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3D printing of continuous-fibers cementitious composites

Anisotropic 3D mortar

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Abstract: Significant developments in 3D concrete have been made over the past few decades. Yet, unreinforced printed components generally do not comply with existing construction standards or regulations and are therefore not used as load-bearing components. There is still a gap between research and use, and despite several proposals, standard commercial solutions for the reinforcement of 3D-printed structural members are still awaited. The proposed technology is inspired by the composites industry and called *flow-based pultrusion for additive manufacturing*. The reinforcement is provided by long and aligned fibers, and produces a transverse isotropic composite mortar. Here we show the first experimental setup, and the material tests performed on the printed material. An increase in tensile strength and ductility is shown. An industrial prototype, in collaboration with the company XtreeE, is being developed. This new equipment has made it possible to print beams of 1m50 whose intrados is reinforced with carbon fibres.

Keywords: Cementitious composite, 3D printing, Long fibers

1 Introduction

With a tensile strength of a few MPa and brittle behavior, cementitious mortars cannot be used unreinforced in tensed configurations. The pre-existing microcracks propagate at an early stage and lead quickly to rupture. The solution is, therefore, to "sew" intimately these cracks with a suitable reinforcement allowing the local discharge of the material.
Two types of reinforcement exist for concretes and mortars, structural ones, rebars, cables, or at the material scale, like fiber reinforcements. Thus the addition of a small ratio of fibers having a high tensile strength allows the improvement of the tensile behavior, by allowing this sewing of micro or macro-cracks, avoiding a sudden and localized rupture. The reinforcement is generally carried out by short fibers introduced into the mortar directly in the mixer. Their addition, however, causes a significant drop

in the fluidity of the mixture [1] which limits the volume fraction introduced (a few percent by volume), and the reinforcement obtained. Many short fibers are used for the reinforcement of cementitious materials [2], [3], metal fibers, polymers, glass, carbon, biosourced... It is thus possible to obtain with metal fibers, the only ones mentioned in structural design regulations, high-performance fiber-reinforced concrete HPFRCC [4], while maintaining good workability [5], [6]. The elastic limit and the strength in direct tension can respectively reach 15 MPa and 20 MPa (1 to 3 for unreinforced mortar) for respective deformations of 0.03% and 0.5%. The variety of existing fibers, in particular synthetic ones, also makes it possible to define a new family of cementitious materials called ”engineered cementitious composite” (ECC), which offers a great diversity of behavior. For example, in direct tension [7], ”Strain-Hardening Cementitious Composites” (SHCC), composed of a fine cementitious matrix and a limited ratio of synthetic fibers [8] present a poor tensile strength (5 MPa), but ductility and a very high ultimate strain (5%) [8], [9].
Finally, there are continuous reinforcement solutions using long fibres, fabrics or nets. Sometimes called ”textile reinforced concrete” (TRC) or ”textile reinforced mortar” (TRM), they were first proposed to make slender structures containing very thin elements [10], [11] that could then be made by pultrusion [12], and to reinforce aging structures [13]–[15].

It should be noted that these cementitious composites, like ferrocement, are made from a cementitious matrix of small grain sizes (absence of centimetric aggregates).

2 Concrete 3D printing and reinforcement methods for additive manufacturing applications

There are two main technologies for the extrusion printing of mortars, mono-component (1K) or bi-component (2K) technology. The first deposits a lace pumped directly into a firstly prepared batch of mortar and having the right consistency to allow the stacking of successive layers. A powerful pump is necessary because the mixture has a relatively high consistency, a yield stress of about a few thousand KPa, which evolves quite slowly but irremediably to a consistency too high for pumping. Bi-component technology prints a much more fluid material (a few hundred kPa) strongly accelerated by an additive just before printing. The initial mixture is therefore easier to pump, more stable, and allows more freedom since the operator has the possibility of modifying it continuously. Fibering can address both technologies.

