Reinvent reinforced concrete with robotics and 3D printing

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Abstract -

3D concrete has undergone significant development over the last few decades. Yet unreinforced printed elements generally do not comply with existing building standards or regulations and are therefore not used as load-bearing elements. There is still a gap between research and use, and despite several proposals, standard commercial solutions for the reinforcement of 3D-printed structural elements are still some way off. The proposed concept is inspired by the composites industry and echoing Pier Luigi Nervi's last century Ferrocement, uses 3D Concrete Printing (3DCP) and a patented technology called FBP for *Flow-Based Pultrusion for additive manufacturing*. The reinforcement is provided by long, aligned fibers, and produces a transverse isotropic composite mortar. The first experiments demonstrate an increase in tensile strength and ductility, and an industrial prototype, in collaboration with XtreeE company, is currently under development to push away the Reinforced Concrete limits proposing a disruptive way to design and build with concrete.

Keywords -

Cementitious composite; 3D printing; Long fibers

1 Introduction

Possessing a tensile strength within the range of a few MPa and a fragile behavior, unreinforced cementitious mortars are unsuitable for tensile configurations. Microcracks, initiating at an early stage, swiftly propagate, leading to rapid rupture. The remedy lies in intimately "stitching" these cracks with a suitable reinforcement so that stresses can continue flowing across the crack, limiting the rupture process. For concretes and mortars, the most developed solutions are structural ones, using macro systems as rebars and cables, usually steel ones. This idea is attributed to the French engineer Joseph Lambot in 1848, who first thought of reinforcing the cement of his agricultural tanks and a small boat with an iron lattice. He patented this concept as "Ferciment" in 1855, which later became "Ferrocement" [1]. Numerous developments followed, particularly for building and civil engineering, with 262 patents filed between 1886 and 1906, leading to the first regulations in France that same year. Then, two approaches emerged. The first approach derived from Lambot's one is promoted by Cottencin, and notably adopted by the architect Anatole de Baudot for the Saint-Jean de Montmartre church (1894-1904) and the vaulted roof of Tulle Theater. The second proposed construction systems like beam and column structures with the progressive use of larger-section steel profiles, known as "rebars". Initially promoted by François Hennebique, this approach eventually prevailed and still constitutes a significant part of current constructions, more "readable" and much easier to build. Many references contributed quickly to its reputation, and Hennebique's system closed the way to the more optimal Cottencin's system. However the famous Italian architect-engineer Pier Luigi Nervi, in the mid-last century, continued to develop this concept of fine steel mesh. "Ferrocement" then became a technique enabling architectural challenges, such as in the Orbetello Aerodrome hangar (Italy) completed in 1940, with astonishing efficiency and aesthetics (see Figure 1). Nervi prefabricated small structural elements and joined them by keying rebars with concrete on site [18], restoring the structural continuity of the work. This solution embodies "resistance through form", a concept Nervi advocates for generalization, making the complexity and beauty of buildings possible. It's time to revisit these choices, with today's tools, robotics, given the visionary concepts and their relevance to today's resources and challenges.

Figure 1. Orbetello Aerodrome in Italy by Pier Luigi Nervi in 1940 (Credits : Hulton Getty)

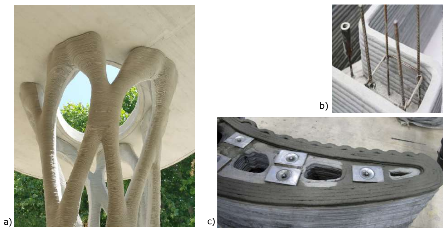

Figure 2. Post-reinforcement: a) Pile with printed formworks [10] b) traditional reinforcement [2] c) reservations for prestressing cables [21]

Figure 3. Prototype of an optimized reinforced concrete beam with printed formworks [23].

2 Reinforcement and 3D printing

There exist three ways to reinforce a 3D printed element : before, during or after printing. The following sum-up these different approaches, starting with the most obvious and easy one, reinforcing the already printed element.

