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Structural Evaluation of Shotcrete 3D Printing and Robotic Fiber Winding for Thin Shell Elements

Philipp RENNEN*, Stefan GANTNER, Tom ROTHE[a], Bilal BAZ[b], Serge NANA[b], Hélène LOMBOIS-BURGER[b], Christian HÜHNE[a], Norman HACK

*Institute of Structural Design, Technical University of Braunschweig, Germany
Pockelsstraße 4, 38106 Braunschweig
p.rennen@tu-braunschweig.de

[a] Institute of Mechanics and Adaptronics, Technical University of Braunschweig
[b] Holcim Innovation Center, Holcim Ltd, France

Abstract

In this research, the potential of Shotcrete 3D Printing (SC3DP) combined with Robotic Fiber Winding (RFW) is explored for producing reinforced thin, flat concrete components. SC3DP offers enhanced concrete embedding, especially when creating uniform, thin surfaces, while RFW allows for the robotic integration of reinforcement within the same manufacturing process. Experiments are conducted to fabricate thin shell-like elements using these techniques, followed by structural testing through four-point bending tests to evaluate their mechanical performance against conventionally casted specimens. Incorporating Green State Post Processing and CNC milling enhances geometric accuracy and surface quality of the produced specimens, which shows well embedded fiber reinforcement. The bending test results suggests that material use could be further optimized, what could lead to structurally sufficient components with less concrete and reinforcement. These findings underscore the efficiency and potential of the symbiosis of SC3DP and RFW in producing complex, shell-like geometries, paving the way for more sustainable and innovative construction practices.

Keywords: Additive Manufacturing in Construction, Digital Fabrication, Shotcrete 3D Printing, Robotic Fiber Winding, Green-State Post-Processing, Four-Point Bending Tests, Structural Evaluation, Textile-Reinforced Concrete, Robotic Areal Shotcrete Printing

1. Introduction

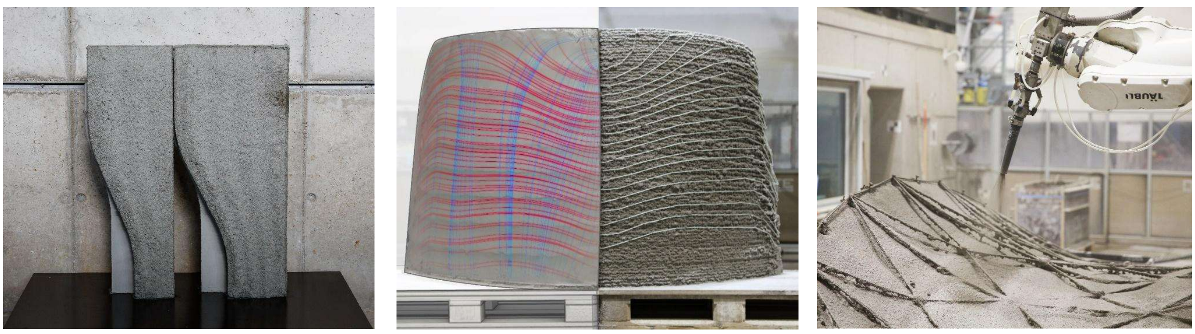
The introduction of shells as structural elements in construction heralded a new era of material efficiency and architectural freedom. Historically, shells have been celebrated for their ability to combine aesthetic appeal with structural integrity, utilizing their form to provide strength while minimizing material use [1]. This attribute of shells, particularly when executed in reinforced concrete, allows for the creation of thin, yet robust structures that can span large areas without the need for internal supports, thus opening up vast possibilities for architectural design and space utilization [2]. Despite their numerous advantages, the construction of shell structures is not without its challenges. One significant drawback is the requirement for extensive and often complex formwork [3]. The intricate shapes that make shells so efficient and visually striking also make them difficult to mold; traditional construction methods require elaborate, often custom-made frameworks to support the concrete until it cures. This not only adds considerable expense and time to the construction process but also limits the feasibility of more complex shapes [4].

