. fig. 7). This module further includes the elements for stripping off the excess resin and adjusting the fibre volume content. For this purpose, the primary strand is pulled through two rubber lips in a first step. The strand is then pulled through an adjustable gap between a rotating roller and a fixed rod to remove further excess resin. The dripping resin is returned to the impregnation bath. The comparison to a direct resin infusion into the fibre strand is planned for future investigations.

The third module represents the surface structuring to increase the mechanical interlocking between reinforcement and concrete and thus the load transfer. Based on literature review and experiments the winding of a secondary yarn in a helical shape has been chosen for surface structuring. This variant corresponds best to the approach of a compact and complexity-reduced machine as pursued here. Multiple options for surface structuring are described in literature, e. g. helical winding (also called wrapping) of a secondary tape or yarn, contour milling, form-pressing, sanding or twisting of the whole strand [11], [36], [37]. In particular, Solyom [36] shows in his work that similar bond strength can be achieved with all mentioned different surface structuring methods. Thus, with appropriate design, each of the surface structuring methods can lead to sufficient bond strength. Consequently, the choice of a surface structuring method for the DWM is made solely on the basis of the requirements for the described concept for a dynamic and automated reinforcement production. Under these conditions, helix winding offers the best combination of ease of implementation and adaptability, as it can be applied continuously in the uncured state. Adaptability refers specifically to changeable secondary fibre materials, e. g. yarn and twisted yarn with different titer, as well as the implementation of a tensioning mechanism for the secondary fibre strand. Like described by Malvar [38] a slack and a tight helical winding is possible and results in different levels of indentations. Potential concepts for the helical winding have been developed and are compared systematically (fig. 8). In version 1-3 of the DWM a bobbin with the secondary yarn is rotating around the primary fibre strand (fig. 8 a)). A pre-tensioning of the secondary fibre is realised by a spring-loaded friction brake. The greater the amount of stored secondary fibre and the higher the rotating speed, the higher the resulting unbalance force. To overcome the unbalance force a double helical winding with to opposite bobbins is possible (fig. 8 b)). The unbalance force is compensated by a fixed positioning in relation to each other and a uniform decrease in mass over time. However, there are barely any investigations on the bond strength with double helix, which can serve as a reference for the comparison. Another more theoretical approach would be the positioning of the secondary yarn bobbin before the primary yarn rovings like shown in fig. 8 c). The advantage would be that the size and thus the amount of spooled fibre material could be arbitrarily large without affecting the process. However, it is questionable whether this type of guidance and movement of the secondary fibre is technically implementable. Finally, the variant shown in fig. 8 d) is selected as the mechanism for version 4 of the DWM. The primary fibre strand is guided through the bobbin with the secondary yarn. Since the bobbin itself does not rotate eccentrically in this arrangement, its size and the amount of stored fibre have little influence on the process stability. Furthermore, the integration of a hysteresis brake for adjusting the secondary fibre tension is easily possible (s. fig. 9 a)).

The fourth module describes an active extrusion of the reinforcement strand. By guiding the reinforcement strand over several actively driven rollers, it can be conveyed by static friction. In addition, this unit serves as a friction brake when reinforcement production is paused. This module has been implemented for the version 3 of the DWM shown in fig. 5 c). The pulling of the reinforcement strand through the machine was previously driven by the movement of the robotic arm. The pulling speed was measured via an encoder and the winding of the secondary fibre was adjusted based on this measurement. As a result, the production speed varied with every movement of the robot and unfavourable movements caused the reinforcement strand to slacken, leading to high irregularities in production. Besides the irregularities mainly in the application of the helical fibre strand high accelerations in the fibre production lead to high loads on the mechanical components of the machine. In combination with the fifth module, the tension and storage unit, the production of the reinforcement strand can be decoupled from the robotic winding, which increased the production quality and stability.

The fifth module, like mentioned, represents a tension and storage unit, which consists of a passive dancer, a guidance and a distance sensor to determine the dancer's position. The pretension is adjusted by applying a weight force to the dancer. The force can be adjusted depending on the application (s. fig. 9 b)). The necessity of this module was recognised during tests with the prototypical version 1 of the machine. In combination with the active extrusion the dancer can be kept in a medial position and high relative accelerations of the robot in relation to the DWM as well as abrupt stopping can be compensated. Furthermore, while using the DWM for the reinforcement integration for large components a storage possibility is needed to compensate a relative shortening of the distance between the outlet of the DWM and the end effector at the robotic arm.

