3D Concrete Printing for Structural Applications

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Abstract

Recent years have seen a rapid growth of additive manufacturing methods for concrete construction. Potential advantages include reduced material use and cost, reduced labor, mass customization and CO2 footprint reduction. None of these methods, however, has yet been able to produce additively manufactured concrete with material properties suitable for structural applications, i.e. ductility and (flexural) tensile strength. In order to make additive manufacturing viable as a production method for structural concrete, a quality leap had to be made. In the project '3D Concrete Printing for Structural Applications', 3 concepts have been explored to achieve the required structural performance: applying steel fiber reinforcement to an existing printable concrete mortar, developing a strain-hardening cementitious composite based on PVA fibers, and embedding high strength steel cable as reinforcement in the concrete filament. Whereas the former produced only an increase in flexural tensile strength, but limited post-peak resistance, the latter two provided promising strain hardening behavior, thus opening the road to a wide range of structural applications of 3D printed concrete.

Keywords

concrete, fiber, reinforcement, structural, methods

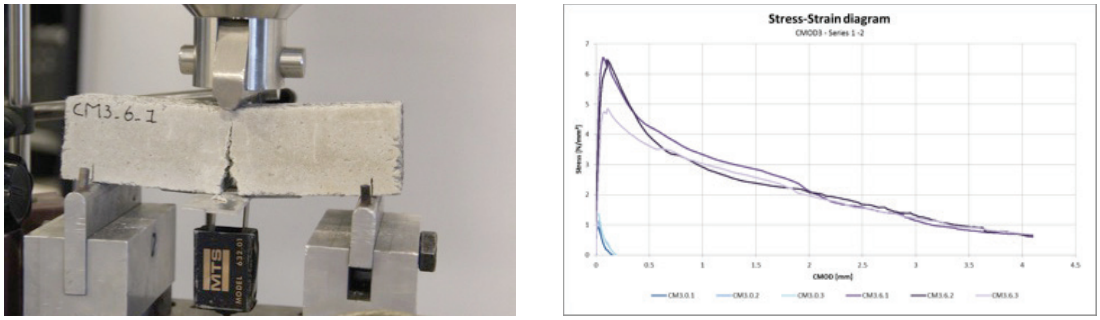
Introduction

The 3D Concrete Printing (3DCP) method, under development at the TU Eindhoven, is one of an increasing number of methods for the Additive Manufacturing of Concrete (AMoC) under development around the globe. Until recently, however, the lack of ductility and (flexural) tensile strength that could be obtain in the printed product severely limited the scope for which these methods could be applied in structural applications. This problem has been addressed in this project. Three conceptual solutions were developed: applying steel fiber reinforcement to an existing printable concrete mortar, developing a strain-hardening cementitious composite based on PVA fibers, and embedding high strength steel cable as reinforcement in the concrete filament.

Steel Fiber Reinforced 3D Concrete Printing

The addition of steel fibers to concrete to replace conventional reinforcement bars or reduce it has been applied in concrete construction for several decades. Applying this concept to 3D concrete printing required the development of a device to add the fibers to the printed filament near the print nozzle, as the steel fibers would clog up and damage the pump and transport system due to their stiffness and abrasive nature. In the project, a prototype of such a device has been developed and tested. In its current state, it proved possible only to print concrete with a short 6 mm straight fiber, although the target quantity of 150 kg/m3 was reached. As expected, this resulted in strong strain softening behavior, but a significant increase in flexural strength was nevertheless achieved (Figure 1). The fiber orientation was highly anisotropic, with the majority aligned in the direction of filament flow, as shown in a cut open sample (Figure 2).

FIGURE 1 Parallel section of 3D printed concrete element, containing 6 mm steel fiber. (source: Raedts, W., MSc graduation, TU/e, 2017).



