Chapter 12
Concrete 3D Printing: Challenges and Opportunities for the Construction Industry

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Abstract Construction 3D printing holds great potential for pioneering a digital transformation in the construction industry. This automated construction technology is introduced in this chapter, and relevant developments and advancements are presented. Next, major existing challenges of widespread adoption of this technology by the construction industry are discussed in detail. These obstacles and areas of uncertainty include the structural performance of 3D-printed elements, concrete reinforcement, process reliability and limitations, and regulatory challenges. Finally, different application domains and new possibilities which could be realized by this new construction method are discussed in detail to provide a comprehensive overview of the extrusion-based concrete 3D printing technology and its implications for the future of the construction industry.

Keywords 3D printing · Automated construction · Reinforcement · Regulations · Cementitious materials

1 Introduction

1.1 Digital Transformation in the Construction Industry

Digital transformation is a result of confluence of new technologies which promote connectivity, advanced analytics, automation, and advanced manufacturing (Siebel, 2019). This major paradigm shift is changing the dynamics in almost every major industry. Based on McKinsey's Industry Digitization Index, which involves 27 indicators for measuring the digital assets, digital usage, and digital workers in each sector,

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construction is categorized as a sector with “low digitization” (Manyika et al., 2015). During the past decades, productivity in the construction sector has been stagnant, while other industries such as manufacturing have experienced significant improvements in the productivity. It is estimated that 5–10 times productivity boost is possible for some parts of the construction industry by adopting a manufacturing-inspired production system (Barbosa et al., 2017). Infusing digital technology, new materials, and advanced automation are key factors in realizing a much-needed productivity boost.

There are various ongoing efforts and technological developments toward digitization of the construction industry. For instance, building information modeling (BIM) is an important development which streamlines design and data collection and analysis by different stakeholders and teams within a digital platform. Recent efforts have demonstrated the benefits of adopting BIM technology, such as automated code-compliance checking, automated cost estimation, scheduling, clash detection between different disciplines, and energy analysis (Azhar et al., 2011; Davtalab et al., 2018).

Although some improvements are achieved by implementing technologies such as BIM in the construction industry, the manual processes involved in the construction phase are still a major obstacle toward realizing a manufacturing-inspired production system. Low construction productivity, growing labor costs, high accident rates, cost and schedule overruns, and poor quality are some of the consequences of these manual construction methods. Robotic construction seems to be a viable path toward digital construction, but it is yet to be proven practical before it is widely adopted by the construction industry.

1.2 Earlier Efforts Toward Automated Construction

Construction automation has remained a challenging topic of investigation for engineers for several decades. In 1980s and 1990s, Japanese construction companies were pioneering the research and development efforts on design and application of robots in their construction projects (Morales et al., 1999). These efforts were initially limited to experimentation with single-task robots and were mostly motivated by the shortage of skilled construction labor in Japan, and the low productivity observed in the Japanese construction industry. Examples of these single-task robots include concrete floor finishing robots, painting robots, and ceiling board installation robots (Castro-Lacouture, 2009). In late 1980s, these efforts aimed at developing integrated automated building construction systems (ABC), which resulted in multiple systems developed by different companies, such as Big Canopy by Obayashi and SMART by Shimizu (Morales et al., 1999). SMART was an integrated system designed to automate various activities such as steel frame erection and welding and wall panel installation. Big Canopy system included four tower masts and a massive canopy at the top, which lifted prefabricated material to the target floor. The control and maneuvering of the components were done using joysticks (Castro-Lacouture, 2009). These

ABC systems were used in several projects but were not continued after a few years. According to the Japanese Construction Mechanization Association, the failure of such construction automation efforts can be attributed to the significant research, development, and manufacturing costs of these systems which could not be recovered, as well as the overall inability of these systems to considerably reduce onsite labor requirements (Taylor et al., 2003).

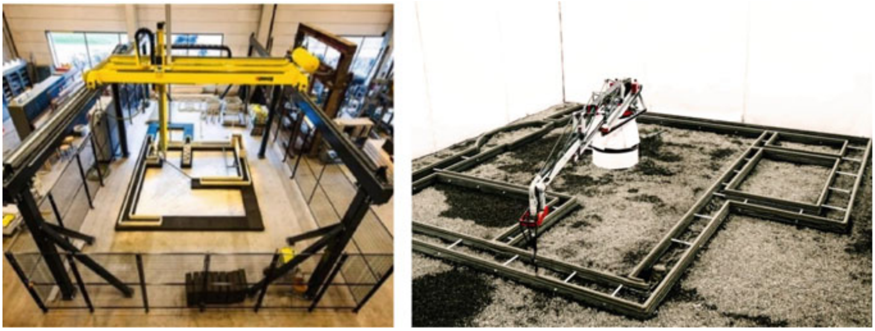
1.3 Recent Developments

A more recent movement toward construction automation started with the invention of contour crafting (CC) in 1997 at the University of Southern California (Khoshnevis, 1998; Khoshnevis & Kazemian, 2020). CC uses computer control, material extrusion, and the superior surface forming capability of troweling to create smooth, accurate, planar, and free-form surfaces. It provides architects the flexibility to design curved surfaces as easily as traditional rectangular shapes (Fig. 1). By automating the construction process using CC technology and reducing the need for human labor, significant reductions in construction time and cost could be achieved while creating a safe working condition (Ghaffar et al., 2018; Khoshnevis et al., 2006). It is reported that only in the United States, over 1100 construction worker fatalities happen each year (United States Department of Labor). The high number of injuries and fatalities on the construction sites can be reduced by adopting automated construction systems, and assigning human workers to supervisory and machine control roles. Such improvement would be contingent on developing and following new measures to ensure safety during human-construction robot interactions. Another major distinction between CC and conventional concrete construction is eliminating the need for formwork to shape the fresh concrete, which makes the CC process significantly faster.

