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3D PRINTED CONCRETE BRIDGE

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ABSTRACT

Industrial and academic partners from the Netherlands realized the world's first 3D concrete printed bicycle bridge. Certification safe use in practice was obtained through the concept of "Design by Testing". Innovative reinforcement concepts were applied to guarantee safe failure behaviour. This paper discusses the design, testing, manufacturing and assembling of the bridge.

Keywords: 3D printing, concrete, pre-stress, reinforcement, bridge

INTRODUCTION

The technology of 3D concrete printing was first being introduced about two decades ago (Khoshnevis 1998, 2004; Khoshnevis et al. 2001, 2006). Ever since, ground breaking projects and case studies have being presented on a regular basis to showcase the potential of digital fabrication with concrete. On a trial-and-error basis, the frontiers of the new technology are rapidly being explored, including buildings (3ders 2015, 2016, 2017a, 2017b, 2017c; Cnet 2016; Mediaoffice 2016; De Ingenieur 2017; cementonline 2017). The use of printed objects in the built environment requires structural safety. Unfortunately, codes are not yet prepared for this disruptive technology. In order to overcome this problem and to demonstrate the potential of 3D printing in the built environment, a bridge has been printed and opened for public usage last year. This paper describes the design, manufacturing and assembling of a 3D Printed Concrete bridge for the purpose of valorization and to exemplify the research on 3DCP at TU/e.

SPECIFICATIONS AND CONCEPTUAL DESIGN

The bridge is part of the renewal of an existing bicycle track in the village Gemert in the Netherlands. It crosses a small local canal. The span of the bridge is 6.5 m and the width 3.5 m. The uniformly distributed design load (q_{Ed}) is 5.0 kN/m^2. The bridge has been designed, starting with the capabilities of the 3D concrete printer at Eindhoven University of Technology (TU/e) in mind. The facility has been described by Bos et al. (2016). The bridge consists of printed elements that are rotated 90 degrees after printing, and then pressed together by post-tensioned prestressing tendons. This allows for an optimized section design composed out of splines. Figures 1a and b illustrate the design concept.

The need to print and stack several single elements with a hollow core by itself makes it self-evident to prestress the components to overcome the lack of bending moment resistant of unreinforced concrete; a technology commonly used in the construction industry. So, prestress tendons are placed in the openings of the printed elements, stressed, anchored at the beginning and

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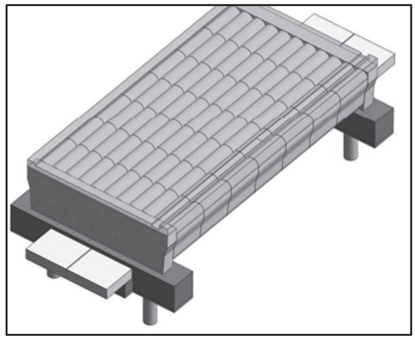
the end, and finally released. The printed concrete elements are stressed to a level that only compression remains in the section, and no additional passive reinforcement in that direction is required.



a **b**

Fig. 1a, b 3DCP bicycle bridge conceptual design. (illustration by BAM)

The cross-section of the bridge elements consists of a series of connected bottle-shapes, alternatively positioned upside down, in combination with a continuous connecting straight line at the bottom. At the front and at the end of the printed bridge deck elements, two solid concrete bulkheads are added to introduce the pre-stress forces. These have been traditionally cast and reinforced.

MATERIALS TESTING

Extensive published and unpublished research was carried out by the TU/e and the material supplier Saint Gobain Weber Beamix into the structural properties of the applied print mortar Weber 3D 115-1. The compressive, flexural and uni-axial tensile strength, modulus of elasticity, density, and directional dependency (Doomen, 2016; Slager, 2017) were determined. The material properties are summarized in table 1.

Table 1 Structural properties of Weber 3D 115-1 print mortar, as used in the structural design of the bridge. For the directional dependency, a relative orientation of axis u, v, w is used (Bos et al., 2016), indicating the direction parallel to the print in the horizontal plane, perpendicular to the print direction in the horizontal plane, and vertically perpendicular to the print direction (or parallel to the robot arm), respectively.

