DESIGN AND MANUFACTURING OF NOVEL THERMOPLASTIC CFRP RODS FOR CARBON CONCRETE COMPOSITES

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Abstract
The substitution of reinforced concrete with carbon concrete allows the reduction of materials used in civil engineering. The use of lighter and more chemically resistant carbon fibre reinforced plastics as a reinforcing material makes it possible to build more thin-walled than with conventional steel reinforcement. This allows the savings of cement and concrete as well as realizing of lighter and more filigree buildings. In addition to planar reinforcement structures, bar reinforcements are used for larger loads, which are focused here. A variant classification for the design of FRP rebars is developed, which shows the variety of design options and forms the basis for the conception of manufacturing processes. Thus, FRP rebars can be manufactured using pure primary forming or primary forming techniques in combination with reforming and separating processes. Variants of new types of thermoplastic CFRP rebars were tested by means of different manufacturing processes. The focus was also placed on efficient manufacturing processes, which should form as few materials as possible into a rebar quickly and in just a few process steps. The originated test specimens were then tested for their tensile strength. For this purpose, suitable testing fixations were developed. The tensile tests showed that all manufactured rod variants have at least 1.5 higher strength than conventional steel reinforcing rods. This shows that an efficient production of load-bearing thermoplastic CFRP rebars is feasible.

1. Introduction

Reinforced concrete has been an established building material for the flexible design of a wide variety of structures in civil engineering for more than 100 years. Due to the increased construction activity and the associated energy requirements, it has recently become necessary to build as easily as possible with minimal use of materials, in order to conserve natural resources and to achieve a higher architectural degree of freedom. In this context, it makes sense to replace the heavy and corrosive steel reinforcement with a lighter and more chemically resistant carbon fibre based material. This substitution saves masses and through lower concrete coverings also volume and thus building material. In addition, larger spans can be additionally achieved in building structures and material can be saved by minimizing the number of support elements such as bridge pier. Furthermore, longer life cycles can be achieved and additional material can be saved since repair is required only at longer intervals.

Depending on the load different reinforcements in the concrete are needed. These reinforcements can be both flat and rod-shaped. Flat reinforcement structures are more suitable for forming contours and for less heavily stressed components. Rod-like reinforcements are predestined to accommodate large tensile loads in a concrete component as reinforcement. In contrast to laminar textile reinforcement structures, they require a textured surface in order to achieve an optimum adhesion to the concrete and to absorb loads. As part of the investigations and developments presented, the focus was on the design, manufacture and testing of rod-shaped reinforcing structures made of carbon fibre reinforced plastics.

2. Conception of CFRP rebars

2.1. Design options

For the design of components, the first step is to clarify the requirements and obligations. Concrete has high compressive strengths combined with low tensile strengths. In many structures, the absorption of compressive and tensile loads is essential. For example, in structures with spanning functions such as ceiling elements in houses or bridges, areas arise on the one hand with compressive load and on the other with tensile load. To support the concrete in the tensile area, elements made of materials with high tensile strengths are used. These areas are load-direction-defined and usually run over longer distances in the component, the optimal shape results in slim reinforcement structures with load guidance in the axial direction. Fibre reinforced plastics (FRP) are predestined for this defined load case.

The transition from an iterative to an interactive approach is expedient for component development processes of lightweight structures in fibre composite construction or in fibre composite metal mixed construction [1]. Therefore, even in early stages of development, the later production process, which has a higher influence on the component shape by these materials, is taken into account. Optimal lightweight solutions are generated and efficient development processes are achieved.

Based on the function of rod-shaped reinforcement structures, appropriate design guidelines can be derived. For optimum load transfer and material utilization during load absorption, the greatest possible ratio of contact surface area to cross-sectional area should be sought. In doing so, the lowest achievable drop in the shear stress in the cross section is achieved and minimizes the stress peaks at the transition between concrete and reinforcement. Furthermore, according to the reinforcement guidelines and for a defined and calculable load transfer, the mantle surface must be profiled in order to achieve undercuts in the axial direction. In the construction industry, this profiling is generally named as the functionalization of reinforcement structures.

