Visions and Strategies for Reinforcing Additively Manufactured Constructions 2023

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Structural performance of textile reinforced 3D-printed concrete elements

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Abstract. The aim of this study is to verify the industrial feasibility of integrating textile reinforcement into the 3D concrete printing process and to determine the flexural strength of 3D-printed concrete reinforced with alkali-resistant glass textiles. Due to the non-corrosiveness of the textile reinforcement, thin-walled concrete elements are feasible, reducing material consumption by up to 80 percent compared to steel reinforced concrete. The proposed method of the authors aims to combine 3D concrete printing with a single-sided, movable formwork in order to reduce the time-, personnel-, cost- and material-intensive formwork effort. As a first step towards that goal, in this study, a single-sided stable formwork following the printing path is designed and tested for its applicability on an industrial scale.

The prototypical implementation of the printing method through a textile reinforcement is tested. For this purpose, test panels reinforced with textiles vertically and horizontally are printed with concrete. The flexural tensile strength of the printed, reinforced elements is investigated in a four-point bending test. Based on the results of the investigations, the requirements for a movable formwork are defined for the industrial application of this study. The movable formwork will replace the formwork frames in the future, so that the 3D concrete printing process can be optimized in a material-saving way and in terms of circular economy.

Keywords: 3D concrete printing, textile-reinforced concrete, reinforcement integration, material characteristics, four-point bending test.

1. Introduction

As part of the digitalization efforts in the construction industry, 3D concrete printing is gaining importance. Automated production, higher productivity and efficient use of materials can be utilized to meet the increased demand for housing and the reduced availability of skilled workers. Low value-added depths and stagnant, low productivity mean poor utilization of existing potential in the construction industry [1]. Digitalization and the interconnection of planning, construction and operation of buildings will make a major contribution to increasing growth and efficiency.

In the context of the United Nations' Sustainable Development Goals, conventional construction methods using reinforced concrete are facing increasing difficulties in terms of ecology, economy and social issues. CO_2 emissions from cement production account for 8 % of global greenhouse gas emissions [2]. From an ecological perspective, this has a significant impact on global climate change. In addition, concrete consumption is higher for steel reinforced concrete than for textile reinforced concrete (TRC) due to the required concrete cover.

Resource scarcity and an increased demand for raw materials jeopardize the long-term supply of important concrete ingredients such as cement and sand. The environmental impact of the construction industry requires a massive rethink towards a circular economy.

With TRC, existing resources can be used more efficiently due to the reduced material consumption [3]. Against this economic background, there is currently a shortage of skilled workers in the construction industry. In addition, the cost of materials has risen sharply in 2021 compared with the previous year: the price of solid structural timber has increased by 77.3 % and that of reinforcing steel by 53.2 % [4]. Because formwork techniques in concrete construction are time-, labour-, and cost-intensive, formwork costs account for approximately 60 % of total construction costs in reinforced concrete construction [5]. In the medium term, this will be negatively affected by poorer material quality, more complaints, and project delays due to reduced manpower capacity [6]. Smaller and more households lead to a tremendous increase in housing demand, especially due to influx into urban centres with urban densification. These social and societal trend changes challenge the construction industry to serve the increased demand with sustainable and automated construction methods.

3D concrete printing is an additive and digital manufacturing technology that enables a seamless and automated process from planning to production. Planning and production processes are digitally accelerated, which is beneficial to the goal of modernizing and digitizing the construction industry. So far, reinforcement integration in 3D concrete printing has been based on the use of short fibres in the concrete mix or on steel reinforcement. The latter is inserted between the 3D-printed walls and subsequently filled with in-situ concrete. In addition to the extra work steps, the use of corrosive steel further promotes high resource consumption and CO_2 emissions, as a larger concrete cover is required for corrosion protection. Instead of steel reinforcement, it is possible to use textile reinforcement. An optimal combination of textile reinforcement and concrete matrix reduces the material consumption of concrete raw materials. The innovative composite material can meet the current challenges of the construction industry in terms of sustainability, automation and reduction of CO_2 emissions. 3D concrete printing already enables the automated production of buildings, the implementation of which has already been proven as inhabited single- or multi-family houses. In combination with textile reinforcement, 3D concrete printing becomes even more sustainable. The textile reinforcement also extremely increases stability and strength compared to previous sandwich methods with unreinforced 3D-printed concrete and internal steel reinforcement that is subsequently backfilled, during less material and space is required. One of the advantages to be mentioned is a more efficient use of resources compared to the conventional reinforced concrete construction methods [7]. In addition, the 3D concrete printer enables a construction progress designed for continuous operation, which is associated with less physical work and higher productivity. Additive manufacturing also opens up new architectural possibilities. Aesthetically challenging geometries can be produced with a 3D concrete printer without the need for complex formwork designs. As a result, material-minimized 3D concrete printing is more efficient than reinforced concrete in terms of personnel, materials, costs and time when it comes to customized design.