Property	Dir.	Age	Symbol	Value
Density		28 days	P	2,000 kg/m^3
Modulus of Elasticity		28 days	E	19,000 MPa
Average compressive strength	u	28 days	$f_{ck,u}$	23.2 MPa
	v	28 days	$f_{ck,v}$	21.5 MPa
	w	28 days	$f_{ck,w}$	21.0 MPa
Average tensile strength (also used for flexural tension)	u	28 days	$f_{ck,u}$	1.9 MPa
	v	28 days	$f_{ck,v}$	1.6 MPa
	w	28 days	$f_{ck,w}$	1.3 MPa
Creep factor*		7 days	φ_7	1.0
		14 days	φ_{14}	2.5
		56 days	φ_{56}	3.0
Shrinkage		7 days	ε_7	0.6
		14 days	ε_{14}	1.2
		56 days	ε_{56}	1.5

* after 28 days.

FINAL DESIGN

The final cross section of the bridge is 3440 x 920 mm. Figures 2a and b show the cross-section design. The design in Figure 2a was used for the 1:2 scale test on the bridge (discussed below). Figure 2b shows the optimized final design.

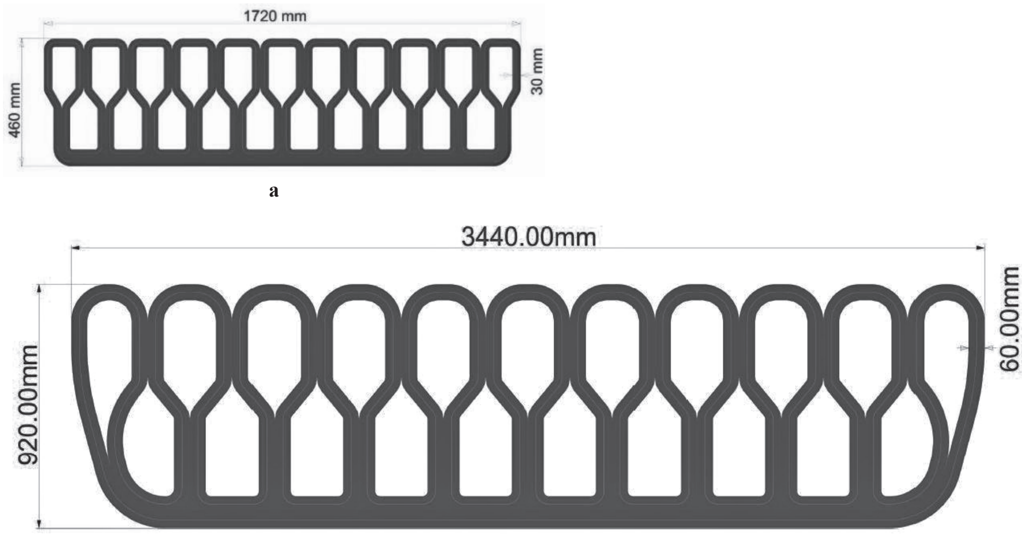
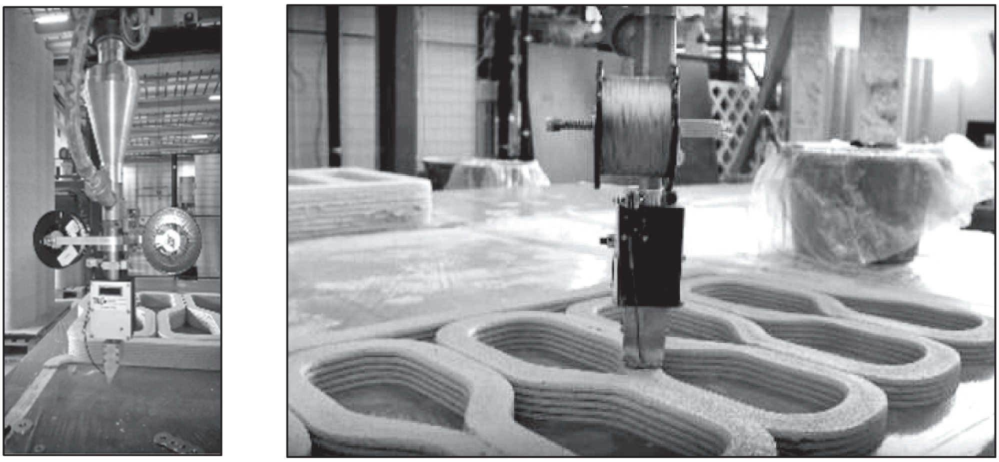


Fig. 2a, b Print paths of the 1:2 scale model for testing (a), and the actual bridge section (b). The optimized pattern of the latter with regard to the former saves 4% of print path length.