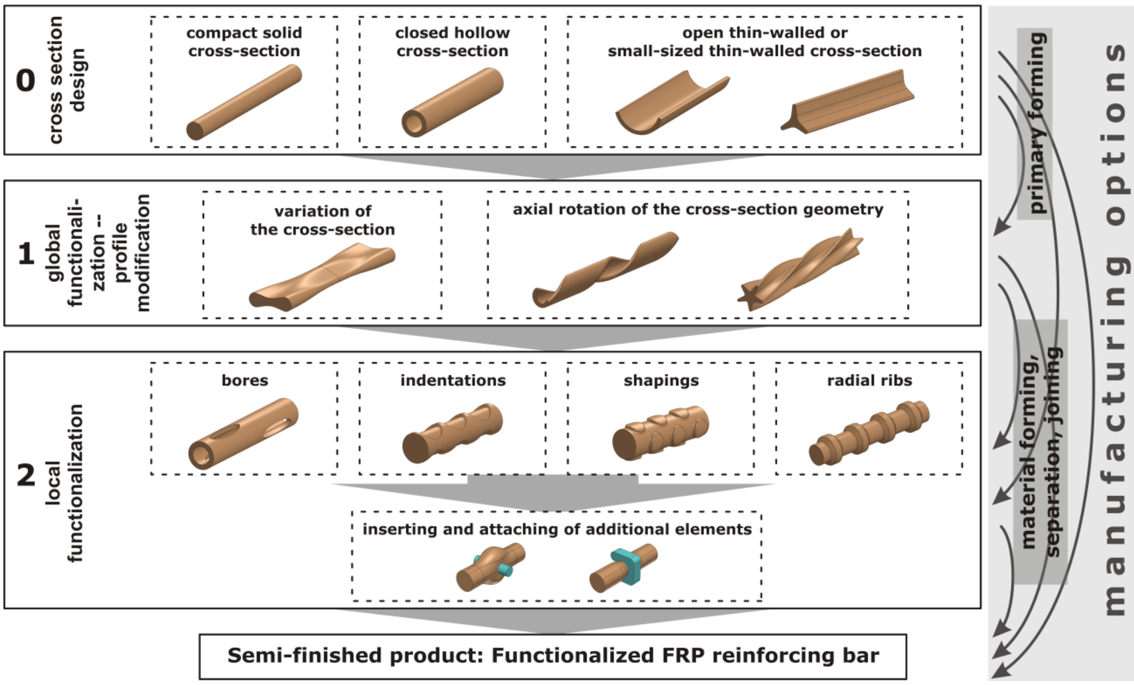

Figure 1. Systematic variant overview of the design of FRP rebars

The implementation possibilities of the design guidelines can be realized on different component levels - starting from the global bar cross section design over the cross section variation to the local realization of the functionalization. Figure 1 shows this wide variety. On the cross-sectional design level, the optimization is carried out from a compact solid cross section through closed hollow cross sections to small-sized or open thin-walled cross sections. At the global tread design level, functionalizations can be realized by variations of the cross section or by the axial rotation of the cross-sectional geometry, with the exception of the circle geometry. Functionalizations that are limited to local areas of the bar allow designs on the smallest component level. They can be realized through bores, radial ribs, indentations and shapes. All of these functionalizations can be implemented independently or even combined with each other. In addition, they can be supplemented with additional elements that produce functionalizations.

2.2. Manufacturing technology implementation

The design options can be transferred to a component or a semi-finished product with different manufacturing processes or production steps. Starting from the primary forming, the final semi-finished product of the functionalized rebar can be produced by means of forming, material joining or material separation. This can, as shown in the design options, be done with a method or the combination of methods.

