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The realities of additively manufactured concrete structures in practice

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ABSTRACT

Extrusion-based 3D Concrete Printing (3DCP) is rapidly gaining popularity in the construction industry. Trial projects are now being realized at an increasing rate around the world to test the viability of the technology against real-world requirements. This step, from the 'simple' deposition of filaments of self-stable concrete to its application in buildings and structures, with all associated requirements and interfaces, comes with challenges. These range from matching the design intent to the manufacturing capabilities (through structural analysis and approval, and reinforcement) to quality consistency (robustness) on large scale, and compatibility with other materials. In many of these areas, much simply remains unknown due to a lack of experimental data or information from projects where 3DCP has been applied. This paper aims at reducing this knowledge gap by presenting a systematic discussion, based on the analyses of eight realized 3DCP projects from around the world. It was found that the structural application of printed concrete is limited, due to a lack of regulatory framework for expedient approval, as well as limited reinforcement options which require to resort to unreinforced masonry analogies. The application of the technology features a host of practical issues that relate to the print process, material, site conditions, building integration and design – or to the 3DCP technology in general. Although some potential risks, such as shrinkage cracking and quality consistency are generally recognized, the measures taken to mitigate them vary considerably, and are largely based on individual expertise. The actual effectiveness is generally unknown. Finally, it was observed that, while the printing itself is fast, the preparation time is generally considerable. This is partially due to a lack of knowledge amongst professionals. In the practical production of a 3DCP project, three expertise areas are crucial: one for the digital part, one for the machine side, and one for the material side. Thus there is a strong need for educational institutions to develop dedicated training courses and incorporate relevant topics into their curricula.

1. Introduction

Additive manufacturing of cementitious materials, particularly in the 'material deposition by extrusion' variant also known (and hitherto referred to) as 3D Concrete Printing (3DCP), is rapidly gaining popularity in the construction industry, and has reportedly progressed to a technology readiness level (TRL) of 6–7 for street furniture and houses [1]. Frequently cited potential benefits of this technology include (expected) reduced material use, decreased labour, increased construction speed, and customized geometries [2]. Thus, after a short but intensive and productive phase of lab-scale exploration, trial projects are now being realized at an increasing rate around the world, to test the viability of the technology against real-world requirements. This step from the 'simple' deposition of filaments of self-stable concrete without

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formwork, although challenging enough from a perspective of competing material properties requirements [3], to its application in actual buildings and structures, with all associated requirements and interfaces, is not a trivial one, for a variety of reasons. These range from matching the design intent to 3DCP manufacturing capabilities, through structural analysis and approval, and reinforcement, to quality consistency (robustness) on large scale, and the integration in a building (compatibility with other materials, amongst others). In many of these areas, much simply remains unknown due to a lack of experimental data or information from projects where 3DCP has been applied on a large scale.

Trial projects are an essential tool to identify and solve these issues, and thus to bring the technology to full maturity. In spite of extensive media coverage of 3DCP projects in general, only a few publications are available in which the technological challenges are discussed in-depth. For example, the design, testing, and construction of a 6.5 m span prestressed bridge is presented in [4], while a larger successor based on the same principles is discussed in [5]. Grasser et al. [6] reported on the design and construction of a small pavilion. A range of mainly practical 'lessons learnt', taken from three projects at sites across the USA, was produced by Kreiger et al. [7]. Weger et al. described the approval and testing concept of the residential house printed in Beckum, Germany (also discussed in the current paper), and argued for the significance of large-scale testing [8,9]. Also, Menna et al. [10], through the analysis of several projects, extensively discussed the challenges that the structural engineer faces when dealing with 3DCP projects.

Altogether, this still provides limited guidance on the relevance of the technical issues involved in the realization of actual 3DCP projects. This paper seeks to reduce this knowledge gap by presenting a systematic discussion, on the basis various 3DCP projects from around the world. This should provide valuable insight into current risks and uncertainties, and thus help academics and practitioners alike to select priorities for research as well as for the development of regulatory guidelines.

The respective projects are presented in Section 2. Subsequently, the analysis has been subdivided into three phases: 1) design & approval, 2) manufacturing & construction, and 3) after completion, which are covered in Sections 3 to 5. A discussion of lessons learnt (Section 6) and conclusions then complete the paper. The project data on which these analyses are based, have been obtained from a mix of public and non-public written sources (reports, papers, websites), interviews with directly involved experts, and direct personal experience of the authors.

Table 1
Analysed 3DCP case study projects.

Fig.	Project short name	Description	Country	Completed
1a	Dermis	Series of street furniture and urban elements for the city of Concepción.	Chile	2021
1b	Reception Centre	Façade elements for the reception centre building on the Civic Square in Nanjing.	China	2020
1c	Holstebro House	Prototype single-storey student house in Holstebro.	Denmark	2021
1d	Dubai Office	Double-storey office building in Dubai.	United Arab Emirates	2019
1e	Beckum House	Double-storey residential building in Beckum.	Germany	2021
1f	B-Hut	Mock-up standard army barracks hut	USA	2019
1g	Milestone House	Single-storey residential bungalow in Eindhoven.	the Netherlands	2020
1h	Striatus Bridge	Temporary footbridge in Venice.	Italy	2021

2. Case studies

Eight case studies, listed in Table 1 and portrayed in Fig. 1a–h, have been analysed in the scope of this study. The selection was based on the following criteria: the projects (i) have been realized for actual use, or at least according to actual use requirements, (ii) represent a significant geographical spread to capture potential differences in construction and approval approaches, and (iii) of which relevant information was expected to be accessible to the authors, either directly through personal involvement or indirectly by interviewing involved experts. The projects have been recently realized and could be considered a next generation of projects compared to those discussed in e.g. [11]. They include a set of urban street furniture elements, six small building structures in which load bearing 3DCP has been applied to an increasing extent, and one arch bridge. A short name has been provided for easy reference in this paper.

In Chile, the Bío-Bío university campus was supplied with a variety of 3D printed street furniture and urban elements, like benches, pillars and low walls. The project constitutes an early 3DCP project in South America. The elements were printed off-site by the Centre for Research in Construction Technologies (CITEC) of the Bío-Bío university and have typical street furniture dimensions, i.e. generally below 2 m in the largest dimension. Cement CBB Especial and aggregate with a maximum size of 2.4 mm was used as print mortar. The print set-up consists of an industrial arm robot on a rail, allowing to print walls of up to 15 m length and 3 m height. The typical filament section size measures 40–50 mm in width, and 20–30 mm in height, with a print speed of 50–100 mm/s.

The recently opened Civil Square in the Jianbei district in Nanjing, China, features a reception centre designed by Prof. Tong Zhang's team at Architects & Engineers Co. Ltd. of Southeast University. This is a two-storey frame structure with a total area of 286 m^2 and a height of 5.15 m. A total of 96 3D printed concrete elements were assembled as walls, while reinforced beams and columns were cast on-site. The elements were printed with a C40 mortar with a maximum grain size of 2.36 mm, through a circular nozzle with a 40 mm diameter, in the factory of Nanjing Institute for Intelligent Additive Manufacturing. The building was designed for a reference service life of 50 years.