The height of each element is approximately 1.08 m, or 89 to 90 layers of 12 mm. This results in six elements to compose the bridge. The element height was limited due to handling and transportation requirements. In total, the bridge features 535 printed layers, with a length of 25.1 m each, and a total print path length of 13.4 km. The prestress is applied by post-tensioning 16 Dywidag-system tendons to an initial load P_0 of 150 kN. To avoid brittle failure due to torsion in the bridge deck case, an automatically entrained reinforcement cable was introduced in the filament. The reinforcement consists out of a thin, high strength steel cable that becomes embedded in the concrete filaments during printing with the Reinforcement Embedding Device (RED, Figure 3a, b) developed at TU/e. This concept has been described by Bos et al. (2017a) and (2017b).



a b

Fig. 3a, b Reinforcement Entraining Device (RED), developed by the TU/e.

PRINTING

The printing of the bridge is shown in Figure 4.

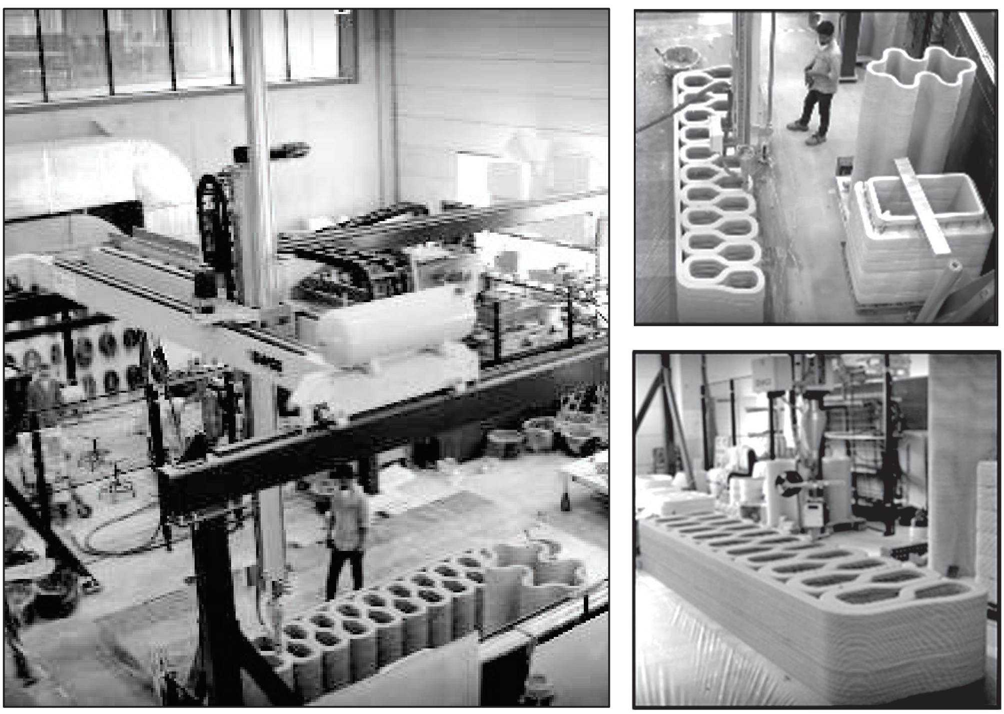


Fig. 4 Printing of an element for the actual bridge.

For this project, a print nozzle with a mouth opening larger than that of the standard TU/e set-up was used. To achieve a print filament of proper consistency, the filament section size, print speed, and pump pressure (and related material flow) need to be attuned carefully, as they are directly related. Further consideration needed to be given to the radii of the curves (Ahmed et al., 2016). This has been investigated experimentally in the past and has been used as design rules for the bridge. Finally, a single layer took around 5 minutes and 20 seconds to print; it took 48 hours to complete printing of all the bridge elements.

DESTRUCTIVE 1:2 SCALE TEST

A 1:2 scale model was produced and tested to prove the structural integrity. The dimensions of the printed elements were scaled down to half the design size: i.e. 1720 mm in width, 500 mm in length, and 460 mm in height. The bridge was tested in a load-controlled four-point bending test, as shown in Figure 5. The load span was 1/3rd of the support span. An alternating loading-unloading sequence was applied from 120 kN onwards, for each 30 kN of additional load, i.e. the load was released at 120 kN, then the scale model was reloaded to 150 kN, released, reloaded to 180 kN, and so forth, until 300 kN, after which the bridge was loaded a final time to 350 kN and the test was discontinued.