Changing the process, going from pouring to extrusion does not radically change the problems or the solutions. Most of what was described above, prestressing, short or long fibers, are possible and already investigated for reinforcement of printed structures. These proposals can be classified according to a criterion proposed in [16] which groups reinforcement methods according to the moment of application. For some of them, the reinforcement is applied a posteriori, inspired by traditional reinforcement methods, for others it is integrated directly into the batch of initial material, as a premix, for the last ones the reinforcement is carried out simultaneously with printing, in line, in the immediate vicinity of the print nozzle.
Concerning reinforced premix, the most used fibers are synthetic fibers (carbon, polyvinyl alcohol: PVA, Poly-ethylene PE) or mineral fibers (glass or basalt). In order to maintain a rupture mode by decohesion of the interface and/or not to block the pumping and extrusion system, the length of the fibers is limited (≈ 10mm) and to guarantee a sufficiently low shear threshold, the volume proportion is generally less than or equal to 2%

[17].
Making mortar printing and reinforcement concomitant, by integrating the reinforcement at the level of the nozzle, is more in line with an integrated digital framework based on advanced robotic manufacturing strategies. Experiments with micro-cables, chains or metal grids [18]–[21] have been carried out. Particular attention must be paid to the quality of the interface between the reinforcement and the cementitious material, which conditions the composite action of the assembly. Mineral fibers are obviously extensively investigated, for example recently in [22] or by the authors of this chapter in [23]. The former use a thin, narrow strip of *Mineral-Impregnated Carbon Fiber* (MCF) unrolled downstream of the nozzle on a concrete layer already printed and which is covered by the current deposit. To guarantee good impregnation of the carbon fiber strip, a pre-impregnation line using a very fine mortar is set up upstream to prepare the strip to be deposited [24]. A very recent variant of the MCF process, named *ProfiCarb* [25], reconditions the pre-impregnated yarns into coils which will be driven directly by the flow of a 1K mortar. Several reinforcements, 6 yarns of carbon fibers, can thus be dispersed in the section of the lace.
This last process is very close to the Flow-Based-Pultrusion concept that we proposed for a 2K technology [23] and which is the subject of this communication. Since the mortar may be more fluid, 2K technology allows naturally better impregnation of the fibers, the use of yarn of smaller diameters, and therefore a more homogeneous reinforcement. It avoids technologies and motors for guiding and driving the reinforcement, which complicate the process and reduce the formal possibilities, such as sharp curves for example.

3 The Concept of Flow-Based-Pultrusion in-line Reinforcement

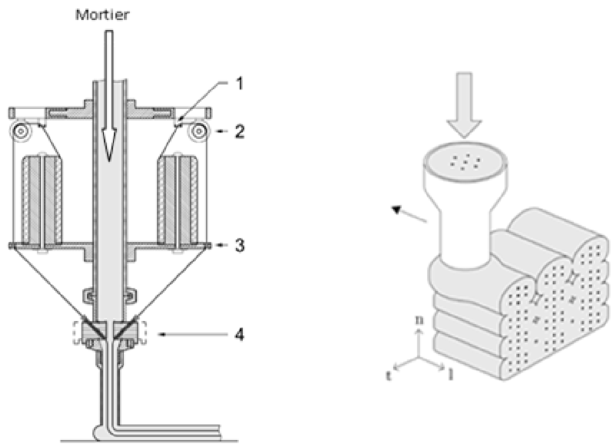
The technology is described in the patent [26] and described in figure 1. An adapted control of the rheological behavior of the cementitious matrix ensures the impregnation of continuous rovings of small diameter (glass, basalt, etc.) and then the routing without any motorization (fig.1 left). The material is transversely isotropic, homogeneously reinforced in a single direction, and offers new possibilities (fig.1 right). Indeed, it can improve the resistance and the ductility of the hardened material but also contribute to better handling the fresh laces during the deposition, allowing more complex paths including slope or cantilever situations as seen later (figure 3 right).

3.1 Prototypes and devices

A first prototype was developed at the Navier laboratory, and was adapted to a bi-component system from the company XtreeE and adapted on an ABB 6200 6-axis robot (figure 2). The first attempts allowed printing with glass, basalt and carbon fibers, and up to 6% by volume ([27]). A second industrial prototype is being developed in collaboration with XtreeE. We see in the figure 3, the XtreeE prototype, the section of a hardened cord reinforced with 1% of carbon fibers (center), and on the right, the printing of a corolla which would not be printable without fibers because of the tension stresses prescibed in the layers.

