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Pre-installed Reinforcement for 3D Concrete Printing

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Abstract. Providing reinforcement is essential for the structural integrity of concrete elements and for safely handling, transporting, and assembling prefabricated concrete parts. However, the integration of reinforcement is a persisting challenge in 3D concrete printing with extruded concrete. This paper presents a production process consisting of 3D printing around pre-installed reinforcement. The reinforcement is composed of conventional reinforcing steel bars, which can be pre-assembled in cages independently of casting, boosting the specialisation and efficiency in production. This approach was used to produce a 3.4 m span T-beam with optimised topology, consisting of three segments connected with matching surfaces. The beam segments were printed upside down, with an open web on top of the flange. Each segment featured reinforcing steel installed in the flange and web. After printing and assembling the segments, a conventional reinforcing bar was inserted in the web as bending reinforcement and grouted subsequently. The structural performance was assessed in a six-point bending test. The fabrication and structural testing of this case study beam showed that pre-installed reinforcement imposes several challenges to the extruder precision, the precision of the bent reinforcement, and – if applied – the casting after printing.

Keywords: Digital fabrication with concrete · 3D concrete printing · Reinforcement strategies · Structural testing · Pre-installed reinforcement

1 Introduction

The immense material and energy consumption of the construction industry have a detrimental impact on the environment. A large portion of this negative impact can be attributed to the extensive use of cement in reinforced concrete (RC) construction [1]. RC slabs consume almost 40% of the concrete use in Switzerland and, accordingly, comprise a substantial potential to improve the construction industry's environmental impact by saving material [2, 3].

Digital fabrication with concrete (DFC) has emerged as a new field in research and industry with the promise to enable a more sustainable future for construction [4]. However, the implementation of this technology in the market is still limited. A critical

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reason is the missing link of the structural performance with generally accepted structural requirements defined in design codes [2]. For example, in 3D printing with extruded concrete (3DCP), one of the most widely applied digital fabrication technologies, the concrete properties strongly depend on the production process. Furthermore, the technology lacks straightforward reinforcement strategies with continuous reinforcing steel [5–8].

This paper discusses the opportunities and challenges of applying pre-installed reinforcement for 3DCP based on the experience from the fabrication and structural testing of a segmented T-beam with optimised topology. The studied T-beam represents a part of a material-saving ribbed slab. Such slabs could be produced efficiently to customised needs, such as varying spans, or rib spacing, by applying 3DCP.

2 Pre-installed Reinforcement

For traditional RC construction, reinforcing steel cages are typically assembled inside a formwork or pre-assembled and installed before casting. The assembly inside a formwork generally allows covering large areas but requires good accessibility for structurally connecting the reinforcement to be installed to the previously placed reinforcement. Prefabricated construction generally uses pre-installed cages, which are crucial for safely handling, transporting, and assembling cast elements. Furthermore, the preparation of a reinforcement cage can be performed independently of casting in simultaneous work steps, boosting the specialisation and efficiency in production.

Pre-installed reinforcement is rarely applied in 3D printed concrete because extruding concrete around a reinforcing steel cage increases the complexity of the process. Nevertheless, applications that use a rough addition of concrete around pre-placed rebar exist, but they are limited in accuracy and geometric complexity. These applications propose (i) extruding on both sides of a pre-installed reinforcement mesh [9] or (ii) using 3D printing with shotcrete to jet concrete through pre-installed reinforcement [10].

3 Segmented and Optimised T-beam

3.1 Design

The length of the simply supported T-beam corresponded to 4 m (3.4 m effective span), while the flange had a thickness of 46 mm and a width of 310 mm. The longitudinal shape of the web followed a parabola, increasing the structural efficiency for distributed loading generally predominant in slabs. The total depth of the beam ranged from 157 mm at the supports to 225 mm at mid-span. The beam consisted of three segments, connected with matching joints incorporating shear keys. Figure 1 shows the geometry and reinforcement layout of the beam.

The structural verifications assumed sufficient bond between the cast concrete and printed mortar, allowing the complete material volume to be utilised. The minimum concrete cover was 15 mm. The flanges were reinforced with a mesh of Ø8 mm reinforcing steel bars. The shear reinforcement was provided by Ø8 mm U-shaped stirrups, with longitudinally offset vertical legs to reduce the web width anchored behind the flange reinforcement. Segments 1 and 3 (edge segments) featured a stirrup spacing of 100 mm, and Segment 2 (middle segment) of 200 mm, respectively. One continuous, curved Ø26 mm conventional reinforcing steel bar served as longitudinal reinforcement leading to a geometric reinforcement ratio of 1.5% at midspan. It was added and grouted after the three segments had been assembled.

