Vision and Strategies for Reinforcing Additively Manufactured Concrete Structures

Reinforcing Methods

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Digital Concrete Production With Vertical Textile Reinforcement

First Trials

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Abstract. One major challenge preventing widespread introduction of digital concrete production is the integration of reinforcing materials. Textile grid structures offer a possible solution for this challenge.

Textile reinforced concrete (TRC) has been researched for approximately 20 years and is currently being commercialized, initially in pre-cast elements for facades and bridges. TRC enables the construction of thin-walled, strong structures with a high freedom of design, properties well suited for the integration in digital concrete production.

First trials for this integration have been performed and published. However, these studies only use short fibres mixed into the concrete matrix or textile reinforcement within the printing plane, which limits the transferred loads.

This study shows the results of preliminary tests of vertical, out-of-plane textile reinforcements for digital concrete production. The textile reinforcement is fixed vertically and the concrete printing process is performed diagonally, “through” the textile. The results of four-point bending tests are presented.

Keywords: Fibre-Based Reinforcement; 3D-Concrete Printing; Textile Reinforced Concrete; Four-Point Bending Test, Digital Concrete Production

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Introduction

Building structures are traditionally made using primary materials such as cement, sand, fly-ash, water and other additives. These primary materials constitute to the formation of what is popularly referred to as concrete. In cases of specific strength requirements, additional reinforcing elements such as rebars are required. The primary drawback of these structures is that they are age limited by the deterioration rate of the steel rebar reinforcing structures. Beyond a certain age, building structures have to be refurbished or rebuilt in order to maintain their structural integrity [1].

This drawback led to the development of a new, innovative building structure material. Typically referred to as Textile Reinforced Concrete or TRC, these new building materials consist of concrete with a textile based reinforcement. These kind of reinforcements comprise of an alkali-resistant fibre based material such as glass, carbon or basalt fiber embedded within a cementitious matrix. The overwhelming advantage of these textile or fiber based materials is their combination of providing enhanced mechanical performance and resistance to corrosion as compared to their steel reinforced counterparts [2]. The extended life of the building structures provided through such materials has proven to possess a game changing effect on the overall economics of advanced building structures in the present day. Further, their ability to form into flexible shapes now provides architects with the freedom to design complex shapes [3].

Several manufacturing processes have been developed for manufacturing TRC based structures. As an example, textile reinforcements are produced using a warp knitting or winding process. These textiles are then coated to ensure the compatibility of the bonds between the textile and concrete mix. One of the drawbacks of such a production process is that it continues to be labour intensive.

Hence there is a need to optimize the production process for the development of such TRC based structures. This paper provides an insight into a new approach of manufacturing TRC based structures using 3D printing techniques.

With the onset of the third revolution and the inclusion of Industry 4.0 principles into the manufacturing sector, automation has become a key element of the manufacturing industry [4]. The advent of 3D printing and the introduction of digital technologies in the concrete construction sector are the result of the appropriation and adaptation of technology initially developed for other materials, such as resins and plastics [5].

State of the art

There are several approaches available for addressing the production of TRC based structures, especially in the area of the concrete printing processes. There are two technologies that exhibit promising results: extrusion- or spraying-based layer-by-layer deposition of a pre-mixed concrete solution and layer-by-layer binding by jetting a binding agent onto a previously laid solid aggregate.

Binder jetting has been used to 3D print sand moulds, but it can also be used to print concrete directly [6]. It offers a high degree of complexity in the design, such as parts connected only from above, due to the supporting surrounding unbound material. However, binding jetting has many drawbacks. For example, the binding process limits the dimensions of the printing process, such as layer height and speed of the nozzle movement. At the same time, the outermost area of the structure can receive an unreliable amount of binder. Additionally, the unbound material (cement) might not be reusable and the inclusion of reinforcement is problematic, due to the need of periodically placing new layers of unbound material.

Extrusion based deposition is the most widely used solution which was explored as early as 2004 [7]. The technical principle has been realized through different approaches, but in all of them, a pre-mixed concrete solution is continuously or discretely pressured through the opening at the end of a stiff nozzle, fixed at the tip of the print head. Its simplicity and flexibility make it an ideal option for on-site use.