This work builds on the preliminary work in [8, 9]. There, a movable laboratory-scale formwork was developed to print concrete through the vertically positioned textiles and to completely enclose them. The acting forces and the length of the linear guide are based on a small-scale test setup. The preliminary tests showed the feasibility of a movable formwork as a modular linear unit. Due to the rigid positioning of the rails, the component heights have so far been limited to 80 cm. However, the advantages of the 3D concrete printer are based on the production of curved geometries and variable print paths along the three printer axes. Since linear rail guidance can only map a one-dimensional path, compatibility with industrial 3D concrete printing is limited to linear wall elements. This problem requires further adaptation of the movable formwork to additional axes in the print room. With further add-on elements and additional guide rails for height adjustment or rotation of the formwork panel, adaptation to other architectural designs is possible. As an optimization of linear guidance, mobile robots are an option to follow a curved path. However, this also increases the complexity of the printing path to be programmed in combination with the movable formwork. The printing room and the floor plan of the building limit the mobility, so the travel distance of a robot would have to be included in the design of the building. The control of the linear guidance with the speed of the slide that carries the formwork is still external and not linked to the control of the 3D concrete printer so far. This requires the cross-device linking of the printing speeds as well as the acceleration and deceleration processes along the printing path. To simplify the process, the movable formwork can be attached to the print head. This allows the concrete extrusion and the shuttering to be carried out in parallel.

The load-bearing behaviour of industrially produced 3D-printed concrete has not yet been investigated in combination with vertically placed textile reinforcement [10]. Therefore, the objective of this work within the CONCR3TEX project is to verify the feasibility of industrial 3D-printed concrete with textile reinforcement. For the material properties of the composite, the flexural tensile strength of 3D-printed textile-reinforced concrete elements is determined. For this purpose, test panels are reinforced with both vertically and horizontally positioned textiles and the concrete is printed through the reinforcing textile mesh. In the four-point bending test, the respective bending tensile strength of the realized structural elements is investigated and presented in a material characteristic. A deficit of 3D concrete printing is the integration of the reinforcement, which so far cannot be applied industrially in a continuous working process. The generative construction of the textile reinforcement structure during the printing process is not considered in this work. Instead, prefabricated textile reinforcements are fixed in a frame in front of the formwork in an upstream work step.

2. Materials and Methods

2.1. Textile reinforcement

Compared to carbon fibres, AR glass fibres, which are cost-effective and readily available, were selected as the fibre material for the textile reinforcement. When weighing up between carbon and AR glass fibres for the production of the textile reinforcement, economic reasons spoke in favour of the use of AR glass fibres. These have a tensile strength comparable to structural steel and are less expensive than carbon fibres, which would have a balanced price/performance ratio if the expected stresses were only very high. AR glass fibres CEM-Fil 5325 from Owens Corning with a fineness of 2 x 1,200 tex are used for the warp and weft threads in the biaxial warp knitting machine from Karl Mayer. The filament diameter of the AR glass fibres of 19 µm at a fineness of 2 x 1,200 tex results in higher strength than when using 2,400 tex (filament diameter 27 µm). The selected mesh size of 16.9 mm allows a high degree of reinforcement with sufficiently large openings so that the concrete mix can completely penetrate and enclose the textile. The binding type is pillar as shown in Figure 1. The textile mesh layers with dimensions of 1 m x 1.35 m are manually coated with epoxy resin L and hardener EPH 161 in a ratio of 100:25 and cured at room temperature for 24h. The surface weight of the dry textiles amounts to 284.5 g/m^2 and of the coated textiles to 431.3 g/m^2.

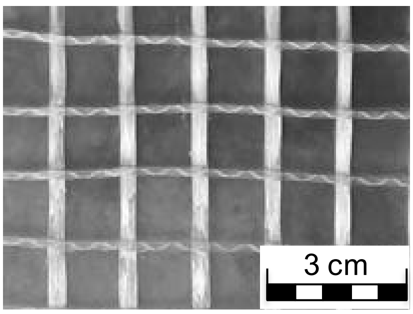

Figure 1. Epoxy coated AR-glass textile with pillar binding.

2.2. Formworks and textile positioning

For the test panels, PERI SE produced one frame for each of the material combinations. High-quality formwork frames with FinPly formwork panels from PERI SE were produced with external dimensions of 1200 mm x 800 mm. The phenolic resin coated formwork panels provide a very good exposed concrete surface. Before fixing the textile reinforcement, the entire formwork surface was additionally sprayed with PERI Bio Clean release agent. As a result, stripping of the specimens is associated with a lower risk of breakage. One of the rear formworks was assembled using 6 mm thick transparent acrylic instead of FinPly formwork panels. This allows the printing process to be observed from the rear to monitor the closing of the printed concrete behind the textile reinforcement. The position of the textile reinforcement is fixed by clamping the textile between the two frame parts. For the activation of the tensile properties of the textile reinforcement, it must be inserted into the frame as tightly as possible or, if necessary, pre-tensioned [11]. The frames were stabilized vertically.