The ongoing development of additive manufacturing and especially 3D Concrete Printing (3DCP), has sparked interest in overcoming these limitations. The technology promises to revolutionize the way we construct by eliminating the need for traditional formwork and allowing for unprecedented geometric complexity. However, current 3D printing methods that are already commercially applied face their own set of challenges [5], especially in the construction of thin, shell-like elements. Most notably, they often lack the ability to freely modulate geometry to the degree required for efficient thin shell design and struggle to incorporate reinforcement directly into the print [6], a critical factor for structural integrity. In response to these limitations, innovative methods such as Robotic Areal Shotcrete Printing (RASP) have been developed on the base technology of Shotcrete 3D Printing (SC3DP) [7]. Unlike traditional 3D printing techniques that build structures by stacking single paths layer by layer, RASP automatically applies concrete on any given base in an areal manner, creating thin, even surfaces that can form the basis of a shell structure.

Furthermore, RASP can incorporate reinforcement within the spraying process, either by applying concrete onto pre-positioned reinforcement structures or by layering reinforcement between sprayed concrete layers. SC3DP profits its superior interlayer bonding and reinforcement embedding capabilities here [8]. This method not only maintains the material efficiency and structural benefits of shells but also reduces the need for expensive, complex formwork.

The traditional approach to reinforcing shell structures has typically involved the use of steel rebar, which dictates a minimum thickness for the shell to ensure sufficient concrete cover to protect against environmental factors and prevent corrosion [9]. However, the development of novel continuous-fiber reinforcement methods, such as RFW, offers a promising alternative [10]. This technique involves the automated application of impregnated fibers during the fabrication process, allowing for greater flexibility in adapting to complex shapes and potentially reducing the required thickness of the shell.

The combination of SC3DP and RFW technologies has been explored in various experimental studies as seen in Figure 1; At first in an experiment of “Hybrid Manufacturing of Façade Elements” [11], where the approach of RASP was used for the first time with prefabricated textile reinforcement mats placed between the thin areal layers in the printing process, what led to well embedded reinforcement. In the "Core Winding" [12] project, the fiber reinforcement was produced on-demand [13] and robotically applied to a printed concrete core before it was fully hardened, and then embedded in a thin concrete cover layer. This approach led to good embedding of the fibers, but also to a cold joint tendency in the cover layer due to its late application. In the more advanced approach of "Robotic KnitCrete" [14], RASP was applied to embed the DFW reinforcement fully, after it was robotically placed in the desired distance from a stay-in-place formwork. This approach led to spray shadows, caused by the reinforcement net and also to imperfections of the printed surface geometry, what was also observed in a recent research of TRR277 [15]. These experiments have shown their unique challenges and improvement potentials of the manufacturing process, but also demonstrated the potential of combining these fabrication methods to create structurally efficient, materially optimized shell structures. The aim of this research is to use the experience gained from past experiments to fabricate an ideal specimens outcome and identify any potential weaknesses or areas for improvement in both the fabrication and design processes.



a b c

Figure 1: a) Thin, functionally integrated, façade elements [11], b) Core Winding wall demonstrator [12], c) Fiber reinforcement embedding using RASP on the KnitCrete bridge demonstrator [14]

This paper seeks to contribute to the evolving field of additive manufacturing in construction by presenting the findings from our investigations to the structural performance of robotically fabricated thin shell panels using a combination of SC3DP and RFW. By analyzing the results of these tests, insights into the potential and limitations of these methods are provided, offering guidance for future research.

2. Methods

2.1. Fabrication Concept

For the purposes of these tests, thirty-six samples were fabricated to enable a comparative analysis between shotcrete and conventionally cast components, as well as to assess various reinforcement layouts within these samples, as shown in Figure 2. A fabrication method known for its low error risk was selected to produce the samples, aiming to achieve an optimal quality state in the load tests. The RASP fabrication methodology, utilized in the production of flat, fiber-reinforced façade elements [11], is particularly suited for creating planar and thin elements with shotcrete, while still providing valid representation of RASP applied to freeform formwork. The evaluation focuses primarily on the area-specific shotcrete spraying and the application of on-demand glass fiber reinforcement. The fabrication process of the samples encompasses the following steps:

1. Prefabrication of frames and bases for precise placement.
2. Winding of fibers onto the frames using a Fiber Winding Machine.
3. Areal spraying of the shotcrete top layer.
4. Placement of fiber reinforcement on the base.
5. Re-application of shotcrete for the bulk mass.
6. Smoothing of the shotcrete surface.
7. Cutting the panels into six samples each.