The consistency of the mixture and the hardening time are the keys to the feasibility and the speed of the printing process. Hasty printing on uncured layers may deform the structure, and too slow printing may mean a weak binding between layers thus limiting the vertical printing rate. The development of technology that incorporates the reinforcement in the automated process is still in nascent stages.

In one of the approaches, the contours of the structure are printed leaving openings in which later the steel cage is inserted, and concrete is poured, in order to bind the reinforcement with the concrete [8]. A similar solution initially places a steel cage structure and then, using a specially designed print head and nozzle, encloses the cage layer-by-layer [9]. This however is limited by the geometry of both the nozzle head and the accessibility of the steel cage structure, especially in large scale structures (Figure 1).

Figure 1. Simultaneous extrusion on both sides of the steel reinforcement cage [9].

Research significance

In order to meet the growing demands, in volume and complexity, of the global construction industry, new production processes and materials are required. The combination of TRC and digital concrete production enables material efficient, quick and safe production of complex geometries. However, the integration of reinforcing textiles into the digital concrete production is challenging and current approaches are limited to the placement of reinforcement within the printing plane [10]. This paper presents a first step towards the vertical integration of reinforcing textiles into digital concrete production, facilitating structural reinforcement and unlocking new applications of digital concrete production.

Experimental investigation

In this study the structural behaviour of 3D-printed concrete elements with vertically positioned reinforcing textile grid structure is investigated under flexural load. The results are compared with the structural behaviour of the TRC specimens produced with the traditional casting method. In the following the material properties and production and testing methods are presented.

Fibre-based reinforcement materials and concrete mixtures

The biaxial warp knitted textile grid reinforcement is realized using alkali resistant (AR) glass rovings, type Cem-FIL® 5325 manufactured by the company Owens Corning. The mesh opening in warp and weft direction is approximately 8.4 mm. The rovings are warp knitted on the machine Karl Mayer Malimo P2-2S by using the binding type counterlaid tricot. This type of binding allows an easy impregnation of the coating material into the single fibres through the oval shaped cross section of the roving. The open mesh structure enables an easy penetration of the concrete matrix through the grid structure. The used knitting yarn is polyester yarn type 167f48. The physical and mechanical properties of the roving material are listed in Table 1.

Table 1. Properties of the roving material.

Property	**AR-glass roving**
Filament Diameter [µm]	19
Filament tensile strength [MPa]	1700
Modulus of elasticity [GPa]	72
Elongation at break [%]	2.4
Linear density of roving [tex]	2400
Density [g/cm^3]	2.68

The warp knitted textile is coated with an epoxy based resin material. The Epoxydharz L with the corresponding hardener EPH 161, produced by the company R&G Faserverbundwerkstoffe GmbH, is used in a mixing ratio of 100:25 parts by weight (resin:hardener). The coating material with its low viscosity and high strength is suitable to create an internal compound structure between the separate filaments of the roving. The mechanical properties of the epoxy resin system are given in Table 2.

Table 2. Properties of the epoxy resin system.

Property	**R&G Epoxydharz L + EPH 161**
Compressive strength [MPa]	123
Tensile strength [MPa]	70
Flexural strength [MPa]	112

For the production of 3D-printed specimens, a cement-based grouting mortar Sika Grout®-551 produced by the company Sika Deutschland GmbH is used. The matrix material has a maximum grain size of 1 mm, is viscous and easily pumpable and offers a fast hardening process at the same time. The compressive strength class is C50/60 (EN 206-1/DIN 1045-2), the flexural strength after 28 days is 10 MPa and the fresh mortar density is given as 2.27 g/cm^3.

To achieve a suitable matrix consistency for the printing process, the hardening accelerator Sigunit® L-5601 AF produced by the company Sika Deutschland GmbH is added to the mortar. The end mixture is printable as desired, sufficiently flowable to penetrate the textile and still dimensionally stable to adhere to the vertical, one-sided formwork immediately after application. The mixing ratio of the final mixture is listed in Table 3.

Table 3. Composition of the printable concrete mixture.

Component	**Quantity [g/kg]**
Sika Grout®-551	857.54
Water	137.21
Sika Sigunit® L-5601 AF	5.25

A fine grained concrete is used to produce the reference specimens. The maximum grain size is 0.6 mm. The flexural strength of the matrix material is 7.6 MPa and the compressive strength is 74.2 MPa, determined after 28 days. The composition of the mixture is given in Table 4.