2.3. 3D concrete printing for sample plate production

The 3D concrete printing of the textile-reinforced frames took place at PERI SE. The 3D concrete printer used is an early model of the COBOD BOD2. It consists of four vertical lattice columns mounted on foundations. Between each two supports runs a cross bridge that can be moved vertically. A trolley with the printer head is mounted on the connecting bridge. This is connected to the external concrete mixer via a 26 m long hose. This design allows the printing head to be moved to any position within the printing area. The 3D concrete printer used for this work has an axis length of 10 m each. The printer head with the nozzle attached to it can be rotated through 360° (see Figure 2).

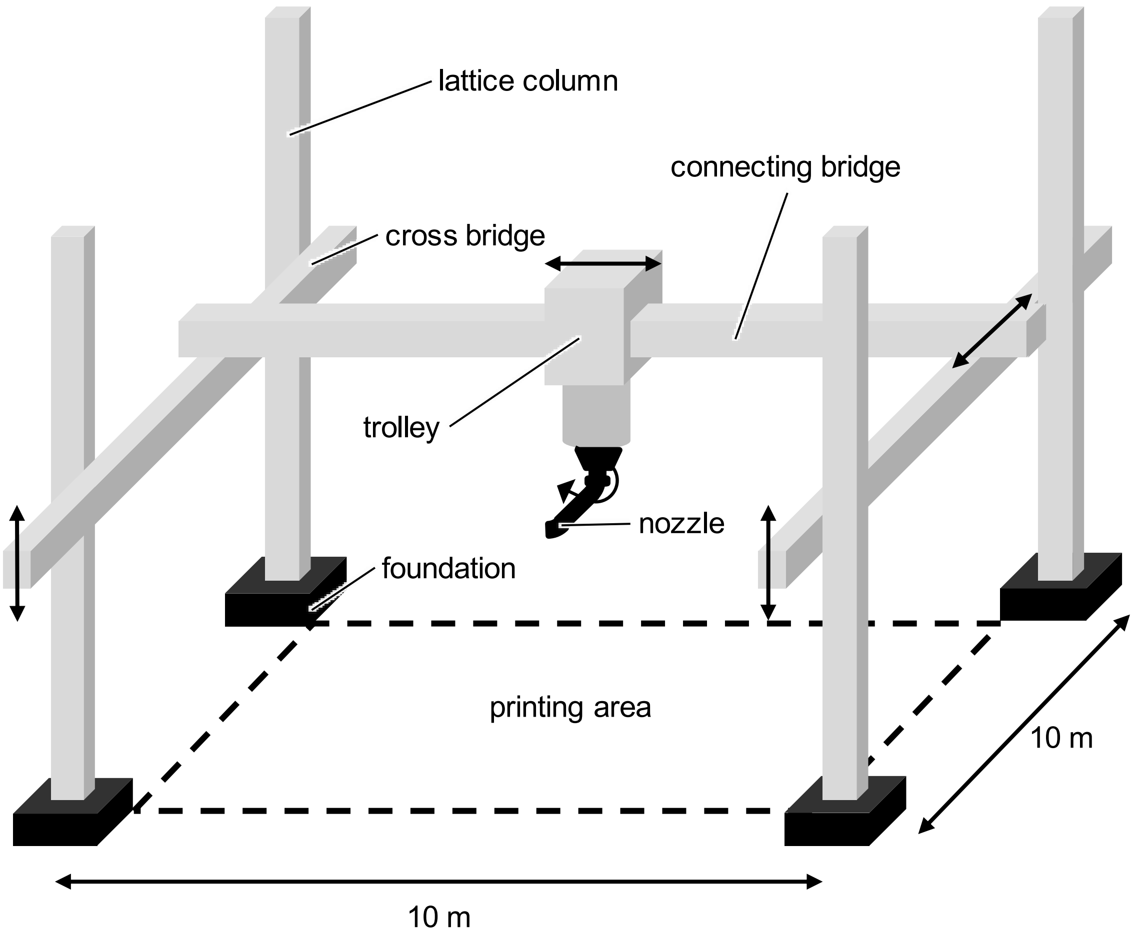

Figure 2. Scheme of 3D concrete printer.

This allows six formwork frames (each 1.2 m wide) to be set up next to each other within the printing area. The frames attached to the grid boxes are lined up at small distances from each other. Due to the slight deviations in the positioning and positional accuracy of the grid boxes, disturbances of the printing path are possible, which are to be avoided by the tolerance distance. For positioning, a minimum tolerance distance of 2 mm is maintained from the top of the nozzle to the outer edge of the frame. Positioning was checked in a dry test print without extrusion to ensure that no deviations occur in the actual printing process. The path length for the print head is 8.5 m in total.

The concrete used in this study is the commercially available mix Holcim TectorPrint 3D provided by Holcim (Deutschland) GmbH, Hamburg, Germany. The physical and mechanical properties of the concrete matrix according to the manufacturer are listed as in the following:

- Max. grain size: 4 mm
- Water content: 16.5 ± 1 %
- Processing time: 30 min
- Setting time: 150-200 min
- Density in hardened state: 2350 kg/m²
- Compressive strength after 28 days: 40 N/mm²
- Flexural strength after 28 days: 2.5 N/mm²
- Modulus of elasticity: 25000 N/mm²

After transferring the concrete mix from flexible bulk containers into the mixing silo, the concrete mix is blended with water. Due to the particle sizes of up to 4 mm, segregation of the aggregate during transfer cannot be avoided. After the mixing process, the moist concrete is pumped and enters a buffer tank directly at the trolley. Here, the concrete is continuously mixed further and held as a reservoir before it reaches the nozzle. The pumping process can be regulated by measuring the filling level in the buffer tank.

