Structures and Architecture. REstructure REmaterialize REthink REuse - Rinke & Frier Hvejsel (Eds)
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Winding fibre thread for 3D concrete robotic printing

F.J.S. Brandão, B. Figueiredo & P.J.S. Cruz
University of Minho, Guimarães, Portugal

ABSTRACT: 3D Concrete Printing (3DCP) is a promising method to increase efficiency and automation in construction yet its adoption hinges on effective reinforcement integration to prevent shrinkage cracking and enhance tensile strength. This study explores a novel in-process reinforcement strategy for 3DCP that integrates continuous fibres via a winding technique, decoupling fibre placement from mortar extrusion. The approach involves a robotic system equipped with a spinning mechanism to intertwine fibre threads with concrete filaments, aiming to enhance structural integrity and sustainability. Two extrusion path strategies, rectilinear and elliptical helices, were tested using glass and basalt fibres. Results indicate rectilinear paths produce thicker walls with better interlocking although these are 125% longer than elliptical paths. Challenges such as fibre entanglement, synchronization issues, and filament carving by the guiding tube were identified. Modifications, including improved guiding tube placement and real-time control systems, partially mitigated these issues. The findings highlight the feasibility of the method while underscoring the need for further refinements. Future work will focus on system optimization, mechanical testing, and incorporating thicker fibres to validate the approach's structural and practical advantages.

1 INTRODUCTION

3D Concrete Printing (3DCP) is a recent technology that has gained considerable interest due to its promise of enhanced production efficiency, reduced material usage and potentially reduced costs. However, its broader adoption hinges on some critical challenges, such as integrating reinforcement to mitigate shrinkage cracking, improve interlayer adhesion, and increasing tensile and shear strength (Gebhard et al. 2021). Applying traditional reinforcement strategies in 3DCP can reduce geometric freedom and lead to increased material use (Hojati et al. 2022). This has led to several different approaches for adding reinforcement into the 3DCP process, ranging from pre-installed (Hack et al. 2014), in-process (Hojati et al. 2022) to post-installed methods (Gantner et al. 2022).

All reinforcement strategies have specific shortcomings that hinder their general applicability. Hence a more targeted approach and possibly mixing strategies is required to increase the scope of application. Beyond improved mechanical properties, desirable characteristics of reinforcement solutions include low-cost, high potential for automation, and reduced need for extra labour or fabrication time (Wu, Memari, and Duarte 2022). Post-installed reinforcement or in-process manually placed rebar are the most widely used method by companies involved in 3D printing. These methods are frequently associated with 3D printed shells for lost formwork and subsequent deposition of conventional concrete, commonly known as contour crafting (Khoshnevis et al. 2006). This is a pragmatic approach whose similarity to conventional methods enables its immediate applicability in construction. However, it fails to fully leverage the advantages of automation, is not suitable for applications with vertical curvature, has questionable environmental credentials (Wangler, Patankar, and Flatt 2024) and presents scalability issues.

DOI: 10.1201/9781003658641-117

Among the various in-process methods, continuous fibre or cable entrainment has been widely researched due to its conceptual similarity with extrusion methods. Fibre integration strategies in 3D printing processes for cementitious mortars involve depositing reinforcing fibres along the filament's extrusion axis. Two primary strategies have been identified in the literature. The first approach deposits the reinforcement at the interface between printed layers (Hojati et al. 2022; Khoshnevis et al. 2006). While effective for linear paths, these techniques are difficult to implement in curved paths. Reinforcement using barbed-wire has shown promising results (Hojati et al. 2022); however, the automation of barbed-wire deposition has yet to be demonstrated. The second strategy introduces fibres directly into the extruder nozzle, embedding them within the mortar filament (Bos et al. 2017; Caron et al. 2021; Ma et al. 2019). This approach has two variations: an active method which feeds the fibre or steel cable into the extruder (Bos et al. 2017; Ma et al. 2019), and a passive method, similar to thermoplastic extrusion with fibres (Caron et al. 2021), in which glass fibres are pulled by the extruded cement.

In-process reinforcement strategies can enhance the flexural strength, ductility, and post-cracking stiffness of 3DCP elements. However, they are insufficient as standalone solutions and necessitate complex, customized printing systems (Wu, Memari, and Duarte 2022). Wu identifies maximising the structural performance from flexible reinforcement in printed concrete a key future challenge.