The dimensions of the produced samples are 400 mm in length, 150 mm in width, and 55 mm in thickness, with the reinforcement layer positioned at one-fifth of the material thickness, i.e., 11 mm. This structured approach to sample fabrication allows for a controlled comparison of material properties and reinforcement effects, contributing valuable insights into the structural performance of concrete shell elements crafted through advanced automated fabrication techniques.

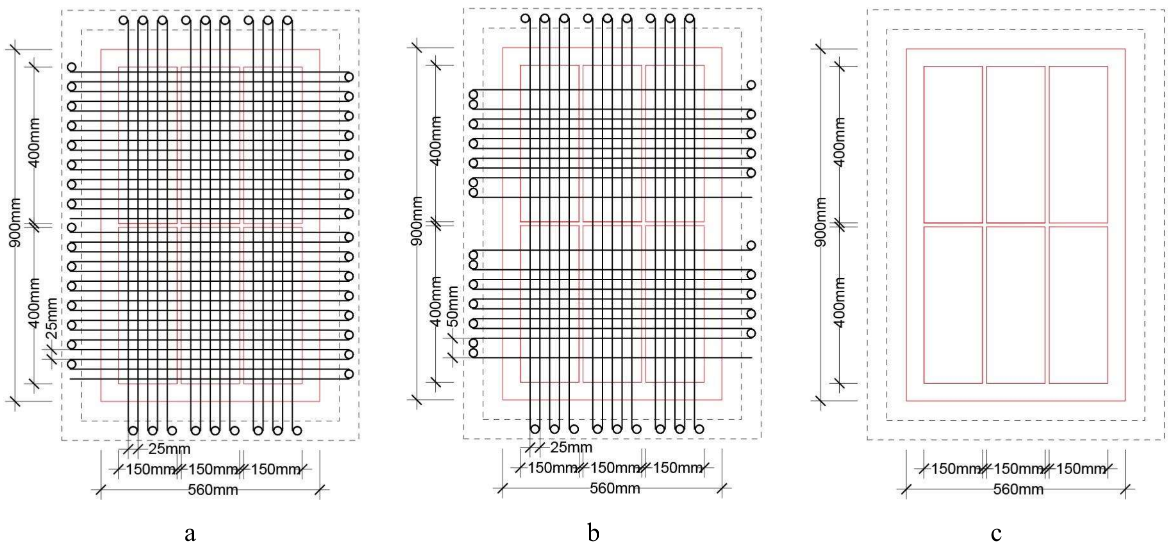


Figure 2: Reinforcement and specimen layout per panel; a) Standard reinforcement layout, b) Optimized reinforcement layout, c) No reinforcement

2.2. Specimen Fabrication

The glass fiber reinforcement structures for the panels are produced in a RFW process with a specially developed Dynamic Winding Machine (DWM) [16]. E-glass direct rovings (total 19600 tex) are used as primary fibre strands resulting in a reinforcement strand diameter of approx. 4 mm. A twisted yarn from Culimeta is used as the secondary fibre material (EC-9 136 X3 S135). The secondary fibre is wound helically with a thread pitch of 7 mm and is pre-tensioned by a hysteresis brake. The setting of the hysteresis brake is 150 mA, resulting in a resistance torque of approx. 24 N/mm. As matrix material an epoxy resin is used (Carboplast resin L 285 and hardener H 286).
For the fabrication, a wooden frame is prepared with pins and the reinforcement strands are wound manually around the pins into the desired grid structure (Figure 3b). Afterward, the reinforcement structure hardens at room temperature on the frame, which is then ready to be stacked on placeholders on the base surface after the first layer of concrete is sprayed (Figure 4a,b).

For the robotic shotcrete process, the Digital Building Fabrication Laboratory (DBFL), consisting of a 9-axis robot for SC3DP and a 5-axis CNC mill for post processing, was used (Figure 3a). Small batches of 25 kg "Nafufill NA 250" bags are each mixed with 4.2 l of Water in 4 minutes, using a "WM Jetmix 125" mixer. The fresh concrete is then pumped to the shotcrete nozzle through a 25 m hose of 50 mm diameter by a "WM VarioJet FU", modified for digital input control.

a b

Figure 3: a) Experimental setup at DBFL for panel fabrication, b) Experimental setup at IMA for fiber reinforcement frames fabrication

The robotic shotcrete path is planned based on a longitudinal meandering motion pattern at a nozzle distance of 400 mm and a feed rate of 5.000 mm/min, aiming for 200 mm of path width and 7 mm of maximum path height. Based on the Shotcrete Path research of Lachmayer [17], a single path cross section is predicted, resulting from 0 % Accelerator use, 0,4 m^3/h concrete flow rate and 40 Nm^3/h air flow rate. Taking this into account, a path overlap of 50 % is included into the planning to even the shotcrete surface with each meander path.