The new nozzle design offers the advantage of stripping the surface and getting more material behind the reinforcement. The speed was set at 26 mm/s (equivalent to 12 minutes per layer in one direction). The extrusion rate was 83%. The water flow in the mixing machine was set to 15.3 l/min to obtain sufficient strength during the stronger extrusion. Seven layers were printed (see Figure 3).

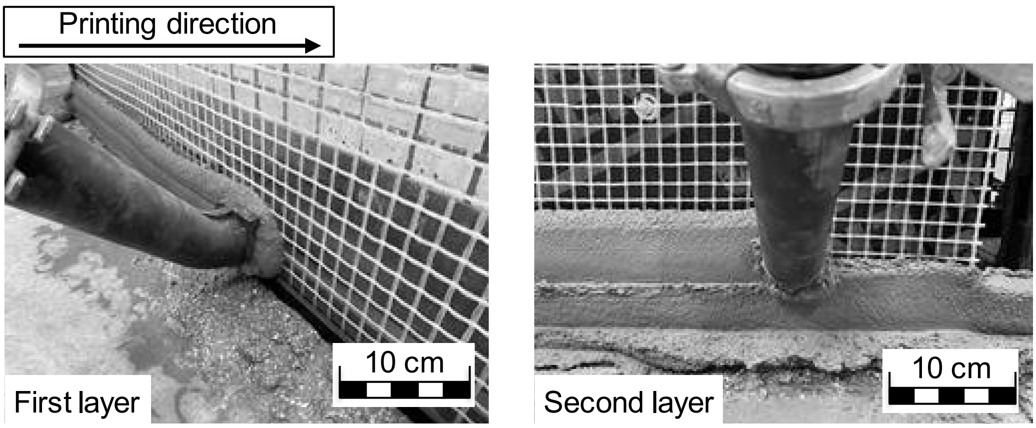

Figure 3. Printing process: First two layers.

Frames were also laid out horizontally along a line and printed vertically with a conventional nozzle. As with horizontal printing, the width of the extruded concrete strand is 5 cm. The 3D concrete printer extrudes concrete continuously as it moves the frames along a continuous printing path. Due to the slightly sloping hall floor, the slab thickness increases by 1 cm at one end. The pictures shown in Figure 4 represent the final state of the printing trials on vertical frames. Printing on horizontally positioned frames could be carried out without any change in consistency.

The surface was not treated or smoothed in the wet state of concrete because the stability was too low. The test panels cured in the standing or lying condition without any change in position. After four days, the slabs were stripped and prepared for cutting.

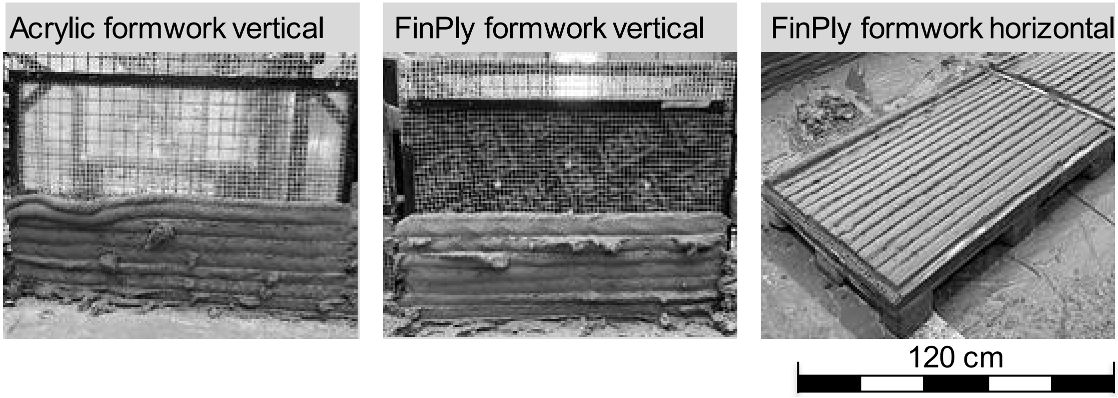

Figure 4. Results of the printing trials on vertical and horizontal frames.

2.4. Flexural strength according to DIN EN 1170-5

The examination of the flexural strength of the test specimens by means of the four-point flexural test is carried out in accordance with DIN EN 1170-5. Deviating from the formwork dimensions of the standard (500 mm x 800 mm), the test specimens for this series of tests are printed in a frame with the external dimensions 1,200 mm x 800 mm (see Figure 5).