This paper presents preliminary research on the integration of in-process reinforcement, namely flexible fibre threads within the framework of robotic 3DCP, aiming to enhance structural integrity and sustainability in construction practices. Contrary to fibre entrainment strategies where the fibres are introduced before the concrete is extruded, in this research the fibres are introduced after the concrete is extruded, with an external active device like Baghi et al (2024). Yet, our process differs from this authors approach where the reinforcement is prestressed to receive the 3D printed concrete on top mainly to serve as a support for further layers of unreinforced 3DCP.

Our research approaches the problem of adding continuous fibres with a winding strategy. This opens several opportunities for exploring the way 3DCP filaments are intertwined with reinforcement fibre threads. The proposed strategy of in-process reinforcement involves the development of following components: (1) an automatic spinning system for fibre and concrete plaiting; (2) an infrastructure for real-time process control; (3) computational design of concrete-fibre plaiting patterns. Several types of natural and artificial fibre threads were considered, and two different winding strategies are explored. The study also investigates other aspects of winding fibre threads with 3DCP filaments, such as printing feasibility, and computational design processes.

2 FRAMEWORK

In this section, we detail each of the components of our method of in-process reinforcement. We begin with the general concept of fibre plaiting and the computational design of the printing path. Next, we describe the infrastructure for real-time process control and the automatic spinning system for fibre and concrete plaiting. Finally, we outline the experimental setup used for the tests we conducted.

2.1 *Plaiting paths*

This approach decouples the fibre introduction process from the mortar extrusion process. To achieve this, the extrusion path geometry is modified to wrap the mortar around the fibre. The primary advantage of this strategy is the simplicity of the fibre-feeding device which shares the same advantages of the pultrusion method reported by Caron et al (2021) while potentially allowing the integration of thicker fibre threads. The fibre-mortar wrapping process involves three critical stages illustrated in Figure 1 parallel to the printing direction: the initial state at the beginning of the plaiting process, with the fibre positioned ahead of the extruder (1 in Figure 1); the intermediate state, after a 180º rotation of the spinning mechanism, where the fibre lies between mortar filaments (2 and 4 in Figure 1); and the final state, with the fibre embedded between a double layer of mortar after a 360º rotation (3 in Figure 1).

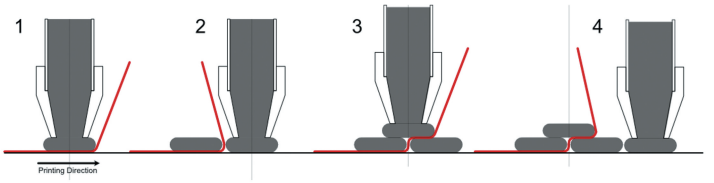


Figure 1. Filament wrapping stages (1) fibre start position (2,4) fibre 180º rotation (3) fibre 360º rotation.

The concrete filament is deposited in a winding path around the intended printing direction, which coincides with the fibre alignment direction, as demonstrated in Figure 2. To validate the plaiting concept, we first developed and tested two strategies for generating the concrete extrusion path, a rectilinear helical path (Figure 2) and an elliptical helicoidal path (Figure 3). In our experiments we use right-handed helices and counterclockwise (CCW) fibre spinning motion. The rectilinear helix is conceptually a double layer rotated relative to the printing axis with a horizontal shift controlled by the following parameters: filament axial distance – iFw – controls the pitch of the helix; filament height – Fh; top layer shift – Ls; helix thickness – Ft (Figure 2).

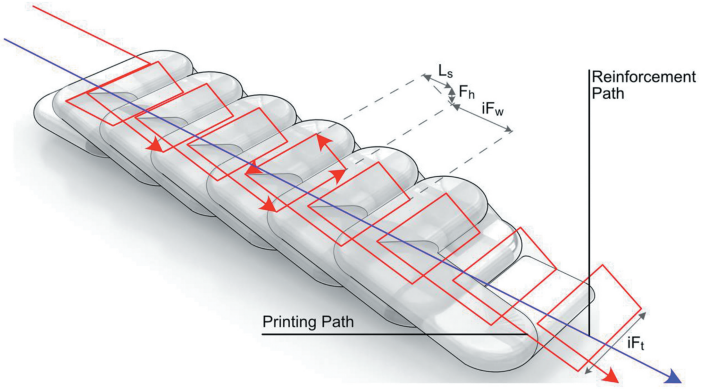


Figure 2. Rectilinear helicoidal extrusion path created around the intended printing curve and reinforcement path.

