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Flow-Based Pultrusion of Anisotropic Concrete : Mechanical properties at hardened state

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Abstract. The issue of reinforcement for 3D concrete printing has received considerable attention, as constructions have to comply with reliability principles and building standards. Here a specific process called Flow-Based Pultrusion for additive manufacturing (FBP), inspired by pultruded composite manufacturing and built on existing extrusion-based 3D printing technology, permits to impregnate numerous continuous fiber rovings pulled by the extrusion flow of a fine mortar[4]. The resulting extruded material, an *Anisotropic Concrete*, is isotropic transverse like unidirectional long fibers composite. The mechanical properties are greatly influenced by the quantity of fibres (reinforcement ratio) and their impregnation quality [2]. These factors are related to the process parameters [3], the mortar rheology for impregnation and the fibre dosage (roving thickness, roving count) for reinforcement ratio. Full-scale experiments are presented, using fibre rovings to increase the reinforcement ratio up to 3 %, which is comparable to the steel/concrete ratios in traditional rebar-reinforced concrete elements. The influence of reinforcement ratio on the tensile strength and ductility of the hardened material is presented.

Keywords: Additive manufacturing · Concrete · Composite materials · Mechanical properties.

1 Introduction

Concrete 3D printing has become popular and industrial applications emerge. Reinforcement is a necessity to make the printed structures mechanically adapted to usual building applications and compliant with reliability standards. Hence many ways of reinforcing 3D-printed concrete have been identified [6] and *In line* methods have been proposed. For such technologies, reinforcement efficiency is questionable and can be sensitive to process parameters [1].

In this paper, we present such a method called Flow-Based Pultrusion (FBP) [4]. Numerous continuous fiber rovings are impregnated and pulled by the extrusion flow of a printable mortar, providing unidirectional reinforcement, similarly

to well-known long fibre composites. With such material, it is necessary to properly set process parameters (mortar type and rheology, fibre type and dosing) to provide the desired mechanical behaviour, namely ductility, reinforcement and toughness (resistance to crack propagation). The bond between fibres and the fine-grained mortar is a key factor driving mechanical properties, and is linked with the mortar yield stress at extrusion τ_e . The type of mortar and fibre play a role but here only the influence of the reinforcement ratio V_f is investigated and strategies to obtain good mechanical properties are given.

After the FBP process is described, mechanical properties of the resulting material, called *Anisotropic Concrete*, are investigated through bending and tension testing and with various V_f settings.

2 Description of the FBP process

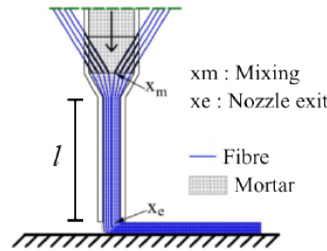


Fig. 1. Schema of FBP [4]

The process is illustrated in Fig. 1. Continuous rovings are impregnated and pulled through an extrusion die where the mortar evolves thanks to the accelerator additives. Fibres are directly dragged by the Herschel-Bulkley flow thanks to shear stresses (see [2],[4] for details). This principle is implemented in an extrusion-based concrete 3D printing system (XTreeE technology and HAL Robotics software) (Fig.2a).

3 Mechanical properties of Anisotropic Concrete

3.1 Materials and methods

In order to assess the mechanical properties of Anisotropic Concrete in the direction of reinforcement, 8 multi-layer and 14 single-layer specimens were printed and tested, respectively, in bending and tension. Matrix is a *Lafarge 3DPG* printable mortar reinforced with 10 AR-Glass rovings of the same type, *NEG AR310S800* (310 Tex), or *Owens Corning* (1200 Tex) which yields, respectively, $V_f = 0.8\%$ or 3% .

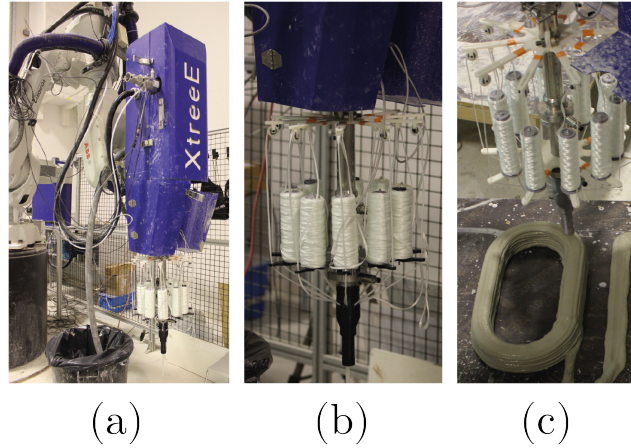


Fig. 2. (a) XtreeE concrete 3D printing system (Build’In Lab), (b) FBP apparatus attached to the 3D printing system, (c) 3D printing of anisotropic concrete.