Table 4. Composition of the reference concrete mixture.

Component	**Quantity [kg/m3]**
Cement CEM I 52,5 N	490
Fly ash	175
Silica fume (Elkem Microsilica® 940 U)	35

Quartz flour	500
Sand 0,2 – 0,6 mm	713
Water	280
Superplasticizer	7

Production of TRC specimens for four-point bending tests

In accordance to DIN EN 1170-5:1997 six 3D-printed Sika Grout, six cast Sika Grout TRC specimens and six reference cast TRC specimens are prepared to perform four-point bending tests. The dimensions of each specimen are as in the following: Length l = 340 mm, width w = 100 mm, thickness t = 15 mm. The textile reinforcement is positioned 5 mm above of the lower specimen face. Each specimen includes equal number of rovings in longitudinal and transversal directions.

3D-printed specimen: The coated textile is positioned in a vertical rectangular frame. The solid and liquid components are continuously mixed with an electric hand mixer for three minutes. Afterwards another two minutes are needed to fill the printing pump.

Each 15 mm wide and 50 mm high layer is printed from left to right, see Figure 2. The feed rate is constant at approximate 2 cm/s. The volume flow is regulated by the rotation speed of the threaded rod in the pump. Each specimen consists of two layers of printed matrix.

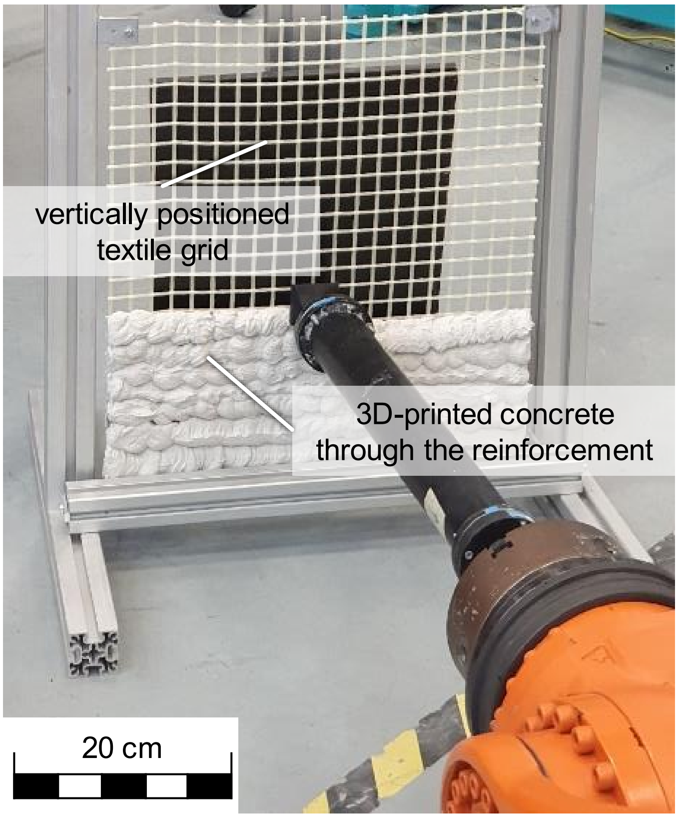

Figure 2. Demonstration of printing process.

Cast specimen: The coated textile is positioned in the same type of rectangular frame and the frame is placed horizontal to allow the casting process. The fine grained concrete mixture is poured into the formwork while applying vibration.

All specimens are cured for seven days. During the hardening process at room temperature, a foil cover protects the free matrix surfaces from water withdrawal for 24 hours. Afterwards the test specimens are removed from the formwork and stored in a water bath at room temperature for another six days until the test.

Four-point bending test: Test set-up

The four-point bending test is performed in accordance with DIN 1170–5 on a Zwick Roell testing device. The specimen is positioned on two support rollers and loaded using two load rollers in displacement controlled manner. A preload F = 1 N is applied to compensate for waviness and thickness deviations between the samples. The load rollers are moved downwards with a uniform test speed of 1.8 mm/min during which the load cell continuously determines the force. Measurements are taken up to a force drop of 70 % of the maximum force or up to a travel distance of 40 mm. Figure 3 shows the set-up of the four-point bending test.

