ICCEPM 2020
The 8th International Conference on Construction Engineering and Project Management
Dec. 7-8, 2020, Hong Kong SAR

3D Printing in Modular Construction: Opportunities and Challenges

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Abstract: Modular construction is a construction method whereby prefabricated volumetric units are produced in a factory and are installed on site to form a building block. The construction productivity can be substantially improved by the manufacturing and assembly of standardized modular units. 3D printing is a computer-controlled fabrication method first adopted in the manufacturing industry and was utilized for the automated construction of small-scale houses in recent years. Implementing 3D printing in the fabrication of modular units brings huge benefits to modular construction, including increased customization, lower material waste, and reduced labor work. Such implementation also benefits the large-scale and wider adoption of 3D printing in engineering practice. However, a critical issue for 3D printed modules is the loading capacity, particularly in response to horizontal forces like wind load, which requires a deeper understanding of the building structure behavior and the design of load-bearing modules. Therefore, this paper presents the state-of-the-art literature concerning recent achievement in 3D printing for buildings, followed by discussion on the opportunities and challenges for examining 3D printing in modular construction. Promising 3D printing techniques are critically reviewed and discussed with regard to their advantages and limitations in construction. The appropriate structural form needs to be determined at the design stage, taking into consideration the overall building structural behavior, site environmental conditions (e.g., wind), and load-carrying capacity of the 3D printed modules. Detailed finite element modelling of the entire modular buildings needs to be conducted to verify the structural performance, considering the code-stipulated lateral drift, strength criteria, and other design requirements. Moreover, integration of building information modelling (BIM) method is beneficial for generating the material and geometric details of the 3D printed modules, which can then be utilized for the fabrication.

Key words: 3D printing, building information modeling, geometry optimization, modular construction, structural connection

1. INTRODUCTION

The construction industry is now confronted with some great challenges like skilled labor force shortages, cost escalation and environmental constraints. Different solutions to address these challenges have been explored in recent decades, including modular construction and 3D printing using concrete. Modular construction is a construction method whereby prefabricated volumetric units are produced and fitted-out in a factory and assembled on the construction site to form a building block. This approach has been introduced and promoted to the industry worldwide, and is proven to be capable of substantially shortening the on-site construction period, improving health and safety of site staff, enhancing construction quality and minimizing the construction waste. 3D printing is a computer-controlled fabrication method first adopted in the manufacturing industry and was utilized for automated construction of small-scale houses in recent years. For the Architecture, engineering, and construction (AEC) industry, 3D printing techniques using different materials including concrete, wood and resin have been explored, though this paper mainly focuses on printing processes using concrete.

3D printing and modular construction complement each other perfectly. On one hand, though modules are manufactured in a factory, formwork is still required in the case of the concrete modules, which places restrictions on module customization/optimization and requires a considerable amount of time and materials for production. 3D printing provides modular construction with a viable solution for getting rid of formwork design, production and erection, by directly building up the designed objects. On the other hand, 3D printing has generic criticism that the scale of the printed object is restricted by the printer's size. For modular construction wherein standardized modules are usually designed as room-sized repeated units to meet the requirements of transportation and assembly, as it is considered more suitable for the adoption of 3D printing. In this paper, the state-of-the-art literature on recent achievements in 3D printing of buildings or components is presented, together with the possibilities and challenges for adopting 3D printing in modular construction. Promising 3D printing processes are critically reviewed and discussed in terms of their main features in practice. A framework for 3D printing implementation in modular construction is proposed and some steps of the framework are further discussed.

2. OVERVIEW OF CONCRETE 3D PRINTING

2.1. Available 3D Printing Techniques

3D printing, which is also referred to as additive manufacturing (AM), is a computer-controlled fabrication process to transform a digital model into a 3D solid object. Generally, in a 3D printing process, the digital model of the object (often in STL format), is sliced into a series of 2D layers using a specific algorithm and is constructed layer by layer. According to ASTM and ISO [1], existing 3D printing processes are classified into seven generic categories according to the technology used to construct the layers, as shown in Table 1. These include the most common material extrusion and powder bed fusion processes (widely adopted in metal printing). The material extrusion process is also widely adopted in the building and construction (B&C) industry, and is a kind of AM process whereby material is selectively dispensed through a nozzle or orifice according to the patteran of object's 2D layer.

Table 1. Seven categories of 3D printing processes [1]

Categories	Definition
binder jetting	A liquid binder is selectively deposited into a bed of powder materials.
directed energy deposition	Material is melted by focused thermal energy when being deposited.
material extrusion	Material is drawn through a nozzle and selectively deposited.
material jetting	Droplets of material are selectively jetted onto the build surface or platform.
powder bed fusion	Selective regions of a material powder bed are fused by thermal energy.
sheet lamination	Sheets of material are cut according to the required shape and bonded together.
vat photopolymerization	Liquid photopolymer is selectively cured by light-activated polymerization.