The materials used, on the one hand, determine the final properties of the component, on the other hand, also the production engineering implementation. Thus, in FRP, a distinction must be made between reinforcing fibres and matrix. The different reinforcing fibres can usually be processed in all conventional FRP production processes and have small influence on the process selection. By contrast, for the matrix materials, in particular, the primary forming processes differed due to the different production characteristics between thermoset and thermoplastic matrix materials. According to the current state thermoset reinforcing rods are more common. However, they are less flexible for subsequent formations for adaptation as an anchoring element or for curved building geometries. Thermoplastics, for example, offer more design freedom with the subsequent forming capability. For efficient production, it is advantageous to use as few basic material variants as possible as well as fewer process steps that are as continuously executable as possible. So the focus here has been on thermoplastics with endless carbon fibre reinforcement (CFRP) for the development of production possibilities. Further design possibilities arise through the development of methods for tailoring carbon fibres in order to specifically adjust the property potential of CFRP to the respective requirements [2].

The pultrusion process is a predestined and widely used method for the production of continuous straight profile structures with continuous fiber reinforcement. Recent developments enable the continuous production of curved profile geometries [3, 4]. In downstream process steps, axial surface contours can be achieved, which are necessary for the use as FRP rebar are listed in various investigations and developments [5-8]. Examples include the sanding of the rods [5], the shaping by pressing a wrapping into a matrix-rich rod [6] and spiral winding on rods with a compact cross section [7]. There are mainly considered glass fibers with thermoset matrix.

For the conceptual design of manufacturing processes for rebars made of thermoplastic endlessly carbon fibre composite, the pultrusion process is used as a basic manufacturing process. The basis for all concepts is the processing of already impregnated fibre material; this can be done by means of finished semi-finished products or by means of an upstream injection section. Table 1 shows manufacturing concepts for implementing design variants from Figure 1. The examples are subdivided according to the respective manufacturing processes or their combinations. For better clarity, only basic combinations are shown.

Table 1. Manufacturing concepts for FRP rebars

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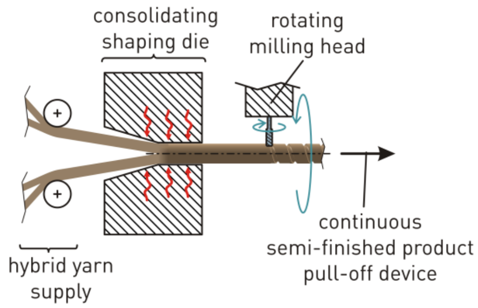
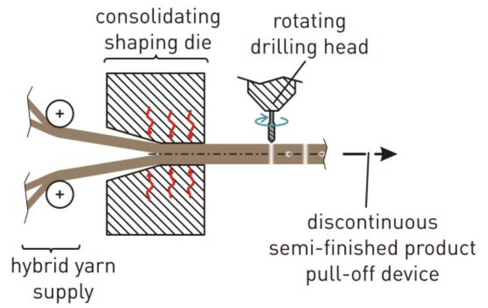
<tr>
<td>Primary forming and separating processing</td>
<td>

Contour milling</td>
<td>

Drilling</td>
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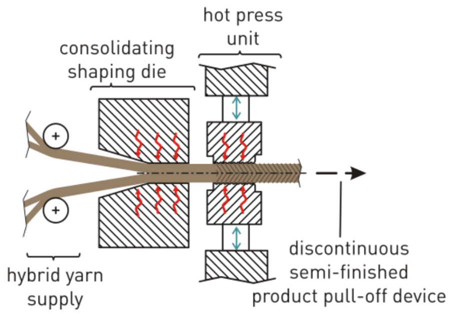
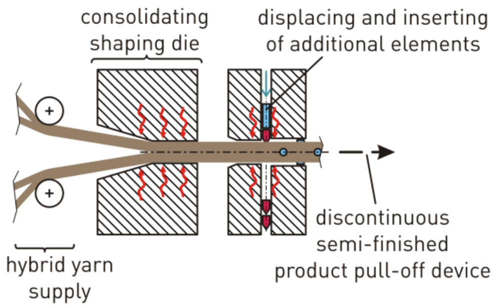
<td>Primary forming and reforming processing</td>
<td>