In Holstebro, Denmark, a prototype student house was realized by 3DCP Group, with technology support from COBOD International. The project serves as a testbed for the deployment of 3DCP with large aggregates, and to assess to which extent potential advantages of 3DPC, such as reduced labour costs, mass customization and waste reduction could be achieved. The 37 m^2 structure features non-load bearing in-situ printed walls, with internal shafts filled with reinforcement and cast concrete to act as load bearing columns. The project used in-situ prepared concrete mainly from locally sourced raw materials, including aggregates of up to 8 mm diameter, supplemented with specific additives for printability from COBOD's BOD2 and CEMEX's D.fab concrete solution lines. The structure was printed with the gantry-style BOD2 5-4-3 3D printer, measuring 12.10 × 9.60 × 5.62 m^3 (length × width × height). Hence, the structure was printed without moving the printer, at a speed of 100–150 mm/s, with a filament of 50 × 40 mm^2 (width × height).

In 2019, possibly the world's largest 3D printed structure (by volume) was realized in Dubai, with the intent to explore construction with minimal labour involvement. The superstructure of this 640 m^2 two-storey administrative building for the Dubai Municipality was printed by Apis Cor in 500 h of printing. The 9.5 m high structure is carried by an RC frame, for which some of the printed parts served as lost formwork. The printable mortar was developed by Engineering Contracting Company LLC (ECC Group) with subcontractors. Apis Cor operated its typical cylindrical robot 'Frank', which was expanded in height to allow to print the 4.7 m high walls in continuous sessions, directly on-site.

The first 3D printed residential building in Germany is a two-storey house in Beckum with a 80 m^2 surface area per floor, designed by Mense


(a) (b) (c) (d) (e) (f) (g) (h)

Fig. 1. a–h. Case study projects. (a) Dermis project elements, (b) Reception Centre Nanjing, (c) Holstebro House (credit: COBOD International), (d) Dubai Office (credit: Apis Cor), (e) Beckum House, (f) B-Hut, (g) Milestone House (photo: Bart van Overbeeke), (h) Striatus Bridge.

Korte Architects. Built by PERI, with a 15 × 12.5 × 6 m^3 BOD2 printer from COBOD International, the structure features 3 printed wall types: 1) non-load bearing partitioning walls, 2) structural walls of printed lost formwork with unreinforced cast concrete, and 3) double-shell walls with a non-load-bearing outer shell with a load-bearing double-stranded inner shell or with a 3D-printed formwork filled with cast-in-place concrete. The printer has a two-chamber silo mixing pump (M-Tec SMP III). Italcementi i.tech 3D NF was used as print mortar, in filament layers of 60 × 20 mm^2 (width × height). The roof of the building is formed by a reinforced cast-in-place filigree slab as the ceiling panel. A cast-in-place filigree slab is also used as a floor ceiling. The vertical load transfer and bracing of the building are carried out via nonreinforced cast-in-place concrete (C25/30) walls and columns, which ensure the stability and stiffening of the building even without the load-bearing 3D-printed elements. Their geometric design is given by printed formwork that is not used for load transfer [8,9].

The Improved B-Hut, developed and printed in Illinois, USA, by the US Army Corps of Engineers with structural design by SOM, was a case study intended to explore the possibilities of printing such standard structures from locally sourced materials rather than constructing them from timber or masonry blocks [7,11,13,14]. The structure, measuring 2.74 × 10.36 × 3 m^3 (47.6 m^2) consists of a cast-in-place reinforced concrete (RC) foundation slabs, onto which two U-shaped morphing wall sections were printed with the gantry style ACES Lite printer in two continuous print sessions. As the printer was smaller than the overall structure size, it was moved between the two print sessions. The monolithic walls start from a 1-ft (approximately 300 mm) triangular wave pattern and morph into a straight line at the top. The roof consists of precast RC slabs. The material mixture contains aggregates up to 9.5 mm nominal diameter, the maximum for which the progressive cavity pump allows. The material delivery system consists of a 50 mm diameter hose and a 29×29 mm^2 square nozzle. Print speed ranged between 170 and 250 mm/s. The walls carry the vertical roof loads, but feature intermediate reinforced cores for stability, connected to the foundation with dowel bars and to the roof beams using grouted in place protruded wall reinforcement.

Project Milestone consists of a series of five 3D printed residential houses to be constructed in Eindhoven, the Netherlands. The house designs aim to demonstrate the freedom in design enabled by the 3D printing technology. All houses will be inhabited, and thus have to comply with regular comfort and quality requirements. The first house, a single-storey dwelling constructed by Van Wijnen, was completed and opened in April 2021, and comprises approximately 94 m^2 enclosed by multiple 3D printed concrete wall elements. The roof is carried by the 2.6 m high walls; no structural cast RC has been used as vertical load bearing elements. Weber 3D 160-1 has been used as print mortar, in a filament size of 70×10 mm^2 (width × height). All walls have been printed at De Printfabriek workshop, at the time a joint venture of Saint Gobain Weber Beamix and BAM, and transported to site on trucks.

The Striatus, designed by the Block Research Group and Zaha Hadid Architects, was realized in 2021 as part of the Time Space Existence exhibition, hosted by the European Cultural Centre during the Venice biennale. This multi-legged pedestrian bridge with a maximum span of 15.1 m and a height of 3.5 m, consists of 53 unique 3D printed parts that together act as a purely compression-loaded arch, thus eliminating the need for wet connections or tensile reinforcement. The parts have a total print path length of 58 km and a weight of 24.5 t. The print head speed was adjusted according to the locally required layer height, with a maximum of 250 mm/s. They were printed in 20 (balustrades) to 25 mm (decks) wide filaments by Incremental3D with a 2-component printable mortar custom developed by Holcim based on their TectorPrint range. The printed concrete is fully load bearing (in compression), and no additional cast concrete has been used. The bridge is accessible to the public for approximately 6 months and will then be demounted.

3. Design and approval

3.1. Project goals and design

In all studied cases, the use of 3DCP was instigated by a desire either to showcase the possibilities of the technology mostly on a national level (e.g. Dermis, Milestone, Dubai Office, Striatus Bridge) or to study specific aspects of large scale applications. In case of the B-Hut, a goal was to test the viability of 3DCP as alternative for conventional methods mainly evaluated on elapsed time (i.e. total construction time – not just printing time). The Holstebro House served as a testbed for printing with a locally produced concrete mixture containing large aggregates and as a mock-up for other studies such as thermal performance, while in the Beckum House a particular objective was to explore new design possibilities such as multifunctional (wall) elements with integrated building services, bath sockets or a fireplace stove. So, currently the projects mainly serve the development of the technology, rather than the other way around. This is a clear indicator that, notwithstanding the progress that is being made and the potential being shown, the technology has not yet matured but is still in a developmental stage.

