Possibilities of extrusion production in concrete construction

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Abstract

Traditional concrete production methods prioritize standardized forms for precast or in situ applications, focusing on minimizing formwork requirements and labor costs rather than material efficiency. However, the utilization of textile-reinforced concrete (TRC) offers the opportunity to increase the load-bearing capacity through the high strength of the reinforcing materials, while reducing the concrete cover and component dimensions. While extrusion has previously been employed as an innovative manufacturing technique for TRC without the need for formwork, its application has been limited to uniform elements, thus hindering the production of shape-optimized components.

This study presents significant advancements in the production of TRC, highlighting the practicality of producing components with varying cross-sections using the adaptable mouthpiece extrusion technique. The profile´s width can be adjusted between 60 and 30 mm, while the profile height can be reduced from 10 to 5 mm. Moreover, the incorporation of stepper motors enabled rapid and accurate cross-section variations, enabling precise adjustments of the concrete strand to align with the precut textile strips. By employing mat-like reinforcements, the ExTRC were able to achieve transverse radii of up to 76 mm, longitudinal radii of up to 80 mm, and even double-curved shapes following the initial horizontal extrusion process. The findings highlight the potential for enhanced design flexibility and structural optimization in concrete construction. Further research and implementation of these techniques can contribute to the advancement of TRC technology and its application to automated serial manufacturing of individualized precast concrete components.

Keywords: extrusion, textile-reinforced concrete, material-minimized, variable cross-sections

Kurzfassung

Herkömmliche Betonherstellverfahren sind lediglich für Fertigteil- oder Ortbetonanwendungen mit konstanten, standardisierten Querschnitten geeignet. Der Fokus liegt meist eher auf der Minimierung des Schalungsaufwandes und der Arbeitskosten als auf der Materialeffizienz. Die Verwendung von textilbewehrtem Beton (TRC) bietet jedoch die Möglichkeit, die Tragfähigkeit durch die hohe Festigkeit der textilen Bewehrung zu erhöhen und gleichzeitig die Betondeckung sowie die Bauteilabmessungen zu reduzieren. Die Extrusion als innovatives, schalungsfreies Herstellungsverfahren für TRC wurde bisher nur für einheitliche Elemente eingesetzt, was die Herstellung formoptimierter Bauteile beschränkt.

Dieser Beitrag stellt einen bedeutenden Fortschritt bei der Herstellung von TRC dar und zeigt, dass es möglich ist, mithilfe eines einstellbaren, variablen Mundstücks Bauteile mit variierenden Querschnitten herzustellen. Die Breite des Betonquerschnitts kann zwischen 60 und 30 mm variiert werden, während die Profilhöhe von 10 auf 5 mm reduziert werden kann. Darüber hinaus ermöglicht der Einsatz von Schrittmotoren eine schnelle und genaue Querschnittsveränderung, sodass der Betonstrang präzise an die vorgeschnittenen textilen Bewehrungsstreifen angepasst werden kann. Durch den Einsatz textiler Bewehrungen konnte der zunächst horizontal extrudierte textilbewehrte Beton (ExTRC) transversal mit Radien von bis zu 76 mm, longitudinal mit Radien von bis zu 80 mm und sogar doppelt gekrümmt umgeformt werden. Die Ergebnisse verdeutlichen das Potenzial für einen größeren Gestaltungsfreiraum und eine Optimierung von Bauteilgeometrien im Betonbau. Fortführende Untersuchungen dieses Verfahrens können zur Weiterentwicklung von TRC und seiner Anwendung in der automatisierten Serienfertigung von individualisierten Betonfertigteilen beitragen.

Keywords: Extrusion, textilbewehrter Beton, materialminimiert, variable Querschnitte

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Numerous contemporary buildings continue to be built using a substantial quantity of CO_2-intensive construction materials, despite the considerable potential for reducing building material consumption [1]. Therefore, it is essential to develop novel construction principles for material-minimized components with a low carbon footprint. One approach to address this challenge involves the integration of thin, shape-optimized components to attain reduced component volumes [2,3]. Optimizing the shape of these components involves adjusting their dimensions to the load, buckling curves, or neighboring building components [2,4–8]. This approach aligns with the guiding principle of "form follows force" [4,8].