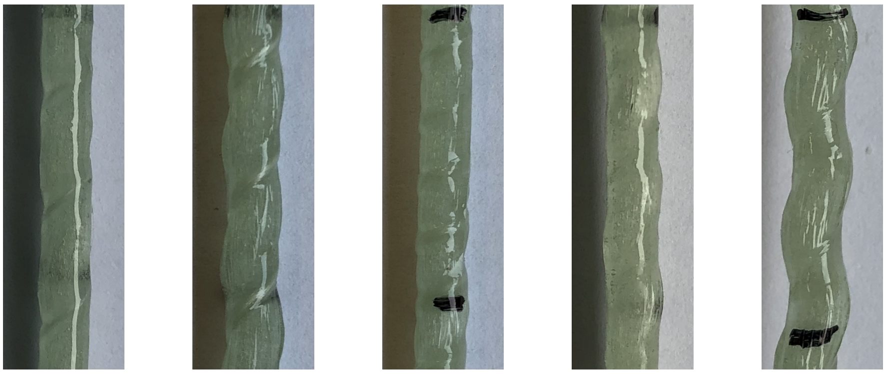
Figure 10. Control panel for the adjustment of the reinforcement strand production

The interconnection of all these modules forms the final DWM. Its controlling is based on an Arduino micro controller. The control of the machine is integrated into a control panel and works on the 24 V industry standard (s. fig. 10). It controls two stepper motors, one for actively extruding the primary fibre strand and one for winding the secondary fibre strand. The motors cover a wide speed range and allow precise adjustment of the secondary fibre pitch. Both motors are operated with stepper motor drivers via open-loop control. In addition, a hysteresis brake is connected to the control panel, which regulates the tension of the secondary fibre strand independently of the pull-out and winding speed. An encoder is used to measures the height of the dancer as a displacement transducer and forms the basis for the automatically controlled operation of the system. It can store about one metre of pre-fabricated reinforcement strand.

5 Production of reinforcement structures

Production tests were carried out with all versions of the DWM described in order to characterize the producible reinforcement strands and to further develop the machine. Particular focus has been placed on the quality of the reinforcement strand itself, the process stability, the repeatability and the upscaling to be able to produce reinforcement strands with a diameter up to 8 mm. In parallel to the investigation of the production and mechanical properties of the reinforcing strands themselves, integration strategies for various 3DCP techniques have been evaluated. These experiments were additionally used to evaluate the performance of the machine under difficult conditions and the production of large quantities of reinforcement strands. E. g. the winding of reinforcement within a defined frame as well as a shape-optimized and force-flow oriented application and integration of reinforcement has been conducted [4], [34]. As part of a demonstrator fabrication, about 100 m of reinforcement was wound continuously around a column manufactured by SC3DP, demonstrating the possibility that the process described can be used on a large scale.

For the evaluation of the reinforcement quality different mechanical properties are determined. Especially the influence of varied production parameters needs to be clarified. Tensile tests are performed to determine the primary performance capability. Furthermore, the interlocking with the concrete matrix to transfer tensile forces from the concrete matrix into the fibres of the reinforcement is essential. Like described above, a surface structuring based on winding a secondary fibre strand is chosen to create a surface structuring for fulfilling this task. Different machine and material settings



(**a**) (**b**) (**c**) (**d**) (**e**)

Figure 11. Reinforcment strands with different surface structuring produced with the DWM: a) Twisted yarn, 8 mm thread pitch; b) like a) with reduced resin at the surface; c) twisted yarn, 4 mm thread pitch; d) yarn, 8 mm thread pitch; e) roving, 8 mm thread pitch

have been used in the production process to produce different shaped reinforcement strands. These strands with different production parameters were mechanically tested. The results are summarized in [35]. Reinforcement strands with different production settings are exemplary shown in fig. 11.

5.1 Robotic fabrication process

Within a digital fabrication setup, the DWM needs to be complemented by a robot arm and an appropriate end effector, in order to automatically guide the reinforcement strand along digitally predefined trajectories. Furthermore, this process always requires a substructure to wind on. The integration strategy for continuous fibre reinforcement strongly depends on the respective 3DCP technique. Following the elementary classification by Kloft [3], shown in fig. 3, the two approaches “Concrete Supports Reinforcement” and “Reinforcement Supports Concrete” are applicable for winding, leading to different implications. Whenever a component is printed at first, it can serve as substructure for winding. In contrast, a wound fibre structure itself can act as formwork for concrete printing.

On that basis, three main strategies regarding the processes of fibre reinforcement integration have been developed and validated by means of case studies of different scale [4]. Both the feasibility of process automation and the resulting compound quality have been tackled. For the approach of Frame Winding, a fibre mesh is robotically wound within an auxiliary frame at first place. Like this, complex geometries can be achieved even with simple frame shapes. SC3DP was identified as most promising for fully enclosing the reinforcement strands with concrete and thus obtaining thin reinforced and geometrically well-defined shells. Investigations for optimizing the compound quality and minimizing the amount of excess material are ongoing [4].