Nowadays, concrete is still the most widely used and publicly accepted construction material worldwide because of its high compression strength, relatively low cost, fire resistant and easy shaping. However, the traditional manufacturing methods also have some drawbacks, which is gaining more attention as the B&C industry is putting more emphasis on construction safety, sustainability and effectiveness. For in-situ reinforced concrete structures, demanding physical labor is required particularly for the erection of formwork and the placement of reinforcements, whereas the formwork is not always reused, and put constrains on mass customization and geometrical optimization. 3D printing of concrete provides a promising solution to address the above drawbacks. Since formwork is not needed in 3D printing, manufacturing special-shape and customized elements is available at no extra cost, which break down the barriers, giving more design freedom. It also offers potential of building in additional functionality and construction automation, reducing the physical labor involved in the manufacturing procedure. In addition, 3D printing of concrete is found to reduce the carbon emissions in the whole manufacturing stage.

2.2. Concrete 3D Printing

Depending on the technologies used in 3D concrete printing processes, most variants of this family are categorized into material extrusion methods including Contour Crafting and Concrete Printing, with the exception of D-shape, which is a kind of binder jetting method. (as shown in Figure 1). Contour Crafting (CC) was first introduced to the B&C industry by Khoshnevis [2] at the University of Southern California as an innovative rapid prototyping process to make large sized complex shapes with smooth surfaced. It is an extrusion-based process stacking concrete-like extrudate onto lower layer. Two trowels are used in this process and serve as solid plane surfaces, allowing the smooth surfaces of the object to be accurately printed [3]. Some preliminary projects were finished by Shanghai-based contractor Winsun, and the company Total Kustom in Minnesota, USA.

Concrete Printing (CP) is another extrusion-based 3DCP process, developed by a research group of the University of Loughborough, UK [4]. This process is quite similar with CC, but has a smaller printing features of deposition (or resolution), which allows for better control of the printed object's geometry. A practical example to iluustrate the design and manufacture of a concrete component called Wonder Bench, was provided by Lim et al. [5], which also demonstrated a suitable reinforcement strategy for printing large components.

Dini [6] developed and exhibited the D-shape process at the Civils 2007 exhibition at Earls Court in London. This process is a kind of binder jetting method, selectively depositing a liquid binder on top of layers that bonds the material powder (dry-mixed sand and magnesia cement) to produce the object. It allows designs to have voids and overhanging features, enabling the printing of complex geometries, which is not that practical or is impossible for other 3DCP processes. However, this particularity also leads to the need for removal of large amounts of unbound material powders. Therefore, the technology is more suitable and mainly used for the off-site manufacture of unique parts such as custom concrete-like sculptures, rather than conventional buildings. The technology has been used in numerous projects including a printed bridge in Madrid, Spain and a 3D printed reconstruction of Palmyra's Arch of Triumph. Universe Architecture and contractor BAM are using the D-Shape technique to develop the Landscape House in Amsterdam, the Netherlands [6].

(a)


Figure 1. Three typical kinds of concrete 3D printing technologies: (a) Contour Crafting [3], (b) Concrete Printing [5], and (c) D-shape [6]

(a)


Figure 2. Elements printed by (a) Contour Crafting [7], (b) Concrete Printing [8] and (c) D-shape [6] respectively

These three technologies have different printing resolutions. The resolutions of material extrusion methods are constrained by the section of the filament, and the later-developed CP process has a smaller resolution than CC. The D-Shape is supposed to have smallest resolution of these three processes, since using material powder allows a minimal distance between layers. But the fact is that the accuracy of the D-

Shape technique was reported to be hard to control because of the spreading of the liquid binder through the powder mix. The quality of the printed elements of the three technologies can be seen in Figure 2.

Because the printing processes are formwork-free and require a high degree of control and early-form stability, material extrusion methods normally operate fine aggregate mixes (usually without coarse aggregates) with low water-cement ratio and of low slump and fast setting, which is quite different from the traditional way. Research on 3D printable materials is reviewed by Suvash [9], including material composition, rheological properties (pumpability, extrudability and buildability) and mechanical properties (compressive and flexural strength, inter-layer bond strength and drying shrinkage). How the material properties influence the parameter settings and printing quality is discussed in next section. For D-Shape, magnesia cement is used, creating concretes with far superior mechanical properties compared to traditional Portland cement, but some crucial drawbacks exist, such as poor water resistance, prone to shrinkage, expansion, cracking and warping, and highly unpredictable bulking behavior.