Form-pressing</td>
<td>

Out-displacing and penetrating</td>
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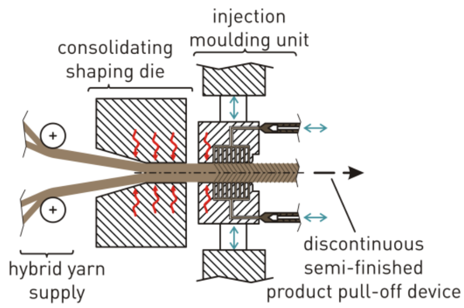
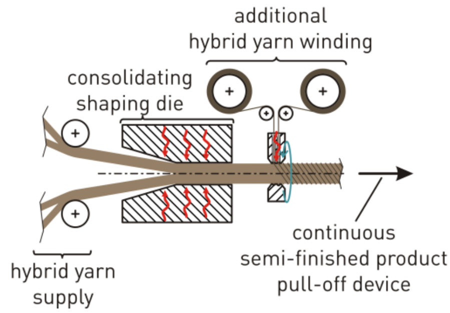
<td>Primary forming and material joining</td>
<td>

injection forming</td>
<td>

Winding, braiding</td>
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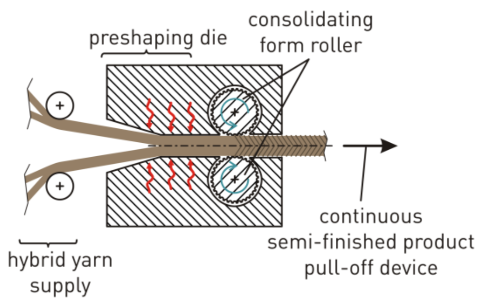
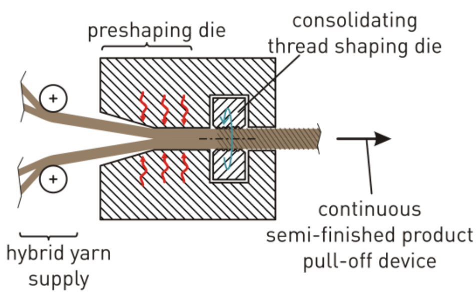
<td>Primary forming as the only process step</td>
<td>

In-situ rolling</td>
<td>

Thread forming, helix pultrusion</td>
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</table>

With the help of the variants systematics and the manufacturing concepts, a selection of preferred variants for FRP rebars was carried out in close coordination with experts from the construction industry. For these preferred variants prototypical manufacturing processes were developed and demonstrator rebars were manufactured. The helix pultrusion was implemented as a novel manufacturing process, which enables the production of a semi-finished bar product with surface profiling with adjustable fibre orientation in a single primary forming step. The manufacturing studies enabled the evaluation of the designed manufacturing processes in practical application as well as the production of test specimens for the evaluation of the manufacturing influence on the processed material.

3. Experimental studies on the strength of prototype rebars

The basis for the strength evaluation of the rebars is the material characterization of the base material. These are thermoplastic pre-impregnated tapes (SGL-CF-PA6-Tape) made of carbon fibre (SIGRAFIL C T50-4.0/240-T140) and polyamide 6 with a fibre volume content (FVC) of 0.45. The characterization was carried out on standard test specimens by means of standardized tensile, compression and shear tests. The determined and relevant mechanical properties are summarized in Table 2.

Table 2. Determined mechanical properties of SGL-CF-PA6-Tape with FVC 0.45

Mechanical property	SGL-CF-PA6-Tape (FVC 0.45)
Tensile modulus E_1 (GPa)	101.6
Tensile strength R_1 (MPa)	1290
Fracture strain A_1 (%)	1.1

The prototypically fabricated CFRP rebar variants are subjected to tension in the axial direction until fracture. For the simple and rapid testing of test specimens with a cylindrical geometry in the clamping area a developed clamping device was used. This is based on the experience of [9, 10] and allows through a rising torque a continuous load absorption in the test specimen with minimized stiffness jumps. Specifically for the test specimens manufactured by means of helix pultrusion, a different fixation of the rods in the testing machine is necessary due to the clamping geometry deviating from the cylinder. Therefore, a conically segmented potting anchorage has been proven, which was designed and manufactured with the experience of [11] for this test. By increasing the cone angle in the individual cone segments, it also enables an increasing tension in the direction of the bar end and thus also the reduction of stress peaks and stiffness jumps. The clamps for both variants are shown in Figure 2.