Textile-reinforced concrete (TRC), in particular, is well suited for this innovative, structure- and material-optimized construction, because of the increasing performance of the building material, both concrete and reinforcement [9–13]. Through the utilization of TRC, especially carbon textile-reinforced concrete (CTRC), it is possible to enhance the load-bearing capacity of a construction component. This improvement is attributed to its high tensile strength of up to 4000 MPa and corrosion resistance of carbon fibers [9,11–14]. Therefore, the thickness of the concrete cover can be reduced to a minimum, only to ensure fire protection as well as transfer bond forces, since no corrosion protection is required [11–14]. Given the high durability of the utilized reinforcements, extended product service lives can be realized, leading to optimized material utilization [13,15,16]. The first examples of material-minimized shaped TRC structures are demonstrated in [11,17–20].

TRC structures are typically fabricated by, casting, lamination, or spraying requiring the use of formwork [18,21]. A promising method for the automated, formwork-free construction of high-performance TRC structures is the extrusion process, which is described in [22–24]. Kalthoff et al. developed a laboratory mortar extruder (LabMorTex) that enables the integration of textiles of varying stiffnesses into the concrete extrusion process [22,24,25]. In addition, the technical limits of shaping these fresh TRC elements were investigated and the first material-optimized concrete components using extruded TRC (ExTRC) were developed [22,26,27]. Currently, only linear cross-sections of TRC elements can be extruded. For the implementation of maximum material-minimized ExTRC elements, the implementation of variable cross-sections is required. [22–27]

Within this work, an innovative extruder mouthpiece was designed, automated, and validated, which can be used for the in-situ extrusion of variable ExTRC elements. Furthermore, the longitudinal, transverse, and biaxial shaping of this novel variable ExTRC elements is discussed in this paper.

1 Materials

Three textiles were chosen for this work. The selected textiles differ primarily in the choice of fiber material, impregnation, mesh size, and yarn thickness. An overview of the material properties is given in Table 1. The textiles were selected with the aim of representing a typical conventional range of textiles already successfully used in LabMorTex. Textiles 1 and 2 had flexible impregnations and small mesh sizes. The small mesh size was chosen to minimize textile damage during cutting of the variable cross-sections and to enable subsequent shaping of the ExTRC. Stiff Textile 3 was chosen due to its tensile strength of over 4200 MPa, enabling the production of high-performance variable ExTRC. The selected textiles are shown in Figure 1.

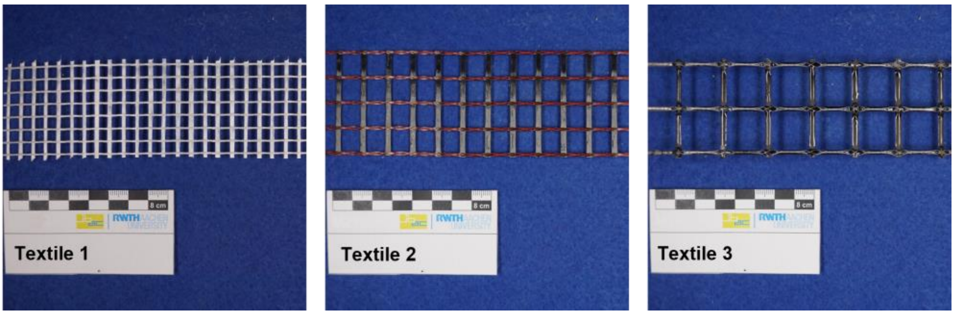

Figure 1 The textiles used. Textile 1 (elastomer-impregnated glass fiber textile), Textile 2 (Polystyrol-impregnated carbon textile), Textile 3 (epoxy resin-impregnated carbon textile).

Table 1 – Parameters of the textiles used from [22,27], the manufacturer's datasheet and own results.

Parameter	Unit	1	2	3
Fiber material	-	AR-Glass	Carbon	Carbon
Impregnation	-	Polymer	Polystyrol	Epoxy resin
Tensile strength (warp)	MPa	1064	1836	4250 ± 260
Modulus of Elasticity	GPa	49	150	240 ± 0.3
Mesh size (warp x weft)	mm	5 × 5	12 × 11	21 × 21
Thickness	mm	0.85	0.95	2.40
Yarn cross-section	mm²	0.29	0.57	0.90

For the investigations, a concrete mix based on [22–27] suitable for the production of ExTRC components was used. The mix design is given in Table 2.