2.3. Types of Concrete 3D Printers

A 3DCP system usually consist of a movement system, a deposition system and material feeding system. The moving system allows the deposition head to move in 3D space and it can be categorized into two kinds, namely: Cartesian and Delta. The Cartesian printer function based on the Cartesian coordinate system and the print head travels linearly on each axis to deposit the filament, while in the Delta printer the print head navigates and is located directly within the 3D print space. The deposition system normally refers to the nozzle(s), and in CC it also includes trowels to create the smooth outer and top surfaces of a layer, while in D-Shape it is made of a series of nozzles placed in a straight line along a beam. The material feeding system for material extrusion processes includes equipment to mix the materials, pump and deliver the composite to a hopper on the top of the deposition head, while for D-shape, two components need to be delivered to the printer: the liquid and the dry powder mix.

(a) (b) (c) (d)

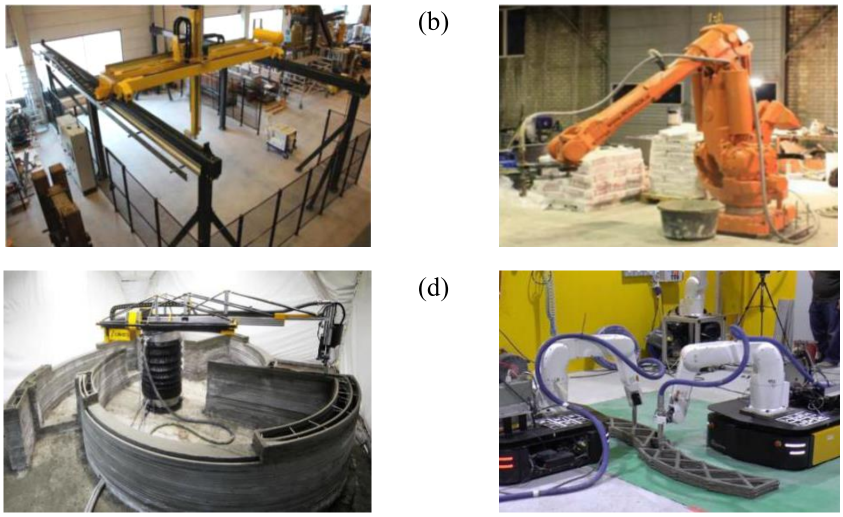

Figure 3. Current 3D concrete printers, (a) four-axis gantry printer [9], (b) six-axis robotic printer [9], (c) crane printer [12] and (d) a team of robots [10]

A gantry robot with 3 or 4 degrees of freedom (DOF) (as shown in Figure 3(a)) and articulated robots with 6 or more DOF (as shown in Figure 3(b)) are most widely used. The former is mainly used in large projects, while the latter is generally adopted to produce smaller objects. Crane systems (as shown in Figure 3(c)) have also been successfully adopted in industry and universities. Gantry and crane printers have the superioritis of being easy to scale in size and lower cost. In contrast, the sizes of robots are typically fixed, leading to difficulty in scaling up of this kind of printers. However, the advantages of using a six-axis robot or robot arm is that its speed and degrees of freedom allows more printing tasks with more complexity to be finished per unit time, compared to a four-axis gantry printer [9].

A replacement to printing with single, large robots was proposed by the Singapore Centre for 3D Printing of Nanyang Technological University – multiple mobile robots printing concurrently using localization and path planning technology working together, as shown in Figure 3(d) [10]. Minibuilders using resin material are also described in detail by Nan et.al. [11], and were proven to be lightweight, compact and have autonomous mobility.

2.4. Main Features of 3D Printing Processes

Compared with conventional 3D printing processes, 3DCP has some prominent features that are worth consideration. These features mostly result from the material used and sheer size of the printed object. Materials used in all 3DCP, usually mortar or cement with special composition, solidify through a curing process, which is much slower than that in conventional processes and results in the pre-setting status of the object during the printing procedure. Some conventional 3D printing techniques also utilize heat or UV to accelerate the material hardening. For material extrusion methods, the section area of filament in 3DCP is hundreds or thousands of times larger than that in conventional processes, requiring extra consideration in printing procedures [9].

Prameter sensitivity: The parameter sensitivity issue is one of the consequences resulting from the pre-setting status of the printing material. Since the solidification time is much longer, the parameters in printing setting including print head speed, pump frequency, material properties and time interval between layers, have a significant effect on the quality of the printed object. The nozzle type also has significant effect on the buildability of 3DCP. For example, by using a circular nozzle orifice instead of a square orifice, the contact area between successive layers can be extended, increasing the inter-layer adhesion [13].