In most projects, the (im-)possibilities of the production technology were explicitly considered from the start, which seems to be highly recommendable to achieve an efficient process. This generally required an intensive collaboration between the architect and a printing expert (either a printer supplier or the printing party). Examples of this approach include the Holstebro, Beckum and Milestone houses. In the case of the Striatus bridge, the application of production constraints was particularly explicit, not only through the close collaboration between the project partners but also because the digital model directly checked for features such as out-of-plane curvatures, in-plane angles, part sizes, and compression loading. For the Dubai office, on the other hand, the production method was not explicitly considered in the initial design. As a result, some significant adjustments to the printer had to be made (increase of printable height from 3 to 4.7 m). The planning of printer placement (12 and 10 different positions for the first and second floors, respectively) and printing trajectory also required extensive additional elaboration.

A specific issue related to the design of printed parts is the use (either or not) of infill patterns (Fig. 2). Regular diagonal infill patterns between parallel outer sheets have been used in the Dubai Office (Fig. 2a) and the B-Hut. Semi-regular or explicitly designed infill patterns were used in the Reception Centre and Striatus Bridge parts, as well as in one of the wall types used in the Milestone House (wall type B; Fig. 2b, c, and d). The infill patterns can serve both to increase object stability during printing and structural resistance after hardening. On the contrary, the Holstebro (Fig. 2e) and Beckum (Fig. 2f) Houses, and another wall type in the Milestone House (wall type A; Fig. 2d) do not feature infill patterns, which allows for higher thermal insulation. In addition, potential differential shrinkage between the inner and outer sheets should produce fewer problems. In another case, namely one type of wall in the Beckum House (Fig. 2f), infill patterns were omitted as the cavities were filled with cast concrete instead, for structural purposes.

3.2. Structural design and approval

The structural design approach of the selected case study projects firstly reflects the intended use of the construction. In general, this represents the primary criterion for the overall approval process due to the innovative features introduced in the printed structures – a common approach in structural engineering reflected, for instance, by the use of ‘Consequence Classes’ in the Eurocode 0 [15]. Indeed, for some applications, the main difference in the design and approval process is related to the load bearing or non-load bearing characteristics of the structure which is printed. Items which do not belong to the primary structure, such as street furniture, façade elements, outer non-load bearing walls or architectural components, may follow a less stringent approval process, limiting the design and investigations to the level of the printed product and/or technology adopted.

The choice to fabricate load-bearing structures through 3DCP, on the other hand, implies the resolution of a number of challenges within the structural design domain, related to, for instance, unknown material properties (affected by the process), calculation input, minimum reinforcement, joints, adaptation to printing capabilities/constraints (e.g., matching architectural drawings and real possibilities of printed objects), and obviously code compliance. Even in the case of load bearing printed structures, the level of investigation (rather extensive or less) of the new properties deriving from the 3DCP technology depends on the design concept of the structure itself. Printed load-bearing structures conceived as completely new structural systems (in terms of concrete material, geometry of elements, reinforcement etc.) require a deep preliminary experimental investigation to support the structural design in all its phases; whereas the combination of traditional load bearing reinforced concrete elements with printed ones might facilitate the design and approval process with reference to the compliance with current structural codes. All these features have been collected for the case study projects with the final goal of pointing out the different implications that the design concept and associated intended use can bring to the overall structural analysis and approval process. Table 2 summarizes the main useful information of the case study projects to distinguish different scenarios; these are organized according to an increasing level of exploitation of 3DCP potentialities with reference to

(a)
(b)
(c)
(e)
(d)
(f)

Fig. 2. a–f. Infill patterns. (a) Regular diagonal infill pattern in the Dubai Office. Also clearly visible are the cavities (with conventional reinforcement) that serve as lost formwork for case concrete columns. (b) Orthogonal infill pattern in Reception Centre façade element. In addition, the horizontal reinforcement bars, placed manually in the interface each 15 layers, are visible. These bars protrude on the left-hand side of the picture to later connect the elements to cast concrete columns. (c) Interior view of a Striatus balustrade element, with designed infill pattern to meet structural demands. (d) Wall elements of the Milestone House, showing type A walls without infill pattern, and type B walls with a double cavity: one without and one with infill pattern, specifically designed to maintain element stability during printing (the right-hand picture shows part of a test print element) (credit, image left: Witteveen+Bos consulting engineers). (e) First layers of the Holstebro House, showing the inner and outer sheets of the wall in parallel, without infill pattern (credit: COBOD International). However, the contours of the lost formwork for the columns that will be cast later, are clearly visible. (f) Plan and picture of the Beckum House walls, with green: cast concrete into cavities of printed walls, and yellow: insulation in cavities of printed walls, without infill pattern. (credits, image left: Mense-Korte engineers + architects, image right: Ingenieurbüro Schiessl·Gehlen·Sodeikat). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 2
Summary of structural design and approval aspects.

Short name	Intended use	Service life	Floors	Main load bearing structure	Design/analysis	Approval
Dermis	Urban elements/street furniture	–	–	Non-load bearing	To study the stability of the elements, and topology optimization, analytic methods were applied	Chilean Ministry of Housing and Urban Development
Reception Centre	Office	50 yrs.	2	Traditional load bearing RC frame (cast, not printed) with 96 3D (off-site) printed elements assembled as façade elements	The design of the building followed green and energy-saving design standards in China (no need to adapt for 3DCP)	The approval of the building was finished based on current Chinese standards
Holstebro House	Residential (student)	Temporary <1 year	1	Traditional load bearing RC structure (cast, not printed), lost formworks for steel columns (shafts)	Initially designed in Revit, afterward in Rhino, then processed by COBOD's slicer tool	Approved as class I building (simple structures) according to Danish regulations
Dubai Office	Office	n/a	2	Traditional load bearing RC frame (cast, not printed), lost formworks for columns/beams/foundations	3D printing adaptation to the architectural design	Unified building codes (Dubai Municipality)
Beckum House	Residential	>50 yrs.	2	Unreinforced concrete structure (cast, not printed), lost formworks for columns/wall elements, load-bearing double-stranded inner shell	3D printing adaptation to the architectural design Printed formwork designed for fresh concrete Experimental testing (multiscale)	The approval was based on existing standards for concrete and masonry construction
B-Hut	Military use	n.a.	1	This structure included 3D printed concrete walls as part of the main force resisting structure	Prototype structure	To be validated to provide sufficient proof that it met the design requirements as stated in IBC Section 104.11
Milestone House	Residential	50 yrs.	1	Multiple 3D printed (off-site) concrete load bearing wall elements	Directly within the printing constraints Experimental testing (multiscale)	Results of the mock-up test phase; required structural calculations; approval by the municipality of Eindhoven
Striatus Bridge	Pedestrian bridge	>50 yrs.	–	53 unique 3D printed (off-site) parts	Directly within the printing constraints. Full scale testing after completion of the structure	Checking engineer. Final authority for approval is with the municipality of Venice

non-load bearing structures toward specific design concepts and structural analyses.