3.2 Characteristic of hardened reinforced material

Tensile and bending tests were carried out on specimens reinforced with different ratios of fiberglass and basalt. Other trials are underway with other fibers such as carbon or



: on the left, fiber printing device: 1/bobbins 2/pulleys 3/guides 4/drive head. On the right, transverse isotropic arrangement in the direction of printing

Figure 1. The Flow-Based Pultrusion process [26]

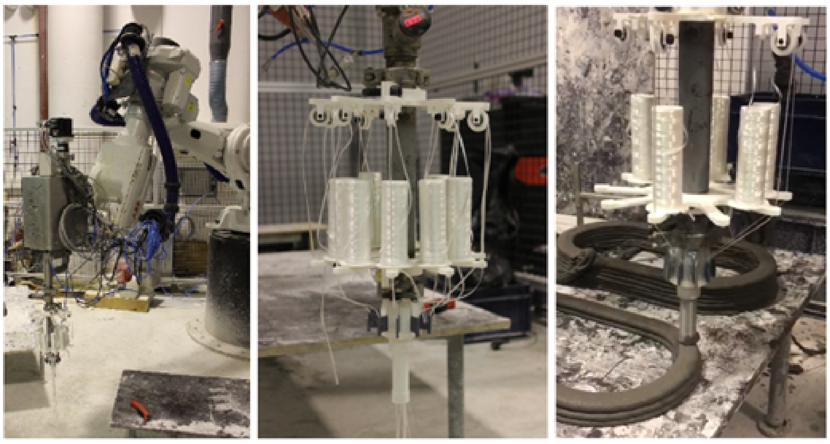


Figure 2. Prototype 1, fiberglass-reinforced-mortar printing at Navier laboratory

Figure 3. Prototype 2, with carbon fibers at XtreeE, evenly distributed in the 10 layers section (center). Printing a fiber structure with tensed rings (right)

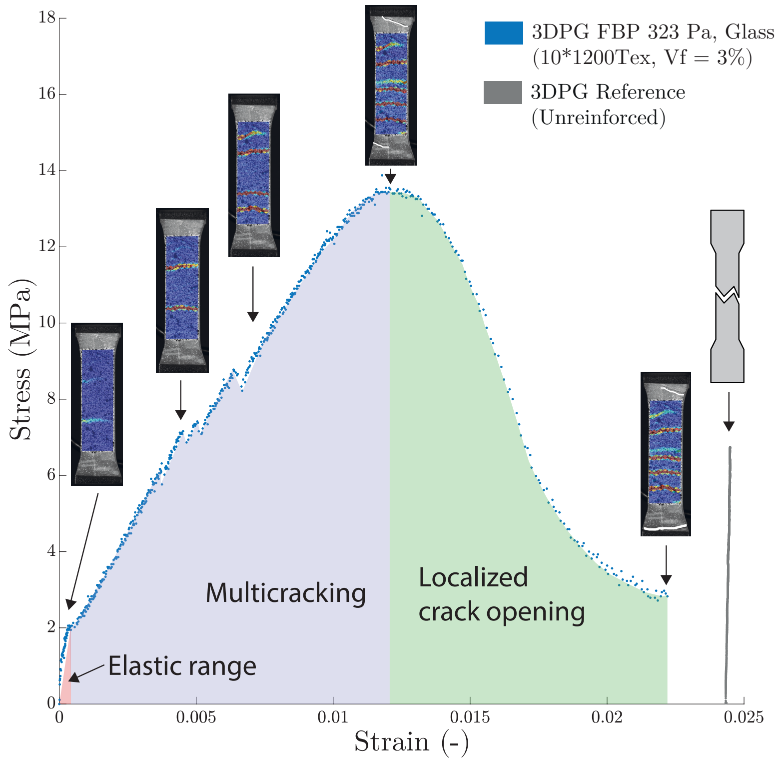


Figure 4. Tensile test of a specimen reinforced with 3% glass fibers, and image correlation revealing the progressive appearance of cracks. On the right the curve in gray for an unreinforced specimen

PVA. The specimens consist of a single layer for tension tests and a multilayer for bending. The figure 4 shows the type of tensile behavior obtained with 3% fibers (here glass), and the high ductility obtained thanks to the diffuse microcracking induced by the fibers. The same type of behavior is seen in bending [28].