Geometrical confinement: There are more geometrical confinements in 3DCP. In traditional processes, when the printing object has an over-hanging part, a support is created by the build material or a second removable material. In the cases of binder jetting and other powder-based processes, the self-weight is supported by the unsolidified material powder, which allows having full three-dimensional printing freedom. For the extrusion-based method, overhang features can be produced by building up a support with a removable material or using corbeling, but these two strategies have their own drawbacks – an additional deposition device is required which needs more maintenance, cleaning and control instructions, and extra labor and difficulties in erecting corbeling. In addition, premature collapse should be taken into consideration oin the printing. For material extrusion processes, when corners are introduced in the printing, there will be a difference in deposition rate between the inside and the outside of the filament, which leads to material inconsistency. To avoid cracking in filaments, the radius of curvature should be larger than a specific minimum value.

With parameter sensitivity in the printing setting and geometrical confinements of the printed object, 3DCP puts more emphasis on the integration of design and manufacturing. Besides, preparation of the printed model in 3DCP requires a different algorithm from that in conventional processes in order to slice the digital model and generate the printing path.

3. CHALLENGES FOR 3D PRINTING IN MODULAR CONSTRUCTION

3.1. BIM-based framework for modular construction using 3D printing

Building information modeling (BIM), as the digital expression of a construction project's physical and functional characteristics, it is widely used in the construction of prefabricated buildings home and abroad [14]. 3D printing as a computer-controlled manufacturing method, requires a digital model of the printed object and instruction on the printing path. It is widely accepted that for 3DCP, the stage of design should not be isolated from the printing procedure as it has a significant effect on the quality of the printed product. By combining BIM and 3D printing in modular construction, the geometrical and other semantic information such as materials, equipment, resource and manufacturing data, stored in the BIM model can be easily used for the production and installation of customized building components. Figure 4 offers a framework for BIM adoption in 3D printing for modular construction.

Building design: Firstly, the architect assembles a customized floor plan using a library of units according to the building layout. Afterwards, a structural engineer is engaged and establishes a structural model for analysis, while the MEP design group makes use of a library of MEP modules to design the building service systems [14].

Module design: Parametric design is then carried out on the printing component or module as a 3D model in the BIM software (like Revit). It is advised to undergo an optimization process for the layer pattern and topology distribution to remove unnecessary material, with consideration of the geometrical constraints and the optimization of the printing procedure. Then the optimized model is converted to STL (Standard Template Library) file format, sliced with a desired layer depth, after which a printing path for each layer is generated and a G-Code file is created for printing. Since currently no family for 3D printing components is available in BIM software like Revit, the authors suggest that some plug-ins like Dynamo in Revit can be used for convenience to extract data from the BIM model and carry out module prototyping and optimization. The process can also take advantage of families being further developed.

Fabrication and assembly: Modules can be produced according to the fabricaiton schedule generated from the BIM model and then transported to the construction site and assembled. The BIM model could also be used for tolerance control of the 3D printing components and overall assembly. Though it makes little sense for a single module since a CAD model and the printed object have different textures and consequently comparison between them could not provide meaningful evaluation of the manufacturing accuracy (a CAD model generally has smooth surface while printed object has a stepped surface) [4]. However, a BIM model together with other hardware, such as total station, could be used to inform construction managers on the assembly tolerance so as to avoid large eccentricity, reducing resulting additional moment.