Fig. 1 3D-printed concrete element using CC technology (Davtalab et al., 2018)

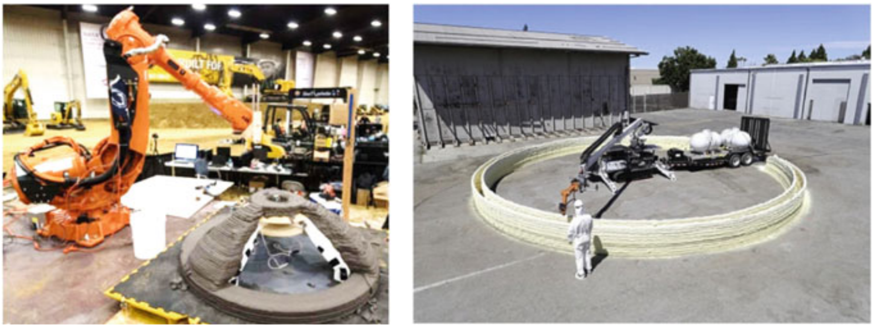
Invention of CC later started the field of construction 3D printing (C3DP). Various similar large-scale 3D printing systems have been developed based on the extrusion of cementitious materials. Continuous mixers and concrete pumps are commonly used to deliver the printing materials to a robotic system which deposits cementitious layers according to the computer-generated commands after processing a 3D model. Different types of robotic systems such as articulated robots, and gantry, delta, and crane type robots have been used for layer deposition within the robot's build envelope (Hojati et al., 2018; Kazemian et al., 2017). Four examples of construction 3D printing systems are presented in Fig. 2.

During the recent years, there have been several other innovative approaches toward automated construction which rely on concepts other than extrusion of cementitious mixtures. D-shape (Colla & Dini, 2013) and smart dynamic casting (Schultheiss et al., 2016) are two prominent examples of these innovative automated construction systems. D-shape is a construction-scale particle bed 3D printing process in which layers of sand are deposited, and then, particles are selectively bonded using a binder material. After the fabrication process is complete, the residual



(A) Gantry C3DP system

(B) Crane type C3DP system



(C) Modified articulated robot used for C3DP

(D) Digital construction platform

Fig. 2 Examples of different robotic systems used for construction 3D printing (Kazemian et al., 2017; Li et al., 2020b; Paolini & Rank, 2019; Zhang et al., 2019)

Fig. 3 Smart dynamic casting (Lloret-Fritschi et al., 2020)

sand is removed, and the object is infiltrated by additional binder, and finally, it is sanded and polished (Lowke et al., 2018). Smart dynamic casting (SDC) is a robotic slip-forming process where an actuated formwork, which is much smaller than the final produced element, is used to shape concrete. SDC requires precise control of material properties and rheology during the process (Lloret et al., 2015) and is able to produce bespoke reinforced concrete elements without any post-processing (Lloret-Fritschi et al., 2018). A concrete column fabricated by the SDC technology is shown in Fig. 3.

Among these recent developments and innovations, extrusion-based C3DP seems to hold great potential in revolutionizing the construction industry and being deployed in a massive scale in the near future. In the following sections, different aspects of this automated construction technology as well as recent advancements and existing barriers to its adoption by the construction industry are discussed in detail.

2 Current Status of the C3DP Technology

Two main scenarios can be considered for widespread adoption of C3DP technology by the construction industry: (1) Using concrete 3D printers in the prefabrication facilities to produce structural elements and (2) Using portable concrete 3D printers for onsite construction. Successful demonstration projects have been carried out for both scenarios. The first scenario, prefabrication, seems to be an easier starting point to facilitate adoption of C3DP technology by the conservative construction industry. Prefabrication facilities provide an ideal environment to implement a tightly monitored and controlled concrete 3D printing process which can operate continuously, with minimal human intervention. The same does not hold true for onsite construction where the ambient conditions (temperature, wind speed, humidity, and rain) can affect the process and impact the construction quality or even lead to process failure, such as collapse of freshly printed walls.

On the other hand, there are several disadvantages that can be attributed to the prefabrication 3D printing scenario. In this method, the production of structural elements is automated; however, transportation and assembly are still needed and can significantly add to the total construction time and cost. The onsite assembly of 3D-printed elements is still a manual and time-consuming task, which needs skilled workforce. These requirements are in conflict with the main goal of improving the construction productivity. In addition, to ensure a successful onsite assembly, tight quality control and high dimensional accuracy are required for the prefabricated 3D-printed elements. These restrictions do not apply to onsite C3DP, where a portable construction printer builds a structure in a single process and allows for minor process modifications. In addition, by shipping only one portable printer and needed materials to the construction site, a large number of structures can be constructed on the jobsite. Therefore, it seems that onsite C3DP is generally more advantageous in terms of productivity and process automation, while it is technically more challenging to design and implement a robust, portable, easy to set up, and reliable C3DP system for onsite applications.

In the following sections, recent developments and advances in printing materials, process quality control, and code compliance of 3D-printed structures are discussed in detail.