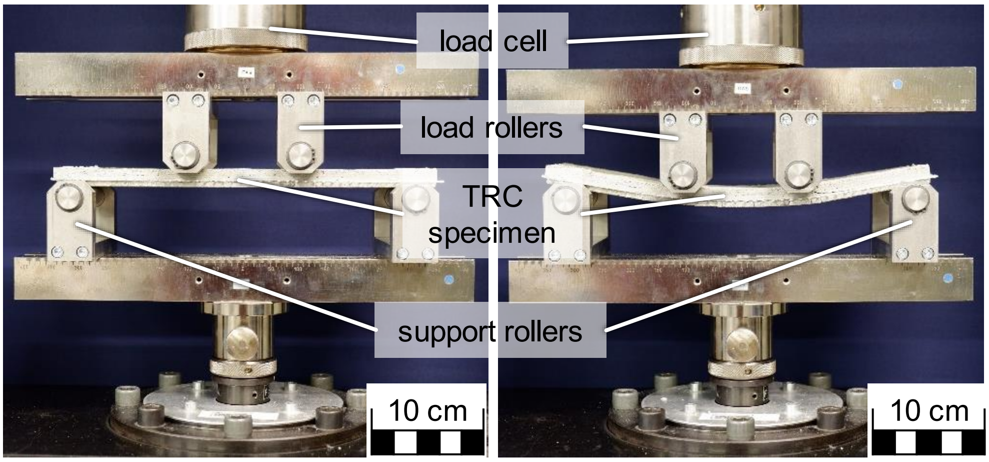

Figure 3. Experimental set-up of four-point bending test.

Experimental results and discussion

The load-deflection-curves of six 3D-printed Sika Grout TRC specimens, six cast Sika Grout TRC specimens and six reference cast TRC specimens are given in Figure 4.

The reference cast TRC specimens show a typical linear elastic response until the formation of the first crack. The cracking load values for each cast TRC specimen are between 7 to 8 MPa, which demonstrate the given flexural strength of the used fine grained concrete. Multiple micro cracks follow the first crack in the load-deflection-curves. The adhesive bond between the concrete matrix and the textile reinforcement gets damaged until approximately 10 MPa. Hereafter the textile continues to carry on the tensile stress by a residual constant friction between the internal filaments of the roving and shows a non-linear response until the average ultimate load around 22 MPa. Several macro-cracks occur on the lower face of the specimens. Beyond the ultimate load the specimen is also cracked on its upper face and the concrete matrix is completely separated into two parts. Only the longitudinal textile reinforcement absorbs the load.

The casted Sika Grout mixture specimens demonstrate an unclear behavior in the linear elastic zone. The first cracks and also a formation of multiple micro cracks are invisible. The reason for this behavior could depend on the additives in the cementitious matrix mixture. The specimens show an almost linear elastic response until the average ultimate load around 23 MPa.