2.1 Reinforce after printing

The structure is reinforced after printing, meaning once it's already in place. Traditional techniques such as reinforced or prestressed concrete, as mentioned earlier, are applied. For instance, it's possible to create structures with printed cementitious materials that include openings for inserting reinforcement bars or prestressing cables, which are secured by injecting a grout, as shown in Figure 2-c. This method can be quickly deployed on construction sites since existing design methods, integrated into regulatory frameworks, are directly applicable. Another approach to achieving complex-shaped structures compliant with regulations using 3D printing is to print the formwork into which traditional concrete, reinforced by traditional methods, will be cast. This is demonstrated by the Chinese company Winsun (see Figure 2-b), positioning reinforcements in a printed mold. XtreeE, on the other hand, prefers the use of ultra-high-performance fiber-reinforced concrete, which is easier to work with, for the construction of the column illustrated in Figure 2-a. In [22, 23] another example concerns a methodology to optimize a Eurocode-compliant beam, using such printed formworks. The potential concrete savings are significant: through a parametric study, they were estimated at 48% on average for beams of housing buildings. A prototype is presented in Figure 3 where the formworks and the robotic setups are also shown.

Other proposals involve reinforcing 3D-printed structures with external reinforcements. In [1], a beam is suggested in which the compression elements are 3D printed in cementitious material using robotic extrusion, while the tensile forces are absorbed by an external metallic framework. In [33], a bridge is constructed with several printed mortar voussoirs assembled using post-tensioned prestressing cables.

2.2 Reinforce before the printing

It is well known that another way to reinforce concrete is to introduce a modest proportion of fibers with high tensile strength enhances tensile behavior, allowing for the sewing of micro or macro-cracks and averting sudden, localized rupture. Typically, reinforcement is achieved through short fibers added directly to the mortar in the mixer with a limited volume fraction (a few percent by volume). Hence are produced high-performance fiber-reinforced concrete (HPFRCC) with metal fibers —the only ones specified in structural design regulations—while preserving favorable workability [32]. A natural idea for 3D printing is to integrate reinforcement in the same way, into the cementitious material from the initial mixing and extrude fiber-reinforced mortar. In order to obtain pumpable mortar, the fibers must be flexible and therefore have a limited diameter. The most commonly used fibers are synthetic fibers (carbon, polyvinyl alcohol: PVA, Polyethylene PE) or mineral fibers (glass or basalt). To maintain a mode of failure by decohesion of the interface and/or not to block the pumping and extrusion system, the length of the fibers is also limited (approximately 10 mm). Finally, to ensure a sufficiently low shear yield stress of the fresh mortar, the volumetric proportion is limited, generally less than or equal to 2% [30]. In [34], such a volumetric fiber rate of PE fibers allowed for a very significant deformation at rupture in the deposition direction of about 10% for a flexural strength of 20 MPa. Despite extrusion difficulties and relatively poor volume ratio of fibers, the effectiveness of this type of reinforcement for printed mortars will see significant improvement in the coming years.

2.3 Reinforce during the printing with robotics

The idea here is to make the mortar printing and the reinforcement placement concurrent. These approaches are more sophisticated and generally developed for non-standard concrete structures within an integrated digital process based on advanced robotic manufacturing strategies.

Several research efforts have focused on the direct adaptation of the reinforced concrete principle using steel bars or rebars, as seen in [8, 31]. This approach is interesting as it provides quick perspectives on acceptability and use by professionals. Most solutions involve robotically inserting small bars, somewhat like nails, into the printed stack, either perpendicular to the stacking direction or at an angle. This has the advantage of reinforcing the crossed interfaces, which can be weak points (cold joints) for the structure if there is poor adhesion between layers due to, for example, too rapid drying of the layer receiving the new deposit.

In [8], a process called Additive Manufacturing of Reinforced Concrete (AMoRC) is proposed. It is a hybrid process involving intermittent stud welding and continuous concrete extrusion. Segmented steel reinforcement bars are assembled to form a three-dimensional reinforcement mesh, simultaneously integrated into the extruded concrete (Figure 4).

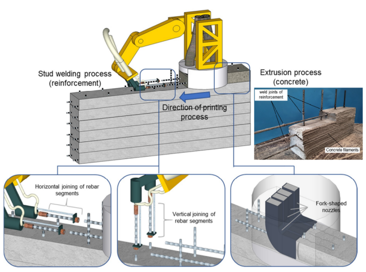

Figure 4. 3D Printing process (AMoRC), concrete extrusion and welding of reinforcements [8].

In [31], experiments with this type of nailing reinforcement on various mortars, already printed, demonstrated effective reinforcement if the nail orientation is correctly chosen, and if the nail surface is rough enough to ensure a good interface with the mortar.