2.1 Printing Materials and Testing

Various materials such as clay, plastic, geopolymer, and sand have been successfully used for large-scale 3D printing (Chougan et al., 2020). However, Portland cement-based mixtures are the most commonly used printing material for C3DP. Portland cement-based concrete is the most widely used engineering material for conventional construction as well, with three primary reasons for its wide application: Excellent resistance to water, deformability in fresh state, and the fact that it is usually the cheapest and most readily available construction material. Unlike wood and ordinary steel, the ability of concrete to withstand the action of water without serious deterioration makes it an ideal construction material. Formability of cementitious mixtures in the fresh state enables engineers to form structural elements into a variety of shapes and sizes. Finally, the relatively low cost of concrete has significantly contributed to its wide application. The principal ingredients for mortar and concrete, namely aggregate, water, and Portland cement are relatively inexpensive and are readily available in most parts of the world. It should be mentioned that there are also other properties which are critical in some applications, such as fire and termite resistance of concrete (Kazemian, 2018).

Portland cement-based mixtures which are commonly used in C3DP have high Portland cement content, no coarse aggregate, and multiple chemical admixtures to modify the rheology and setting time of the printing mixture (Nerella et al., 2016; Kazemian et al., 2017). Considering the widely known negative environmental impacts of Portland cement production, high Portland cement content printing materials are not desirable from a sustainability standpoint. Extensive research is being carried out to eliminate or reduce the Portland cement content in the C3DP materials (Bhattacherjee et al., 2021; Bong et al., 2019; Panda & Tan, 2018). In addition, to improve the tensile strength and ductility of Portland cement-based printing materials, inclusion of discontinuous and uniformly dispersed fibers—such as steel and PVA fibers—has been studied by different researchers (Arunothayan et al., 2021; Bos et al., 2019; Ding et al., 2020).

There have been numerous studies on development and characterization of mortar and concrete mixtures for C3DP (Kazemian et al., 2017; Nematollahi et al., 2018; Panda & Tan, 2018; Sanjayan et al., 2018; Wolfs et al., 2018). With respect to the characterization of the fresh properties of printable cementitious mixtures, two categories can be recognized: (1) fundamental rheological properties and (2) performance-based workability tests. Fundamental rheological studies rely on measuring parameters such as yield stress and plastic viscosity of fresh printing mixtures and enable evaluation of the structuration rate and thixotropic behavior of different mixtures. Therefore, these rheological measurements provide a deep understanding of behavior of different mixtures over time and reveal the influence of different admixtures on the printing materials (Jeong et al., 2019; Perrot & Pierre, 2016; Roussel, 2018). The other approach for characterization of fresh properties of printing materials is based on performance-based testing, where the workability aspects, which are critical during the C3DP process, are defined and tested. Extrudability, shape stability, and printability timespan are some of the performance criteria which have been defined by researchers, and different test methods have been proposed for evaluating these workability aspects (Kazemian et al., 2017; Le et al., 2012). Shape stability is considered as the most critical property of a fresh printing mixture and is defined as the ability to resist deformations during layer-wise concrete construction. There are three main sources of layer deformation during C3DP: layer's self-weight, weight of following layer(s) which will be deposited on top of it, and the extrusion pressure (Kazemian et al., 2017). Addition of viscosity modifying agents (VMA) and nano-clay has been reported as effective measures to improve the shape stability of printing mixtures (Kazemian et al., 2017; Zhang et al., 2018).

2.2 Process Quality Control

In order to realize the full potential of C3DP and promote its wide application in real-life projects, robust and reliable processes should be designed such that variations in the ambient conditions or material properties do not lead to process failure (Ghaffar et al., 2018). Regarding the printing materials, in specific, some variations seem inevitable due to inconsistencies in the moisture content and grading of aggregates, as well as other sources such as imprecision of material dosing and measurement units. In C3DP, the stability of fresh concrete layers is an important topic, which needs process optimization accounting for different factors such as printing speed and material stiffening rate. Even at an optimized printing speed, however, variations in the rheological properties of a deposited layer could result in the collapse of freshly printed components and structures. Therefore, an inline real-time quality monitoring system is required to detect variations in the properties of the printing material during the process.

Kazemian and Khoshnevis (Kazemian, 2018; Kazemian & Khoshnevis, 2021) proposed and evaluated four different techniques for real-time extrusion quality monitoring. These four techniques are described in Table 1. In this study, change in the free water content was considered as the major source of variations in the printing mixture. A previously tested printing mixture was selected as the reference, and six levels of variation (error) in the free water content was intentionally applied to the mixture, resulting in a total of seven mixtures. These variation levels include ±5, ±10, and ±15 L/m^3 change in the water content of the printing mixture.

Table 2 presents the obtained results for the proposed real-time extrusion quality monitoring, where a higher sensitivity index shows a greater change in the measured parameters as result of material variations. The technique based on computer vision was proved as the most accurate and reliable extrusion monitoring technique, which was able to detect all the tested variation levels. These results imply the high potential of computer vision for C3DP process monitoring. In another study (Kazemian et al., 2019), the developed computer vision system was successfully used to develop a closed-loop extrusion system where the feedback by the vision system is used to automatically adjust the extrusion rate and constantly produce layers with consistent dimensions. Such intelligent extrusion systems could be used to improve the dimensional accuracy of 3D-printed elements and also eliminate the need for extrusion calibration and to enable multi-material 3D printing.

In a recent study, Davtalab et al. (2020) designed and implemented an automated layer defect detection system for C3DP. This automated inspection system builds upon a customized deep convolutional neural network which distinguishes concrete layers from surrounding objects by semantic pixel-wise segmentation. This model was trained, tuned, and tested using 1 million labeled images. Then, an innovative defect detection approach was designed and used to detect deformations in the printed concrete layers. The results showed a total accuracy of 97.5% and a miss rate of less than 6% for the defect detection model. The results of this study further highlight the great potential of computer vision and deep learning for quality control and inspection during concrete 3D printing (Fig. 4).