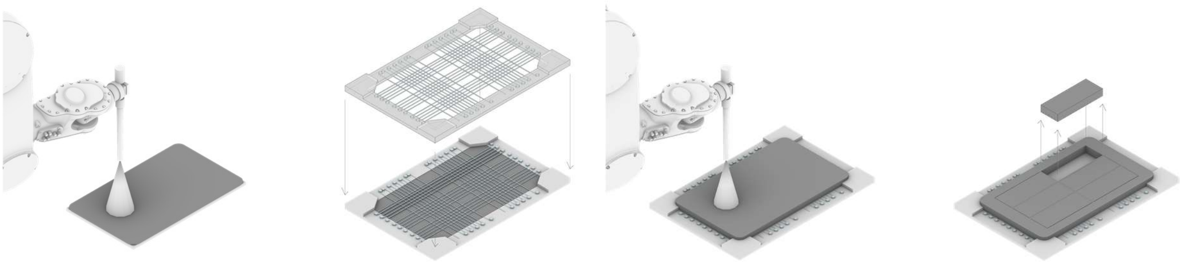
The described parameters are applied to the whole shotcrete process with a break after the first 2 layers at 11-14 mm printed height. During the break of roughly 10 minutes, the preproduced reinforcement frames are placed on its placeholders on the base surface, allowing precise placement.

After the reinforcement is embedded in shotcrete and the effective concrete mass of minimum 44 mm is layered, the concrete panels were post processed by the CNC Mill, using a modified trowelling disc by "rokamat", to redistribute the uneven shotcrete Surface to the target height of 55 mm for the whole panel.

While the Shotcrete panels are post processed, the concrete pumps continues pumping the same batch of concrete into molds, that already contain the specific fiber reinforcement variants at the correct height of 11 mm to produce the casted panels.

After 45 minutes, the shotcreted panels get earth-dry and are going through another iteration of automated surface smoothening to minimize small bumps, that could influence the structural tests.

After one day of curing, the casted panels are demolded and all six panels are prepared to be cut into desired sample dimensions at 5 days of age, again using the CNC Mill of the DBFL, but with a 1200 mm diameter stone milling disc.



a b c d

Figure 4: a) SC3DP base layer, b) Fiber mesh frame placement, c) SC3DP and CNC post processing of structural mass, d) CNC cutting of hardened concrete to final sample size

2.3. Structural Testing

The structural integrity of the long-fiber reinforced concrete samples is assessed 28 days post-fabrication using a standardized four-point bending test setup. The test employes a state-of-the-art testing machine (Model: Roell Amsler) capable of applying a maximum force of 250 kN. The apparatus is equipped with high-precision displacement sensors and is configured with a prismatic support setup to ensure sample stability.

Adherence to the DIN 1170-5 [18] standard is ensured, guiding the flexural testing protocol. This involved carefully calibrated machine parameters, with displacement control set to a precise rate of 25 mm/min, to simulate realistic stress conditions on the samples.

The evaluation also includes prism testing of 7x7x28 mm specimens to complement the macro-scale bending tests, providing insight into the material's micro-scale behavior. This dual-scale testing approach allows for a comprehensive analysis of the material's structural performance.

Data from the tests are used to calculate the flexural strength (MPa), using a calculation model that accounts for the sample dimensions and loading conditions. This rigorous testing methodology provides a detailed understanding of the material's capabilities and lays the groundwork for an in-depth discussion of the results in the subsequent chapter.

3. Results and Discussion

3.1. Fabrication Results

The fabrication of fiber-reinforced concrete panels via RFW and SC3DP processes (Figure 5) yields insightful results, pertinent to the advancement of automated construction methodologies. The winding time for each panel is around 20 minutes, with the standard reinforcement layout (Figure 2a) panel utilizing 41.73 m of fiber reinforcement, whereas the optimized reinforcement layout (Figure 2b) panel requiring 33.53 meters, aiming for a more efficient use of materials in the latter.