The elliptical helix is given by the elliptical equation, in the polar form, with n sampling frequency centered at the rotated plane *Pn*. *Pn* x-axis is defined as a tangent of the curve and the y-axis as the CCW rotation of the x-axis. To constrain the printing process to layer pressing 3DCP, the major axis of the ellipse a is defined in relation to the filament height, such that $F = F_h/2$, hence the radial distance in polar equation becomes Equation 1:

$$Rn = \frac{F * b * \csc\theta}{\sqrt{(F * \csc\theta)^2 * \sin^2\alpha + b^2 * \cos^2\alpha}} \tag{1}$$

Where θ is the angle of the plane *Pn* with the trajectory and α is the angle around the trajectory such that $0 < \alpha < 2\pi$, and b is the minor axis of the ellipse.

In both cases for robotic fabrication the points in the helical paths were transformed into XY planes with the aim of testing the applicability of the proposed method to a wider range of printing setups.

2.2 *Infrastructure*

The proposed framework relies on real-time communication between the robot controller, a PC and an Arduino for activation of the winding system, as illustrated in Figure 4. The live

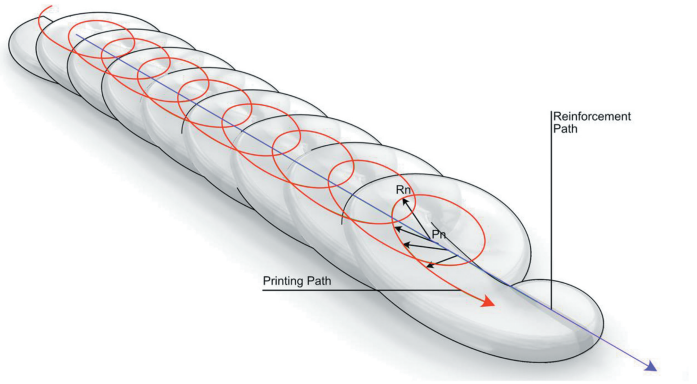


Figure 3. Elliptical helix extrusion path created around the intended printing curve and reinforcement path.

position of the extruder and the robot speed are exposed by the KukaVarProxy server, running in the robot controller, over TCP/IP. A Java program running in a PC connected over LAN to the KR C4 controller reads the variables using the JOpenShowVar library (Sanfilippo et al. 2015) and publishes the values over UDP. In the Grasshopper environment these variables are read and used to issue commands to the Arduino device over serial port using a custom protocol implemented with the Funken plugin (Stefas, Rossi, and Tessmann 2018). The Arduino device receives the commands and controls the stepper motor.

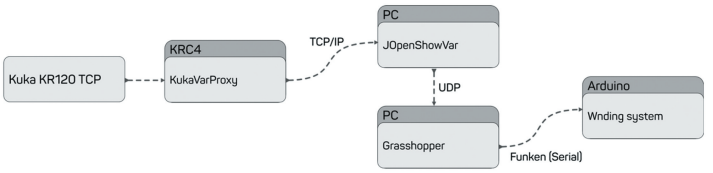


Figure 4. Communication diagram between different hardware devices and software processes.

2.3 *Spinning system*

The advantage of layer pressing with circular nozzles is the omnidirectionality of the extruder, which can operate independently of the geometry being extruded. However, n in-process reinforcement methods with externally added reinforcement, aligning dispensers with the filament axis is crucial. In our process, the fibre needs to be positioned opposite to the extruder as it progresses in the helicoidal path. The developed spinning mechanism consists of a pair of gears mounted on a direct extruder attached to the robot flange (Figure 5).