Dimensional accuracy of 3D-printed components and consistency of as-built dimensions with the initial CAD model are very important in the prefabrication construction. Other than computer vision, there are other well-established measurement approaches such as laser 3D scanning and structured light scanning which are frequently used in other fields. These techniques could be used to create a digital twin

Table 1 Proposed techniques for real-time extrusion quality monitoring

Technique	Hypothesis	Implementation notes
Agitator motor power consumption	By monitoring the changes in the electrical power consumption of an agitator motor, undesirable changes in the rheology of printing material could be instantly detected to prevent deposition of unacceptable layers	3D-printed blades were installed on a shaft connected to a DC motor. The design of the blades is similar to the continuous concrete mixers which are commonly used in construction, while the functionality of these blades is similar to a viscometer paddle. The power consumption of the DC motor is used as an indication of material viscosity
Extrusion pressure measurements	At a constant extrusion rate, monitoring the changes in the extrusion pressure could reveal the variations in the viscosity of printing material	A 0.5 mm thick resistive pressure sensor with an active sensing area of 38 × 38 mm, a microcontroller, and a customized 3D-printed nozzle was used to measured extrusion pressure inside the nozzle every 15 ms
Electrical resistivity measurements	Monitoring the changes in the electrical resistivity of printing material reveals the unacceptable changes in the water content of the printing material	To simplify the testing conditions, the electrical measurements were carried out on 100 × 200 mm cylinder specimens of fresh printing mixture. A preliminary experimental program was carried out to find the optimum frequency (1 kHz), amplitude (8 $V_{\text{p-p}}$), and waveform (sine wave), before the main experiments
Computer vision	By capturing and analyzing top-view images of the extruded layer using a camera, the layer width can be continuously measured in real time and compared to the target width, for automatic detection of over-extrusion or under-extrusion conditions	A computer vision algorithm was developed to detect the extruded layer and to measure the layer width in real time to compare to the target layer width and detect over-extrusion or under-extrusion conditions. To calibrate the system, layers with precise dimensions were cast and used

of the as-built structure and therefore enable real-time detection of geometrical inconsistencies. Buswell et al. (2020) discussed applications of digital measurement techniques for C3DP and the assembly of a set of 3D-printed elements. These researchers have suggested the application of these measurements during four different stages: before the printing process starts (for process and material assessment), during the process (to compensate for plastic deformation), after the printing process (for application of secondary processes), and after assembly of 3D-printed components (for documentation) (Buswell et al., 2020).

Table 2 Sensitivity index of the proposed techniques at different variation levels

Variation level (liter/m^3)	Proposed quality monitoring techniques			
	Power consumption	Extrusion pressure	Electrical resistivity	Computer vision
+5	x	x	x	2.8
−5	x	x	x	−2.4
+10	x	x	x	8.8
−10	4.9	✓	x	✓
+15	6.5	x	−2.9	15.7
−15	10.0	✓	x	✓

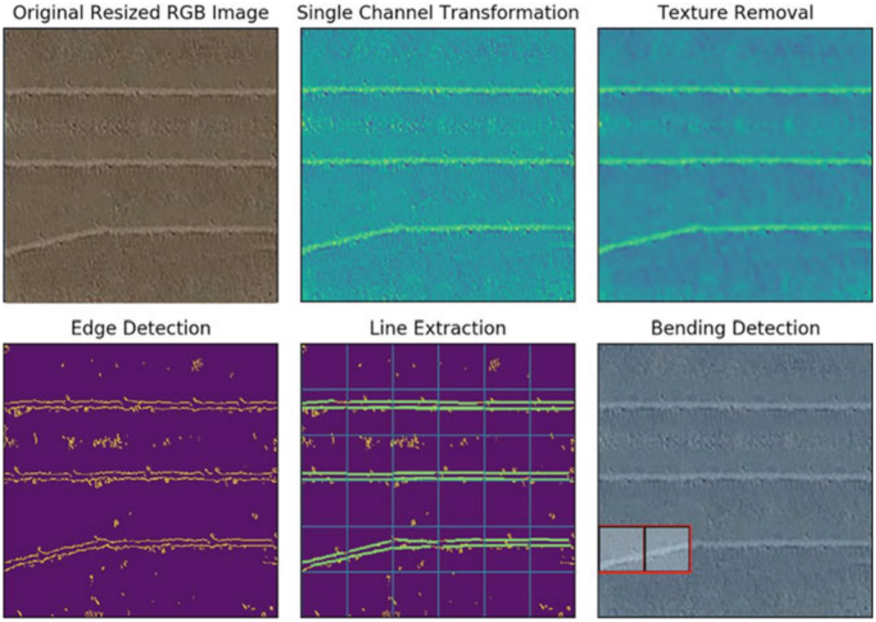


Fig. 4 Automated layer defect detection system (Davtalab et al., 2020)

2.3 Design Code Compliance

Design engineers and architects are usually guided by national and local design codes. The design codes become especially important when compliance with the legally adopted code is mandated by a jurisdiction having the authority to approve construction projects. In this section, “building” construction is used in specific to discuss code compliance of C3DP as a new construction method and the recent advancements. In some countries, such as most European countries, there are national building codes which are usually developed under central government supervision and enforced uniformly throughout the country by the central government. However, in other countries such as United States (US), since the power to regulate construction is vested in local authorities, a system of model building codes has been used. The international building code (IBC) and the international residential code (IRC) are the two model codes that have been developed to establish the minimum requirements to safeguard the public health and safety in building construction and are currently enforced throughout the US. To this date (2021), IBC and IRC do not include provisions for building construction using C3DP technology. Chapter 19 of the IBC refers to ACI 318 ("Building Code Requirements for Structural Concrete, 2019) for design of reinforced concrete buildings; similarly, ACI 318 also does not address building construction using C3DP technology.