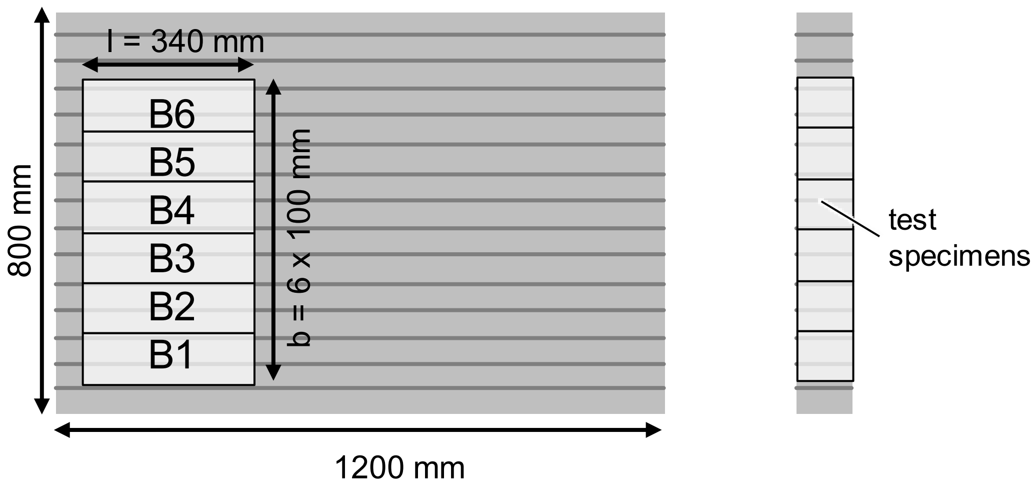

Figure 5. Cutting of the test specimens.

In deviation from the standard, the panels were demoulded after four days and the test specimens with the dimensions 100 mm x 340 mm were cut out. At least six rovings in the longitudinal direction and 21 rovings in the transverse direction are stressed on this surface. The degree of reinforcement in the longitudinal direction was about 0.55 cm^2/m. The number and the location of the interfaces in a sample are varied. It has to be mentioned that this fact has an effect on the mechanical properties. Textile reinforcement was placed in the tensile zone and was positioned at 5 mm height.

The test specimens were air-conditioned for 24 hours in the laboratory at the Institute for Textile Technology of RWTH Aachen University. The laboratory conditions have a temperature of 20 °C ± 2 °C and a humidity of 65 ± 4 % [12]. The cut test specimens B1 to B6 were measured to an accuracy of 1.0 mm before installation in the test fixture [13]. Due to time constraints the age of the test specimens at the time of testing was 13 days. The surface condition of the test specimens shows height differences of up to 1 cm. In order not to change the material properties of the test slabs in their fresh concrete state, no surface treatment was carried out. Since the test specimens could not be smoothed in the 3D concrete printing process, they hardened with an uneven surface. Subsequent smoothing by grinding or cutting the test specimens to half their height would also influence the material characteristics. Also due to the risk of cracking of the specimens, no mechanical treatment was applied. The test specimens were positioned with the formwork side facing downwards on the supports of the universal tensile testing machine [13]. This means that the reinforcement is located in the tensile zone (see Figure 6). The uneven top surface of the test specimens was compensated for by a movable fin, which adjusted itself by applying a pre-load to the surface before the load was recorded. The tests are carried out on the ZMART.PRO 1455 testing device from ZwickRoell GmbH & Co. KG. For test specimens with a length of l = 340 mm, the support span is L = 300 mm. The load is applied with two load rollers at a distance of 100 mm. The clamps have a radius of 10 mm (see Figure 6).

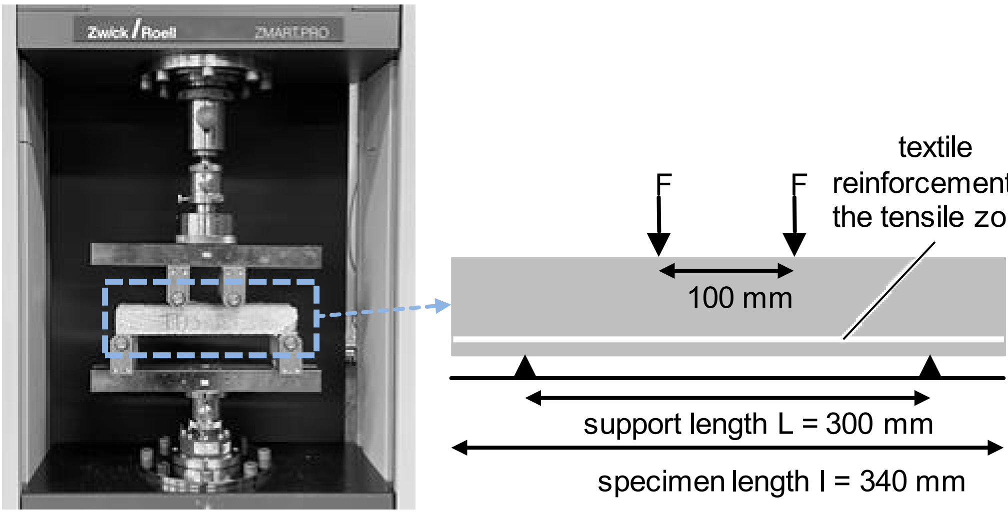

Figure 6. Test set-up in the four-point bending test.