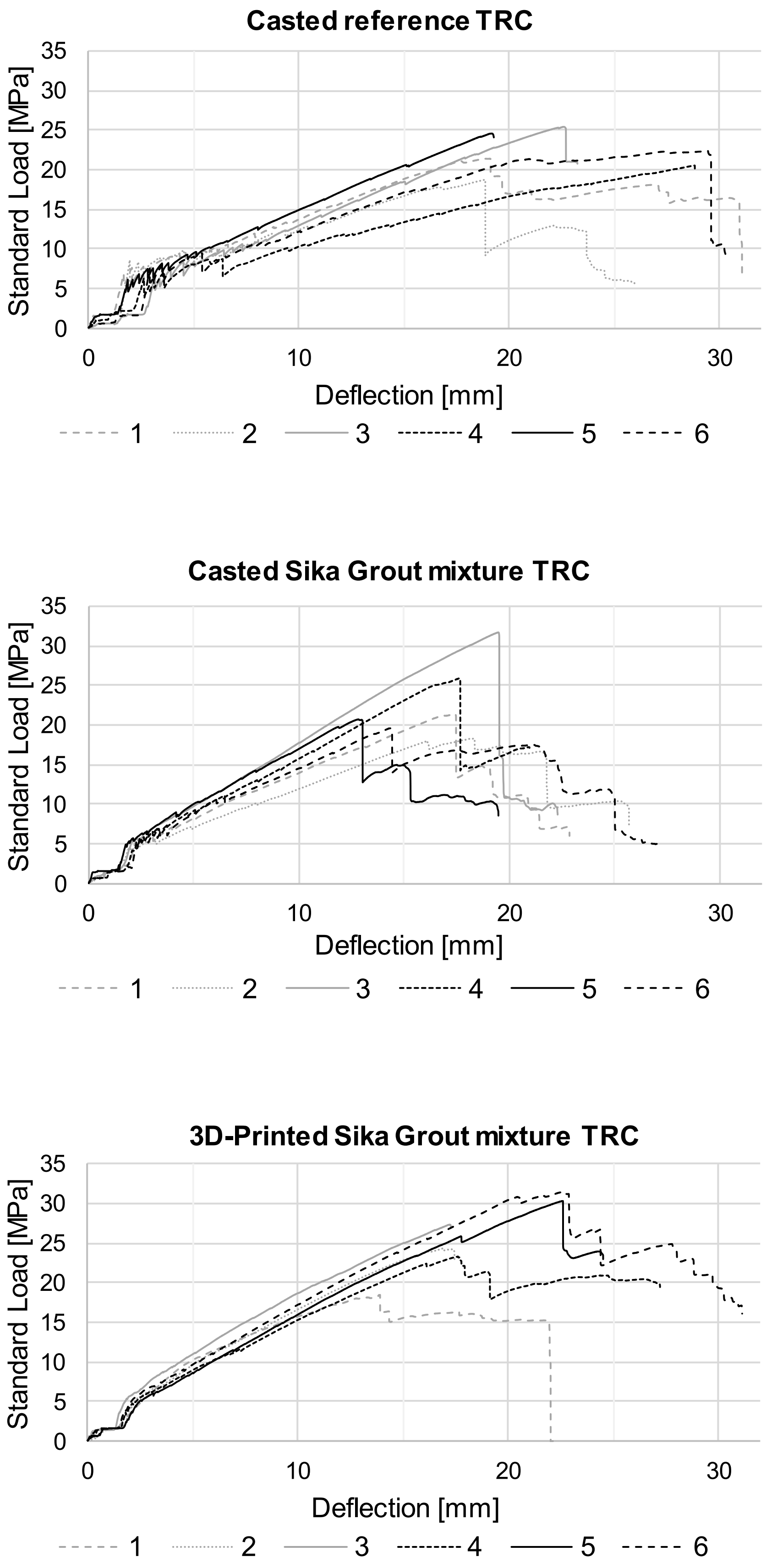

Figure 4. Load-deflection-curves of tested specimens.

The 3D-printed Sika Grout mixture specimens show an almost linear elastic response until the average ultimate load around 25 MPa. The reached ultimate load and its deflection value are similar on the basis of the relatively small sample even more preferable than these of the cast TRC specimen. The application of the cementitious matrix through the vertically positioned reinforcement grid does not affect the structural performance of the TRC elements adversely.

Conclusions

Based on the challenges in vertical reinforcement integration into the 3D concrete printing process, this study presented an alternative idea to integrate vertical reinforcement into the 3D-printed concrete structures. An experimental investigation of the effect of two different production methods for the TRC structures is presented. The AR-glass based textile grid reinforcement is positioned vertically and the concrete is printed horizontally through the textile grid. The structural behavior of the 3D-printed Sika Grout TRC specimens produced in the first trials is investigated under flexural load and compared with cast TRC specimens of the same matrix. To classify the new specialized Sika Grout mixture, there is a further comparison with traditional cast TRC specimens. Six specimens for each test series are loaded to perform four-point bending tests in accordance to DIN EN 1170-5:1997. The load-deflection behavior of all three test series are similar. In case of 3D-printed TRC the reached ultimate load is approximately 2 MPa higher than in case of the cast TRC (+9 % load). It can be concluded that the 3D-printing of the cementitious matrix through the textile grid structures has no negative effects on the structural performance of TRC elements and must be further developed.

Data availability statement

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

Author contributions

Gözdem Dittel: Conceptualization, Investigation, Methodology, Visualization, Writing – original draft, review & editing. Martin Scheurer: Methodology, Writing – review & editing. Steffen Dringenberg: Investigation, Methodology, Visualization, Writing – original draft, Joaquin Velasco Jitton: Investigation, Visualization, Writing – original draft. Thomas Gries: Supervision, Writing – review & editing.

Competing interests

The authors declare no competing interests.

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