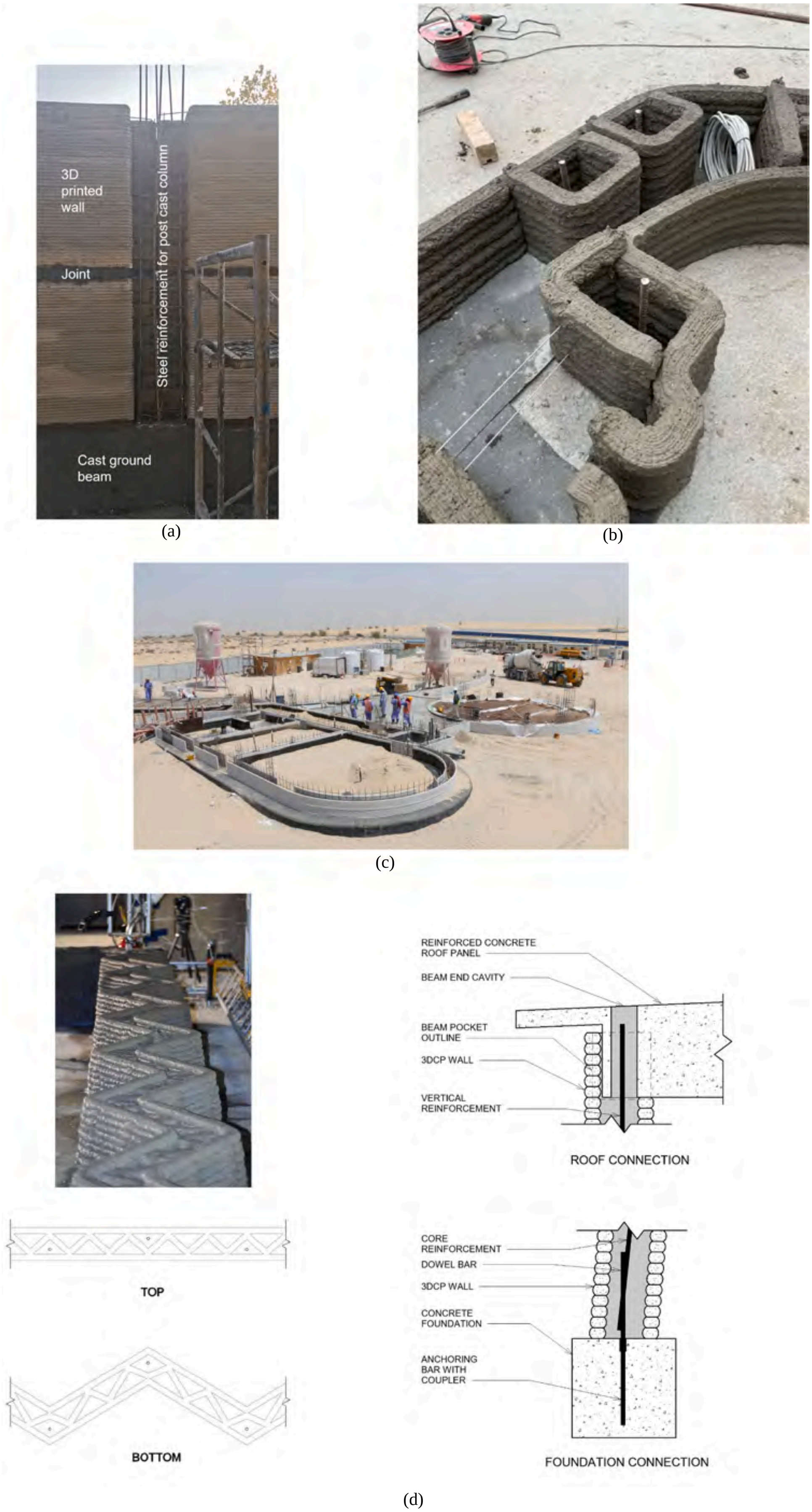
The fabrication of urban furniture such as benches, lounge chair or architectural (low) walls, represents a real scale example of self-standing non-load-bearing structure obtained from 3DCP. Since in most cases there is no prolonged interaction with human lives (as for residential or infrastructure uses), the design is not strictly related to the ultimate failure of the structure, rather it utilizes basic knowledge of the printed material properties to define a mechanically efficient structure against dead loads and actions associated to the use of the furniture. For instance, in the case of the Dermis project, the design followed simple guidelines from the Ministry of Housing and Urban Development whereas the control for the approval concerned the verification of the concrete compressive strength against the minimum value allowed for such types of elements. On the contrary, from the technology point of view, these types of elements require the adaptability of the architectural shapes (typically obtained from optimization) to the stability of the layer-by-layer deposition during printing.

When considering residential uses of printed structures, the structural design and verification may vary depending on the scale of application of the printed objects, i.e. the product scale or (global) building scale.

As for product scale, a possible basic strategy is to consider a typical cast-in-place reinforced concrete frame to which printed elements are attached or incorporated. In this case, the structural design and assessment of the load bearing structure follows common structural code rules (e.g. regarding building design lifetime, actions and material properties) whereas the interaction with printed elements – intended as products – is limited to detailing and connections. This is the case in the Reception Centre Façade, in which 3D printed elements were assembled as prefabricated walls, while integrated columns were cast on-site to produce the RC load-bearing structure in combination with other conventionally cast RC elements (Fig. 3a). The printed parts themselves have been reinforced with steel bars that were placed in the layer interface every 15 layers horizontally, which were in turn connected to the vertical reinforcement in the cast columns (Fig. 2b). This ensured element integrity in case of e.g. shrinkage cracks. Overall, this approach required only limited testing, specifically the determination of the cubic compressive strength and flexural strength at 28 days, which reached 44.6 and 7.4 N/mm^2, respectively. In this way, a level II seismic grade according to the Chinese code [16], could be achieved.

As an alternative to the use of printed objects connected to a traditional primary structure, a different structural design strategy considers the use of 3DCP technology to create code-compliant cast-in-place RC load bearing systems; within this approach, the printed elements act as lost formworks for traditional structural elements which can be (i) mostly integrated in outer walls/partitions of the building or (ii) specifically fabricated to accommodate cast beams/columns. In doing so, the load bearing structure design and assessment follows current regulations and codes, while the extent of investigations on printed components (which are functional to the structural analysis of the whole building) depends on the layout of the structure (e.g. single or multiple storey), service life, type of action (e.g. seismic actions), and reinforcement. In the case of the Holstebro House, a few columns shafts (i.e. hollow parts, Fig. 3b) were integrated in the printed walls, and subsequently cast with conventional concrete. They serve as the load bearing structural elements of the building, both in vertical and horizontal direction. The local authorities approved this as a construction class 1 project according to Danish regulations. This class, intended for simple and/or traditional load bearing constructions, includes single family homes and row houses with no horizontal partitions, industrial and warehouse buildings, and garages and similar structures.