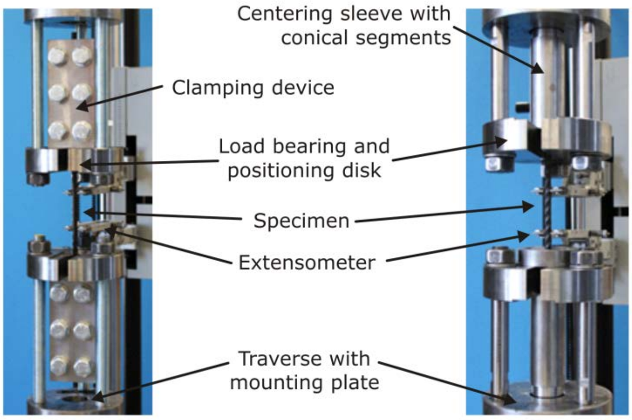

Figure 2. Testing fixations – Clamping plates (left), inversely segmented cone casting (right)

Each test geometry specimen was examined with 6 specimens and the fracture force was determined. For the comparison of the individual test specimen variants with each other, only the load-bearing cross-section of the test specimen geometries is taken into account. That is, the projected continuous cross-sectional area without the functionalized areas. For the reference rods without functionalization, the entire cross-section is considered to be bearing. Due to the addition of rotationally offset introduced additional elements in the specimen with additional elements results in no projected cross-section, which is consistently supporting. Thus, the projected supporting cross-section is considered in the area of an additional element for the test specimen and transferred to the entire specimen.

Table 3. Overview of the prototypically manufactured bars and the determined carrying capacity

Functionalization	Specimen	Fracture strength relative to the load-bearing cross-section (MPa)
Reference (no Functionalization)		1285
Winding-forming by means of semi-finished tape		1052
Contour milling of functionalization		1240
From-pressing of functionalization		895
Primary forming only with helix pultrusion		867
Out-displacing and penetrating of cylindrical elements		755

The individual test specimen variants with functionalization detail and the results for the fracture strength relative to the load-bearing cross-section are summarized in Table 3. It can be determined that all test specimens achieve higher fracture strength than conventional steel reinforcing rods (B500S) with 525 MPa [12]. This underlines the potential of the material. As expected, the test specimens with the least deviation from the axial fibre profile show the lowest drop in tensile stress at break to the base material. For final statements on the load-bearing behaviour of the rebar specimens in concrete, the results on composite investigations such as the concrete pull-out test are still pending. Thus, in a pure axial fibre orientation without additional fibre support between functionalization and supporting cross-section alone, the shear strength of the matrix material for the load capacity is crucial. Thus, especially in the winding forming and the milled contouring shear the load introduction areas without being able to exploit the full carrying potential of the cross section. This will lead to a reassessment of carrying capacity after the pull-out tests.

4. Conclusions

Based on the systematic recording of requirements for FRP-rebars, a design systematic was created. These shows, which design options can be implemented for rebars, based on the component level. In addition, this enables an overview of possible future manufacturing processes. This created a fundamental basis for systematic rebar developments as a conception tool was laid.

The developed and illustrated production process concepts show approaches to realize different rod variants. They allow the selection of efficient variants for the production of FRP rebars and form the basis for the prototypical production testing of different rod variants. Helix pultrusion, for example, has been able to successfully implement a manufacturing process for the production of bar structures with surface profiling in a primary forming step, which at the same time offers scope for design with regard to surface contour and fibre orientation. This allows great optimization potential for the FRP-rebar design.

The prototypically manufactured rebar specimens could be successfully tested with regard to their load-bearing behaviour. In comparison to the characteristic values of the base material, an estimation of the degrading behaviour of the production methods can be made. For a final and provable suitability of the manufacturing processes, composite tests with concrete are still pending. However, the investigations show that by means of thermoplastic CFRP such as carbon fibres in polyamide matrix, rebars can be efficiently produced which achieve higher strengths than conventional steel rebars. This enables developments in the construction industry towards resource-saving construction methods for a new type of construction.

Acknowledgments

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