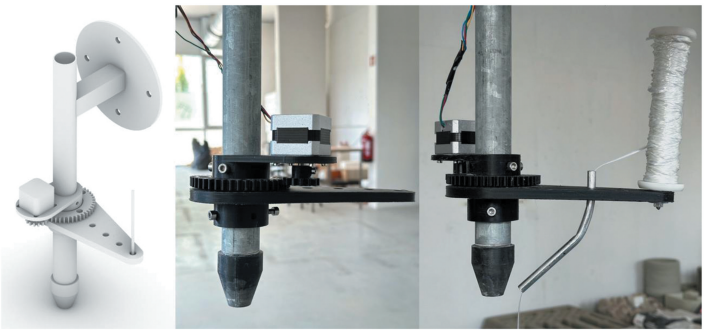


Figure 5. Spinning system: (Left) Concept model, (Middle) first version of the spinning device, (Right) second version with guiding tube.

One is coupled to the axle of a stepper motor; the other is attached to the winding arm and rotates freely around the extruder. The arm supports the fibre spool and the dispenser that directs the filament to the nozzle. The second version of the device contains a guiding tube to minimize the deflection of the fibre caused by the spinning (Figure 5 Right). The stepper motor is controlled in real time by the Arduino device through the Funken protocol.

2.4 *Experimental setup*

We conducted several experiments with the spinning system attached to a Kuka KR120 2700 robotic arm. The mortar was produced and pumped with a MAI®MULTIMIX-3D Generation II Universal connected with ø25mm 5m hose to a direct extruder attached to the robot flange. The robot tool speed was set to 100mm/s, the pump frequency was 15Hz (1,24 L/min). A Secil dry-mix mortar was used in these experiments. The water was set to 230L/h at the pump.

Experiments were conducted to evaluate different path strategies—elliptical and rectilinear—both without reinforcement insertion and with the introduction of glass and basalt fibres. The selection of the fibres considered the thickness and stiffness of the threads. Table 1 summarizes the typical physical properties of the fibres used.

Table 1. Typical physical properties of the tested fibres.

Physical properties	Unit	Basalt fibre	Glass fibre
Tensile Strength	MPa	3100-4840	2000-3500
Modulus of Elasticity	GPa	85-95	70
Density	g/cm3	2.8	2.5
Elongation at Break	%	3.15	2.5

Prototypes with two different shapes, a single line with one layer (T1) and a prismatic shape with 5 layers (T2), were produced for each path strategy without fibres. Finally, fibre plaiting tests were conducted with simultaneous printing using glass and basalt fibres.

3 RESULTS

Figure 6 shows the side view and top view of rectilinear and elliptical helicoidal paths in T2 prototypes. The rectilinear path parameters were 30mm (iFw), 8mm filament height (Fh),

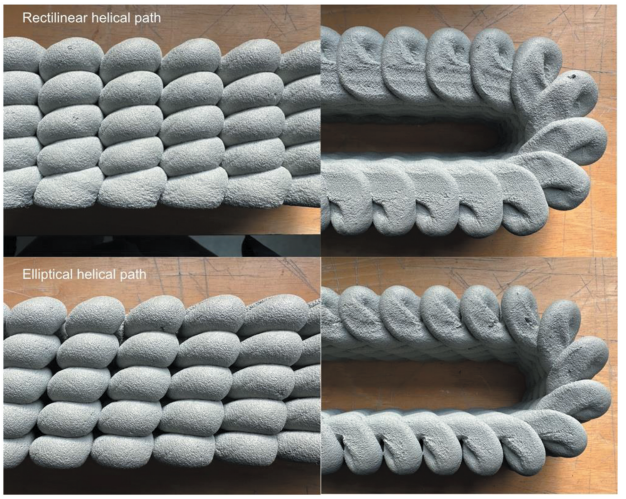


Figure 6. Comparison of rectilinear and elliptical helix paths (Left column) side views (Right column) top view.

18mm top layer shift (Fs) and 60mm helix thickness (Ft). The elliptical path parameters were set to 8mm filament height, 17,3º θ angle, filament width of 30mm and minor axis b = 32mm.

Rectilinear paths are on average 125% longer for the same intended curve, producing thicker walls with better coverage on curves with small radius. Elliptical paths require at least 2x more points and produce thinner walls.