3.3 First tests on small beams

This new equipment made it possible to print 1m50 beams whose intrados is reinforced with 1% carbon fiber. The geometry proposed in the figure 5 is imposed by the number of bobbins and the total fiber length which remain limited for this prototype. The fibers are thus concentrated in the tensed part.

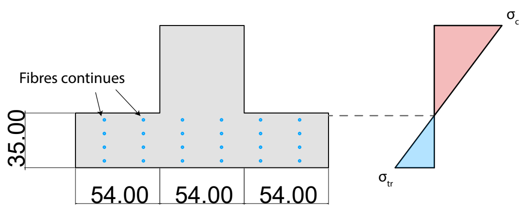


Figure 5. Beam section (in mm), fibers position, and axial stress diagram.

4-point bending tests were carried out on reinforced and non-reinforced beams. The non-reinforced beams present the expected brittle fracture and a low tensile strength in the intrados around 5 Mpa (fig.6 left), the reinforced beams exhibit a very significant ductile and hardening behavior and an ultimate tensile strength, multiplied by 3, namely 18 Mpa with only 1% of fibers (fig.6 right). The ductility is obtained thanks to

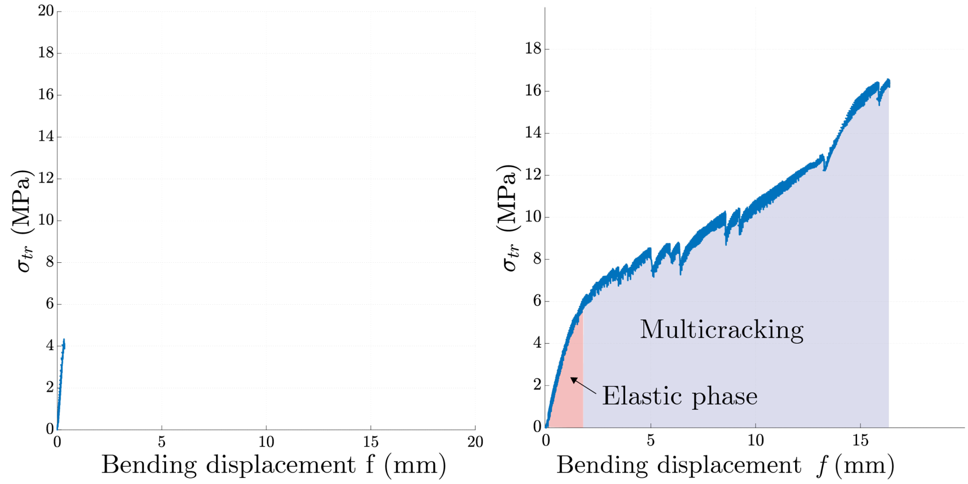


Figure 6. Maximum tensile stress as a function of the deflection, for an unreinforced beam on the left, and reinforced with 1% long fibers on the right.

a progressive transverse multi-cracking (corresponding to the various peaks observed) in the intrados (see Figure 7)

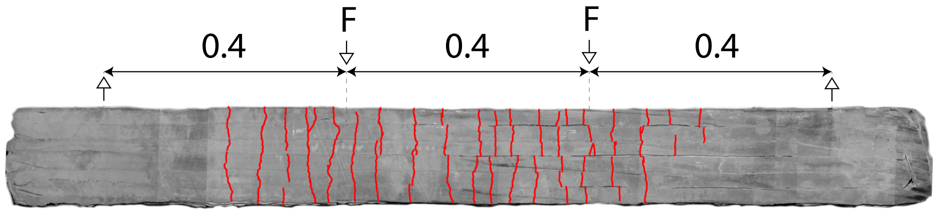


Figure 7. Multi-cracking of the tensile part (intrados) of the beam.

Some cycling tests were carried out. We observe in figure 8 a reversible and fairly linear behavior (inside the blue area), the slope corresponding to the slope observed in figure 6 right during the multi-cracking phase. The cracks open and close elastically which testifies to a good anchorage of the fibers which do not seem to come off nor break before the break of the beam itself. This ended up (yellow area) breaking under the shear force under the central supports and in the compressed part (figure 9). It's also worth noting the very large deflections obtained, 15mm at the level of the center of the 1m20 long beam, corresponding to L/80 which is considerable for a beam made of cementitious material.