Preparation of specimens Multilayer bending specimens were cut from printed samples such as shown in Fig. 2 (c) after being cured in water for 28 days. As their geometry varies slightly because of the printing, their cross-section is photographed and geometrical parameters (i.e. area moments and neutral axis) computed using a CAD software. Single-layer tension specimens are printed laces, softly re-shaped into dog-bones at fresh state using a mold.

Testing of specimens Tension tests are illustrated in Fig. 3. They are displacement controlled at a speed of 0.005 mm/s, using an Instron universal testing machine. In order to perform Digital Image Correlation (DIC) strain measurements, a speckle pattern is applied to one side of specimens which is filmed by a camera. More details on the setup can be found in [2]. Bending tests are operated similarly. Installation (see Fig.3) and testing speed (0.05 mm/s) are adapted. An LVDT sensor is placed on the middle point of the specimen in order to measure its maximum deflection.

3.2 Influence of reinforcement ratio

Representative stress-strain curves of unreinforced, 0.8% and 3% reinforced samples are shown in Fig. 4. Unreinforced samples are brittle as 0.8% samples show a ductile phase after the initiation of the first crack.

3% reinforced samples show an improvement of final resistance (+80%) and more ductility with strains up to 2%. For tensile tests, the standard deviation for reinforced samples is 3.03 MPa ($V_f = 3\%$) and 1.04 MPa (0.8%) which is comparable to unreinforced ones (2.60 MPa). Bending is similar with standard deviations of 2.18 MPa (3%), 4.02 MPa (0.8%) and 3.57 MPa (unreinforced).

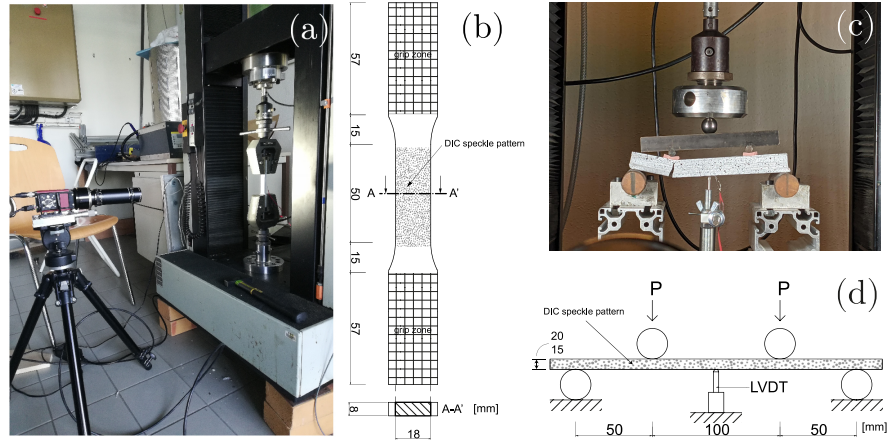


Fig. 3. (a) Tensile test setup with DIC measurement. (b) Schema of tensile test specimen. (c) 4-point bending test setup. (d) Schema of bending test and specimen.