Alternative Construction Methods and Building Codes: To accommodate new and innovative construction materials and methods, IBC allows the integration of alternative materials, designs and methods, systems and technologies not specifically addressed in the code, permitting manufacturers to demonstrate that their products comply with the intent of the provisions of the building code. To this end, Section 104.11 of IBC/IRC allows an alternative material, design, or method of construction to be approved where the building official finds that the proposed design is satisfactory and complies with the intent of the provisions of this code, provided that the material and method under evaluation is at least the equivalent of that prescribed in IBC/IRC in the following six parameters: quality; strength; effectiveness; fire resistance; durability; safety.

The building code compliance is typically accomplished through product testing in accordance with an established and peer-reviewed acceptance criteria (AC). The AC document outlines specific product sampling, testing, and quality requirements to be fulfilled in order to obtain code-compliance verification. The required tests are typically conducted by accredited laboratories, and the results are summarized in a research report made available to code officials, as set forth in Section 104.11.1 of IBC/IRC, which allows such reports to be issued by approved sources. The research reports are typically issued by certification bodies that are accredited as complying with ISO/IEC standard 17065 (2012a).

Besides testing in accordance with the AC requirements, an equally important aspect of product evaluation is the requirement for documentation of quality control measures during the manufacture of the materials. Among other things, the measures are intended to verify that the produced materials will match the performance as previously demonstrated by testing. As a means of verification, the quality system needs to be inspected by an accredited independent inspection agency conforming to requirements stipulated in ISO/IEC 17020 (2012b), as determined by a recognized accreditation body. The evaluation agency is charged with requiring that the inspection agency inspects each manufacturing location regularly, and not less than once per year, to provide assurance that the materials are produced and conform to critical performance and measurements set forth in quality documentation.

Acceptance Criteria AC509: Since building construction using C3DP technology is not within the current code provisions, AC509 was developed under Section 104.11

of IBC and IRC, with a final approval date of December 2020. AC509 applies to the automated C3DP technology, and cementitious mixtures used to construct interior and exterior concrete walls, with or without structural steel reinforcing, used as bearing walls, non-load-bearing walls, and shear-walls, in one-story or multi-story structures. The walls are to be constructed by extruded concrete layers to create two parallel outer face shells, then placing an especially designed concrete core (self-consolidating mixture) between the 3D-printed shells to form a solid wall. AC509 contains provisions for the evaluation of the material and durability properties of the printing concrete and the evaluation of structural performance of 3D-printed concrete walls. AC509 material tests are described in the following paragraphs:

- Concrete Compressive Strength and Slump Testing: AC509 requires a minimum of five replicate specimens for each printing concrete mixture design used for the outer face shells, and for the core, tested for compressive strength in accordance with ASTM C39 (2020) or ASTM C109 (2020). Prior to casting test specimens for compressive strength testing, the slump of concrete must be measured and reported for quality control purposes. AC509 requires a minimum average 28-day compressive strength of 2500 psi (17.2 MPa), and that the compressive strength be used for quality control purposes.
- Freezing and Thawing Durability: The purpose of this test is to evaluate the durability of each printing mixture, used for the outer face shells, and for the core, that is subjected to exposure or freezing and thawing conditions. Tests must be performed in accordance with Procedure A of ASTM C666 (2015) for a minimum of 300 cycles. AC509 requires that the average durability factor of all specimens after 300 cycles must be a minimum of 80.
- Shrinkage and Volume Change Testing: The purpose of this test is to evaluate the shrinkage-cracking response of printing concrete. AC509 requires that the tests are performed in accordance with ASTM C157 (2017) with the following acceptance conditions: The average strain measurements of all tests of printing concrete with fibers or with aggregate size larger than 0.5 inches at 28-days must be less than 0.065%, and all printing mixtures without fibers and with maximum aggregate less than 0.5 inches at 28-days must be less than 0.050%.
- Fiber Compatibility: Because presence of fibers in a printing mixture affects the performance of 3D-printed concrete walls, AC509 requires that fibers used in the printing mixture comply with a consensus acceptance criterion for the purpose of quality control.
- Test for Minimum and Maximum Extrusion Time Intervals: Performance of a 3D-printed wall may be affected by the time interval between extrusion of concrete from the printer nozzle. Therefore, AC509 developed a procedure to understand the effect of minimum and maximum time intervals between extrusions of cementitious layers on the bond between the extrusion layers. The specimens must be 3D printed with the same C3DP technology that will be used for full-size construction. Flexural bond tests must be conducted in accordance with Section 5.2 (Method A) of ASTM E518 (2015) on three replicate sets of specimens cast at both minimum and maximum extrusion time intervals between layers. Test results must show

that the tested flexural bond strengths at minimum and maximum extrusion time intervals are statistically equal. Otherwise, the difference in strengths must be considered by use of a reduction factor in structural design calculations. AC509 also requires that the average flexural bond strength and acceptable extrusion time intervals be reported in the final research report for jobsite inspection use.