A more articulated design solution based on the integration of 3DCP technology with a reinforced concrete frame structure was implemented



(a)

(b)

(c)

(d)

Fig. 3. a–c. Printed concrete-case concrete integration. (a) vertical shaft between façade elements. Reinforcement has been placed, the open side is to be closed, and the area filled with cast concrete. (b) close-up of the connection between the printed structure and the foundation plate (credit: COBOD International). Reinforcement bars protrude from a designated opening in the foundation plate, into the printed lost formwork cavities, which will be filled with cast concrete. (c) printed lost formwork for foundation beams. Reinforcement had been placed, concrete will be cast later. (credits: Ali Mustafa) (d) Zig-zag walls of the B-Hut, with the cavity filled with cast concrete; roof and foundation connection details; wall top and bottom plans.

in the Dubai Office project. Here, the two-storey layout of the building entailed the need of producing different structural elements using printed lost formworks which were partially embedded in outer and "growing" non-load bearing concrete walls. This allowed the fabrication of cast-in-place foundations (Fig. 3c) and reinforced concrete columns and beams (Fig. 2a), which were connected to precast slabs at the roofs. First, walls and formworks for columns and beams were simultaneously printed. Then reinforcing steel bars were manually installed in the formworks, followed by conventional pouring of concrete. As the precast roof slabs and reinforced concrete frame structure were the load carrying components in this building, the design was conducted according to the local structural design codes. The building matched all the local building regulation requirements and Dubai Municipality gave permission for its construction, oversaw the construction, and approved it for public use by issuing a building completion certificate.

3DCP was used more extensively with a more pronounced structural purpose in the Beckum House and B-Hut projects, in which a combination of cast and printed concrete is used in a load bearing fashion. The Beckum House features two load-bearing wall types (Fig. 2f): a printed cavity wall with insulation in which the printed concrete is load bearing, as well as a triple layer printed wall with one cavity filled with cast concrete and the other with insulation. In this case, only the (unreinforced) cast concrete, is considered in the structural analysis. The project required an in-depth investigation to understand the effects of using printed lost formwork on both the normal concrete casting process and global structural behaviour of the building. Indeed, to comply with existing standards, it was required that the unreinforced cast-in-place concrete walls and columns would be able to ensure the stability of the structure on their own. However, no reliable data on the maximum capacity of 3D-printed formwork to withstand the pressure of fresh concrete were available. Therefore, the maximum capacity of the formwork and the minimum number of wall anchors were defined by in situ cast-in-place tests on wall elements. To predict the resistance to the fresh concrete pressure and to plan the experimental setup, the relevant material properties of the 3D-printed mortar (including bending tensile strength in vertical and horizontal directions and the pull-out resistance of formwork anchors) were determined and implemented in finite element method (FEM) calculations. In terms of structural design and assessment, the process involved the results of the material tests and the large-scale element tests which were used to calculate characteristic as well as design values for static verifications and durability predictions. In particular, the following properties were determined in the hardened state: compressive and flexural strength, elastic modulus, adhesion between the layers after different environmental impacts, freeze-thaw resistance, pull-out and push-out resistance of wall anchors. All tests were performed both on laboratory-cast specimens and 3D-printed specimens in two or three directions, also taking the effects of cold joints into account. Large-scale wall elements were also considered, including impact as well as flexural strength tests on load-bearing and non-load-bearing walls (Fig. 4c). The approval was based on existing standards for concrete and masonry construction and required the monitoring of the material and executing of the design details during construction, as well as long-term monitoring. The approval for this project was also obtained for the 3D-printing mortar in combination with the 3D-printed wall types and the 3D printer that was used.

A different structural system, compared to classical RC load bearing frame, is the B-Hut, which tries to conjugate new wall structures with code compliance. The building project consisted of a cast-in-place reinforced concrete slab with perimeter footers, morphing 3D printed concrete walls (fabricated in modules) with intermediate reinforced cores, and a precast reinforced concrete roof. The intermediate reinforced cores connected to the foundation with dowel bars, and to roof beams with grouted in place protruded wall reinforcement [3] (Fig. 3d). The introduction of 3D printed concrete walls as part of the main force resisting structure required additional structural testing to obtain approval. As there were no existing code provisions for such a structure, to meet building code requirements it was necessary to provide adequate proof that it met the design requirements as stated in IBC Section 104.11 [17]. To this scope, testing on the printing process, materials, and structural elements was carried out prior to printing: a stability print representative of the wall was performed in August of 2017, a structural test was performed in July of 2018 (Fig. 4a), and materials testing was performed ahead of the print. From design, the required dead load capacity and out-of-plane moment were determined to be 1.3 kN/m and of 8.5 kNm, respectively. From out-of-plane testing, the test moment was determined to be 40.7 kNm, 4.8 times the design moment, validating the


(a)

(b)

(c)

Fig. 4. a–c. Large scale testing: (a) B-Hut wall element, (b) Milestone wall type B element, (c) Beckum House wall.

design for construction.

The leading design principle of applying 3DCP technology to create a new structural element, allowing the efficient use of the material was also pursued in the case of multiple off-site 3D printed concrete wall elements of the Milestone House. Here, instead of copying masonry principles commonly applied for single-storey dwellings, the 3D printed wall elements fulfilled the primary load-bearing function and carried the full roof structure. As such, the aim was to use less material (thinner walls) and use the freedom in shape to realize stiffer walls through curvature. The validity of the wall structural design as well as the manufacturability of two applied wall types (A: relatively straight and B: with a strong cantilever of the outer shell) were tested by large-scale mock-up testing at TU/e. Each of the wall elements was 3D printed on a 1:1 scale to assess stability during printing, and once hardened, subjected to in- and out-of-plane loading to validate structural performance (Fig. 4b). Following the successful mock-up phase, the final structural calculations toward a permit were made. After an initial 3D analysis of the full wall elements, the structural engineer decided to focus exclusively on the load-bearing inner shells of the wall elements. These parts were checked for (eccentric) vertical loading and horizontal wind loading, in a geometrical non-linear FEM analysis, following applicable building codes. The sandwich principle was thus not included, although the insulation material was considered via a horizontal spring stiffness supporting the inner wall. Finally, the curvature of the walls was also not considered in the structural analysis. All in all, this led to a conservative (safe) lower bound approach. Then, the whole structure was checked regarding allowable deformations (serviceability limit state, SLS) and stresses (ultimate limit state, ULS). The material properties (compressive and tensile strength, and Young's modulus) followed from experimental research on printed mortar prisms. The design value of the (critical) tensile strength was defined as roughly 2.5 MPa. The results of the mock-up test phase, combined with all required structural calculations, provided the input for approval by the municipality of Eindhoven, and the corresponding building permit of the full house.