The first visually noticeable crack appeared between the load points, at approximately 300 kN loading. Initially, it runs vertically along one of the interfaces between the filaments. Later, it diverges horizontally through the printed mass. The location of the crack indicates that it is induced by bending. This is a desired failure mechanism, as it is more ductile than shear failure.

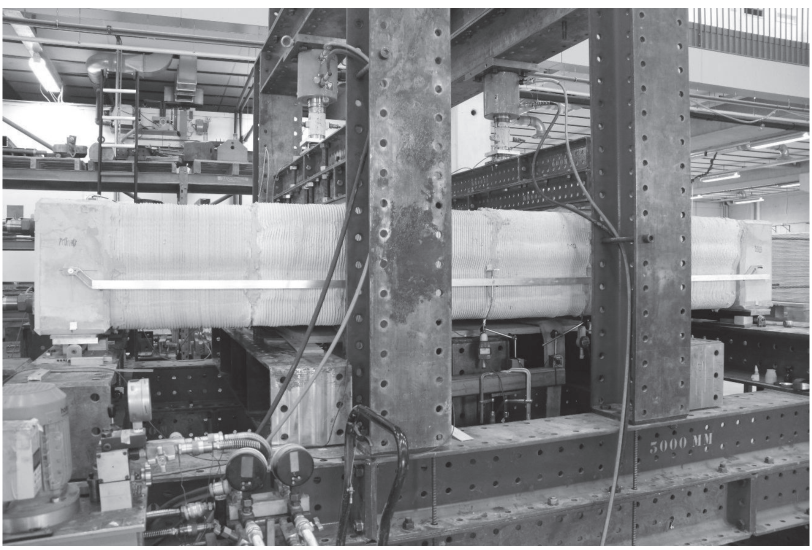


Fig. 5 Scale model in test 4-point bending test set-up.

ASSEMBLY AND IN-SITU TEST

The assembly of the printed elements is shown in Figure 6a, b, in Figure 7 the bridge is hoisted into place.

a b

Fig. 6a, b On-site assembly and prestressing.

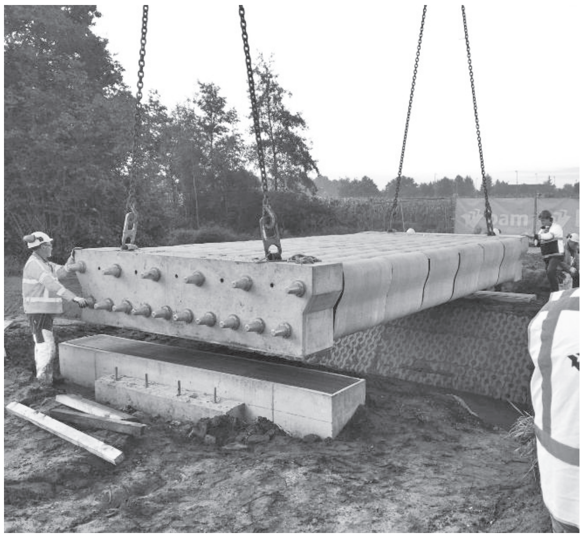


Fig. 7 Hoisting the bridge into position.

A final full-scale test was performed in-situ to guarantee the bridge to behave as expected. The resulting deflections were too small to measure. As also no other response was observed, and in consideration of the previous material and scale testing, the bridge was considered to comply with the Dutch building regulations. On October 17, 2017, it was opened to the public (Figure 8).

CONCLUSION

A 3D concrete printed bicycle bridge was presented. It was printed at the TU/e 3DCP facility, and the first in its kind (prestressed, FDM printed) worldwide to be put into service. The process of design, printing, testing, and assembly, and their interaction, was discussed. A thorough procedure was followed both for the structural and the construction aspects. Assembly trials were performed to identify potential problems and hazards. Material testing, destructive scale model testing, and in-situ testing was performed to show the bridge complies with Dutch building regulations. The bridge was opened in October 2017 and now forms part of the cycling infrastructure around Gemert, the Netherlands.

Fig. 8 Completed bridge at the opening. (photo: Kuppens fotografie)

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- Client: Province Noord-Brabant, the Netherlands,
- General contractor, initiator: BAM Infra, the Netherlands,
- Structural design and engineering: Witteveen+Bos consulting engineers, the Netherlands,
- Research, print design and manufacturing of printed elements: Eindhoven University of Technology, the Netherlands,
- Material supplier print mortar: Saint-Gobain Weber Beamix, the Netherlands,
- Prestress system and application: Dywidag, the Netherlands,
- Reinforcement cable supplier: Bekaert N, Belgium.

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