In addition to the material tests, AC509 requires full-scale structural tests for each 3D-printed wall configuration, with or without structural steel reinforcement and for each printing mixture design to be tested to justify the design provisions. The following details must be considered while preparing the test plan: each printing mixture design, reinforcing details (rebar size and spacing), if applicable; variation in geometry of the 3D-printed outer shells (such as thickness and width of the extrusion layers) and the proprietary concrete core; minimum and maximum time intervals between extrusion layers to be evaluated. The following load tests are required by AC509:

- Wall Axial Compression Test: A minimum of six specimens, with three replicate specimens of two different wall heights, must be tested. One set of specimens must be of the maximum wall height with the minimum wall thickness to be evaluated.
- Wall Flexure Test: A minimum of six specimens must be tested. The specimen preparation and dimensions must be the same as those used in the wall axial compression test.
- Wall Static In-Plane Shear Test: A minimum of three replicate specimens must be tested for the thinnest wall width to be evaluated. If multiple wall thicknesses are to be included in the evaluation report, an additional three replicate specimens of the maximum wall thickness to be considered must be tested.
- Wall Connection Load Transfer Test: A minimum of three replicate specimens of the connection between the floor and the 3D-printed wall must be tested for the thinnest wall width to be evaluated in accordance with AC509 test provisions. If multiple wall thicknesses are to be included in the evaluation report, an additional three replicate specimens of the maximum wall thickness to be considered must be tested.

In addition, AC509 requires that a design criteria report be submitted by a registered or licensed design professional which must include complete analysis, and interpretation of the qualification test results demonstrating that 3D-printed walls can be designed in accordance with the applicable sections of the IBC. The design characteristic strengths used in the analysis and design must be qualified by the test data. Any deviation from design must be established in the analysis for inclusion in the final research report. Also, per AC509, where loading conditions result in combined transverse and axial loads, the sum of the ratios of actual loads over design loads must not exceed one.

Finally, the following building code-compliance requirements and limitations have also been included in AC509:

- The 3D-printed concrete walls are limited to non-fire resistance-rated construction unless qualified by testing in accordance with ASTM E119.

- At the moment, the 3D-printed concrete walls used as the lateral-force resisting system are limited to seismic design categories (SDC) A and B only until further research is available.
- The foundation, floor, roof, and their anchorage to the 3D-printed walls using code-complaint anchorage provisions are required to be submitted to the code official for approval and are outside the scope of AC509.
- The structural design equations for 3D-printed walls constructed with the specific C3DP technology are to be outlined in the final research report. If applicable, any deviation from code-calculated design to be included. If applicable, the reduction factors coming from different extrusion interval times must also be reported.
- Structural design calculations and details of the 3D-printed walls must be prepared by a registered design professional and submitted to the code official for approval. The structural calculations must also address design and detailing of openings and loads on headers.
- Exterior envelope requirements of the applicable codes have not been evaluated and are outside the scope of the final research report.

3 Existing Challenges and Future Prospects

3.1 Existing Challenges

In this section, some of the most important challenges facing C3DP as a construction method are discussed. Structural performance and reinforcement of 3D-printed structures and elements, process reliability and limitations, and regulatory challenges are three main existing concerns that need to be addressed in order to enable widespread use of this automated construction technology.

Structural Design and Reinforcement: To date, several attempts have been made worldwide to 3D print structures such as concrete buildings and bridges using C3DP (Kreiger et al., 2019; Salet et al., 2018). Due to the lack of the design codes to evaluate the performance and integrity of printed structures, physical experiments at different scales have been used to determine whether the printed systems meet the design criteria and resist the expected service loads. For instance, Salet et al. (2018) performed testing at three scales including material testing of printed concrete specimens to determine material properties, bending testing of a 1:2 scale bridge model to determine the structural performance of the bridge in the laboratory, and load-bearing capacity testing of the full-scale bridge before opening for public use. As another example, Nerella et al. (2019) performed micro- and macro-scale experiments to study the effects of printing direction and time interval between layers, and the introduced anisotropy and heterogeneity, on the mechanical properties of 3D-printed elements.

Different studies have shown that it is feasible for 3D-printed elements and structures to achieve adequate compressive strength capacity similar to the cast-in-place concrete. However, the tensile strength of cast-in-place concrete is significantly low, and 3D-printed concrete is not an exception. One approach to achieve the required performance in tension and bending is to reinforce 3D-printed concrete with steel rebars, similar to the cast-in-place concrete structures. Since automated rebar reinforcement for 3D-printed elements and systems is a complex task, most of the existing studies (e.g., World's largest 3D-Printed Building Completes in Dubai (https://www.dezeen.com/); Kreiger et al., 2019) have considered manual rebar installation, which can significantly diminish the central promises in automating and accelerating the construction processes. Therefore, a main question to be answered is how to enhance the ductile and strain hardening behavior of 3D-printed elements in tension while minimizing or eliminating the need for steel rebars (Ghaffar & Mullett, 2018). Classen et al. (2020) discussed existing methods for 3D printing of the reinforced concrete. Examples are manually post-installed or pre-installed reinforcement as discussed above, multi-arm 3D printing of steel reinforcement and concrete in parallel (Mechtcherine et al., 2018; Schutter et al., 2018), online reinforcement integration through placement of steel wires or cables within concrete layers (Bos et al., 2018a), automated installation of segmental reinforcing elements with locking mechanisms in parallel with the concrete 3D printing process (Khoshnevis & Bekey, 2003), and pre- or post-tensioned tendons to realize pre-stressed 3D-printed concrete behavior (Asprone et al., 2018; Bos et al., 2018b). Figure 5 presents two examples of these reinforcement possibilities explored by the researchers. Most of these methods are not fully automated and call for human intervention; furthermore, existing data on the structural performance of these reinforcement methods are limited. Therefore, extensive physical experiments are needed to investigate the effectiveness of these strategies in different applications and to use the achieved understanding in developing design codes for reinforced concrete 3D printing. It should be mentioned that use of innovative printing materials can be part of the solution to the C3DP reinforcement problem. For instance, using steel fiber-reinforced concrete (SFRC) as a self-reinforced printing material seems to be a viable solution, especially in the regions with moderate and low seismic activity. Steel fibers have already been