At the beginning, a pre-load of 150 N is applied to uniformly stress the test specimens before the recording of the load begins. Subsequently, the specimens are tested in a displacement-controlled test. This means that the lower, movable crosshead is moved upwards via two lateral spindles. The load cell measures the applied force during this process. The clamped test specimens are loaded at a speed of 1.8 mm/min. The force cut-off threshold is 90 %. The flexural tensile strength σ_{MOR} [MPa] and the deformation [mm] are recorded. Due to manual cutting, the specimens have different dimensions. The height H was measured and documented in the centre of the specimen.

4. Results and Discussion

4.1. Concrete consistency and printing process

Segregation of the concrete constituents cement and aggregates in the filling process changed the consistency during the printing process. At the beginning, mainly larger grains were conveyed, which made penetration of the textile reinforcement more difficult. Uneven grain distribution affects the strength of the concrete because the constituents are not homogeneously distributed. Since the concrete has a short processing time of only 30 minutes, the duration of the mixing process, the length of the hose, the printing speed and the length of a strand determine the consistency at the tip of the nozzle. The concrete consistency can be adjusted directly at the silo by changing the amount of water added. However, this does not directly change the consistency at the print head, since the hose still contains the old consistency. Only after the volume in the hose has been fully used does the new consistency setting come into play. The buffer tank at the printer head continues to mix the concrete. If the pauses are too long, the concrete begins to harden. Since the consistency changes were made during the printing process, different strengths may have developed depending on the layer. The printing direction exhibited good surface finish and penetration of the textile reinforcement. The most important feature here was that as much concrete as possible was extruded in the direction of the formwork before lateral movement prevented penetration of the reinforcement. As the extrusion rate increased, more concrete got behind the textile reinforcement. At the same time, beads formed upward and downward outside the 5 cm nozzle width, conveying excess material to the next higher and lower layers, respectively. On the one hand, this was advantageous for filling the rear pressure space with concrete. On the other hand, this changed the position of the lower layers in particular.

The rigid consistency was necessary so that the strands, placed one on top of the other, achieved a sufficiently high stability in the fresh concrete state. However, this meant that the backward bond of the extruded concrete was not always complete. For the complete enclosure of the textile reinforcement without splash shadow formation, the consistency would have to be softer. The softer consistency offers the advantage that the concrete is not "cut" by the textile reinforcement. However, if the consistency is too soft, the stability of the layers for load transfer of their own weight in the fresh concrete state is no longer guaranteed. Since the stability of the layers was prioritized for 3D concrete printing, a stiffer consistency should be preferred. The splash shadowing did not show any detrimental bond adhesion in the four-point bending test. The textile reinforcement was sufficiently embedded and enclosed in the concrete so that tensile loading did not cause spalling of the textile reinforcement.

4.2. Textile reinforcement

The textile reinforcement separates the stiff concrete before it flows together again behind it. Despite fixing the textile reinforcement as tightly as possible to the frame, it was not possible to prevent deflection of the textile reinforcement as a result of the extrusion compression. This is due to the size of the frame, which should be reduced by at least half for future specimen fabrication. As a result, the textile has a shorter span length, which improves the positional stability in combination with closely placed spacers. The mesh size of 16.9 mm was not a limitation for positional stability. Larger mesh sizes could cause the rovings to deflect between nodes. Also, the degree of reinforcement would be reduced, minimizing the flexural tensile strength. Smaller mesh sizes are not recommended because they make it difficult for concrete to penetrate the textile reinforcement. Accordingly, the maximum grain size of the concrete would have to be reduced even further, which can have a negative effect on the strength. Manual coating shows uneven results. Due to the different absorbencies of the material and the substrate, deviations are possible. This should be automated by the use of a coating machine, as with the textile reinforcement does not unintentionally reduce the load bearing capacity. Brittle fracture of the epoxy coated textile material is a hazard because the load curve cannot be accurately predicted. However, by predicting several small cracks in the concrete, it is possible to estimate when the maximum load will be reached. As a result of the brittle fracture, there is a material failure of the reinforcement. The remaining rovings can only transfer lower tensile forces. Although the concrete was cracked in several places and the strain of the reinforcement could be distributed, the rovings are cracked.

4.3. Four-point bending test

In two test series, six specimens each (B1 to B6) were tested. The results are compared with the flexural strength of the unreinforced concrete which is 2.5 MPa after 28 days. All horizontally printed specimens showed a very similar load-deformation curve to each other. The mean value of the flexural tensile strength is 7.65 MPa. Load increases up to a maximum of 8.5 MPa are possible (specimen B4). The minimum value of the flexural tensile strength is 6.91 N/mm^2 (specimen B5). Due to the low scatter of the results of test specimens B1 to B6, the standard deviation is only 0.604 MPa. The small load collapses with further increasing standard force were caused by several fine cracks in the concrete. Only when the tensile strength of the reinforcement was reached the test specimens fail abruptly at a deformation of more than 8 mm. For the B2 and B5 specimens, residual load-bearing capacities of 2 and 1 MPa were still present up to a deformation of 17.5 and 20 mm, respectively (see Figure 7 left).