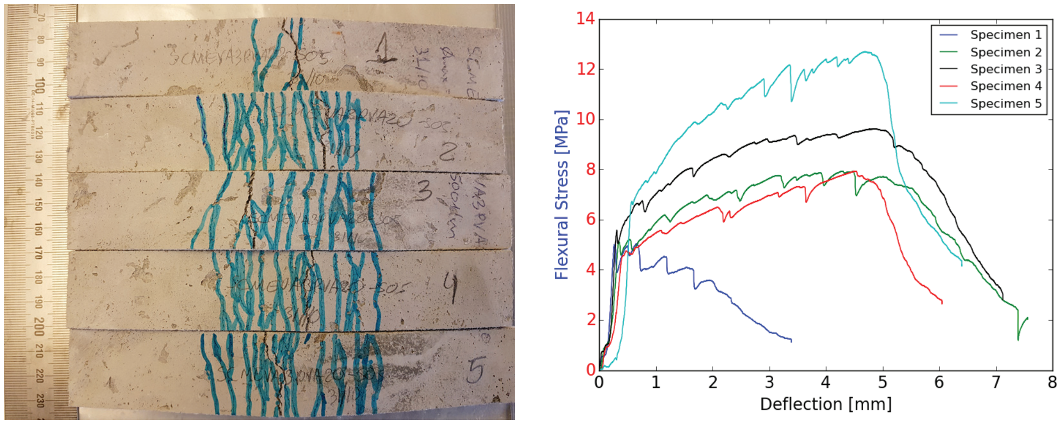
(a) *(b)*

FIGURE 2 CMOD test and resulting stress-CMOD curves for printed beams, without fiber (CM3.0.1-3) and with 6 mm fiber (CM3.6.1-3). (source: Raedts, W., MSc graduation, TU/e, 2017).

PVA Fiber Based Strain Hardening Cementitious Composite

Recently, strain hardening cementitious materials have been developed. These are based on the application of very finely distributed PVA fibers, which possess a relatively high strength (for polymers) and excellent adhesion to concrete. These materials are usually self levelling. For the purpose of this project, a material was developed based on an extensive rheology characterization in relation to the properties of the 3DCP facility. After an intense trajectory of fine-tuning the material properties, two printable mix designs (Figure 3) were obtained that both showed clear strain hardening behavior (Figure 4). Due to the flexibility of the PVA fiber, they could be added to the initial mix and be pumped to the printer head. Contrary to the steel fiber, no additional device is required although a careful mixing of the fibers in highly viscous mix proved crucial to avoid clogging in the linear displacement pump. The structural performance of the materials that have been developed is extremely promising and will be the subject of future research and development.

FIGURE 3 Printing with one of the developed PVA-fiber reinforced Strain Hardening Cementitious Composites.



(a) *(b)*

FIGURE 4 Printed PVA SHCC specimens after test with cracking pattern indicated and stress-strain curves from 4-point bending test.

Steel Cable Reinforced 3D Printed Concrete

A completely different approach is to rethink the conventional reinforcement bars and apply highly flexible high strength steel cables instead. A device was developed to entrain the cables in the concrete filament during printing (Figure 5). Pull-out and bending tests were performed using 3 types of cables of different strengths (Figure 6). It was confirmed that common calculation approaches for conventional reinforced concrete could be applied to cable reinforced printed concrete as well. Ductility is readily achieved, but strain hardening highly depended on the concrete element design, as in many cases the stronger cables failed in cable slip rather than breakage, and were thus not able to develop their full strength. Research to improve bond behavior is ongoing. Entraining steel reinforcement cable improves the structural safety significantly and was therefore applied as lateral reinforcement in the layers of the world's first MDM-printed concrete bridge for bicycles in Gemert, Noord Brabant (Figure 7). Several hundred meters were applied.

FIGURE 5 3D printing concrete with a directly entrained reinforcement cable.

FIGURE 6 Bending test on 3D printed concrete beam with cable reinforcement.

FIGURE 7 The world's first MDM-printed concrete bridge for bicycles in Gemert, Noord Brabant, on opening day. The printed layers contain steel cable as lateral reinforcement (the bridge is prestressed in the longitudinal direction).

Concluding

The project '3D Concrete Printing for Structural Applications' has resulted in two quite different but highly promising concepts to achieve ductility and (flexural) tensile strength in printed concrete. This will greatly increase the possibilities to apply the new technology of 3D concrete printing to structural designs.