Table 2 – Mix design of the concrete for the extrusion process.

Parameter	Unit	Amount
CEM I 42.5 R		700
Silica fume powder		70
Fly ash		210
Water	kg/m³	278
Sand: 0.1-0.5 mm		670
Quartz powder: 0-0.250 mm		278
Methylcellulose		7.0
Basalt microfibers	Vol.-%	0.50

2 Methods

2.1 Production

The extrusion process has been comprehensively explained in [24]. A brief description of the production procedure is given below. The concrete utilized for the extrusion process was prepared using an Eirich R05T intensive mixer with a maximum capacity of 40 L. For each batch, 18 L of fresh concrete were produced. For the extrusion itself, a Händle laboratory extruder known as the LabMorTex was used. A picture and a sketch of the extruder are featured in Figure 2. After the concrete leaves the mouthpiece, it is transported on a conveyor belt for further processing.

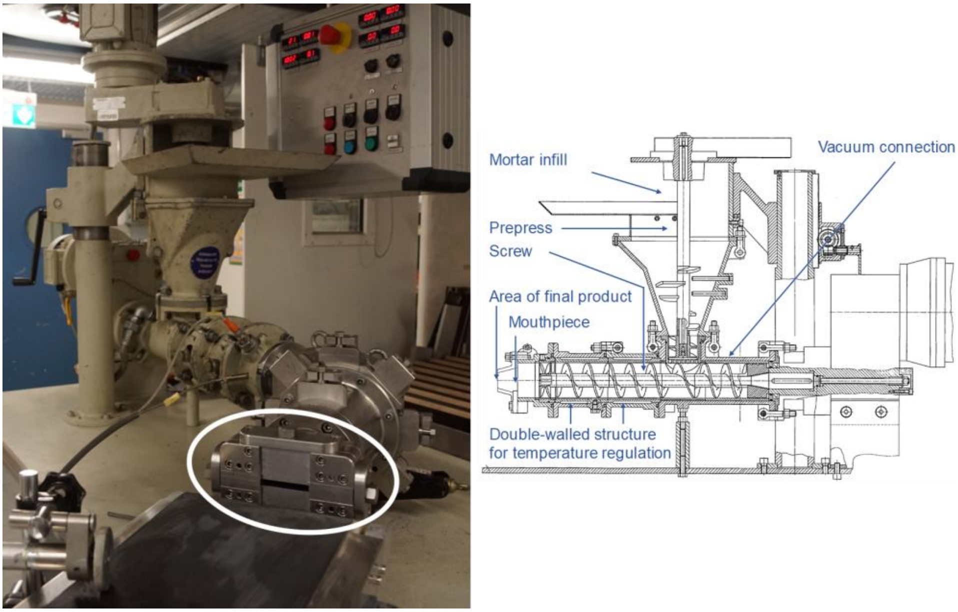

Figure 2 (a) Laboratory extruder LabMorTex design with adjustable mouthpiece (white outlined) and (b) Schematic sketch of the underlying extruder [24].

2.2 Adjusting the cross-section

In collaboration with ZMB Braun, an innovative adjustable mouthpiece was developed. This mouthpiece incorporates adjustable screws and sliding bolts, enabling both horizontal and vertical movement in front of the opening. The design facilitates precise modifications to the cross-section area. The adaptable mouthpiece allows the variation of cross-section width from 60 to 30 mm, as well as cross-section height from 10 to 0 mm. The aim was to adjust the cross-section width of ExTRC within the 60 to 30 mm range and to demonstrate the feasibility of reducing the cross-section height to 5 mm. The mouthpiece is illustrated in Figure 3.