In the Striatus Bridge, the 3DCP technology was applied in an ancient structural system: the compression arch. Printed parts act as masonry blocks in compression (although local tensile stresses under specific load conditions such as point loads can occur), while thrust forces are counteracted by steel tension ties. The infill print path of the parts was designed from a combination of structural and process-based considerations, such as the required outer layer thickness, inner force distribution, continuity of the print path, location of the layer shift, and stacking of filaments. A combination of structural analysis approaches was applied to obtain the final design. Form-finding was initially applied to determine the arch shape. Subsequently, the discrete element modeling (DEM) was applied to determine the 'brick' layout, interface orientation, and to determine the stability and load carrying capacity of the overall arch. DEM is more often used in masonry analysis, see e.g. [18]. The more severely loaded parts were subjected to a 3D FEM analysis to verify stress distributions, while 2D FEM and analytical calculations were applied to define internal print path spacings (governed by local point loads).

Material design strengths were used to simulate the structural behaviour. Considering the structural system, all checks for unreinforced masonry had to be performed. The final approval was conducted by the municipality of Venice. The municipality involved a consulting structural engineer to check the validity of the structure. In consultation between the checking engineer and the project team, it was concluded that the project team would numerically analyse a range of potentially critical load cases and determine the critical load case. After completion of the structure, the structure was loaded with the critical load case, at least until the ULS value, while measuring relevant deflections. During testing, the structure was required to: (i) not collapse, (ii) not develop any noticeable damage such as cracking, (iii) show deformations smaller than the numerical predictions. In the actual testing, the applied load was significantly higher than required, i.e. >1000 kg on an 0.5 m^2 area. A seismic check was not required for this type of application, due to the temporary nature of the structure. The project was approved based on a customized procedure and no post-completion monitoring was required by authorities.

The review of all case studies shows that the structural use of printed concrete ranges from not at all to main load bearing structures, with several intermediate levels in between. The approval regimes vary accordingly. However, also for comparable levels of structural use, the approval processes are not uniform. The required extent of testing differs from one project to another, and when large scale elements must be tested (as still in most cases), the required test regime – though generally based on the ultimate limit state, depends mainly on the specifications of the acting approval expert(s). The reliance on the expertise of professionals involved is also reflected in the use of calculation methods. A mix of approaches is used as considered fit. 3D FEM is often used to a certain extent, but little clarity exists on the exact analysis approaches.

4. Manufacturing and construction

4.1. Print process

A variety of print filament sizes has been applied in the case studies, all in the range of several centimeters wide and up to several centimeters high, resulting in filament section areas measuring between approximately 200 and 2000 mm^2. Print head speeds range from 50 to 250 mm/s. Not enough data was available to compare flow rates.

Considering the variety of robots used, there are different approaches to printability. Most off-site printed projects in this analysis used industrial arm robots (e.g. Fig. 5), the majority of them in stationary positions (Dermis, Striatus), while in one case on a rail track to allow printing of larger or multiple objects (Milestone). The Reception Centre façade elements, on the other hand, were printed with a gantry printer. Likewise, all of the on-site printed projects used gantry type robots (Fig. 6a–c), except for the Dubai office, where a stationary cylindrical robot was moved by hoisting between 22 different positions (12 positions at the first, and 10 at the second; Fig. 6d). In two cases (Holstebro and Beckum houses), a gantry printer was used that exceeded the building size, but for the B-Hut, the walls were printed in two separate sections, later tied together at the doorways, by a smaller gantry robot that was moved during the project. This, as well as the Dubai Office, highlights that the size of the complete structure is not limited by the build envelope of the printer.

The need to consider the curing process to avoid excessive shrinkage (and eventual cracking) was recognized in most projects (no data available for some). The measures taken to avoid this, however, varied considerably. In two cases, the environmental humidity was artificially controlled to maintain a minimum level of 65% (Milestone) or 70% (Striatus, by using a water mist system). For the Dermis project, this was

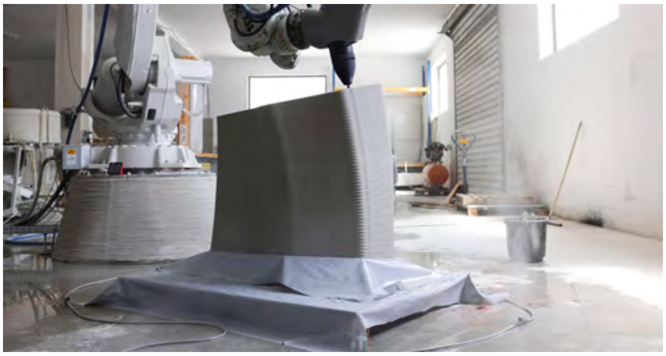


Fig. 5. Off-site printing of Striatus element. The inclination is achieved by printing faster on one side of the element, and slower on the other, thereby creating a difference in layer thickness.

(a) (b)

(c) (d)

Fig. 6. a–d. On-site printing. (a) Holstebro (credit: COBOD International) and (b) Beckum Houses, both with a larger-than-building BOD2 printer, on one position. (c) B-Hut with a gantry on 2 subsequent positions. (d) Dubai office with cylindrical robot, on 12 positions.

omitted as the average natural humidity in Concepción is already 80%. The elements for the Reception Façade were steam cured at 40 °C for 10 h, before an additional 7 days of curing in the factory. Water was sprayed on the elements in the Beckum House and Striatus projects, while at the Milestone House and the B-Hut a curing agent was used. Protective foil to prevent drying was used at least in the Beckum and Milestone Houses and the Striatus Bridge (taking care to avoid marks of the foil on the concrete), but in the Milestone House, the foil was cut open over the cavity to allow for the dissipation of hydration heat and limit the temperature increase, which could also be detrimental to the concrete. At the Beckum House, which was printed on-site, the printing was temporarily stopped when the wind became excessive. Insufficient data was available to evaluate and compare the effectiveness of these approaches.

Quality control (QC) is a fundamental aspect in every concrete construction process. In the case of 3D printed elements, QC associated with the printing process as well as the mixture composition is particularly relevant, and specific measures have been reported in the B-Hut, Beckum and Holstebro Houses, and Dermis projects. Regarding the mix design, it is important to sample the materials delivered, remove undesired constituents, such as oversized aggregates, and to account for moisture content and absorption of aggregates in the mix. Once the mix is produced, properties as extrudability, slump, penetration can be checked, as was done e.g. in the Dermis project. At the Holstebro House, slump tests were carried out for every batch, and complemented with regular shear vane tests especially where slight changes to the mix were made. The objective was to measure the strength build-up of the material over time as the evolution of yield stress. At the Milestone House, on the other hand, it was reported that hardened samples (printed and stored under the same conditions as the off-site printed elements for the house itself) were cut and tested after 28 days, in several directions as a QC measure to check the layer bond, both vertically and horizontally. At the Beckum House project, both fresh state tests (mini slump flow, setting time) and hardened state tests (compressive and flexural strength on cast and printed samples) were performed on material batches of the supplied dry mortar. The cast samples were prepared and stored under laboratory conditions, while the printed samples were produced during the actual printing of the house and stored under the same ambient conditions near the house until cutting and testing. Several samples are still stored there for testing in the coming five years.