The application of the DWM produces a tightly wound helix with an even epoxy coating, demonstrating the efficacy of the machine's design in achieving uniform fiber reinforcement. However, the 4 mm diameter of the fibers necessitated significant force for tensioning, revealing a limitation in manual winding techniques compared to potential robotic applications. The design of the pins, with their maximum diameter and wide curvature, effectively minimized fiber breakage in bending areas during winding, contributing to a clean and consistent reinforcement mesh.

The robotic shotcrete process is executed in 440 seconds, dispensing approximately 49 l of concrete per panel. Despite the meander shift logic in path planning, which generally yields an even surface (Figure 5a), local discrepancies in base layer heights are noted. These are partially mitigated by incorporating an additional 1 mm of over-height per layer, addressing inconsistencies in material application. The initial two layers, intended for reinforcement embedding, exhibit over-heights ranging from 1 to 6 mm, necessitating manual intervention to correctly position the reinforcement (Figure 5b). Subsequent layers accumulate an excess of 8 to 16 mm (Figure 5c), which are partially rectified through CNC troweling in the green state (Figure 5d), although some material require manual removal to prepare for the final smoothing process.

Upon cutting, the panels reveal neatly embedded reinforcement without visible voids, affirming the efficiency of the fabrication process in achieving integral structural components. Notably, the samples exhibit precise x,y-dimensions, attributable to the accuracy of CNC cutting. The z-dimension, reflective of the panel's height, presents intriguing findings. The researched fabrication method results in superior height precision and surface quality compared to the casted samples, potentially influenced by the skill level in manual surface smoothing executed by the research team.

However, the automatically smoothened surface reveals minor troweling artifacts, characterized by thin lines of material residue along the distribution disc's path. These findings underscore the importance of refining post-processing techniques to enhance surface finish quality, integral to the structural and aesthetic considerations of fabricated concrete elements.

a b c d

Figure 5: a) First cover layer SC3DP, b) Fiber reinforcement frame placement, c) SC3DP of effective concrete mass, d) Green-state surface smoothening by CNC-troweling

3.2. Structural Testing Results

The tensile performance of the reinforced concrete is evaluated by performing four-point bending tests on plates with dimensions of 400 mm×150 mm×55 mm and a span's length of 300 mm. Figure 6 gathers the flexural stress – displacement curves obtained. The flexural tensile stresses are conventionally obtained by assuming a linear stress distribution over the midspan cross section, where M is the midspan bending moment and W is the section modulus of the cross section. Following this assumption, the mean residual flexural tensile strengths are calculated as per the following equation, where σfl (MPa) is the residual flexural tensile stress, F (N) is the corresponding load, l (mm) is the span length, b (mm) is the specimen width and d (mm) is the plate thickness:

$$\sigma fl = \frac{F \times l}{b \times d^2} \quad (1)$$

From the results obtained, it can be firstly seen that the shotcrete specimens perform similar to casted specimens, and secondly, that the reinforcement layouts perform similar to each other. This observation suggests good bonding behavior and that the transversal reinforcement does not have a significant effect on performance.