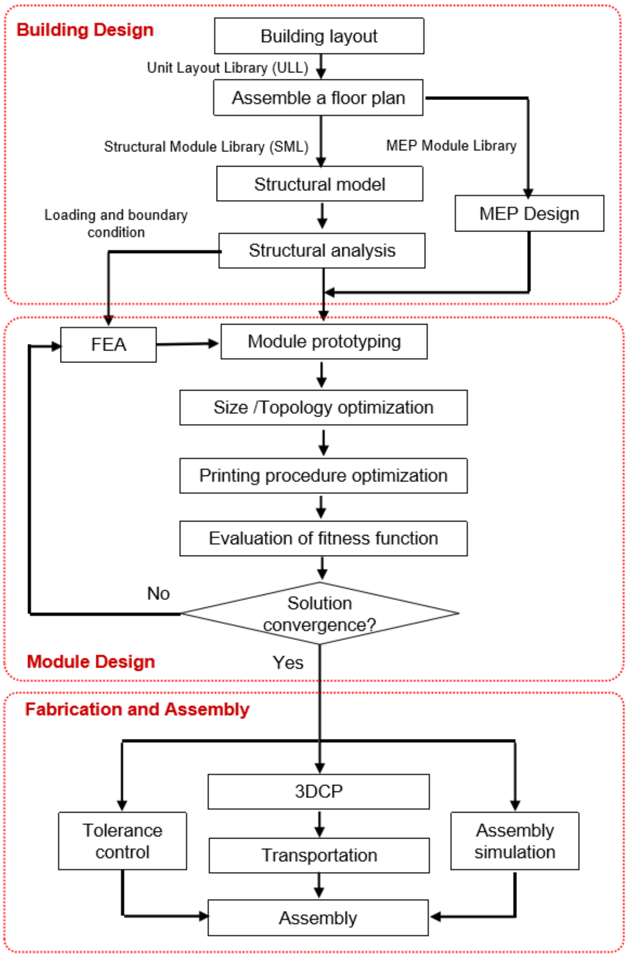

Figure 4. Framework for 3D printing adoption in modular construction

3.2. Structural design for entire modular buildings

Some strategies to provide stability and robustness have been proposed to extend the modular construction method to high-rise buildings [15]. A structural system with one or several concrete cores, as shown in Figure 5, is widely used, in which modules are designed to resist compression and the core provides overall stability. Modules are either clustered around a core without a separate structure or connected to in-plane trusses placed within the corridors. In the formal case, the horizontal load is directly transferred to the concrete core, while in the latter case, the horizontal load is first transferred to the trusses and then to the core. An alternative to this system is to design a ‘podium’ or platform structure on which the modules are placed. In these structural systems, the module units are mainly subjected to compression force. For 3D printing modules, the inter-layer shear capacity is relatively lower due to the layer-by-layer manufacturing process and the difficulty of adding reinforcements in the printed object. Therefore, in terms of mechanical properties, these kinds of systems are suitable for adopting 3D printing in module prefabrication.

Structural systems that are widely used in commercial high-rise buildings seem to correspond with the concept of using a concrete core to resist horizontal force, like the core and outrigger structural system. Modular buildings are mainly adopted in buildings having standardized units such as residential units, hotels and dormitories, which usually require a higher degree of design freedom to meet functional requirements. Therefore, those structural forms with regular layout may not be suitable for modular construction, even though some parts of these types of buildings can be fabricated and assembled on site. Very few research works mentioned how to carry out structural analysis on modular buildings, especially for concrete modules. For example, Alawneh et al. carried out finite element analysis on a 3D printed and assembled concrete structure [16]. However, the calculation model and assumption for such analysis are not clear.

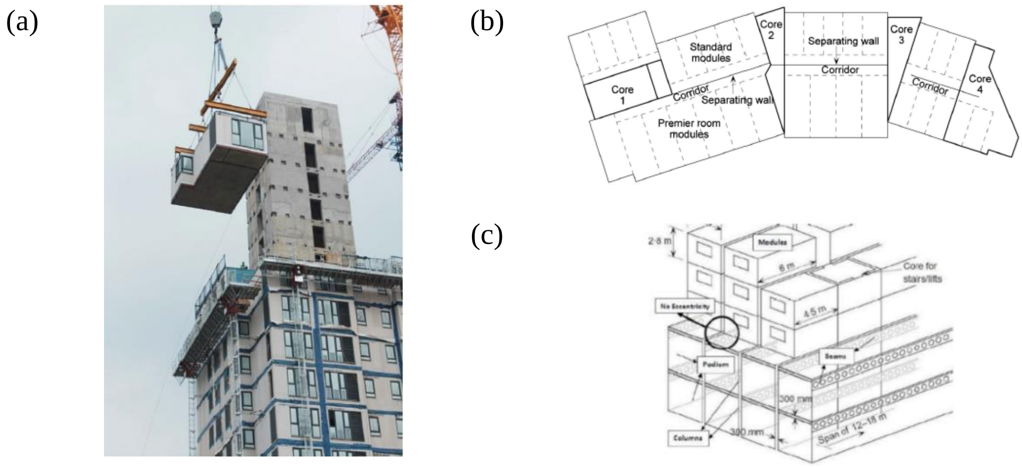

Figure 5. Some typical structure systems of modular building: (a) concrete core [17], (b) braced cores [15] and (c) podium structure [15].

3.3. Geometry design and optimization for 3D printed modules

Since objects are usually not printed in solid form in 3DCP, an additional post-processing step is required on the BIM model to prepare the data for printing. Clash detection, geometrical confinement and constructability analysis should also be taken into consideration during this prefabrication stage. Figure 6 illustrates the concept of module prototyping and manufacturing, including a procedure using Dynamo in Revit to generate the section pattern of a structural wall, in which a sine curve is used as the middle layer. Note that any customized pattern is also allowed since formwork-free 3DCP does not have extra difficulties in creating elements with different sections. Finite element analysis (FEA) on specific elements can also be carried out using the loading extracted from the structural analysis, and optimization of the geometrical pattern of each layer can be carried out based on the FEA results.