The vertically printed test specimens were tested analogously in the four-point bending test. The curves of the load-deformation record show strong variances within the test series. The minimum bending tensile strength of 2.77 MPa was measured for specimen B2. In comparison, test specimen B4 exhibits a bending tensile strength of 6.54 MPa, which is more than twice as high. The mean value of the flexural tensile strength was 4.79 MPa with a standard deviation of 1.34 N/mm^2. The test was carried out up to a maximum deformation of 17 mm (see Figure 7 right).

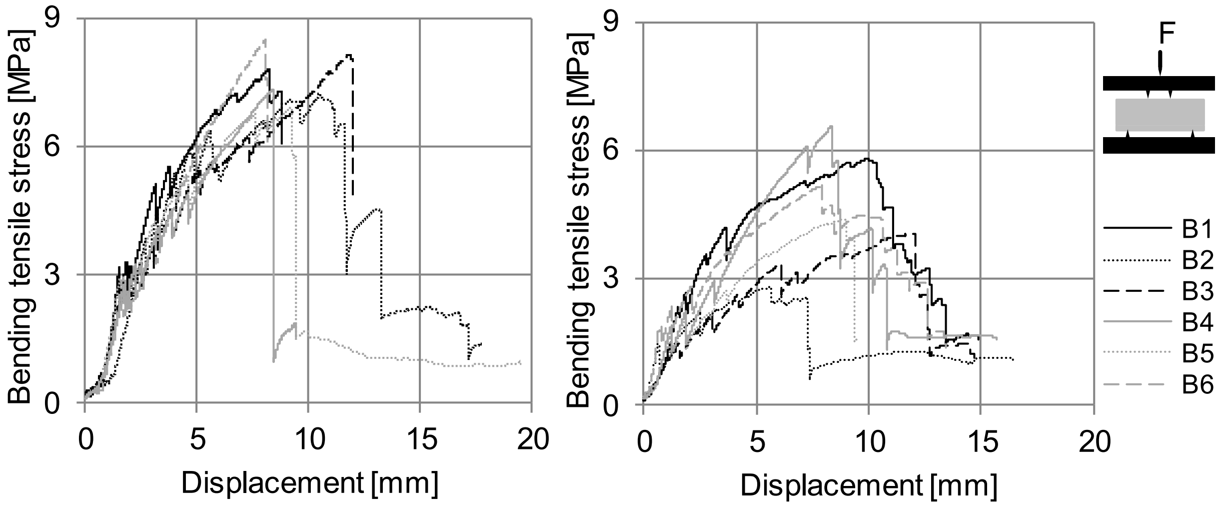

Figure 7. Four-point bending test results: Specimens with horizontal (left) and vertical positioned textiles (right)

The optical results of the printed test specimens with horizontal positioned textiles showed a finely distributed crack pattern with 4 to 5 clearly visible cracks in the concrete in each case. The crack widths were limited to 2 to 4 mm and widened only minimally during progressive loading. The rovings partially tore through. As a result, the test specimens failed after a deformation of 8.5 mm at the latest (see Figure 8 left).

Visually, the test specimens with vertical positioned textiles showed similar results to those of the horizontal test panels. The use of epoxy-impregnated reinforcement textiles resulted in a finely distributed cracking pattern of the concrete. Since the top surface had more pronounced unevenness, the test specimens could not be loaded uniformly. The load fin rested only on the higher layer, which resulted in uneven loading of the specimen (cf. Figure 8 right).

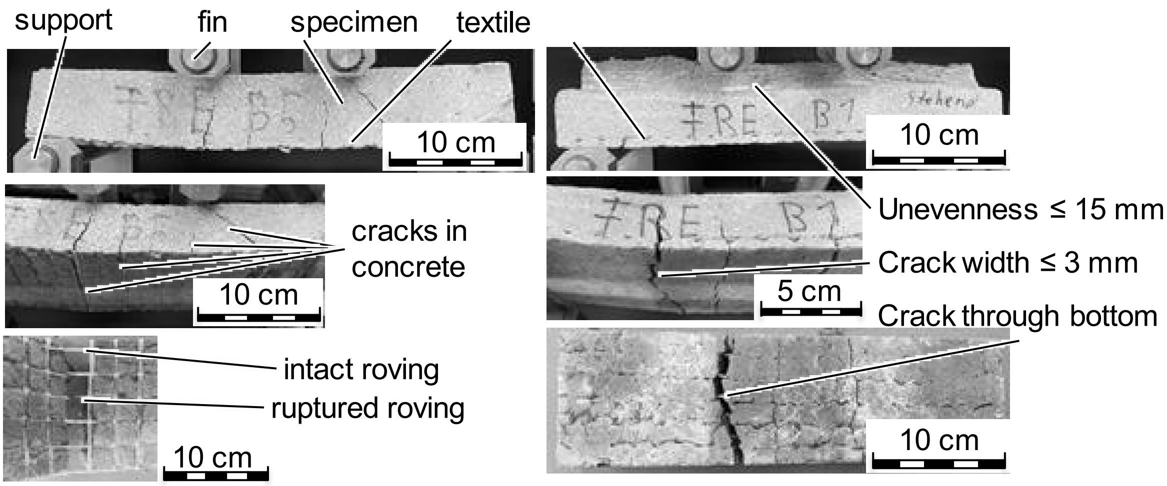

Figure 8. Optical results: Specimens with horizontal (left) and vertical positioned textiles (right)