With respect to the printing process, examples of variables to be controlled are the printing speed, extrusion flow rate, print nozzle height, length of printing cycles, layer interval time, and ambient conditions like temperature, humidity, and wind speed. In the case of the B-Hut and Beckum House, printer starts, stops, and layer run times were meticulously documented to be used for QC of the printing times to ensure that those do not exceed the timing for cold joints formation.

4.2. *Dimensional deviations and building integration*

Dimensional deviations can generate a host of problems, particularly to fit building components together. Hence, the dimensional accuracy is of key importance. Experiences in this matter vary. Generally, the accuracy of the robotic positioning of the print nozzle is very high, well within the margins used in the construction industry. However, the flow and deformation behaviour of the print concrete in the fresh state varies from one project to another, partially due to self-loading conditions, which can nevertheless result in dimensional inaccuracies both in width and height of the object. Deviations in filament width are mostly less consequential from a construction point of view (although the structural implications might require attention [10]) than deviations in height.

The accuracy of the Reception Centre façade parts and Striatus parts was very high, as reported by the project experts. In the latter case, height deviations were less than 2 mm, and did not pose any problems during assembly (Fig. 7a, b). The deviation after printing 3 m in height at the Dubai Office was 5 mm. In the Beckum House, similar deviations (several mm) occurred. Regular adjustments to the model were needed to achieve e.g. level windowsills around the whole building. Due to variations in fresh state properties in the concrete mix used during printing, the Holstebro House reached a wall height of only 2280 mm after 58 layers, instead of the intended 2320 mm. Thus, an additional layer was printed to reach the target height. In the Milestone House, the layer width and height of the first layers was measured during printing as part of the QC process, and visually checked for the remainder of the print. Although advanced 3D scanning equipment exists [19], this has not been used in the evaluated case studies. Rather, conventional measurement devices were used.

5. After completion

Compared to the extensive effort to design, test, and approve 3DCP structures, it seems the phase after realization is receiving relatively little attention in these case studies. The design life is either not explicitly considered, or set to the conventional duration, which is generally 50 years or more. Periodical visual inspection regimes have been instigated by the project teams but were generally not mandated by authorities, except for the Beckum House, where an annual visual inspection is required for the first five years after completion. More advanced inspections are not being carried out.

Notwithstanding curing measures taken, cracks have been reported in several projects, such as the Holstebro, Milestone, and Beckum Houses. In the Holstebro House, while the cause was not reported, the cracks were only observed at the first layer during printing. To overcome that, the concrete mix was adjusted by adding fibres. After that, no cracks were observed. In the Beckum House, cracks were attributed to drying shrinkage caused by strong winds. In the Striatus, observed hairline cracks are considered to have resulted from differential settlements. They are visually being monitored in length and width, but have remained stable since their initial occurrence, and do not appear to be the result of shrinkage. In the Reception Centre, cracks perpendicular to the print plane have appeared after around a month or more in several façade elements. It is assumed these have been caused by shrinkage, which is expectedly high due to the cement content and lack of aggregates. Even though shrinkage cracking is not widely reported in public documentation, based on informal observations of the authors, as well as reporting e.g. in [6], this is likely a common issue in printed concrete. Possibly due to high humidity during printing and curing, cracks have not appeared in the Dermis project elements.

Considering 3DCP elements are generally thin-walled, cracks could easily run through a structural section entirely. Measures to avoid shrinkage and other cracking should be taken, and post-completion inspections are advisable, particularly in structural applications.

Although it should be kept in mind that these structures have all only been realized quite recently, it is noteworthy that no other problems, e.g. with regard to strength, have been reported to have arisen after completion.

6. Lessons learned

6.1. Use, design, structural analysis and approval

A first observation when considering the analysed projects, is that although the number of projects employing 3DCP is rapidly growing, the main motivation of its use is not (yet) the inherent qualities of this manufacturing method, but showcasing its *potential* – not necessarily already achieving it. 3DCP currently still mainly operates in a commercially protected environment.

During the design phase, the possibilities of the technology are considered explicitly by the designers, on the one hand to benefit fully from the geometrical freedom that is offered, but on the other to nevertheless stay within the boundaries these technologies have too. Generally, the applied variant of 3DCP technology is specifically considered, as their capabilities can vary significantly with regard to aspects such as filament size, continuity, and cantilevering. The required expertise is usually supplied by printing companies who are involved in a very early stage of the project development.

In most cases, the printed concrete is not actually applied in a primary load bearing capacity. Also from literature, very few cases in which the printed concrete is load bearing, are known [4,5]. Of the projects analysed in this study, only the Striatus and Milestone projects feature fully load-bearing 3DCP structures, while hybrid cast/printed concrete structures have been applied in the B-Hut and Beckum House. In both former two, analogies with unreinforced masonry were used to obtain approvals. Although this is a feasible strategy for these specific cases, it brings significant restrictions for applications in which compression is not the dominant action, such as floors and slabs. In the other projects, printed concrete is mainly used as non-load bearing walls, façades, and as lost formwork for cast RC. This allows for relatively straightforward processes of structural analysis and approval, at least avoiding large scale testing – although in some cases specific procedures are still in place due to secondary uses of the printed concrete (e.g. Beckum House).

An important reason for the hesitance to allow the printed concrete to play the role of main load bearing material, seems to be the lack of feasible reinforcement options (hence also the unreinforced masonry approaches in projects that do use printed concrete structurally). Although a range of reinforcement strategies is being explored in academia [20], none of these have yet been applied in these case studies. This gap needs to be bridged to enable a more widespread application of the 3DCP technology.

6.2. Manufacturing and construction

The case studies show that both industrial arm robots and gantry robots are used for 3DCP. In the presented cases, industrial arm robots


(a) (b)

Fig. 7. a, b. Assembly of the Striatus Bridge. The elements were found to have sufficiently accurate dimensions to be placed without additional adjustments.

(in fixed position or on a rail) have been applied in the projects in which printing took place off-site, whereas gantry robots were used on-site (as well as a cylindrical robot in Dubai). However, it is known from published data that this can also be the other way around. Gantry style printers seem preferable when continuous elements with a large in-plan size need to be printed, as industrial arm robots will have a smaller reach. The required installation time of a print system in a certain position in relation to the volume that can be printed from that position (relevant mainly to on-site printing), should be considered.

In general, the printing process quality is (highly) sensitive to the fresh material behaviour, and thus to its composition. Although relevant variations can even occur in ready-mix printable mortars, when a mixture is used that is designed based on locally available raw materials, it has been reported from the B-Hut project that it is particularly important to sample delivered materials. Care should also be taken to avoid excessive vibration (required due to thixotropic behaviour) in the hopper of the pump, which could result in segregation of the aggregates. On-site printing can also come with challenges regarding the environmental conditions; printing for the Dubai Office took place mostly at night as the day temperatures exceeded 40 °C at the construction site, which would induce printability problems as well as deteriorate the printed concrete. At the same project, the strong winds of the desert carried sand covering the printer guides and bearings. After trying dozens of options, a lubricant for motorcycle chains in the form of spray was the solution, having excellent protective properties, high viscosity, besides the sand did not stick to it. In the Beckum project, on the other hand, weather conditions occasionally caused printer down time as a silo had to be loaded on site with 1 t ‘big bags’, which could only be done under dry weather conditions. In follow-up projects this has been solved by using a common silo-truck.