4 Conclusion and perspectives

The reinforcement of 3D mortar impressions is an imperative and highly strategic research for the commercial development of the technology. Several initiatives inspired by the long and rich history of cement and cast concrete reinforcement technologies exist, and already provide answers to the different situations encountered. Some propose to reinforce online what is probably more in line with the spirit of technology and construction 4.0. We describe here a patented process called Flow-Based-Pultrusion, which allows a uniaxial in-line reinforcement with long fibers of small diameter (between 500 and 1000 Tex), a good anchoring of the fibers in the cementitious matrix, and a relatively simple technology. This opens the way to more massive reinforcements, in competition with steel systems for conventional concrete, more flexible in use, and

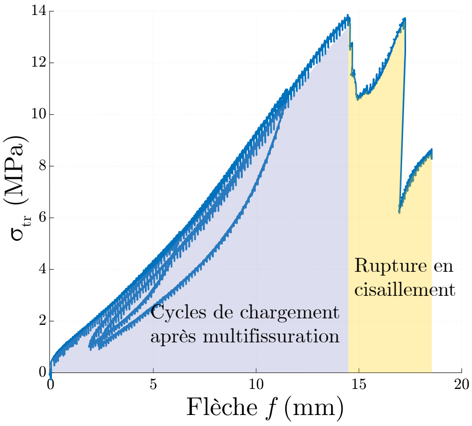


Figure 8. Cycling in bending on a beam reinforced with 1% long fibres.

Figure 9. Ultimate shear failure in the thickness of the beam, initiated under the load.

adaptable according to the need and the object to be reinforced. This process is also a source of inspiration for new constructive systems, which can help for example to get out, according to the expression of the great engineer Pier Luigi Nervi, "of a plank architecture" imposed for concrete by the use of wooden formwork. The "ferrocement" he developed in the middle of the last century, which dispenses with formwork and uses thinner, more conformable steels than "concrete reinforcing bars", has led to architectural feats such as the hangar at Orbetello airfield (Italy), built in 1940, (figure 10) of stunning, inspiring efficiency and aesthetics. The material/form/structure adequacy and a controlled anisotropy, obviously allow a more virtuous construction. It's in this spirit, but with today's tools and people, that our proposal is based.

Figure 10. Orbetello aerodrome, Italy, Pier luigi Nervi in 1940 (Credits: Hulton Getty)

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References

[1] Martinie, "Comportement rhéologique et mise en œuvre des matériaux cimentaires fibrés," Ph.D. dissertation, Université Paris-est, 2010.

[2] A. M. Brandt, "Fibre reinforced cement-based (FRC) composites after over 40 years of development in building and civil engineering," en, *Composite Structures*, vol. 86, no. 1-3, pp. 3–9, Nov. 2008, ISSN: 02638223. DOI: 10.1016/j.compstruct.2008.03.006. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S0263822308000597 (visited on 05/03/2020).

[3] F. Hamidi and F. Aslani, "Additive manufacturing of cementitious composites: Materials, methods, potentials, and challenges," en, *Construction and Building Materials*, vol. 218, pp. 582–609, Sep. 2019, ISSN: 09500618. DOI: 10.1016/j.conbuildmat.2019.05.140. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S0950061819313194 (visited on 04/29/2020).

[4] K. Wille, S. El-Tawil, and A. Naaman, "Properties of strain hardening ultra high performance fiber reinforced concrete (UHP-FRC) under direct tensile loading," en, *Cement and Concrete Composites*, vol. 48, pp. 53–66, Apr. 2014, ISSN: 09589465. DOI: 10.1016/j.cemconcomp.2013.12.015. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S0958946514000055 (visited on 04/30/2020).

[5] P. Rossi, "Ultra-high-performance fiber-reinforced concretes," *Concrete international*, vol. December 1982, pp. 46–52, Dec. 1982.

[6] P. Rossi, "Influence of fibre geometry and matrix maturity on the mechanical performance of ultra high-performance cement-based composites," en, *Cement and Concrete Composites*, vol. 37, pp. 246–248, Mar. 2013, ISSN: 09589465. DOI: 10.1016/j.cemconcomp.2012.08.005. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S0958946512001692 (visited on 05/04/2020).