In [16], U-shaped reinforcement elements, called "riders", staple vertically through the layers simultaneously during printing. The staples penetrate multiple layers but also interlock to form a reinforcement network. Finally, in [15], a device with a dispenser (Figure 5) deposits needles horizontally between the layers to achieve reinforcement along the axis of the strands, approaching traditional reinforced concrete. Mechanically integrating continuous and unrolled reinforcement at the nozzle level, such as micro-cables, chains, or metal grids [4, 20, 3, 24] (Figure 6), is also a possibility. Particular attention must be paid to the interface quality between the reinforcement and the cementitious material, which determines the composite behavior. Mineral fiber elements are widely investigated, for example, in [26] or by the authors of this chapter in [14]. The former implements a thin and narrow strip of Mineral-

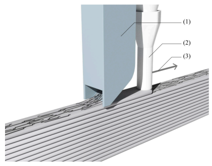

Figure 5. Deposition of needles between printed strands [15].

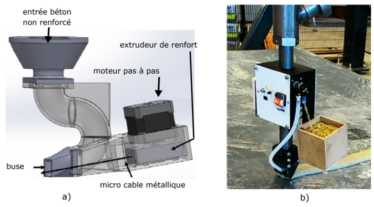

Figure 6. Co-extrusion a) with a metal cable [20] b) and with a metal chain [4].

Impregnated Carbon Fiber (MCF) unrolled downstream of the nozzle on an already printed layer, covered by the current deposit. In [28], to ensure good impregnation of the carbon fiber wick, a pre-impregnation line using very fine mortar is set up upstream to prepare the strip to be deposited (Figure 7). The threads are then mechanically placed between the layers upstream of the printed strand (Figure 8). A variant of the MCF process called ProfiCarb

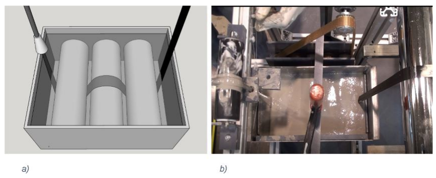

Figure 7. Pre-impregnation system of the MCF process [27].

[29] repackages pre-impregnated threads into coils that will be directly driven by the flow of a single-component mortar (Figure 9). Several reinforcements, here 6 twisted carbon fiber yarns, can thus be dispersed in the section of the strand (Figure 9). This latter process is very close to the Flow-Based-Pultrusion concept proposed by the authors of this paper [14], which will be detailed in the following paragraph. This approach allows more homogeneous, "in-line" reinforcement and avoids technologies and motorizations for guiding and driving reinforcement, which complicate the process and reduce formal possibilities, such as pronounced curves, for example.

All these continuous reinforcement solutions naturally align with traditional reinforced concrete techniques. They

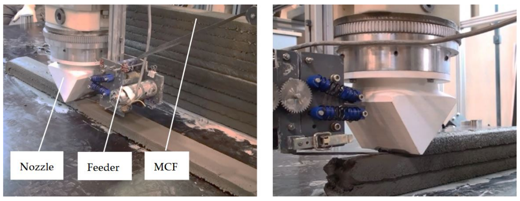

Figure 8. MCF nozzle with motorized routing of reinforcement under the extruded strand [27].

Figure 9. ProfiCarb process and view of the nozzle with 6 yarns [17, 29].

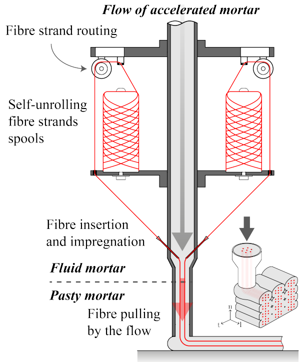

Figure 10. Left: Fiber printing device: 1/coils 2/pulleys 3/guides 4/drive head. Bottom right: Transverse isotropic arrangement in the printing direction via the patented Flow-Based Pultrusion process [5]

reinforce the material in a preferred direction [2], induce anisotropy, and are therefore very effective for the structure's bending behavior, even for moderate volumetric fractions of reinforcement. To go further, they must fit as much as possible into the formal freedom offered by robotics.

The next paragraph focuses on the Flow-Based Pultrusion concept [14, 6], which seems to meet the imperative of efficiency, simplicity, and adaptability to new construction system proposals.

3 Details on a Specific In-Line Reinforcement: The Flow-Based Pultrusion Concept

What is proposed here is an in-line approach and material strategy, heavily inspired by long-fiber composite material technologies. On the contrary of localized rebars in reinforced concrete, the extruded material is reinforced in a more uniform manner, with continuous aligned fibers distributed inside the extruded lace. We will briefly describe the technology, experiments, and the performance of the reinforced material.