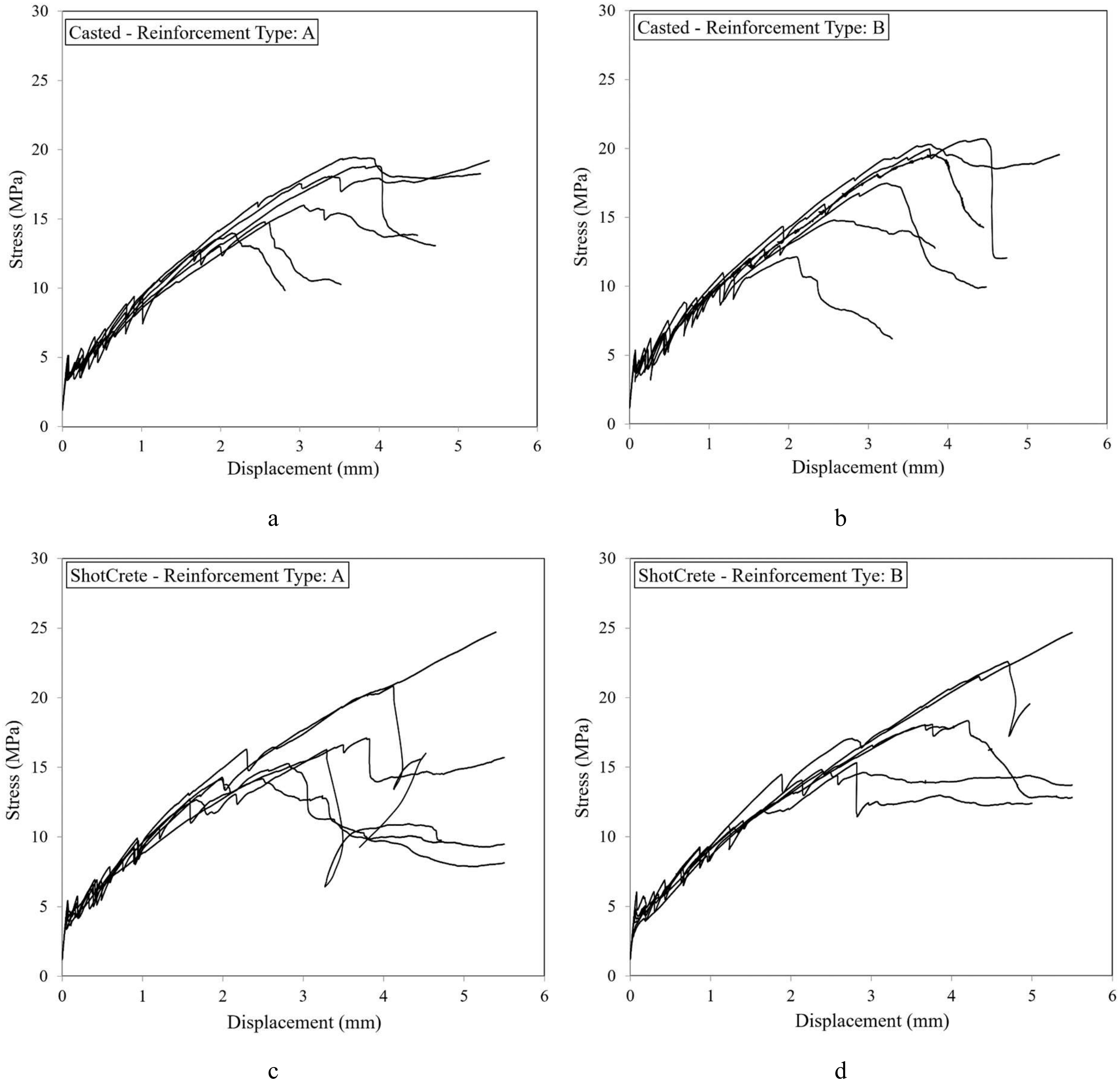
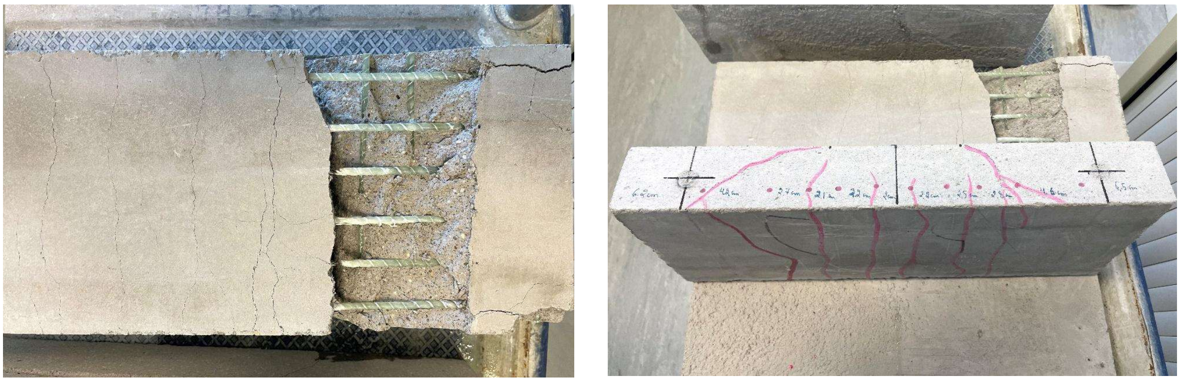