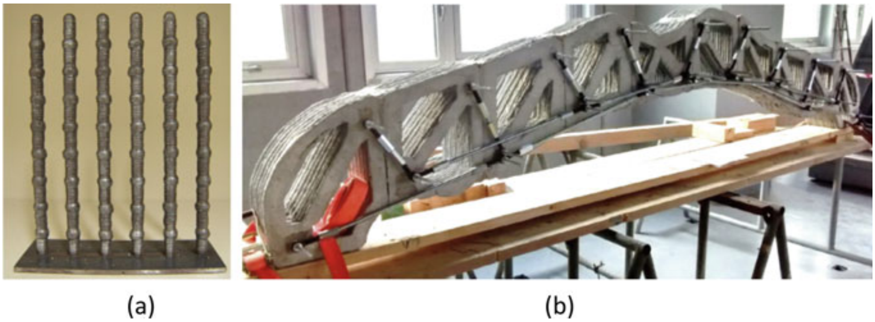


Fig. 5 **a** 3D-printed profiled reinforcement bars by Mechtcherine et al. (2018). **b** External steel reinforcement technique proposed by Asprone et al. (2018)

used for construction of various structures including rebar-free safety houses that meet FEMA requirements for EF5 tornados (Helix Steel). Engineered cementitious composite (ECC) is another fiber-reinforced high performance material with high tensile ductility which has great potential to reduce or eliminate the need for steel rebar reinforcement in 3D-printed concrete structures (Li et al., 2020a).

Moreover, for multi-hazard resilient housing and infrastructure development using C3DP, printed structures need to be designed to withstand the static and dynamic loads imposed due to extreme events, such as hurricanes and earthquakes. Today, no guideline exists for designing such 3D-printed structures, and the existing experimental data about their performance are minimal. Therefore, similar to cast-in-place structures, systematic, and holistic experimental programs should be designed to determine the performance of 3D-printed elements and structures against different design loads. The outcome of such experiments can be used to enhance existing computational frameworks for representing the behavior of 3D-printed structures at micro- and macro-scales. One important research need in this area is developing constitutive relations and the associated energy dissipation mechanisms to define the material stiffness, damping behavior, and anisotropy under both static and cyclic loading scenarios.

Process Reliability and Limitations: The second major existing challenge with respect to the industrial-scale implementation of C3DP is related to the process robustness. Despite some early regulatory efforts to address the quality control measures for C3DP (discussed in the previous section), currently, there are not any universally accepted technique and guideline for quality control and monitoring during C3DP. Failure or malfunction of the system components, variations in the printing materials, and the impact of ambient conditions are the most common issues which are observed in different large-scale 3D printing systems. Process failure due to material preparation and delivery equipment malfunction have been frequently reported, which is mainly because the existing commercial equipment is not specifically designed for the C3DP application. For instance, most of commercial continuous mixers are designed for highly flowable or self-leveling mixtures, and when used with a viscous printing material, the mixing quality and consistency of the produced material are not acceptable. After the mixing stage, in order to deliver the freshly mixed mixture to the concrete 3D printer, a commercial pump (such as a progressive cavity pump) is commonly used. These pumps usually have limitations with respect to the size and percentage of aggregate that can be used in the mixture, as well as the ability to process fiber-reinforced mixtures. The pumpability requirements for a printing mixture can be considered as the major reason for the widespread use of mixtures with aggregate size of less than 5 mm in C3DP. The reduced aggregate size and percentage also leads to an increase in the Portland cement content of printing mixtures—usually in the range of 500–900 kg/m^3 (Kazemian et al., 2017; Murcia & Reda Taha, 2020; Zhang et al., 2018)which has a negative impact on the cost, sustainability, and dimensional stability of the printing material. Therefore, to resolve some of the existing challenges, customized material preparation and delivery systems specifically designed for C3DP are needed. These systems should be able to process mixtures with different type, dosage, and size of aggregate and fiber.

Regulatory Challenges: Another major challenge facing C3DP as a new construction method is related to the construction regulations. One main barrier is the approval of 3D-printed structures where building officials need to determine if the proposed design complies with the intent of the provisions of the legally adopted building code. As mentioned before, currently, IBC and IRC do not include provisions for building construction using C3DP technology. Therefore, a major hurdle in building code compliance is the lack of legally adopted regulations that can be used for project approvals by building departments and building officials in charge of plan checks. Since predominant building and residential codes in the US do not cover this construction technology, two pathways are available:

- The building code must incorporate the technology into the building code through the public hearing process of International Code Council (ICC), or,
- Building code compliance is shown, based on Section 104.11 of IBC or IRC.

The first case may be accomplished if mandatory language design code books and material standards can be developed and adopted into building codes through ICC public hearing process. This could be accomplished by the American Concrete Institute (ACI) committee on 3D printing with cementitious materials, ACI 564, by developing design codes or material specifications using mandatory-code-language. The second case requires that the proponent of the alternative material and technology, in this case C3DP technology, demonstrates building code compliance via acceptance criteria and a resulting research report under Section 104.11 of the IBC.

A second regulation barrier could be lack of jobsite inspection details for C3DP technology. Section 110 of the IBC requires that construction or work for which a permit is required must be subject to inspection by the building official, and such construction or work must remain accessible and exposed for inspection purposes until approved. In addition, some works require detailed scrutiny, but the building official cannot stay at one job all day; therefore, special inspection provides additional surveillance in accordance with Chapter 17 of the IBC. To this date, Chapter 17 of the IBC does not contain any provisions for C3DP technology. Therefore, the inspection process for 3D-printed structures are based on the decision of the individual jurisdiction in charge of overseeing the construction.