Preliminary tests with the first version of the spinning system showed that the fibre tended to bulge in the path from the support to the concrete filament because of the rotation speed. This caused the fibre to get caught by and to start winding around the nozzle. To address this issue a guiding tube from the support to the tip of the nozzle was introduced. To avoid the intersection of the guiding tube with the concrete, the tube was positioned 8mm above the nozzle tip. Results of T1 tests with the second version of the spinning system are presented in Figure 6. Rotation speed of the spinning system was set to 50,96 RPM.

The first test showed the fibre was still being caught by the nozzle (Figure 7A). In the second run of the test, the tube was lowered to be coplanar with the nozzle. This resulted in a successful fibre insertion, but as foreseen, the fibre tube carved the concrete filament (Figure 7B). In the third run of the test the height of the tube was increased to 5mm above the nozzle (Figure 7C). As expected, there was a reduction of the carving by the fibre tube, yet close to the end of the path the fibre was again trapped by the nozzle. Careful analysis revealed that the carving increased as the path progressed, which may be attributed to deviations on the base surface or a mis calibrated base plane. Furthermore, it was also noted that there was a slight deviation of the reinforcement path as the printing progressed which was caused by a desynchronization of the spinning system with the printing path. The last test was run with the fibre tube again at an 8mm position, with similar results as the first test (Figure 7D).



Figure 7. 3DCP winding with fibre spinning with fibre tube at different heights: (A) 8mm, (B) 0mm, (C) 5mm, (D) 8mm.

4 DISCUSSION

This study introduces a novel in-process reinforcement strategy for 3DCP, integrating continuous fibres via a winding method. By decoupling fibre insertion from mortar extrusion, this approach enables greater flexibility in reinforcement integration. The experiments demonstrate that the strategy is feasible, yet some challenges remain to be solved such as synchronization of the spinning mechanism with the extrusion process. Issues such as fibre entanglement with the nozzle and path deviations were identified, underscoring the need for further refinement of the spinning system and its alignment with the extrusion path. The introduction of a guiding tube improved fibre placement but introduced new concerns, such as carving into the concrete filament.

Both rectilinear and elliptical paths show adequate properties to be used in the proposed method, but there are trade-offs between wall thickness, coverage efficiency, and geometric precision. While rectilinear paths produced thicker walls, better curve coverage, and better filament interlocking, elliptical paths resulted in thinner walls. Compared to other methods of

fibre insertion, this approach changes the typical layering strategy of 3D printing and creates different surface finishes. Also, the proposed path strategies will have issues in polygonal curves which future research should focus on.

For the same nozzle and pump, this approach will produce walls with double the thickness of a conventional layering approach. The relevance of this limitation depends on the application. The general tendency in prefabricated 3DCP is leaning towards smaller filament sections (Anton et al. 2024) and higher number of shells to account for a combination of reinforcement strategies. For those applications, our proposed reinforcement approach might reveal beneficial. Compared to Caron et al (2021) increasing reinforcement section does not change the machine setup. In future experiments we aim to address the issues of the guiding tube by using non-planar robotic targets instead of a typical 3-axis approach. This will reduce the scope of application of the proposed method to robotic arms.

5 CONCLUSION

The preliminary results of the proposed winding-based reinforcement strategy show that this method is promising step forward in achieving integrated, automated reinforcement in 3DCP. Continued development should focus on enhancing the robustness of the spinning system, improving real-time synchronization, and exploring alternative ways of fibre guiding. Additionally, long-term testing of the reinforced elements under operational loads is essential to validate the structural benefits of the proposed method. In future research we aim to conduct mechanical tests and explore the introduction of other artificial and natural fibres.

ACKNOWLEDGMENTS

This work is co-funded by the Agência para a Competitividade e Inovação IAPMEI, I.P. through the Programa operacional C5. Capitalização e Inovação Empresarial of the Plano de Recuperação e Resiliência (PRR), Project "INOV.AM Innovation in additive manufacturing, WP19 Rein4-concrete", Funding reference: PRR/49/INOV.AM/EE. The first author work was funded by IN2PAST – Associate Laboratory for Research and Innovation in Heritage, Arts, Sustainability and Territory, funding reference LA/P/0132/2020. This initiative was supported through the Multiannual Funding of the Landscape, Heritage, and Territory Laboratory (Lab2PT), Ref. UID/04509/2020, financed by national funds (PIDDAC) through the FCT/MCTES. We would like to thank the material support of Fibrenamics and MendesInov.

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