[7] V. C. Li, F. P. Bos, K. Yu, *et al.*, "On the emergence of 3D printable Engineered, Strain Hardening Cementitious Composites (ECC/SHCC)," en, *Cement and Concrete Research*, vol. 132, p. 106 038, Jun. 2020, ISSN: 00088846. DOI: 10.1016/j.cemconres.2020.106038. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S0008884620300557 (visited on 04/29/2020).

[8] V. C. Li, "On Engineered Cementitious Composites (ECC)," en, vol. 1, no. 3, p. 17, 2003.

[9] P. Jun and V. Mechtcherine, "Behaviour of Strain-hardening Cement-based Composites (SHCC) under monotonic and cyclic tensile loading: Part 2 - Modelling," en, *Cement and Concrete Composites*, vol. 32, no. 10, pp. 810–818, Nov. 2010, ISSN: 09589465. DOI: 10.1016/j.cemconcomp.2010.08.004. [Online]. Available: http://linkinghub.elsevier.com/retrieve/pii/S0958946510001162 (visited on 11/16/2016).

[10] J. Hegger and S. Voss, "Investigations on the bearing behaviour and application potential of textile reinforced concrete," en, *Engineering Structures*, vol. 30, no. 7, pp. 2050–2056, Jul. 2008, ISSN: 01410296. DOI: 10.1016/j.engstruct.2008.01.006. [Online]. Available: http://linkinghub.elsevier.com/retrieve/pii/S0141029608000126 (visited on 11/16/2016).

[11] J. Hegger, M. Curbach, A. Stark, S. Wilhelm, and K. Farwig, “Innovative design concepts: Application of textile reinforced concrete to shell structures,” en, *Structural Concrete*, vol. 19, no. 3, pp. 637–646, Jun. 2018, ISSN: 14644177. DOI: 10.1002/suco.201700157. [Online]. Available: http://doi.wiley.com/10.1002/suco.201700157 (visited on 06/19/2020).

[12] A. Peled and B. Mobasher, “Properties of Fabric–Cement Composites made by Pultrusion,” en, *Materials and Structures*, vol. 39, no. 8, pp. 787–797, Oct. 2006, ISSN: 1359-5997, 1871-6873. DOI: 10.1617/s11527-006-9171-3. [Online]. Available: http://link.springer.com/10.1617/s11527-006-9171-3 (visited on 05/13/2020).

[13] A. Brückner, R. Ortlepp, and M. Curbach, “Textile reinforced concrete for strengthening in bending and shear,” en, *Materials and Structures*, vol. 39, no. 8, pp. 741–748, Oct. 2006, ISSN: 1359-5997, 1871-6873. DOI: 10.1617/s11527-005-9027-2. [Online]. Available: http://link.springer.com/10.1617/s11527-005-9027-2 (visited on 06/19/2020).

[14] V. Mechtcherine, “Novel cement-based composites for the strengthening and repair of concrete structures,” en, *Construction and Building Materials*, vol. 41, pp. 365–373, Apr. 2013, ISSN: 09500618. DOI: 10.1016/j.conbuildmat.2012.11.117. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S0950061812009555 (visited on 10/07/2019).

[15] L. A. S. Kouris and T. C. Triantafillou, “State-of-the-art on strengthening of masonry structures with textile reinforced mortar (TRM),” en, *Construction and Building Materials*, vol. 188, pp. 1221–1233, Nov. 2018, ISSN: 09500618. DOI: 10.1016/j.conbuildmat.2018.08.039. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S0950061818319792 (visited on 03/20/2019).

[16] D. Asprone, C. Menna, F. P. Bos, T. A. Salet, J. Mata-Falcón, and W. Kaufmann, “Rethinking reinforcement for digital fabrication with concrete,” en, *Cement and Concrete Research*, vol. 112, pp. 111–121, Oct. 2018, ISSN: 00088846. DOI: 10.1016/j.cemconres.2018.05.020. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S0008884618300309 (visited on 01/06/2020).

[17] H. Ogura, V. N. Nerella, and V. Mechtcherine, “Developing and Testing of Strain-Hardening Cement-Based Composites (SHCC) in the Context of 3D-Printing,” *Materials*, vol. 11, no. 8, p. 1375, Aug. 2018, ISSN: 1996-1944. DOI: 10.3390/ma11081375.