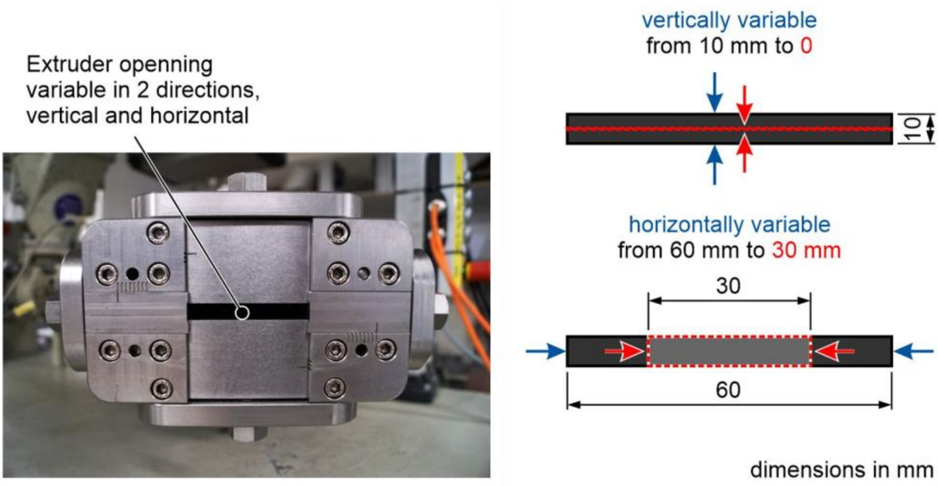

Figure 3 (a) Close-up of the adjustable mouthpiece and (b) the maximum and minimum possible cross-sectional dimensions

The adjusting screws of the variable extruder mouthpiece were operated in various ways during this work: by hand, cordless screwdrivers, and stepper motors. The three types of adjustment used for the variable extruder mouthpiece are shown in Figure 4.

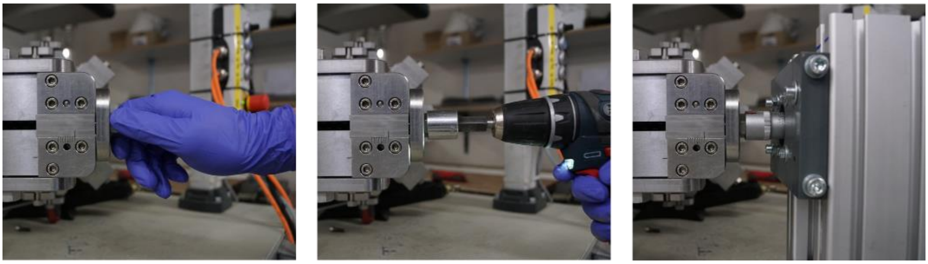

Figure 4 Adjusting the cross-section by (a) hand, (b) cordless screwdrivers, and (c) stepper motors.

The manual adjustment of the cross-section was carried out independently by two operators. The cordless screwdrivers that were used rotate with speeds up to 400 rotations per minute (RPM). Given that these screwdrivers were managed by two different operators, an effort was made to initiate their operation simultaneously and subsequently accelerate them at full speed.
Two stepper motors with a speed of up to 3,000 RPM were used. A reference point was defined for both stepper motors, designating the position at which the mouthpiece was completely opened. Additionally, a customized program was run on both stepper motors to determine the precise endpoint corresponding to complete closure of the mouthpiece. Furthermore, the motors are operable through remote control following programming. This approach enables the initiation and cessation of motor operations, along with the specification of rotation direction (for opening and closing) and rotation speed. For the purpose of aligning and transferring the motor functions to the adjusting screws, a framework has been designed. This framework facilitates the horizontal and vertical shifting and positioning of both motors. The motors and the framework are shown in Figure 5.

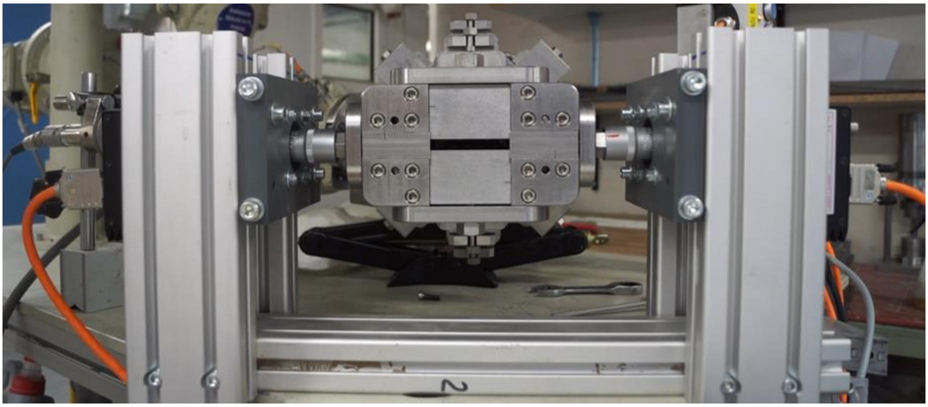

Figure 5 Stepper motors and framework.