Acceptance criteria AC509 provides suggestions for the consideration of building officials for special inspection of C3DP. AC509 suggests that special inspection must be in accordance with Sections 1705.1.1 and 1705.3 of the IBC during the mixing, printing, and placing of the 3D-printed concrete shells and the concrete core. In addition, the report applicant must submit inspection procedures to verify proper usage. The inspection must include verification that the concrete compressive strength and flexural bond strength are consistent with the published code-compliance research report. Concrete cylinders of the outer face shells and core are to be field cured in accordance with ASTM C31 (2019) and tested in accordance with ASTM C39 (2020). Testing of flexural bond strength in accordance with ASTM E518 (2015) must be compared with published values in the code-compliance research report with a maximum variability of 10 percent. It should be mentioned that currently there is no ASTM standard specifically developed for construction-scale 3D printing. However, the newly formed ASTM F42.07.07 subcommittee is tasked with addressing the construction applications of 3D printing technology.

3.2 Future Prospects and Potential Applications

In addition to the improved productivity, C3DP also offers new possibilities for design and construction of structures. By eliminating the need for formwork, C3DP allows for fabrication of complex geometries which were impossible or very difficult to create using traditional concrete construction techniques. This unprecedented design freedom offered by C3DP enables architects, designers, and structural engineers to explore new possibilities and adopt innovative techniques such as topology optimization (Vantyghem et al., 2020). In topology optimization methods, a material distribution problem is solved to create an optimal geometry, resulting in a more efficient use of materials. The algorithms can achieve cost minimization as well as performance maximization based on structural requirements (Vantyghem et al., 2018). To this aim, Vantyghem et al. (Vantyghem et al., 2020) presented a digital design-to-manufacture process that combines topology optimization, C3DP, and post-tensioning. The feasibility of this process was demonstrated by fabrication of a post-tensioned girder with optimized geometry (Vantyghem et al., 2020).

Another interesting possibility which can be realized by C3DP is use of functionally graded materials (FGM) in structures. C3DP makes it possible to dynamically mix, grade, and vary the proportions of printing material ingredients, resulting in gradual change in properties and optimized designs with an efficient use of construction materials and reduced waste (Oxman et al., 2011). By changing the dosage or type of aggregate, fiber, cement, admixtures, and other ingredients during the process, properties such as density, modulus of elasticity, mechanical strength, impact resistance, and thermal conductivity of the printing material can vary according to the actual "local" loading, insulation, and deformation requirements (Ahmed et al., 2020; Kazemian et al., 2019). In a recent study, Ahmed et al. (2020) designed and implemented two systems to enable graded functionality in C3DP. The first system was based on the selective addition of fibers and lightweight aggregates to the printing mixture in a second stage mixing process at the print head. The other system was based on the addition of particles in between the layers of printed concrete. Functionally graded specimens were fabricated in this study using each system to demonstrate the possibilities with respect to the use of FGMs to achieve an optimized design and construction using C3DP (Ahmed et al., 2020).

In terms of applications, C3DP is best described as a platform technology which can be adopted in various domains. House construction, disaster relief (shelter construction), infrastructure development (towers, bridge, etc.), and construction of habitats and settlements on other planets such as Moon and Mars are some of the applications for which demonstration projects have been carried out using C3DP technology (Khoshnevis & Kazemian, 2020; Khoshnevis et al., 2016; Kreiger et al., 2019; Salet et al., 2018). For each application category, the specifications and requirements for a suitable C3DP system could be different in terms of the robotic system configurations and printing materials. Furthermore, for industrial-scale adoption of the technology in each category, economic considerations and overall process efficiency play an important role. For instance, C3DP is currently used mainly for automated construction of building shell, which is only portion of the total house construction process, therefore diminishing the attractiveness of this construction method for developers and builders. Integrating different tasks such as roof construction, insulation, plumbing, and finishing into the automated construction process can significantly increase the viability of C3DP as a commercial construction method and promote its widespread adoption by the industry. In addition, a well-studied and effective automated reinforcement approach could be a key enabler for utilization of C3DP in numerous applications.

4 Conclusions

Construction industry is known as a "low digitization" sector suffering from poor productivity and has not yet undergone digital transformation, as opposed to other major industries such as manufacturing. Although some improvements have been achieved by implementing technologies such as BIM, the manual processes which are involved in the actual construction process are still a major obstacle against a digital revolution in construction. Robotic construction seems to be a viable solution which is yet to be proven reliable and practical. In this chapter, some of the major historical efforts on developing integrated robotic construction systems were briefly reviewed. Then, construction 3D printing (C3DP) was introduced as a more recent and high potential automated construction technology, and relevant developments and advancements were presented. Printing materials, quality control, and code compliance of 3D-printed structures are three important aspects of C3DP as an emerging construction method, which were discussed, and the ongoing activities promoting advancement of C3DP in each area were reviewed. On the other hand, the existing barriers and challenges against widespread adoption of this technology by the construction industry are noteworthy. Lack of sufficient data on the structural performance of 3D-printed structures, concrete reinforcement, process reliability and limitations, and regulatory challenges are examples of existing barriers which were discussed in this chapter. By addressing these shortcomings through extensive research and testing at different scales, and advancing toward a fully automated construction process (by integrating various activities such as reinforcement), industrial-scale adoption of C3DP for many applications such as house construction, disaster relief, and infrastructure development would be facilitated.

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