Figure 6: Deflection Curves of Specimen Groups; a) Casted - standard reinforcement layout, b) Casted - optimized reinforcement layout, c) SC3DP - standard reinforcement layout, d) SC3DP - optimized reinforcement layout

In addition, the samples exhibit a strain hardening behavior somewhat similar to what is often found with conventional reinforced concrete or Ultra High Performance Fiber Reinforced Concrete (UHPFRC). This is also visible on the cracking pattern marked by multi-cracking typical of ductile behavior (Figure 7). The performance levels reach approximately 20 MPa for the quantity of reinforcement used which is relatively high, and the associated moment capacity of the 55 mm thick section would be MRD = 10 kN.m/ml with an elastic solution. Indeed, considering for example an isostatic facade panel 3 m high and 1 m wide, supporting an usual ULS wind force of 0.9 kN/m2, the acting bending moment would be MED = 1.0 kN.m/ml, therefore 10 times less than the resistance of the section tested. This implies that the thickness of the wall can be reduced from 55 mm to 20 mm (MRD = 1.33 kN.m/ml > MED = 1.0 kN.m/ml) or keep the same thickness of 55 mm and reduce the quantity of reinforcement. It therefore seems that the solution can compete with UHPFRC or conventional reinforced concrete applications if the alkali resistance behavior is also validated and if the cost is competitive.



a b

Figure 7: a) Breaking behavior of a reinforced shotcrete sample, b) Crack pattern of a reinforced shotcrete sample

4. Conclusion

The results of this investigation into the structural performance of thin shell panels produced through the synergistic application of SC3DP and DFW techniques highlight a significant advance in the field of additive manufacturing in the construction sector. The structural evaluations carried out provide a solid basis for confirming the reliability and effectiveness of these innovative manufacturing methods. Most notably, the first structural testing of a panel produced using RASP represents a crucial milestone in the empirical evaluation of advanced construction technologies.

These results reinforce confidence in the potential of SC3DP and DFW to meet and possibly exceed the structural requirements prevalent in today's construction practice. The positive outcomes of these structural tests argue for deeper exploration of the potential and limitations of these techniques and set a precedent for future research efforts aimed at increasing geometric complexity and material efficiency through robotic fabrication and design. This research should focus on exploring additional alternative fabrication methods. The aim remains to achieve a comparable level of excellence in terms of print density and embedding of textile reinforcement, with an increased focus on achieving geometric complexity and structural slenderness. Such advances promise to revolutionize architectural design possibilities and facilitate the realization of more intricate and ambitious structures that were previously constrained by manufacturing limitations.

However, the research identifies critical areas for advancement:

- Reinforcement layout optimization: The optimized reinforcement layout of the tested elements was still relatively conventional despite the novelty of the manufacturing process. Considering the strong mechanical bonding between reinforcement and shotcreted concrete, the layout of reinforcement could be further optimized by computational force analyses, leaving only essential fibers following the tensile force flow and not the transversal fibers.
- Adaptive layer height adjustment: the prospect of minimizing excess material by dynamically changing the layer height during the manufacturing process is a promising area for improvement. Implementing real-time adjustments based on scanned data to regulate nozzle spacing and robot feed rate could lead to more efficient material use and an improvement in the overall structural integrity of manufactured panels.
- Surface quality improvements: The observation of surface defects, such as material residues and thin lines of excess material, shows that post-processing techniques were sufficient for this particular project but could be improved. Alternatives, such as bidirectional troweling or the use of different smoothing tools, could potentially improve these problems and thus increase both the aesthetic and functional quality of the manufactured elements, if relevant.

In summary, this research provides important insights into the structural load-bearing capacity of thin, textile-reinforced concrete panels manufactured using SC3DP and DFW, with the first structural test of a panel manufactured using RASP being a particular highlight. The positive results of the structural tests provide a solid foundation for future investigations and emphasize the need for continued innovation and refinement of manufacturing technologies in construction. As the field progresses, it will be paramount to address the areas of improvement identified in order to realize more complex, efficient and aesthetically pleasing shell structures in the construction industry.

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