[18] F. P. Bos, E. Bosco, and T. A. M. Salet, “Ductility of 3d printed concrete reinforced with short straight steel fibers,” en, *Virtual and Physical Prototyping*, vol. 14, no. 2, pp. 160–174, Apr. 2019, ISSN: 1745-2759, 1745-2767. DOI: 10.1080/17452759.2018.1548069. [Online]. Available: https://www.tandfonline.com/doi/full/10.1080/17452759.2018.1548069 (visited on 03/31/2019).

[19] J. H. Lim, B. Panda, and Q.-C. Pham, “Improving flexural characteristics of 3d printed geopolymer composites with in-process steel cable reinforcement,” en, *Construction and Building Materials*, vol. 178, pp. 32–41, Jul. 2018, ISSN: 09500618. DOI: 10.1016/j.conbuildmat.2018.05.010. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S0950061818310675 (visited on 08/31/2018).

[20] F. Bos, Z. Ahmed, E. Jutinov, and T. Salet, “Experimental Exploration of Metal Cable as Reinforcement in 3d Printed Concrete,” en, *Materials*, vol. 10, no. 11, p. 1314, Nov. 2017, ISSN: 1996-1944. DOI: 10.3390/ma10111314. [Online]. Available: http://www.mdpi.com/1996-1944/10/11/1314 (visited on 08/31/2018).

[21] T. Marchment and J. Sanjayan, “Mesh reinforcing method for 3D Concrete Printing,” en, *Automation in Construction*, vol. 109, p. 102 992, Jan. 2020, ISSN: 09265805. DOI: 10.1016/j.autcon.2019.102992. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S0926580519306132 (visited on 04/29/2020).

[22] V. Mechtcherine, A. Michel, M. Liebscher, and T. Schmeier, "Extrusion-based additive manufacturing with carbon reinforced concrete: Concept and feasibility study," *Materials*, vol. 13, no. 11, 2020, ISSN: 1996-1944. DOI: 10.3390/ma13112568. [Online]. Available: https://www.mdpi.com/1996-1944/13/11/2568.

[23] N. Ducoulombier, L. Demont, C. Chateau, M. Bornert, and J.-F. Caron, "Additive manufacturing of anisotropic concrete: A flow-based pultrusion of continuous fibers in a cementitious matrix.," *Procedia Manufacturing*, vol. 47, pp. 1070–1077, 2020, 23rd International Conference on Material Forming, ISSN: 2351-9789. DOI: https://doi.org/10.1016/j.promfg.2020.04.117. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S2351978920311732.

[24] V. Mechtcherine, A. Michel, M. Liebscher, K. Schneider, and C. Großmann, "Mineral-impregnated carbon fiber composites as novel reinforcement for concrete construction: Material and automation perspectives," *Automation in Construction*, vol. 110, p. 103 002, Feb. 2020, ISSN: 0926-5805. DOI: 10.1016/j.autcon.2019.103002.

[25] T. Neef and V. Mechtcherine, "Simultaneous Integration of Continuous Mineral-Bonded Carbon Reinforcement Into Additive Manufacturing With Concrete," *Open Conference Proceedings*, vol. 1, pp. 73–81, Feb. 2022, ISSN: 2749-5841. DOI: 10.52825/ocp.v1i.80.

[26] J. Caron and N. Ducoulombier, "Method and device for manufacturing anisotropic concrete," *Patent*, vol. wo2020249913/fr3097152, 2020.

[27] L. Demont, N. Ducoulombier, R. Mesnil, and J.-F. Caron, "Flow-based pultrusion of continuous fibers for cement-based composite material and additive manufacturing: Rheological and technological requirements," *Composite Structures*, vol. 262, p. 113 564, 2021, ISSN: 0263-8223. DOI: https://doi.org/10.1016/j.compstruct.2021.113564. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0263822321000258.

[28] J.-F. Caron, L. Demont, N. Ducoulombier, and R. Mesnil, "3d printing of mortar with continuous fibres: Principle, properties and potential for application," *Automation in Construction*, vol. 129, p. 103 806, 2021, ISSN: 0926-5805. DOI: https://doi.org/10.1016/j.autcon.2021.103806. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0926580521002570.