The second technique, Core Winding, was developed to robotically implement a reinforcement strand along the outside of a freshly printed element. In combination with SC3DP, it has been proven that complex curved layouts, especially force-flow-oriented reinforcement, can be approximated with help of a specially developed end effector that allows fixing the fibre strand at specific points. A SC3DP cover layer is used to fully embed the reinforcement in the concrete. [34]

Figure 12. Exemplary application of the dynamic winding process: Robotically integrated fibre reinforcement as part of an additively manufactured pedestrian bridge

The third approach of Pin Grid Winding aims at the preproduction of flat and slightly double curved meshes which can be placed between printing steps. The integration of flat inlays has been tested for different particle bed printing techniques so far (e.g. Large particle 3D concrete printing [39]). Furthermore, a double curved mesh has been integrated laterally into a SC3DP-wall-element.

This classification is further differentiated by new use cases. For example, a printed, non-standardised column was reinforced with continuous fibres instead of stirrups. For this geometric special case, the Core Winding could be simplified without pointwise fixation. Furthermore, a modified version of Pin Grid Winding was applied to a pedestrian bridge, in which the pins are distributed over a double-curved surface and remain permanently in the component (fig. 12). The range of different case studies evolved together with the continuous development of the DWM and always posed new challenges for the dynamic production of the fibre reinforcement.

5.2 Required data and parameters for production

A basic prerequisite for dynamic winding is the flexibility of the reinforcement strand, which is provided by the room-temperature curing resin. However, it has been found that larger strand diameters also increase the minimum bending radii at which the strand structure remains undisturbed. The parameters for the secondary yarn have an additional influence on the bendability. The pitch and pre-tension of the helix are, along with the compaction of the primary fibre strand, the central parameters for influencing the surface structuring.

For robotic processing, the maximum reinforcement production rate and the range of adjustable tension applied to the outgoing strand represent boundary conditions. The production rate has an influence on the scope of realisable experiments but is not decisive for applicability in research. However, for the economic viability of the process, the scalability of speed has been considered in the conceptual design.

The adjustability of tension on the strand is crucial depending on the application and the strand diameter. Larger diameters require higher tensions to be pulled straight. For smaller diameters, tension should be reduced accordingly to avoid unnecessary stress on the strand itself, the robotic system and the support structure. Core Winding in particular is limited in terms of tension so as not to loosen the pointwise fixations.

Ultimately, the DWM provides a certain operating range, which must be taken into account in the planning of the digital fabrication. From this in turn, parameters such as the choice of diameters and the required tension on the strand are derived.

6 Conclusion and outlook

This paper presents a novel and holistic process for reinforcing additively manufactured concrete components. Based on preliminary work, a Dynamic Winding Machine (DWM) was developed with which reinforcement strands can be produced from fibre-reinforced plastic. By using a room-temperature curing resin, these strands can be processed into reinforcement structures after production by means of robotic winding using various strategies that were developed simultaneously. By keeping the machine design as simple and compact as possible, it is possible to produce reinforcement strands in situ and on demand. The overall process is already designed in such a way that production is possible directly on the construction site in combination with mobile manipulators.

The positioning of the DWM within a robotic manufacturing process was discussed and a final concept was developed. Based on this, requirements for the machine were derived and a final version of the Dynamic Winding Machine was developed over several iteration stages. During development, reinforcement strands were produced in parallel and examined for their mechanical performance. The machine was tested with the robotic integration concepts and its performance has been evaluated during the production of various demonstrators.

Future research will aim to increase the degree of automation in production by integrating additional sensors. The authors expect this to lead to a more precise adjustability of the production process and thus to highly qualitative and repeatable reinforcement properties. The reliable applicability under real construction site conditions will be verifiable thanks to a novel research facility, the Digital Construction Site, which is currently being built at the TU Braunschweig.

Data availability statement

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

Author contributions

Conceptualization, T.R., S.G., N.H. and C.H.; methodology, T.R., C.H.; software, T.R. and S.G.; validation, T.R.; formal analysis, T.R.; investigation, T.R. and S.G.; resources, T.R. and S.G.; data curation, T.R.; writing—original draft preparation, T.R and S.G.; writing—review and editing, T.R., S.G., N.H. and C. H.; visualization, T.R.; supervision, N.H. and C.H.; project administration, N.H. and C.H.; funding acquisition, N.H. and C.H. All authors have read and agreed to the published version of the manuscript.

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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