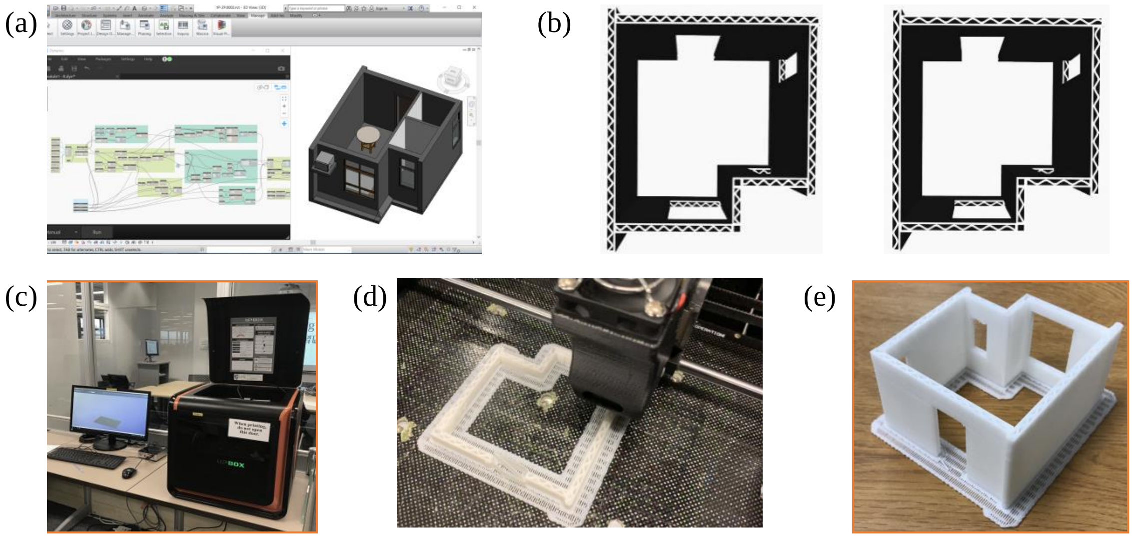

Figure 6. Conceptual illustration of module prototyping and manufacturing including (a) parametric model in Dynamo, (b) optimization, (c) STL file for 3D printing, (d) manufacturing using material extrusion process and (e) finishing.

3DCP requires a different algorithm to slice the model and generate the printing path from those used in other AM processes. As previously mentioned, printing parameters have great influence on concrete printing, and may result in catastrophic failure if inappropriately selected. In material extrusion processes, the flow rate should properly match with the print head speed to avoid inconsistency in the layer thickness. In addition, the time interval between layers should be controlled in an appropriate range according to the material properties, in order to ensure the adhesion between layers. Therefore, optimization is necessary for the printing path of the deposition head to avoid material over-print, minimize the non-printing movements of the deposition head and improve the printing quality, while considering flow rate, print head speed, material properties and et al. as input variables.

3.4. Module manufacture and installation: reinforcement

Concrete is material with low tensile strength and ductility. In conventional construction, reinforcements or post-tensioning steels are generally added to the concrete to for better structural performance and structural reliability. However, in 3DCP, the addition of concrete is not that straight forward. Post-tensioning reinforcement and imbedded reinforcements or steel mesh on intermediate layers [Figure 7 (a) and (b) respectively] are used in some projects, such as the office building in Dubai [16]. However, so far these methods are carried out manually. To achieve the potential benefits of construction automation, the process of placement of the reinforcements in different directions should be fully automated. Steel modular components [Figure 7 (c)] were proposed by the inventor of Contour Crafting for automated reinforcement [3]. Van Zijl et al. provided a solution for the extrusion of strain-hardening cement-based composites (SHCC) with steel bars [18], as shown in Figure 7 (d). In this case, steel bars are entered horizontally and drawn automatically through special openings. Bos et al. developed a device to directly entrain a reinforcement medium into the filament of the printed concrete, as shown in Figure 7 (e) [19]. In this method, wire reinforcements with high flexibility are used, allowing the print head movement in 3D space, like turning a curve or rise from the lower layer to the next. Using composite fibre mixed into printing filament is another adjustment 3DCP technology, which has been found effective for improving the structural capacity and ductility of concrete objects [20]. Researchers in Singapore Centre for 3D Printing offered an innovative approach, in which steel fibres are automatically injected into an existing layer by a robot before the next layer is deposited, as shown in Figure 7 (f), though the approach is still at a preliminary stage and requires much research work for successful adoption [9].

Nevertheless, most solutions discussed above, placed reinforcements on intermediate layers or between the filament layers, which had little effect on improving the shear capacity of the layer interface. Therefore, vertical reinforcements are necessary and much benefit in regard to structural integrity would be gained, but practical difficulties exist because vertical reinforcements may block the movement of deposition head.