3.1 Technology

The technology described in the patent [5] is called FBP, which stands for Flow-Based Pultrusion. Control of the rheological behavior of the cement matrix ensures the routing and impregnation of continuous small-diameter strands (glass, basalt, etc.) without any motorization (10 left). Such technological simplicity has numerous advantages : it is cost-effective, more reliable since the absence of motors decreases potential points of failure, and reduces the complexity of the system control. The resulting material, called *Anisotropic Concrete*, is thus uniformly reinforced in a single direction, offering new possibilities (10 right). It can improve the strength and ductility of the cured material and contribute to better handling of fresh laces during deposition, allowing for more complex paths on slopes or cantilevers, as shown later (Figure 12 right).

3.2 Prototypes and Devices

A first prototype was developed at the Navier laboratory and adapted to a two-component printing head from XtreeE, mounted on a 6-axis ABB 6200 robot (Figure 11).This current prototype works with fine-grained mortar, and not with large aggregates. An important challenge in this technology is that the reinforcement should be sufficiently flexible to match the curvature of a printed lace, and should provide sufficient anchoring capacity in the printed material. Not all reinforcement strands are compatible due to these challenges: first experiments using "piano cord" metallic wires were not satisfactory due to poor adhesion with the mortar and bending radius limitations [13]. So-called roving yarns are more favorable. They are constituted of multiple microfilaments, are much more flexible, and easier to bond to the mortar due to their microfilamentary structure.

In 3D concrete printing by extrusion, there are two main technologies: single-component or two-component. The first deposits a lace directly pumped from a batch of mortar prepared and having the right consistency to be stacked. A powerful pump is necessary because the mixture is relatively thick, having a high yield stress (a few thousand KPa) that evolves quite slowly but irreversibly until a consistency too high to be printed is reached. The two-component technology prints a much more fluid material (a few hun-

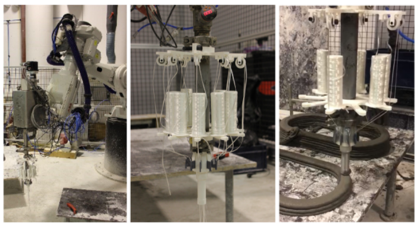

Figure 11. Prototype 1, Navier laboratory, with fiber-glass printing

dred KPa) accelerated strongly by an additive just before printing. The initial mixture is therefore easier to pump, more stable, and allows more freedom since the operator can continuously modify it based on what is sought or needs correction. Our FBP process is closely linked to this technology, which allows easy introduction of fibers into a fluid material that quickly solidifies. The impregnation is very effective, and the drive is assured because the mortar quickly structures around the fiber. Initial prints have been made with glass, basalt, and carbon fibers, up to 6% by volume. Details on the process technology can be found in [9]. To hope to go further, a second prototype for industrial purposes is under development in collaboration with XtreeE. In Figure 12 is shown from left to right : the

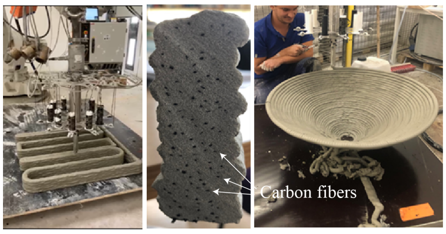

Figure 12. Prototype 2, XtreeE:carbon fibers, uniformly distributed in the cross-section (center). A fiber-reinforced corolla structure (right).

XtreeE FBP prototype, the cross-section of a cured cord reinforced with 1% carbon fibers in the center, and the print of a corolla with an overhang angle of more than 60 degrees, that would not be printable with a regular tool-path slicing and unreinforced printing mortar because the rings quickly reach a state of uniform axial tension that the mortar alone cannot sustain.

3.3 Characteristics of the Reinforced Cured Material

Tensile and flexural tests were conducted on reinforced laces with different rates of glass and basalt fibers. Cracking evolution and strains were monitored with Digital Image Correlation (DIC) using a custom MATLAB code called *NavDIC* [25]. Other tests are underway with other

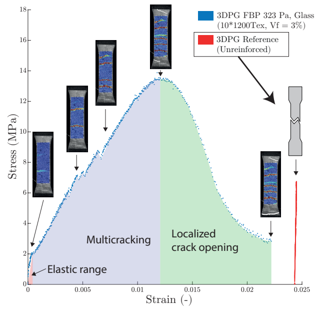

Figure 13. Tensile test of a 3% glass fiber-reinforced tensile specimen, and image correlation revealing the progressive appearance of cracks. On the left in red, a non-reinforced specimen.