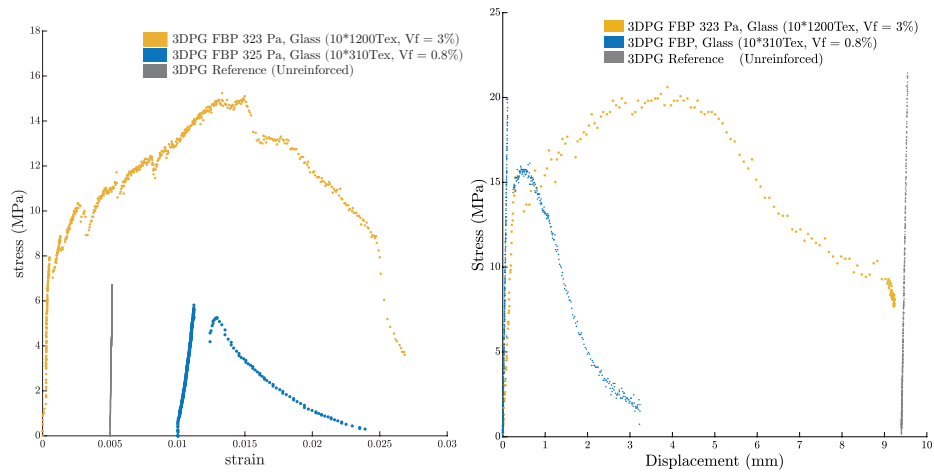


Fig. 4. Representative stress-strain curves for direct tension (left) and bending (right) specimens with varying reinforcement ratios. Curves are offset for clarity.

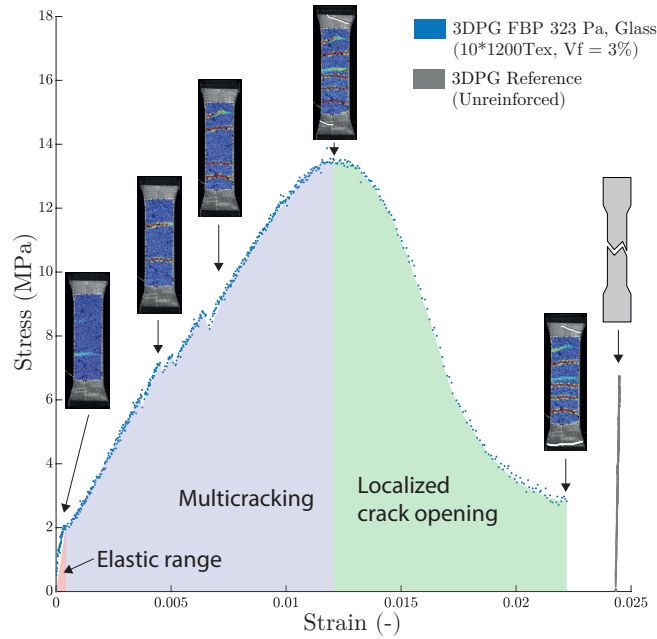


Fig. 5. Left : Representative stress-strain curve and associated cracking behavior of a 3% reinforced tensile sample. Curves are offset for clarity.

Representative stress-strain curves and associated cracking behaviour for tension tests are shown in Fig. 5. After an elastic phase, a first crack appears and unreinforced samples fails at an average stress of 7 MPa. Reinforced samples crack earlier and shows a shorter elastic range, until 2 MPa, due to the presence of defects induced by the introduction of fibers in the mortar's packing. This earlier cracking permits the following multicracking phase, depending on the matrix (mortar) fracture energy [5] which relates to its strength : the stronger the matrix, the harder it is to crack. Early crack activation prevents excessive localized stress gradients and the fibers remain able to "sew-up" these damages. During this phase, the load increases until a strain of about 1%-1.5%. Finally, a strain localization up to 2-3% due to one of the cracks, leads to a smooth load decrease until rupture. At the same dosages, the observed rupture profiles may vary but are consistent with the testing conditions : in most cases the first crack is transverse (to the fibre direction) or slightly angled, and in the gage area. For some samples, fracture initiates near the grip zone due to stress concentrations but the following multiple cracks are transverse and in the gage area. Exceptionally, for 3% reinforced samples two tests shown some longitudinal crack developments along the reinforcement direction, similar to splitting for composite materials, suggesting the exceeding of the fiber-matrix interface strength due to the bifurcation of a transverse crack. Nevertheless, the stress-strain response of these two samples were similar to the other ones.

For bending, the behaviour is very similar. Comparison with unreinforced material shows the reinforcement's efficiency : final resistance is improved and the material becomes ductile.

4 Conclusion and perspectives

The aim of this study was to investigate how Flow Based Pultrusion can provide a solution to reinforce 3D-printed concrete, by studying the effect of reinforcement ratio V_f . Thanks to a good setting of parameters (type of fibers and matrix, rheology parameters...) process operates successfully at 1:1 scale and the material presents an improved tensile resistance (+80%) and ductility (strain up to 2%). Its unidirectional character permits to add reinforcement at the right place and in the right direction. This is already familiar to the composite industry, where cross-ply laminates orientation can be optimized. But it's also not so far from traditional reinforced concrete philosophy, rebars positioning is adapted to account for specific efforts. The FBP process proposes more versatility and disruptive solutions.

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