2.3 Shaping and bearing constructions

To accomodate the varying cross-sections and possible loads, the shape of the ExTRC had to be adapted. For this purpose, the ExTRC were first horizontally extruded and then shaped into various bearing constructions. Initially, two shaping axes and three different shaping types were defined, as depicted in Figure 6.

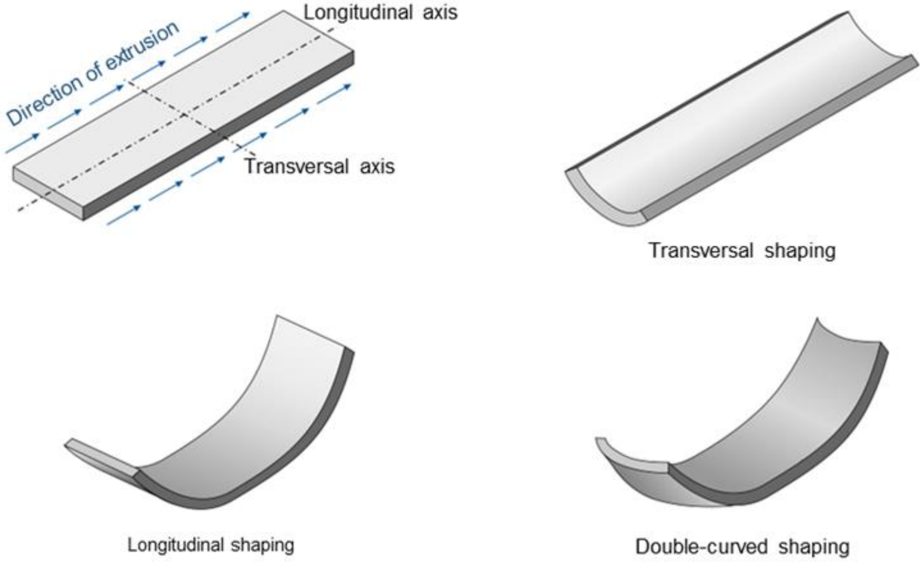

Figure 6 Definition of the shaping axes and shaping types.

The various bearing constructions are illustrated in Figure 7, indicating the different targeted shaping radii in Table **3**.

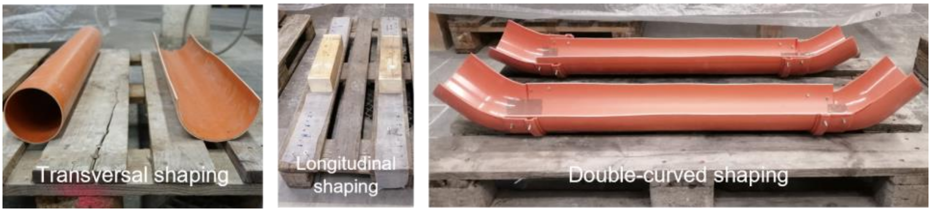

Figure 7 The bearing constructions for shaping around the (a) transversal axis, (b) longitudinal axis, and (c) both axes.

Table 3 – Targeted shaping radii of the bearing constructions used.

Bearing construction	Transversal radius in mm	Longitudinal radius in mm
Transversal shaping	52	-
	76	-
Longitudinal shaping	-	80
	-	80
Double-curved shaping	76	92
	76	112

3 Results and Discussion

3.1 Range of possible cross-sections

The cross-section width was successfully varied over the entire possible spectrum from 30 to 60 mm during variable extrusion with textiles. Furthermore, a reduction in cross-section height from 10 mm to 5 mm was sucessfully realized.

3.2 Optimization and automation of the mouthpiece adjustment

The objective of cross-section variation during extrusion was to enable fast and targeted adjustments for both narrowing and widening. Throughout the extrusion process, efforts were made to maintain a uniform adjustment of the cross-section width to match the precut textiles from both the left and right sides.