At the current state of development, there is still a considerable gap between the actual printing time, and preparation time needed to set-up the system (as already noted by Diggs-McGee et al. [12]). At the Beckum House, once the printer was running the actual print process was very smooth, but the preparations for the print were time consuming because of dry runs required to adjust the levelling of the printer to the flow and deformation behaviour of the print concrete in the fresh state (see chapter 4.2). Due to some slight deformations in the 3D printed structures (in order of several mm), the elevations of the printed object did in the reality not equate to the model. Hence, regular adjustments to the model were needed to achieve e.g. level windowsills around the whole building. This can be avoided in the future with the help of laser scanning during the printing process.

Then, the print path geometry may also cause issues, as was experienced in the Holstebro House. The top part of the building features a much shorter print path length. The print speed had to be reduced, occasionally to a complete stand still, to allow sufficient structuration of the mortar and avoid in-print failure. In the Milestone project, on the other hand, due to the long printing times required for the individual elements, challenges were encountered regarding the curing, which already starts in the bottom part of an element. Curing compound in combination with a high humidity (≥65%) was applied, as covering the elements with foil is not possible during printing.

During the printing process, it is furthermore of key importance to document printer starts, stops, and layer run times. These can later be used for quality control during and after the print to confirm that the print times did not exceed curing limits of cold joint limits [21].

In relation to the B-Hut, it has been reported that seemingly minor details in the printing equipment in general, and the materials delivery system in particular can significantly influence the success of the printing process. An extensive list of detailed remarks was already reported by Diggs-McGee et al. [12]. Of key importance is controlling the system temperature, so that unintended acceleration of the mortar curing is avoided. System temperatures increase due to motor-generated heat (in turn caused by the overall resistance in the system) and through friction between stationary system parts and the moving mortar. Normally, it will reach stable value shortly after the start of printing. Excessive temperature increases can occur due to high ambient temperature, too stiff material mixture, or an unfavourable hose layout (e.g. with vertical sections or sharp bends). Some printing facilities employ continuous measurements of the system temperature to timely signal overheating. Sharp bends or sectional changes in the material flow can also lead to gradual material build-up and eventually to blockage. Other projects operating long printing times with one-component materials have reportedly used two alternating material delivery systems to avoid long-term effects of gradual heat build-up in the system and potential blockages due to material curing within the system [4].

Due to inertia of the robot, the print speed inevitably reduces when cornering. Besides at element corners, this also occurs in often observed zig-zag infill patterns in hollow wall elements. This should either be compensated by a reduction in material flow, or (slightly) larger deposition volumes need to be locally accepted. Finally, care has to be given to the nozzle design, as an improper internal geometry (e.g. with sectional changes just before the nozzle mouth) can result in uneven material deposition.

When off-site printing is applied, the logistics require credulous attention as well. Since printed parts are often thin-walled, and feature little to no reinforcement, they can be susceptible to peak stresses caused by lifting and hoisting, as well as impact caused by careless handling during construction. In the case of Striatus, this has required reprinting one part.

Building integration also needs to be checked for, including material compatibility. The sandwich wall elements of the Milestone house are filled with sprayed insulation. As it was known [22] the expansion and consecutive contraction of the material may cause the concrete to fracture, extensive trials were performed to find an insulation material that least posed this issue. Nevertheless, it could not be entirely avoided, and had to be remedied post factum.

Building component compatibility, another aspect of building integration, can also be challenging, particularly between printed and non-printed parts. For instance, in the Milestone project, connecting the printed elements to prefab elements such as the roof structure, and window and door frames, required significant attention, mainly to make sure no thermal bridging between would occur. In the case of the Striatus bridge project (Venice, Italy), although slight misalignments in positioning the parts were produced, the use of neoprene pads of 4 mm thickness helped to level any inaccuracies. In the Holstebro House, to avoid connection problems between 3D printed walls and non-printed elements, printed formworks were incorporated for roof slabs ensuring a perfect fit into the 3D printed structure. In the Reception Façade, the horizontal joints between elements were connected with cement mortar, while the vertical joints were filled with polymer modified cement mortar.

7. Closing remarks

In this paper, eight recent 3DCP projects have been analysed on several aspects relating to their realization in practice, ranging from design, structural analysis and approval procedures, to manufacturing and construction aspects. All projects serve as showcases and/or study objects, not yet in a commercially fully competitive environment. Only in a few cases, the printed concrete is used structurally. Often, the printed concrete is used in a non-structural fashion to allow approval based on existing regulatory frameworks. In the case of structural applications, approval procedures rely on exemptions and case specific testing. The lack of suitable reinforcement methods remains an obstacle. Thus, unreinforced masonry analogies are often applied.

In the realization, a host of issues were encountered relating to the particular print process, material, site conditions, and design – or to the 3DCP technology in general.

Perhaps the most notable observation is that the applied procedures of design, analysis, approval, manufacturing, construction, and quality control are generally based on the expertise and understanding of the individual persons, companies and institutions involved. Notwithstanding the obvious success in projects, the effectiveness of their approaches cannot be independently established, evaluated, or compared. Thus, further study is necessary to serve as a basis for the development of common approaches to these issues (references such as [23–25], provide valuable directions for the related fresh and hardened state experimental work, and geometrical conformity measuring). The range of different printing systems, print materials, and construction strategies (on-site versus off-site), will significantly encumber the development of a fully general regulatory framework, and strict scope definitions of such regulations may need to be set initially.

In connection to this consideration, a strong need for knowledge and expertise development in the sector has been observed. The printing itself is fast and efficient (underlining the potential of the technology), but the preparations in every step of the process are still time-consuming owing for a large part to the lack of experience in the entire construction chain (observed e.g. in the Beckum and Holstebro House projects). In the practical production of a 3DCP project, three expertise areas are crucial: one for the digital part (3D model, slicer, running and controlling the print from a computer), one for the machine side (monitoring the 3D print and mechanical issues), and one for the material side (oversight of mixing, ensuring material quality, integration with reinforcement, insulation and other functionalities, and so on). Educational institutions on all levels need to incorporate digital construction in general and 3D printing in particular into their curricula to allow the technology to become mainstream.

CRediT authorship contribution statement

As coordinating author on behalf of all co-authors, I hereby certify that the manuscript for the article '**The Realities of Additively Manufactured Concrete Structures in Practice**', authored by F.P. Bos, C. Menna, M. Pradena, E. Kreiger, W.R. Leal da Silva, A.U. Rehman, D. Weger, R.J.M. Wolfs, Y. Zhang, L. Ferrara, V. Mechtcherine,

- has been seen and approved by all authors,
- is the original work of the authors,
- hasn't received prior publication,
- isn't under consideration for publication elsewhere.

Freek Bos, coordinating author.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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