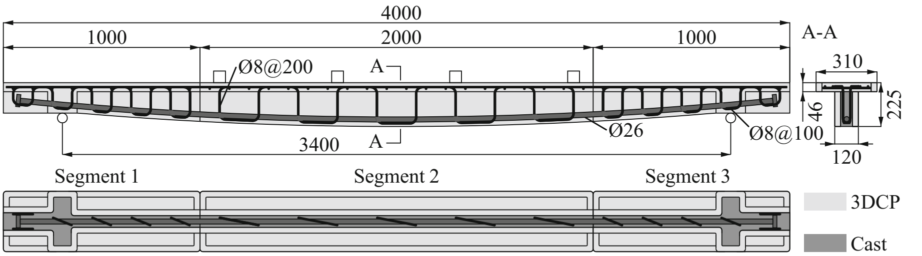

Fig. 1. Overview of the geometry and reinforcement layout of the T-beam (dimensions in [mm]).

3.2 Fabrication

The beam was fabricated in the 3DCP facility at ETH Zurich [11]. Figure 2 illustrates the fabrication process. The printed mortar had a maximum aggregate size of 1.2 mm and a cement content of 500 kg/m^3. The average printing speed was 60 mm/s resulting in a filament width of 30 mm. First, Segment 2 was printed between two edge formworks with shear keys (see Fig. 2b). Second, Segments 1 and 3 were "match-printed" against Segment 2 (see Fig. 2d).

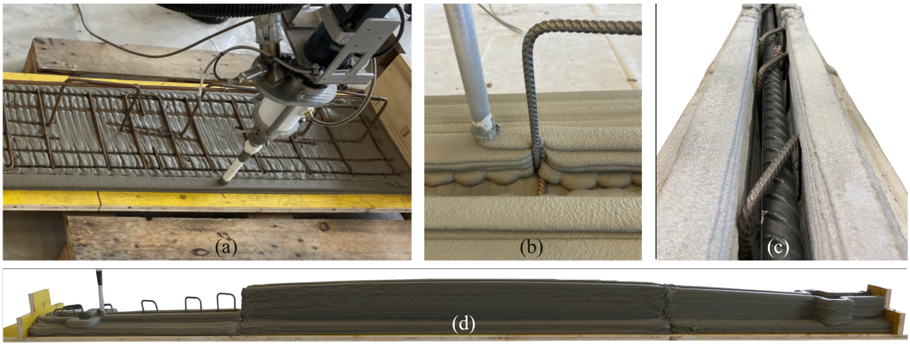

Fig. 2. Images from the fabrication process: (a) Printing of the second half of the flange after placing the pre-assembled reinforcement cage; (b) Close-up of the extruder passing next to a U-shaped stirrup; (c) View of the web with the installed bending reinforcement before grouting; (d) Side view of the entire beam during printing of the last segment.

After printing the first half of the flange (half thickness), the pre-assembled reinforcement cage (including the flange reinforcement and stirrups) was placed on the fresh mortar (see Fig. 2a). Subsequently, the second half of the flange was completed, resulting in a fully printed flange. The last printing step included the printing of layers for the web on top of the flange (see Fig. 2b). The web of Segments 1 and 3 was fabricated with 23 layers, while Segment 2 consisted of 30 layers. The height of the web layers varied to reach the parabolic shape. The variation was achieved by changing the printing speed. After curing, the segments were joined to insert the continuous longitudinal reinforcing bar within the stirrups (see Fig. 2c). The anchorage of the longitudinal reinforcement consisted of steel plates behind the supports. Finally, a grout with a maximum aggregate size of 4 mm was used to cast the hollow core of the web and support areas. After curing, the beam was turned into the testing position and placed in the loading frame.