The test results of the vertically printed specimens exhibit several problems. Due to the uneven surface and loading of the test specimens, the results may not be meaningful enough. In a new test, the surface would have to be smoothed so that unevenness of more than 0.5 mm would be removed (cf. DIN EN 1170-5). Compared with the test specimens from the horizontally printed test sheets, however, an analogous fracture pattern was observed, which can be attributed to the epoxy impregnation. The test specimens exhibited a brittle fracture with cracks in the reinforcement, which appeared after 13 mm deformation at the latest.

5. Summary and outlook

3D concrete printing in combination with textile reinforcement could be realized on an industrial scale. After the consistency adjustments of the preliminary tests, the concrete could be printed through the textile grid into the vertically positioned formwork frames. Shuttering frames were then also positioned horizontally and printed vertically. This allowed comparable test results to be obtained in the four-point bending test. For the production of precast concrete elements, the vertical printing direction can also be advantageous; however, it does not meet the requirements defined in this paper for textile-reinforced 3D concrete printing for vertical wall elements. The test specimens from the horizontally positioned specimen plates exhibited higher flexural tensile strength. Testing of the vertically printed specimen plate showed difficulties in terms of surface finish and deviations from specimen height. Nevertheless, the results of the load-deformation curve showed an increase in ultimate load from 2.5 MPa (unreinforced concrete) to up to 4.79 MPa (vertically printed element) and 7.65 MPa (horizontally printed element). The up to twofold higher flexural tensile strength allows the realization of higher stressed walls or buildings with several floors.

3D concrete printing requires a concrete mix with high green strength. The decisive factors are the water content, the maximum grain diameter and the strength of the fresh concrete, so that the printed strands have a high dimensional stability under their own weight load. Sufficient penetration and enclosure of the textile reinforcement is achieved with a less stiff concrete consistency. The adaptation to both requirements is decisive for the printability of textile-reinforced concrete elements. Therefore, the properties of the fresh concrete in new material mixes must be iteratively adjusted to the usability with a textile reinforcement.

Textile production shows a very high degree of automation with a degree of reinforcement that can be individually adjusted to the load. The number, fineness and material of the rovings can be adjusted to sufficiently reinforce components subjected to higher loads. At the same time, textile reinforcement does not require a minimum concrete cover for corrosion protection. Compared to reinforced concrete, textile-reinforced and 3D-printed concrete elements reduce the need for primary concrete raw materials by 75 %. On-line coating is favoured to ensure uniform coating application. Only by fully impregnating the rovings can consistent quality standards be achieved. Due to the continuous build-up of textile reinforcement along the printing path, just-in-place production can lead to higher productivity on the construction site.

Within the scope of the preliminary tests on a laboratory scale, the essential requirement criteria for the movable formwork were defined. In order to reduce the amount of formwork required and the material consumption, a movable formwork panel will be designed on an industrial scale and integrated into the process in the future. Instead of a full-surface formwork, a linear unit can carry the formwork panel along parallel to the extrusion at the nozzle. This creates a counter pressure to the extrusion pressure so that the surface is smoothed and the reinforcement is fully embedded in the concrete. To improve the adaptability of the movable formwork, a freely movable robot with a formwork panel can be designed instead of the linear unit. This means that even the complex shuttering of non-linear floor plans, which is possible with a 3D concrete printer, is covered by the traveling shuttering. Further optimization of the concrete consistency and processing can completely eliminate the required formwork, leaving only the components of the composite to be processed. The textile reinforcement can be both a form-giving and static component in 3D concrete printing. Further steps are required for mass production of 3D-printed and textile-reinforced concrete elements:

- Characterization of the composite behaviour
- Testing of alkali resistance of rovings and coating during aging
- Fire testing
- Automation of coating application
- Integration and handling of reinforcement in the construction process
- Automation of a movable formwork parallel to the 3D concrete printer
- Use of recycled concrete or fibres
- Compatibility of the composite material for the circular economy.

The above steps characterize the need for further research into the innovative composite material. For a sustainable consideration and further development, a full life cycle assessment is required already at an early stage. This will allow the analysis of the effects of primary raw material production, transport chain, production, service life and waste utilization with recyclability of 3D-printed textile-reinforced concrete elements.

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: Writing – review & editing. Clara Evers: Investigation, Methodology, Visualization, Writing – original draft, review & editing, Fabian Meyer-Brötz: Writing – review & editing. Ankiet Patel: Conceptualization, Methodology. Michael Osswald: Conceptualization, Methodology. Thomas Gries: Supervision.

Competing interests

The authors declare no competing interests.

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