Manual placement of reinforcements [Figure 8(a) and 8(b)] has been adopted as a simple workable method in some projects, such as a 6-story apartment building printed by Shanghai-based WinSun 3D [21]. In this approach, reinforcements are placed in the space between the filaments, and the voids are further grouted to ensure the integrity of the reinforcements and printing parts. Direct deposition of concrete on the side of the manually pre-tied reinforcement cage is also used in some cases [22] [Figure 8(c)], but it seems the method has poor applicability when the size of reinforcement cage becomes larger.

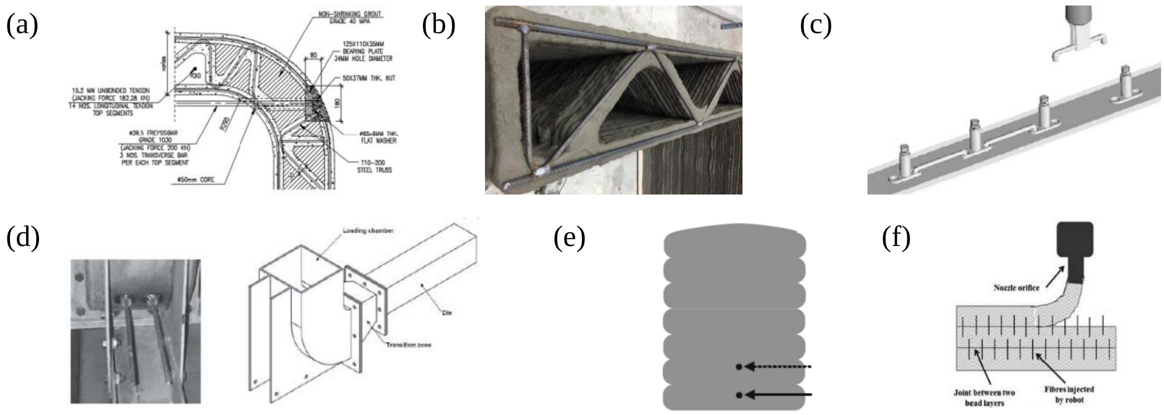

Figure 7. Strategies to install reinforcements in printing objects: (a) post-tensioning steels [13], (b) imbedded reinforcements [13], (c) steel modular components [3], (d) extrusion of composites with steel bars [18], (e) extrusion of filaments with steel wires [19] and (f) automated injection of steel fibres [9].

As discussed above, reinforcement installation using different arrangements is practical in the 3D printing module, and the connections between the modules and those between the modules and the main structure could be further established. The prefabrication industry has developed rapidly in recent decades in mainland China, and also offers some methods for reinforcement connection for modular construction. It could be found from Figure 8 (b) that sleeve connections have already been adopted in reinforcement connection in 3DCP. Some experiments conducted on prefabricated components or structures using specific connecting techniques could also provide evidence for the assumptions used for connections in structural analysis.

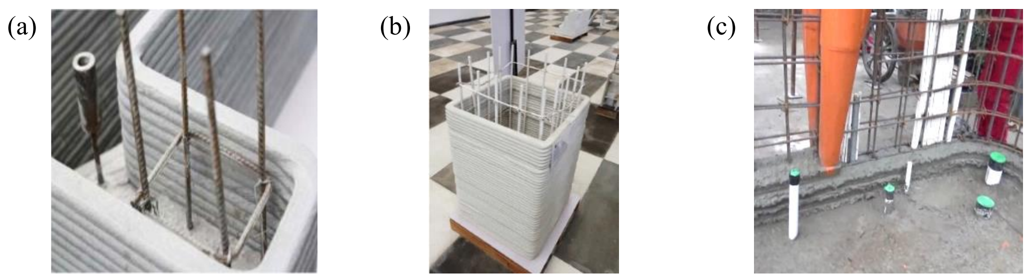

Figure 8. Application of vertical reinforcements in 3DCP. (a) (b) Manual placement of reinforcements [9, 21] and (c) direct deposition of concrete on the side of pre-tied reinforcement cage [22].

4. CONCLUSIONS

Adopting 3D printing in concrete modular buildingS is a new concept, but one that can take advantage of prefabrication and computer-controlled manufacturing. In this paper, existing 3D printing processes are reviewed and three typical 3D concrete printing processes are discussed from the perspective of the characteristics and system components. It is found that 3DCP has distinct features such as parameter sensitivity and more geometrical confinement compared with conventional processes, which should be taken into consideration in module building design. A BIM-based framework is also proposed to illustrate how these techniques can be integrated to gain higher productivity. Some aspects in this framework are further discussed and some workable solutions are provided, including selection of the modular building structural system, module prototyping and optimization and reinforcement installation. In some procedures, challenges still exist, and elimination of them would allow full automation of the printing process, with the benefits of better accuracy control, higher productivity and reduced material waste.