3.3 Structural Performance

The structural performance of the beam was assessed by conducting a six-point bending test, simulating a quasi-continuous load. The forces were applied on Segment 2 with a spacing of 600 mm (see Fig. 3). Digital Image Correlation (DIC) instrumentation was used to obtain full-field deformation measurements, from which results of crack kinematic measurement were obtained using the Automated Crack Detection and Measurement (ACDM) approach [12, 13]. Figure 3b shows the load-deformation behaviour of the beam. After multiple bending cracks had formed, the deformations localised in the joint between Segment 2 and 3. A sudden brittle failure occurred at the peak load (i.e. 46 kN), with a mid-span deflection of 28 mm, due to an unstable shear crack in Segment 3 (see Fig. 3a, c and d). The inspection of the T-beam's web revealed that the main reinforcing bar was not surrounded adequately by grouting concrete (see Fig. 3c and d). The bending and the shear reinforcement were not properly bonded. Shear forces could not be transferred to the stirrups but were merely carried by the unreinforced printed mortar.

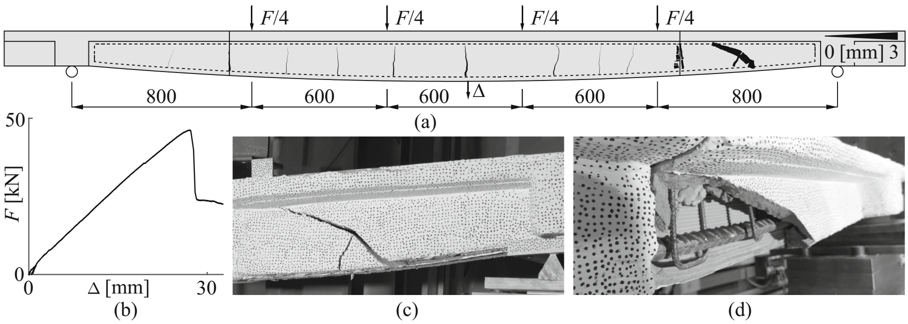

Fig. 3. Structural behaviour of the beam: (a) Crack pattern of the beam at peak load generated with ACDM [12, 13]; (b) Load-deformation behaviour of the beam; (c) and (d) Images from the critical shear crack and the failed beam.

3.4 Discussion

The presented T-beam showcases a system to fabricate material-saving ribbed slabs with 3DCP. The printing in horizontal (lying) position, upside down, allowed (i) optimising the production time efficiency by reducing the use of additive shaping for contours while casting the rest of the volume and (ii) including reinforcement in all required directions, which is highly challenging when printing in vertical (standing) position. When using additively shaped layers as lost formwork, the reinforcement requires sufficient cover to the layers to ensure durability and a proper bond with the subsequently cast concrete. Such an approach antagonises the aim to produce slabs with material-saving ribs, as the printed layers are structurally unnecessary.

The alternative of embedding the web reinforcement sufficiently in the printed mortar has a higher potential to minimise the use of materials but requires a printing path close to the reinforcement. Such a path may provoke (i) collisions between the print head and the reinforcement cage or (ii) tiny spaces between the printed layer and the reinforcement, leading to entrapped air in the subsequent casting. The cage's assembly precision and positioning decide over the risk for collision or entrapped air.

The presented T-beam failed prematurely due to insufficient execution precision, highlighting the challenge of designing the printing path adapted to pre-installed reinforcement.

4 Conclusion

The necessary improvement of the ecological impact attributed to the construction industry entails the need for slender, material optimised members. 3D concrete printing (3DCP) can meet this need. However, the technology struggles to fulfil necessary structural requirements defined in design codes, such as integrating reinforcement. Reinforcement is indispensable for structural safety in several design cases (production, transport, assembly, and service life).

The design, fabrication and testing of a segmented and optimised T-beam showcased that (i) 3DCP in combination with pre-installed reinforcement has the potential to produce structurally optimised elements with conventional reinforcement, (ii) reinforcement detailing according to design codes is possible when using 3DCP, and (iii) the structural performance of the additively shaped beam strongly depends on the capability of the fabrication processes to provide a sufficient and homogeneous embedment of the reinforcement.

The premature failure of the beam highlighted that the fabrication and assembly of slender segmented members using 3D printing with extruded concrete requires careful design when implementing pre-installed reinforcement. First, quality control measures such as scanning the pre-installed reinforcement cage could serve as a basis for optimising the printing path. Second, the design of the presented T-beam was based on the assumption that printed mortar and grouted concrete are monolithic. This assumption requires further assessment. Third, the grout workability and quality may need pretesting to ensure the soundness of this last production step. Finally, investigating post-tensioning as the main bending reinforcement may be of interest.

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