Initially adjusting the mouthpiece manually demonstrated the feasibility of achieving variable cross-section extrusion. However, challenges arose with manual mouthpiece adjustment, notably the slow and inconsistent rotation speed. In addition, only small cross-section variations could be achieved over a large specimen length. A significant improvement over manual operation was the use of cordless screwdrivers. The suitability of the mouthpiece for faster variations with an electric drive was verified. Variations could be performed at high speeds of 400 RPM and 8.33 mm/s. At these high speeds, minor inaccuracies in the timing of the variation had a very large effect.

The integration and programming of the two stepper motors, along with the creation of the framework, led to the establishment of a digitalized variable co-extrusion process. This approach effectively resolved issues encountered with prior operational methods. Both motors were started and stopped simultaneously by remote control. The desired variations could be precisely set in increments of $3.125 \cdot 10^{-3}$ mm. These adjustments could be made at speeds up to 750 RPM (15.63 mm/s). However, at higher speeds, the concrete strand often tore off or showed imperfections as the cross-section was reduced.

3.3 Shaping of ExTRC with variable cross-sections

The shapeability of the ExTRC mainly depended mainly on the stiffness of the textiles. Due to its high formability, the extruded concrete was shaped as desired in the bearing structures. The concrete mixture, which was already known to be suitable for extrusion, could also be successfully used for variable extrusion without any adaptation.

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Transverse shaping was performed up to a radius of 76 mm. Since the specimens had a maximum width of only 60 mm, the transverse shaping was not very visible in some cases. While the concrete conformed to the bearing construction, especially on the inside, the textile was initially forced into the required shape. As the textile rebounded during the curing process, localized delamination effects occurred locally between the concrete and textile. In addition, the shaping of the concrete was hindered by the stiff textiles acting as a support. Transverse shaping was possible for Textiles 1 and 2, but not for textile 3 (Figure 8).

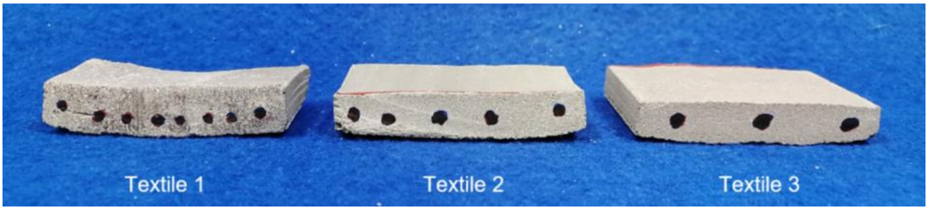

Figure 8 Transversal shaping with the shaping radius 76 mm of ExTRC of all textiles.

For the longitudinal shaping of the stiff Textile 3, a bearing construction was developed in which the textile can be clamped. Longitudinal shaping with Textile 3 was successfully carried out up to a radius of curvature of approximately 80 mm (Figure 9).

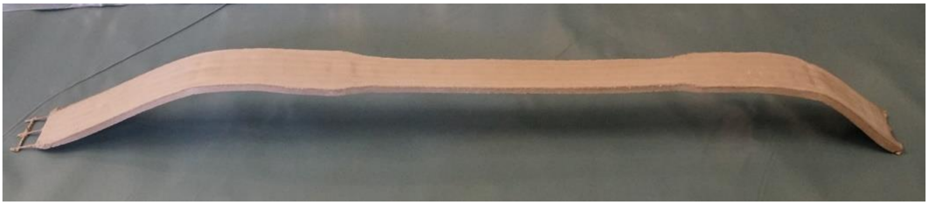

Figure 9 Longitudinal shaping of an ExTRC reinforced with Textile 3.

Double-curved shaping was successfully demonstrated in both transverse and longitudinal ExTRC. Specifically, it achieved successful transverse shaping at a radius of 76 mm and simultaneous longitudinal shaping at radii of 92 mm and 112 mm, as shown in Figure 10. For Textiles 1 and 2, double-curved shaping proved feasible. The shaping allowed the shape of the specimens to be adapted to the varied cross-section width.