REFERENCES

[1] ISO/ASTM52900, "15 Standard Terminology for Additive Manufacturing–General Principles–Terminology." Available at: https://www.iso.org/standard/69669.html (accessed Jan 24, 2019).

[2] B. Khoshnevis, R. Dutton, “Innovative rapid prototyping process makes large sized, smooth surfaced complex shapes in a wide variety of materials.” Materials Technology, 13(2), 53-56, 1998.

[3] B. Khoshnevis, “Automated construction by contour crafting—related robotics and information technologies.” Automation in construction, 13(1), 5-19, 2004.

[4] S. Lim, R.A. Buswell, T.T. Le, R. Wackrow, S.A. Austin, A.G. Gibb, T. Thorpe, “Development of a viable concrete printing process.” Proceedings of the 28th International Symposium on Automation and Robotics in Construction (ISARC2011), Seoul, South Korea, pp. 665 – 670, 2011.

[5] S. Lim, R.A. Buswell, T.T. Le, S.A. Austin, A.G. Gibb, T. Thorpe, “Developments in construction-scale additive manufacturing processes.” Automation in construction, 21, 262-268, 2012.

[6] Monolite UK Ltd., “D-shape.” Available at: https://d-shape.com/ (accessed May 24, 2019)

[7] J. Zhang, B. Khoshnevis, “Optimal machine operation planning for construction by Contour Crafting.” Automation in Construction, 29, 50-67, 2013.

[8] T.T. Le, S.A. Austin, S. Lim, R.A. Buswell, A.G. Gibb, T. Thorpe, “Mix design and fresh properties for high-performance printing concrete.” Materials and structures, 45(8), 1221-1232, 2012.

[9] S.C. Paul, G.P. van Zijl, M.J. Tan, I. Gibson, “A review of 3D concrete printing systems and materials properties: Current status and future research prospects.” Rapid Prototyping Journal, 24(4), 784-798, 2018.

[10] X. Zhang, M. Li, J.H. Lim, Y. Weng, Y.W.D. Tay, H. Pham, Q.C. Pham, “Large-scale 3D printing by a team of mobile robots.” Automation in Construction, 95, 98-106, 2018.

[11] Nan, Cristina. "A New Machinecraft." International Conference on Computer-Aided Architectural Design Futures. Springer, Berlin, Heidelberg, 2015.

[12] N. Cheniuntai, "What Construction 3d Printing Is: Perspectives and Challenges." Available at: https://www.apis-cor.com/perspectives-and-challenges (accessed 10 Jan, 2018).

[13] F. Bos, R. Wolfs, Z. Ahmed, T. Salet, “Additive manufacturing of concrete in construction: potentials and challenges of 3D concrete printing.” Virtual and Physical Prototyping, 11(3), 209-225, 2016.

[14] J. Zhang, Y. Long, S. Lv, Y. Xiang, “BIM-enabled modular and industrialized construction in China.” Procedia engineering, 145, 1456-1461, 2016.

[15] I.J. Ramaji, A.M. Memari, “Identification of structural issues in design and construction of multi-story modular buildings.” Proceedings of the 1st Residential Building Design and Construction Conference, pp. 294-303, 2013.

[16] M. Alawneh, M. Matarneh, S. El-Ashri, "The world’s first 3D-Printed Office Building in Dubai." Available at: https://www.pci.org/PCI_Docs/Convention-Papers/2018/32_Final_Paper.pdf (accessed 24 May, 2019).

[17] W. Pan, C.K. Hon, "Modular integrated construction for high-rise buildings." Proceedings of the Institution of Civil Engineers-Municipal Engineer, Thomas Telford Ltd, 2018.

[18] G.P.A.G. Van Zijl, S.C. Paul, M.J. Tan, "Properties of 3D Printable Concrete." Proceedings of the 2nd International Conference on Progress in Additive Manufacturing (Pro-AM 2016), Singapore, pp. 421-426. 2016.

[19] F.P. Bos, Z.Y. Ahmed, R.J. Wolfs, T.A. Salet, “3D printing concrete with reinforcement.” in High Tech Concrete: Where Technology and Engineering Meet, Springer, Cham, pp. 2484-2493, 2018.

[20] Y.Y. Kim, H.J. Kong, V.C. Li, “Design of engineered cementitious composite suitable for wet-mixture shotcreting.” Materials Journal, 100(6), 511-518, 2003.

[21] P. Wu, J. Wang, X. Wang, “A critical review of the use of 3-D printing in the construction industry.” Automation in Construction, 68, 21-31, 2016.

[22] Huashang Luhai Ltd., “3D printing process.” Available at: http://www.hstdgm.com/plus/list.php?tid=6 (ac cessed 24 May, 2019).