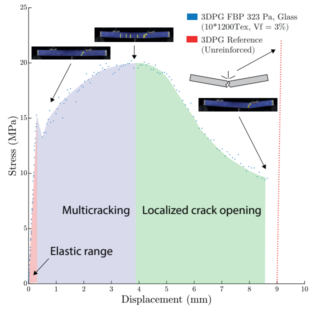

Figure 14. 4-point bending test of a 3% glass fiber-reinforced tensile specimen, and image correlation revealing the progressive appearance of cracks. On the left in red, a non-reinforced specimen.

fibers such as carbon or PVA. The specimens consist of one layer for tension and multiple stacked layers for flexion. Figure 13 shows the type of tensile behavior obtained with 3% fibers (here glass), and the high ductility obtained thanks to the diffuse microcracking made possible by the presence of fibers [19]. Flexural behavior is very similar, as seen on Figure 14, and more details can be found in [6]. Meter-scale tests on beams with a reinforced intrados are underway, the initial results are very promising [7] and suggest that the pseudo-ductile diffuse microcracking behaviour works at the structure scale.

4 Conclusion and Perspectives

Considering the low mechanical characteristics obtained in tension and the regulatory framework, reinforcing 3D printed mortar is imperative. It is an highly strategic research and industrial issue for the commercial development of the technology. While there is currently no off-the-shelf solution, several initiatives exist and already provide possible solutions that now need to be developed further. Often inspired by the long and rich history of cement and cast concrete reinforcement technologies, they also try to leverage new tools available today, such as robotics, parametric design, or materials science. A brief reminder of existing initiatives is proposed and a classification is made according to whether they post-reinforce the structure, reinforce the initial fresh batch or in-line. The first one has the advantage of being quickly implemented in real situations, through demonstrators, and thus promoting the technology. The second one is very promising, as this type of fiber mortar is already widely accepted and regulated in the community. Technical progress is still needed to improve achievable fiber rates and the workability of mortars, but the initial results in terms of strength and ductility are very encouraging. Finally, in-line reinforcement is certainly an interesting avenue, perhaps more in tune with the spirit of technology and construction 4.0. This should allow for stronger reinforcement, especially when a composite material approach is adopted with small and numerous fibres, in competition with steel systems for conventional concretes, more flexible in use, and adaptable to the needs and objects to be reinforced. However, these latter systems still pose some problems, anchoring and flexibility of reinforcements, technological simplicity, and compatibility with the formal performance expected from 3D printing, which should enable new structural systems to be proposed. A closer look is given at the initiative of the authors of this paper, an in-line reinforcement method called Flow-Based Pultrusion, which could address several challenges: good anchoring of fibers in the cement matrix, technological simplicity, and inspiration for new construction systems. As an example an original concrete truss concept, illustrated in Figure 15, and presented in [11] is realized through robotically free-form deposition [12]. In this type of structure, the elements work only in tension or compression. The anisotropy brought by a robotized in-line fiber extrusion process would therefore be particularly suitable and disruptive in terms of concrete construction systems : It leverages the opportunity to go beyond the specific performance of additive manufacturing (putting *the right material in the right place*) by putting *the right reinforcement in the right direction*.

In conclusion, the competition between two reinforcement systems proposed at the end of the 19th century and mentioned in the introduction, the *Hennebique* system (reinforced posts and beams) and the *Cottencin* system (thin ferrocement slabs), could well be replayed in favor of the latter thanks to new printing processes and in-line reinforcement as proposed by Flow-Based Pultrusion. This could reinvent more free and lighter structures such as those proposed by Candela or Pier Luigi Nervi (Figure 1). The latter wanted, in his own words, to "get out of a formwork architecture" by making the use of wooden formwork unnecessary and serving a vision that coupled material, form, and structure for more virtuous constructions.

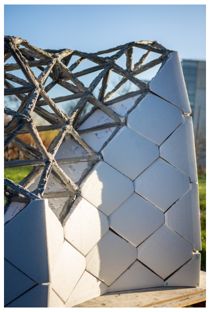

Figure 15. Curved concrete truss [11], Photo credit Stefano Borghi

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