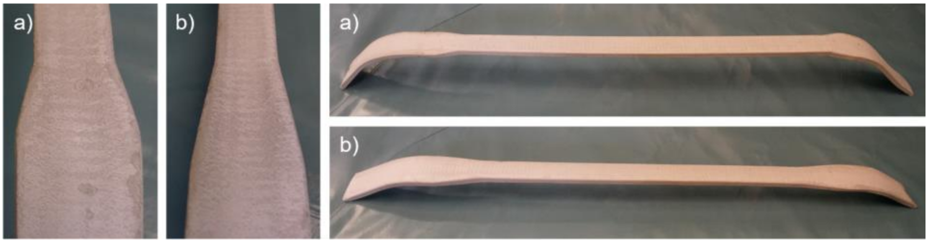

Figure 10 Double-curved shaping of ExTRC with (a) a taper from 60 to 40 mm, Textile 2, with a longitudinal radius of 112 mm, and (b) a taper from 60 to 30 mm, Textile 1, with a longitudinal radius of 112 mm.

Both elastomer-impregnated Textiles 1 and 2 are particularly suitable for shaping. The maximum textile thickness is limited by the extruder setup. Nevertheless, textiles with a thickness of up to 2.4 mm could still be successfully extruded. Textile 1 stood out as the optimal choice for precise cutting of the textile strips. This preference was due to the large number of longitudinal yarns per meter of width. This allowed the textile reinforcement to be evenly distributed across the varying widths of the cross-section. In addition, Textile 1, similar to Textile 3, could be ensured to maintain its form after the strip was cut because, unlike Textile 2, it was impregnated after weaving. This imparted strength to the nodal

points of the yarns. Because of their higher corrosion resistance, the two carbon fiber textiles can be regarded as more durable reinforcement options in concrete compared to Textile 1.
Shaping was successfully carried out for cross-section widths ranging from 30 to 60 mm. While shaping test specimens with cross-section heights of 7.5 mm, fewer cracks emerged during curing, even though these could be extruded flawlessly prior. Hence, shaping was viable for any cross-section width but limited to a cross-section height of 10 mm.

4 Conclusions and Outlook

This work aimed to develop an adaptable extruder mouthpiece and to experimentally investigate its use in the extrusion process. The research was conducted to identify materials suitable for variable extrusion. The extruder setup was tailored for the automated manufacture of concrete components optimized in terms of both shape- and material. Additionally, the potential for shaping variable ExTRC was investigated. The main findings are:

- ExTRC can be manufactured with a 50 % reduction in extrusion width, achieved by adjusting it within the range of 30 and 60 mm. Similarly, the cross-section height can be reduced by 50 %, from 10 to 5 mm, resulting in the sucessful production of exceptionally flat ExTRC.
- The variation of the cross-section has been effectively automated through programming and the installation of stepper motors. This enhancement has lead to significant improvements in the speed, synchronization, and precision of cross-section adjustments.
- Variable ExTRC could be shaped transversely, longitudinally, and even with double curves utilizing radii of up to 76 mm radius. The ability to shape depended on the characteristics of the textile rather than the concrete used. Elastomer-impregnated textiles demonstrated remarkable shape adaptability, while epoxy-impregnated textiles could only be longitudinally shaped when securely fixed in place.
- Suitable for extrusion of TRC with variable cross-sections, using the applied extruder, are mainly textiles with a thickness of up to 2.40 mm and the minimal permissible mesh size.
- It was demonstrated that the co-extrusion process developed at ibac is fundamentally suitable for a formwork-free, material-optimized, individualized, and automated application in precast concrete production under the premise of using an adjustable mouthpiece.

In further research, the following points should be investigated in greater depth:

- The strength and stability of ExTRC with variable cross-sections should be investigated. For example, shaped ExTRC could be tested in three-point bending tests. Furthermore, a comparison between the performance of varied and constant non-shaped ExTRC should be conducted using uniaxial tensile tests.
- An exploration of the possible cross-section dimensions and geometries should be conducted. Textiles with greater thicknesses could potentially be installed in multiple layers or alligned vertically.
- The co-extrusion process should be further automated. There is potential, especially in mechanisms that guide the textile during extrusion or in synchronizing the extrusion with the conveyor belt speed.
- For variable extrusion, the suitability of the concrete mixtures optimized in [24] with respect to their CO_2 footprint should be demonstrated.
- Possible applications of the double-curved ExTRC produced in this study include ther use as connecting elements in slab systems and as facade elements, particularly in the case of flat and plane ExTRC.

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